4th INTERNATIONAL CONFERENCE ON NUCLEI FAR FROM STABILITY

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PROCEEDINGS

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Abstract
The possibility that a new deformation region far from stability starts near Z=11, N = 20 is examined through three types of experimental evidence: nuclear binding energy, location of the first 2+ level in even-even nuclei, and isotope shift. The results collected so far as well as current theoretical calculations provide a growing and consistent evidence for the reality of permanent prolate deformations for this nuclear region.

I. INTRODUCTION
Fragmentation of heavy nuclei by high-energy protons, and on-line mass separation have proved to be a prolific and selective source of very neutron-rich light nuclei. High separation efficiencies and short diffusion times, comparable to the shortest (β-decay half lives, have been accomplished for alkali elements, although some other elements have also been separated). Several contributions to this conference present the results obtained by our group for Li and Na neutron-rich isotopes. They deal with the (β-decay delayed γ, n, α and even 6He emission).

These spectroscopic results shed a new light on the question of a possible region of deformation appearing far from the valley of β stability in the vicinity of Z ~ 11, N ~ 20. Such a possibility was clearly indicated by mass measurements of the neutron-rich Na isotopes and subsequent Hartree-Fock calculations which accounted for the masses measured and found that Na isotopes experienced a sudden increase of their proton deformation at N ~ 20. It is the purpose of this paper, six years later, to examine what new information for or against this deformation has been gathered.

2. SOME POSSIBLE EXPERIMENTAL CRITERIA OF DEFORMATION FOR A NUCLEUS FAR FROM STABILITY
None of the usual experimental evidence can be used to prove that an exotic nucleus is deformed, since only at or near stability can we measure cross sections for Coulomb excitation and inelastic scattering, relative transition probabilities, or excited level lifetimes. The nuclei which can be produced and mass-separated in high-energy fragmentation have no spin anisotropy and are slow-moving. Hence, most of the techniques of modern nuclear spectroscopy are unapplicable.

Up to now, only three types of quantitative information have helped to provide some evidence for nuclear deformation of exotic nuclei: i) two-neutron binding energy; ii) excitation energy of the first 2+ level in even-even isotopes; iii) variation of the mean square charge radius $\langle r^2 \rangle$, or isotope shift.

Recent evidence for the onset of a deformation region at Z ~ 11, N ~ 60 illustrates the consistency of these three criteria: i) binding energy: a direct mass measurement of Rb isotopes shows a marked increase of S2n binding energy against two-neutron emission for N ~ 60 over the smooth decrease of S2n with increasing N extrapolated from less exotic isotopes. This extra binding energy is interpreted, as for Na isotopes, as due to a shape transition.

ii) location of the first 2+ level of an even-even isotope: the 98,100Sr daughters of β-active 98,100Rb have extremely low first 2+ states. The empirical formula $E(2^+) = \frac{3}{2} \hbar \omega = 2244 \langle R^2 \rangle A^{7/3}$ - 1 associates a large deformation to a low value of E(2+).

iii) isotope shift: the values of $\langle r^2 \rangle$, the variation of the mean square charge radius among the Rb isotopes, measured by atomic beam laser spectroscopy, exhibit a sharp increase at N ~ 60, indicating a discontinuity in the variation of the nuclear shape.

Finally, one should note that self consistent mean-field calculations successfully account for experimental results i) and ii) simultaneously, and associate them with an increase of the $\beta_2$ quadrupole deformation parameter.

This set of criteria for nuclear deformation which has proved its consistency for nuclei near 98,100Rb can provide clues for the possible deformation of those near 32Na.

3. SYSTEMATICS OF TWO-NEUTRON BINDING ENERGIES
The earlier results on S2n have been confirmed with smaller uncertainties for the neutron-rich Na isotopes. A similar investigation of the daughter Mg isotopes is in order to examine if they also experience a larger deformation above N ~ 20. For that purpose, Q(α) measurements were undertaken. Our improved knowledge of β-decay schemes makes this a reasonable approach in spite of the possible systematical errors which sometimes affect this method. A very preliminary run with poor geometry and low statistics has been performed at the CERN Syn-
chrotron in our continuing investigation of the β-decay of neutron-rich Na isotopes. The method which consists in fitting the stretched E_β spectrum to a spectrum of reference with a known value of E_β(max) was used to determine the Q(β) value of 32Mg. From the known 32Na mass, the 32Mg mass, hence the value of S_2n(32Mg), was deduced (fig 1). The very large uncertainty is due to the low statistics collected and, to a lesser extent, the large stretch factor of this high Q-value β transition. An experiment is planned for later this year with a better geometry for the plastic detector.

Fig. 1. Variation with N of the two-neutron binding energy. The masses used are from current tables except for the neutron-rich Na isotopes (ref. 1,5), for 46S (ref 21) and for 32Mg (see text).

an improved efficiency, and a longer collecting time. The preliminary results tend to indicate that the uncertainty in S_2n can be reduced significantly enough to determine whether a “bump” is seen for Mg isotopes near N = 20, or if S_2n decreases monotonically with increasing N values of Mg isotopes.

4. LOCATION OF THE FIRST 2^+ STATE IN 32Mg

We report elsewhere at this conference the activities from the β decay of 30Mg and 32Mg.

For the latter, the values of the γ-intensities are now accurate enough to definitely confirm earlier results which indicated that the 885 keV γ-ray is by far the most intense. It can then be assigned to a transition to the 32Mg ground state. This implies that the lowest excited state of 32Mg lies at 885 keV. As for nearly all even-even nuclei this level should have J^π = 2^+, as should the lowest level of 30Mg, at 1483 keV, now well established from the detail level scheme reported in ref. 4.

Whether the 885 keV level of 32Mg is fed directly by a (3^-)-branch from 32Na remains an open question since the sum of all the other γ activities from 32Na approximates the intensity of the 885 keV γ-ray. Hence the latter might only result from cascade feeding from higher-lying 32Mg levels. However if it were not so, i.e. if the other γ activities would not all feed the 885 keV level, hence if that level was directly fed by a (3^-)-branch from 32Na, it would not preclude a 2^+ assignment. The reason is that a negative parity for the 2 = 11, N = 21 32Na ground state is not a necessity, since (see sect. 6) a crossing of d-shell and f-shell single particle energy levels can occur for large prolate deformation in this mass region.

To conclude on this point, there is a definite confirmation of the occurrence of the first excited state of 32Mg at an energy as low as 885 keV, much lower than the 1483 keV excitation energy measured in 30Mg. A 2^+ assignment appears the most likely.

5. ISOTOPE SHIFTS IN THE Na ISOTOPES

A sudden change of the nuclear deformation in a chain of isotopes manifests itself by a correlated change of the mean square charge radius, which can be measured by the isotope shift of an optical atomic line. The isotope shifts of the Na isotopes were measured recently by optical atomic line experiments. They show a fast and continuous increase of δR(2) above A = 26, without the brutal discontinuity observed in the case of Rb mentioned in sect. 2 and expected at A = 31 from the predictions of a shape transition.

However this does not rule out the occurrence of a large prolate deformation since three alternative explanations can account for the above behaviour of δR(2).

First the shape transition might take place at A = 32 rather than 31. Second it might set in less abruptly than the calculations suggest, the actual nuclear shape being more a superposition of the two Hartree-Fock states with small and large deformations,
respectively. Third, at $A < 31$, even if the permanent prolate deformation is small, there might already be large zero-point quadrupole vibrations which might enlarge $\mathcal{S} \sim r^2$ and wash out its expected jump at $A = 31$ when the permanent deformation sets in.

6. SUMMARY OF EXPERIMENTAL EVIDENCE AND THEORETICAL MODELS FOR THE NEUTRON-RICH Na ISOTOPES

Out of the three possible experimental criteria for deformation tested in sect.2 in the region of $^{100}$Sr, two give positive answers for the $^{32}$Na region: i) there is an extra two-neutron binding energy; ii) the first excited state of $^{32}$Mg, assigned to be $2^+$, lies indeed at a very low energy. But the third criterion is apparently not fulfilled since there is no abrupt change in the variation of $\mathcal{S}(r^2)$ for $^{31}$Na. In the three above sections, qualifications to these conclusions have been discussed. At this point it appears that there is enough evidence to conclude that a new deformation region has indeed been reached at $Z \sim 11$, $N \sim 20$. While this conclusion was growing firmer in the last few years, calculations in increasing number tried to account for such a striking departure from the magic character of $N = 20$. As indicated, Hartree-Fock calculations reproduced the dependence of $S_{2n}$ with $A$, and found large prolate deformations. For such deformations, Nilsson's level diagram shows that the $1/2^-$ and $3/2^-$ states associated with the $7/2^2$ shell actually cross the $1d_3/2$ level. In that sense, the failure of conventional sd-shell calculations to reproduce the experimental results can be seen as an indirect confirmation of the above conclusion. This is further indicated by recent shell-model calculations with an extended basis which find a large number of particles occupying the $f 7/2$ shell for the Na and Mg isotopes as soon as $^{30}$Na and $^{32}$Mg.

On quite different grounds, two other calculations support the idea of a large deformation near $^{32}$Na. An earlier work using the energy density method indicated that there is a large major neutron shell extending from $N = 8$ to $N = 34$ for neutron-rich nuclei, which implied that large deformations might occur in the middle of that shell. Recently, the extensive calculations of Möller and Nix using a Yukawa-plus-exponential macroscopic model with microscopic corrections again observe large quadrupole deformations for $A \geq 31$ in Na and $A \geq 32$ in Mg.

Therefore a consistent description of these neutron-rich nuclei is emerging both from the experimental and theoretical works, showing that indeed a new region of nuclear deformation has been discovered far from the valley of $\beta$-stability.

Références

3) C. Détraz et al., M. Langevin et al., C. Zaidins et al., contributions to this Conference.
4) D. Guillemaud et al., contribution to this Conference.
DISCUSSION

H. Baun: Due to the finite resolution of your mass spectrometer, a small amount of say $^{19}$Na will occur on mass position 32. Can you give a number for how much?

C. Détomi: We never observed such contamination at the level of sensitivity of our experiments, although we actually looked for them by setting the mass spectrometer at a non-integer mass value. This is clearly illustrated by the measurements presented in Physics Letters 94 B, page 307.

J. Jastrzebski: I would like to ask a rather provocative question: What do you find so exciting in trying to establish a new region of quadrupole deformation with a huge amount of experimental effort? Personally, I believe that it is a transitional rather than a well-deformed region. On the nuclear chart we already know a number of transitional nuclei, which may be studied more easily. In spite of this, we still do not understand unequivocally what is going on in those nuclei.

C. Détomi: First, the occurrence of large static deformations at a so-called magic number helps to understand the reality of the validity of this concept. Second, establishing a far undiscutable and rather unexpected fact about the exotic N=20 nuclei sets very binding constraints on theoretical descriptions of the light nuclei, hence helps to provide a better understanding of them.

P. G. Hansen: Jastrzebski's comment is so central that it probably deserves a further remark. We have an enormous knowledge of Nilsson states in the "old" deformed regions. In the new regions, near $^{32}$Mg and $^{185}$Sr, we still have not identified one Nilsson orbital! I believe that the first such case is very important and deserves a lot more effort than the last case in the rare earths!

H.-J. Kühn: You did not mention the possibility to determine the nuclear deformation by a measurement of the spectroscopic quadrupole moment. What about that in the case of the heavy Na isotopes?

C. Thibault: The quadrupole moments have been measured by laser spectroscopy for $^{21},^{23},^{27}$Na and by double resonance (laser excitation from g.s. to excited state + radio frequency excitation in the excited state $P_{3/2}$) for $^{21},^{25},^{29}$Na. The measured values are all small. $Q_{E}(^{22}$Na) is slightly positive, $Q_{E}(^{24},^{26}$Na) are slightly negative. Others ($^{27},^{29}$Na) are compatible with zero (see results in these proceedings in "Masses and radii of alkali elements"). So, they do not help very much to conclude for $^{24},^{28}$Na except that they support the assumption that they could be vibrational since the radii are large and the $^3P_2$ value in $^{31}$Mg too. We thought of measuring $Q_{E}$ for $^{31}$Na but the statistics is so low (0.5 count per PS pulse) that even a fantastic effort would lead us at best to a 3-4 MHz accuracy on $B(2P_{3/2})$ while the expected value, if deformed, would be about 5 MHz and, if not, about 2 MHz.
HALF LIVES OF EXOTIC SODIUM ISOTOPES $^{23}_{11}$Na

C. Thibault, M. Efferre, G. Audi, G. Huber, R. Klapisch and F. Touchard.
Laboratoire René Bernas du CENSM, Orsay - France
D. Guillemaud and F. Naulin
Institut de Physique Nucléaire, Orsay, France.

Abstract
The half lives of $^{23}_{11}$Na ($T_{1/2}=8.2±0.4$ms) and $^{3}\text{Na}$ ($T_{1/2}=4.6±0.9$ms) have been measured by means of $^{14}$On counting following on-line mass spectrometry. New measurements of the half lives of $^{28}_{11}$Na and $^{32}_{11}$Na are also reported.

1 - Introduction

The extensive study of the very neutron-rich sodium isotopes, produced in the interaction of the 200GeV proton beam of the CERN PS with a heavy target, and analyzed through mass spectrometry techniques, started some years ago. Many properties of their ground state have been measured - i.e. half lives, beta decay modes, masses, spins, magnetic moments and isotope shifts. Detailed nuclear spectroscopic studies in these isotopes are still pursued, e.g. gamma activities, beta delayed particle emission, Qβ measurements. We report here on half-life measurements performed in 1977 when $^{3}\text{Na}$ was first observed.

2 - Experimental method

The experimental set up was the same as used for the beta decay studies (see fig. 1 of ref. 3). The mass spectrometer was installed in a fast extracted beam of the PS. Short ($2.1\mu s$) and intense ($\sim 10^{13}$ protons) bursts were delivered every 2 to 10 seconds and focused on a $3g/cm^2$ U target. The nuclei here produced recoil out of U and are thermalized in graphite. Alkali elements diffuse selectively out of the heated graphite in a short-time (fig. 1). They are ionized through thermal ion effect on the rhenium exhaust tubing of the target, which enhances the selectivity of the process, and are mass analyzed in the mass spectrometer. Ions of given A and Z are then transported in a well shielded counting area and collected on the first dynode of an electron multiplier, capable of counting single ions.

The method used for half life measurements is recalled briefly: the decrease of the ionic current with time (see fig.1) of a long lived isotope is purely due to diffusion while radioactive decay results in a faster decrease for a short lived isotope. The ratio of currents as a function of time then gives directly the radioactive decay of the short lived isotope. More generally for 2 isotopes which radioactive constants are $\lambda_1$ and $\lambda_2$ this ratio decays as $\exp(-(\lambda_1-\lambda_2)t)$. The background and natural contamination if any, are measured in the same conditions by applying a triangular modulation to the accelerating potential. It results in a series of peaks at times

Fig. 1 - Decay with time of the $^{23}_{11}$Na and $^{28}_{11}$Na ionic currents. The yields are normalized to equal amount of both isotopes at time zero when the proton burst impinges the target. The faster decay of $^{23}_{11}$Na is due to its shorter half life.

*x present address : Johannes Gutenberg Universität, Institut für Physik D-6500 Mainz
when the ion beam is in phase with the slit (fig. 2). They are recorded alternatively for the 2 isotopes first after the proton burst and then after one second delay. The background is measured in between the peaks and the natural contamination determined from this is delay. The ratios between the area of corresponding peaks for two isotopes $^{23}$Na et $^{25}$Na are analyzed with a least square procedure in order to fit the function $R_0 \exp (-\lambda t)$ (fig. 3) where $\lambda = \lambda_1 - \lambda_2$ (or $1/T_1 - 1/T_2$) and $R_0$ is the ratio at time zero when the proton burst impinges on the target.

3 - Results

The results are presented in table 1. Each value of $T_e$ given in column 4 is a mean value from 5 to 50 measurements on the same isotopes $A_1$ and $A_2$. The weighted mean values determined in this work lead to $\chi^2 = 16$ for 15 degrees of freedom. Individual errors are at least equal to 4% because of the uncertainties in piling up corrections.

A good agreement is obtained with previous measurements. For $^{23}$Na which half life had been roughly estimated $^{23}$ (20±15ms) the value is now accurately determined: $8.2 \pm 4.3$ ms. During this experiment $^{25}$Na was observed for the first time. The first 3 peaks of fig. 2 show a signal unambiguously above the background and above the residual peaks due to natural contamination. Its half-life determined as 4.6±0.9ms is the shortest $\beta$-half-life observed until now. Records have also been performed on mass 35. The statistics were too low to enable any half-life determination in particular to discriminate between $^{35}$K ($T_e/2 = 160$ms) and $^{37}$Na which half-life must be much lower. Other considerations based on cross section and mass systematics$^8$ indicated that $^{37}$K was likely observed in this experiment.

References

7 - See contributions to this conference
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(1) deduced from $1/T = 1/T_1 - 1/T_2$
(2) from Ref. 3
THE γ ACTIVITIES FROM THE β DECAY OF 27-34Na AND THEIR DESCENDANTS

D. Guillemaud, C. Détraz, M. Langevin, F. Naulin
Institut de Physique Nucléaire, BP N° 1, 91406 Orsay, France
and
M. Epherre, R. Klapisch, M. de Saint-Simon, C. Thibault, F. Tuchard
Laboratoire René Bernas du CSNSM, BP N° 1, 91406 Orsay, France

Abstract

The γ activities from the β decay of Na isotopes up to 34Na, which are formed in high energy fragmentation, are observed. The γ intensities and delayed-neutron branching ratios Pn are measured. Preliminary decay scheme are obtained.

1. EXPERIMENTAL METHOD

Neutron-rich isotopes are formed in high-energy fragmentation of Iridium by 20 GeV protons from the CERN synchrotron, and are on-line mass selected by a spectrometer [1].

The γ activities are measured by two Ge(Li) detectors in coincidence with the emission of a β particle.

The energy from the Ge(Li) detectors, the time correlation between the β and γ events, and the time elapsed between the proton beam burst and the decay event are stored on magnetic tape for off-line analysis.

Single γ energy spectra for A = 27 to A = 34 Na isotopes, and two-dimensional energy spectra from A = 27 to A = 32 Na isotopes are obtained.

The γ activities are assigned to a given β emitter according to the half-life derived from its time dependence.

2. PRELIMINARY RESULTS

The analysis of the data is in progress.

As an example, figure 1 shows the single energy spectrum of the γ activity from 30Na. The energies of the γ rays labelled by numbers are listed in Table 1.

They are assigned to the β emitter 30Na or its descendants 30Mg, 30Al, or to a A = 29 β emitter after delayed emission of one neutron. Two γ activities are observed with the half life of 30Na and energies which correspond to transitions between levels of 29Mg. They are assigned to a process

![Energy spectrum of the γ rays observed in the decay of 30Na](image)

Fig. 1 - Energy spectrum of the γ rays observed in the decay of 30Na. The energy values of the γ rays are listed in Table 1.
led a) correspond to transitions in $^{29}$Mg nucleus reached after delayed emission of one neutron.

![Diagram](A.png)

**Fig. 2. Proposed decay scheme of $^{30}$Na. The $\gamma$ transitions are labelled in the same way as in fig. 1. The corresponding energies are listed in table 1.**

In which the delayed neutron from an unbound state of $^{32}$Mg feeds an excited state in the daughter nucleus $^{29}$Mg.

![Diagram](B.png)

No other level scheme has been reported for $^{30}$Mg since our earlier measurements2). We can tentatively propose excitation energies for these levels by noticing, in particular, that some $\gamma$ energies are exactly the sum of two others. The simplest level scheme which can be constructed in this way is presented in fig. 2. It is hoped that the complete analysis of coincidental $\delta$ rays will further substantiate it.

As an example figure 3 shows the single energy spectrum of the $\gamma$ activity of $^{32}$Na. The most important $\gamma$ rays from $^{32}$Na are listed in table 2 with their relative intensities. As compared to our earlier results2), new lines are observed and lower uncertainties on I $\gamma$ and energies are achieved.

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Table 1. $\gamma$ activities from the $\beta$ decay of $^{30}$Na. The emitting nucleus and the $\gamma$ energies are indicated. Single and double escape peaks are labelled by the energy of the photopeak and s and d respectively. The uncertainties of the energy values are in the range 0.5 to 1.5 keV. The two $\gamma$ rays label-
Fig. 3 - Energy spectrum of the $\gamma$ rays observed in the $\beta$ decay of $^{32}\text{Na}$. The energy values of the most important $\gamma$ rays from $^{32}\text{Na}$, labelled by numbers, are listed in Table 2.

The $\gamma$ rays labelled a, b, and c are $\gamma$ activities from $^{31}\text{Mg}$ and $^{31}\text{Al}$, the $\gamma$ rays labelled d, e are $\gamma$ activities from $^{30}\text{Mg}$, which indicates that $^{32}\text{Na}$ is a $\beta$ delayed one - and two - neutron emitter. The $f$ activity corresponds to a process in which the two delayed neutrons feed an excited state in the $^{30}\text{Mg}$ nucleus (see text).

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<td>13 ± 4</td>
</tr>
</tbody>
</table>

Table 2. Energy and relative intensity of some $\gamma$ activities from the $\beta$ decay of $^{32}\text{Na}$. The uncertainties of the energy values are in the range 0.5 to 1.5 keV.

3. SUMMARY

The $\gamma$ activity from the $\beta$ decay of 27-34Na isotopes is observed and measured. Decay schemes will be obtained for Na isotopes up to $^{32}\text{Na}$.

As of now, the data analysis shows that $\beta$-delayed emission of one neutron is observed for all the Na-isotopes of mass 27 through 34. $\beta$-delayed emission of two neutrons for $^{30,32,34}\text{Na}$.

In spite of the poor statistics of the two-dimensional $\gamma - \gamma$ spectrum obtained for $^{32}\text{Na}$, we can deduce that the 885.2 keV $\gamma$ ray is in coincidence with the 2151.2 keV and 1972.8 keV $\gamma$ rays.

We confirm our earlier result2) that the most prominent $\gamma$ ray from $^{32}\text{Na}$ has a 885.2 keV energy. It is assigned to the lowest $2^+ \rightarrow 0^+$ transition in $^{32}\text{Mg}$. This low energy of the $2^+$ level is taken as evidence for an increased deformation of this nucleus3). The systematic study of the location of the lowest $2^+$ level in the even Mg isotopes could not be extended further since, in the case of $^{34}\text{Na}$, no $\gamma$ ray from the $A = 34$ isobar is observed. The spectrum is dominated by $\gamma$ rays from mass 33 and 32 isotopes. This indicates that, within the limits of
our experimental statistics, all $\beta$ branches from $^{34}$Na feed neutron-unstable levels.

References

1) M. de Saint-Simon et al., 10th International Conference on electromagnetic isotope separators and techniques related to their applications, EMIS (1-6 sept 1980) Zinal (to be published in NIM)


3) C. Détraz, Contribution to this Conference
FIRST OBSERVATION OF THE DECAY OF THE NEUTRON-RICH NUCLEUS P-36

John C. Hill
Kernforschungsanlage Jülich, Germany and Ames Laboratory USDOE, Iowa State University, Ames, Iowa 50011, USA

H.R. Koch and K. Shizuma
Kernforschungsanlage Jülich, Germany

Abstract

Sources of $^{36}$P were prepared using the $^3$Cl(n,2p) $^{36}$P reaction. The neutrons were generated by 70 MeV deuterons on a thick Be target. The $^{36}$P half-life was measured to be 5.9 ± 0.4 sec. The observed $\gamma$ rays were postulated to depopulate levels in $^{36}$S at 3291 ($^{2+}$) and 4193 ($^{3+}$) keV. Our results are compared with results from the $(d,t)$ and $(t,p\gamma)$ reactions and the dominance of $\beta$ decay to the $^{35}$S level is discussed.

1. Introduction

1.1 Production of neutron-rich nuclides

The production and study of neutron-rich nuclei outside of the region accessible by fission is generally more difficult than similar studies in other parts of the nuclear chart due to the lack of suitable production reactions and large contamination from neutron-deficient species with high production cross-sections. Fast neutrons generated by spallation of appropriate targets with high-energy protons at both the high and low A ends of the nuclide chart to identify and characterize new neutron-rich nuclei.

A survey of the nuclide chart shows that in principle it would be possible to produce and study many new nuclear species using the $(n,2p)$ reaction, but such experiments are hindered by the low $(n,2p)$ cross-section, which is due to suppression of neutron emission by the Coulomb barrier. The above reaction has been used at the isotope separator ISOLOE to synthesize $^{207}$Hg($^{31}$P/2 = 2.9 min) with fast secondary neutrons generated by spallation of a Pb target by 600 MeV protons. Also $^{35}$S ($^{1}$P/2 = 11.5 s) was synthesized by the reaction of fast neutrons with an Ar target. The neutrons were generated by spallation of Cu by 800 MeV protons from the LAMPF accelerator and fast radiochemical procedures were required.

Although spallation generated neutrons are useful, neutrons produced in stripping reactions offer several practical advantages. In the reaction of 70 MeV deuterons on C the outgoing neutrons are strongly peaked in the forward direction with an energy distribution peaked at roughly one half of the energy of the incident deuteron. One can also avoid the generation of large quantities of (n,$\gamma$) products from thermal neutrons and very neutron deficient nuclides from the high energy neutron tail of the typical spallation spectrum.

1.2 Status of knowledge on $^{36}$P

The nuclide $^{36}$P has been previously observed as a fragment from the reaction of 290 MeV $^{40}$Ar on Th targets, but no information on its decay is available. Levels in the daughter nucleus $^{35}$S have been studied using the $^{37}$Cl(d,$^3$He)$^{35}$S reaction, but the most extensive information was obtained in a study of the $^{39}$S(t,p$\gamma$)$^{36}$P reaction in which 13 excited states up to 7.12 MeV were observed.

2. Experimental methods and results

2.1 Source preparation

Sources of $^{36}$P were prepared using the $^3$Cl(n,2p) $^{36}$P reaction. Neutrons were generated by a beam of 70 MeV deuterons from the Jülich cyclotron stopped on a thick Be target. The Cl target was a cylinder of commercial PVC [(CH$_2$CHCl)$_x$ having a mass of 14 grams and placed at 0° to the deuteron beam. After irradiation the target was transferred in a time of about 1 sec a distance of 7 meters to a shielded counting position by a compressed air "rabbit" system.

In initial runs it was found that in the first few seconds of counting, the spectrum was completely dominated and the Ge(Li) detector paralyzed by annihilation radiation from $^{35}$Cl($^{31}$P/2 = 1.53 s) produced in the $^{35}$Cl(n,2n)$^{34}$Cl reaction. Therefore first runs were carried out with 3 cm of Pb between the source and the detector.

2.2 Half-life measurement

In order to measure the $^{36}$P half-life the PVC target was irradiated for 5.5 sec. The current of the deuteron beam was about 500 nA. After a 2 sec delay to allow the target to arrive at the counting position, a series of 8 successive 2K channel $\gamma$ spectra each 2.6 sec long were accumulated. Each target was irradiated twice before exchange for a fresh one to minimize the buildup of activities of intermediate half-life. A total of 236 irradiations were carried out on a set of 18 targets.

A decay curve for the $\gamma$ ray from $^{36}$P at 3291 keV is shown in Fig. 1 (a). The change of the dead time in the analyzer with time has been corrected by normalizing the intensity of the $^{36}$P $\gamma$ peaks to that of the 3103 keV $\gamma$ ray from $^{35}$S($^{31}$P/2 = 5.06 s). From the decay curve in Fig. 1 (a) we determine the half-life of $^{36}$P to be 5.9 ± 0.4 s. The half-life curve for the 902 keV $\gamma$ ray from $^{36}$P is shown in Fig. 1 (b). The error is much larger due to the very high Compton background in that energy region. The plotted results were obtained by adding 2 successive time bins for better statistics. The resultant half-life of 7.6 ± 0.47 sec is consistent with the half-life determined from the 3291 keV transition, but because of the large error was not used in determining the $^{36}$P half-life.

2.3 $\gamma$ ray singles measurements

The $\gamma$ spectrum for our PVC target was measured after an irradiation of 5 sec in duration, using 3 cm of Pb absorber between the target and the Ge(Li) detector. After return of the target from the irradiation position a series of 5K spectra were collected successively in time bins of 2, 4, 8, 16 and 32 sec duration. A total of 40 irradiations were made.

A spectrum resulting from summing the results from the first two time bins (first six seconds of counting) is shown in Fig. 2. The spectrum below 500 keV is completely dominated by Compton events from very strong annihilation radiation and no other $\gamma$ peaks were observed. All $\gamma$ peaks between 500 and
3. Decay scheme and discussion

3.1 Construction of decay scheme

The above information along with data on levels in $^{35}$S from charged particle reactions$^{2-5}$ was used to construct a preliminary decay scheme for $^{36}$P, which is shown in Fig. 3. Our measured half-life of $5.9 \pm 0.4$ s is in good agreement with the gross theory of $\beta$ decay$^{7}$ which predicts a range of values from 2 to 8 s. The $2^+$ level at 3291 keV is well established from reaction studies$^{6,8}$. In the $^{35}$S(t,p)$^{36}$S reaction study a $3^-$ level was established at 4193 keV. This is the only level definitely postulated to have negative parity$^{9}$ and appears to receive most of the strength in the $^{35}$P $\beta$ decay.

We postulate the 4193 keV level to receive about 73% of the $\beta^+$ feeding, but there is a large error in the relative intensities of the two $^{36}$P $\gamma$ rays. It is unlikely that there is very much feeding to the $2^+$ level so any extra feeding could be accounted for by the decay of weakly-populated high-lying levels to the $2^+$ state. Coincidence measurements are in progress in order to search for such transitions.

The log ft for $3^-$ decay of the $3^-$ level was calculated assuming a feeding of 73% and a mass-excess for $^{36}$P of -20.82 MeV from an update by Jänecke of theGarvey-Kelson relations$^5$. A value of 9.85 for 80 resulted in a log ft of 5.0 for feeding to the $3^-$ state. This implies an allowed $\beta^-$ transition and thus limits $J^+$ for the $^{36}$P ground state to $2^-$, $3^-$ or $4^+$. This is consistent with the single-particle model picture in which a f$_{7/2}$ neutron couples to a s$_{1/2}$ or d$_{3/2}$ proton. In $^{31}$P and $^{33}$P the ground state is $1/2^+$ with the $3/2^+$ state at 1.266 and 1.431 MeV respectively. The situation in $^{35}$P is unknown, but we favor a $s_{1/2}$ assignment for the 15th neutron thus a $J^+$ of $3^-$ or $4^+$ for $^{36}$P.

3.2 Comparison with reaction studies and conclusions

In the study of levels in $^{35}$S by the $^{35}$S(t,p)$^{36}$S reaction$^6$ 13 excited levels from 3.29 to 7.12 MeV were observed. Our level energies of $3290.8 \pm 0.2$ and 4193.2 $\pm 0.6$ keV are in fairly good agreement with values of $3291.0 \pm 0.6$ and 4192.5 $\pm 0.7$ obtained in the (t,p) study. In contrast to the reaction study where 13 excited levels were observed, we detected $\beta^+$ feeding to only the $3^-$ state at 4193 keV. The low log ft of 5.0 suggests a decay process in which the 21st f$_{7/2}$ neutron in $^{36}$P decays to a f$_{7/2}$ proton (the 16th proton) in $^{35}$S. This proton could then couple to the odd s$_{1/2}$ or d$_{3/2}$ proton to give a $J^+$ of $3^-$ for the 4193 keV level. A similar situation is observed in the decay of the $2^+$ ground state of $^{37}$Cl, to a $3^-$ state at 3.81 MeV in $^{31}$Ar$^{20}$ with a log ft of 4.9.

3.3 Use of fast neutrons to produce new nuclear species

A glance at the latest chart of the nuclides shows that a number of unstudied neutron-rich nuclei outside of the region accessible by fission could be synthesized and their decays established using fast neutrons. About 30 unstudied species could be reached by the reactions (n,2p)n, (n,2p) or (n,4p). Such studies are difficult due to the anticipated low cross-sections, but many could be carried out successfully using fast radiochemical procedures.

Products from all three of the above reactions on $^{37}$Cl have been observed and in Table 2 we present a list of "relative cross-sections" normalized to the $^{37}$Cl(n,p)$^{37}$S reaction. The estimates though crude should give the reader an idea of the magnitude of useful cross-sections for the synthesis of neutron-rich nuclides.

---

Table 1: Energies and relative intensities for $\gamma$ rays from $^{36}$P decay.

<table>
<thead>
<tr>
<th>$E_\gamma$(keV)</th>
<th>$T_Y$</th>
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<tr>
<td>902.4 $\pm$ 0.5</td>
<td>73 $\pm$ 9</td>
</tr>
<tr>
<td>3290.8 $\pm$ 0.2</td>
<td>100 $\pm$ 15$^b$</td>
</tr>
</tbody>
</table>

$^a$ Intensity normalized to 100 for 3291 keV $\gamma$ ray.
Fig. 2: γ ray spectrum from 800 to 3600 keV for a PVC target. Energies for γ rays from $^{36}P$ decay are given in keV.

Table 2: "Relative cross-sections" for various reactions from fast neutrons on $^{35}Cl$ and $^{37}Cl$.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma_R/\sigma(n,p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}Cl(n,\alpha)^{34}P$</td>
<td>3.4</td>
</tr>
<tr>
<td>$^{35}Cl(n,2n)^{34}Mg$</td>
<td>1.9</td>
</tr>
<tr>
<td>$^{37}Cl(n,p)^{37}S$</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{37}Cl(n,y)^{36}Cl$</td>
<td>0.87</td>
</tr>
<tr>
<td>$^{37}Cl(n,2p)^{35}P$</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{37}Cl(n,p)^{33}S$</td>
<td>0.057</td>
</tr>
<tr>
<td>$^{37}Cl(n,2p)^{36}P$</td>
<td>0.012</td>
</tr>
</tbody>
</table>

\[ (3,4)^- \quad T_{1/2} = 5.9 \pm 0.4 \text{s} \]

\[ 36P \quad 15 \quad 21 \quad \beta^- \]

% $\beta^-$ Log ft.

\[ \sim 73 \quad 3^+ \quad 4193.2 \]

\[ 2^+ \quad 3290.8 \]

\[ 0^+ \quad 36S \quad 16 \quad 20 \]

Fig. 3: Decay scheme of $^{36}P$. 

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References

3) P.G. Hansen, private communication
10) A.H. Mapstra and K. Bos, Atomic Data Nucl. Data Tables 17 (1976) 474

DISCUSSION

W.R. Walters: As you see $^28$Al, $^{29}$Al, and $^{30}$Al most likely produced in the $^{37}$Cl(n,4pxn)$^{34}$-2$^8$Al reactions or the $^{17}$Cl(n,2xn) reactions, have you used these yields to estimate whether you can also produce enough $^{31}$Al to observe its decay?

J.C. Hill: It is not entirely clear what is the source of the Al isotopes we see, but some part may come from (n,p) reactions on Si impurities in the target. Assuming that all the Al comes from (n,4pxn) reactions, the yield of $^{31}$Al from the $^{37}$Cl(n,4pxn) reaction would probably be roughly a factor of 10 lower than that of $^{31}$Al (seen by us) from the $^{37}$Cl(n,2xn) reaction. Unfortunately, $^{31}$Al has a half-life of about 600 ms, thus is a bit too short for us to easily observe.
A STUDY OF LIGHT NEUTRON-RICH NUCLEI BY TWO-BODY NUCLEAR REACTIONS

F. Naulin, C. Détraz, M. Roy-Stephan, M. Bernas, J. de Boer*, D. Guillemaud, M. Langevin, F. Pougheon and P. Roussel

Institut de Physique Nucléaire B.P. no. 1, 91406 Orsay, France

Abstract

$^{14}$C or $^{18}$O-induced two-body nuclear reactions are used to measure the mass excess and in some cases the excited state energies of $^{14}$B, $^{16}$C, $^{18}$N and $^{18}$N. Upper limits only are obtained for the cross sections of the $(^{14}$C, $^{14}$He) and $(^{18}$O, $^{16}$O) reactions.

1 - Introduction

Charge-exchange, double charge exchange and complex rearrangement reactions induced by the $^{14}$C and $^{18}$O beams from the Orsay MP-Tandem have been used to produce the neutron-rich nuclei $^{14}$Be, $^{14}$B, $^{16}$C, $^{18}$N and $^{20}$O. For each of the two-body reactions studied, we tried to observe the exotic nucleus itself with an experimental method which is detailed elsewhere\(^1,5,3,4\).

2 - $^{14}$Be

The $^{4}$He$(^{14}$C, $^{14}$Be)$^{18}$Tl reaction was used to try to measure the mass of particle-bound $^{14}$Be. The target was 1.3 mg/cm$^2$ thick. The incident energy was 87.4 MeV and the angle of the detected ejectiles was in the range between 4° to 8°. The solid angle of the detecting system was 4.8 msr. No $^{14}$Be event was detected within an energy range of 8 MeV encompassing the expected energy of $^{14}$Be particles calculated from the mass predictions. One single event would have corresponded to 20 nb sr$^{-1}$ in the laboratory system.

3 - $^{14}$B

The $^{1}$H$(^{14}$C, $^{14}$B)$^{16}$N single charge exchange reaction was induced on a 50μg cm$^{-2}$ $^{14}$C target. The energy spectrum of the $^{14}$B emitted nuclei appears in fig. 1.

The ground state peak corresponds to a 23.67 ± 0.03 MeV mass excess for $^{14}$B. This is in agreement with previous values\(^1,5\). The ground state cross section is 7 ab sr$^{-1}$ in the laboratory system.

However there is no evidence for the reported\(^5\) excited level at 0.74 MeV. One event corresponds to an excitation energy of 0.575 MeV. The full width at half maximum of a peak in the energy spectrum is 120 keV. The total statistics collected so far in our study of $^{14}$B yields 50 events for the $^{14}$B ground state and none for the reported excited state at 0.74 MeV (ref.1) and this work). Therefore either this level does not exist or its production is strongly inhibited in the $(^{14}$C, $^{14}$B) reaction.

$^{18}$O

A total of 43 $^{18}$O nuclei have been produced in the $^{48}$Ca$(^{18}$O, $^{18}$O)$^{48}$Ti reaction on a 1.3 mg/cm$^2$ thick $^{48}$Ca target. The energy spectrum of these nu-
The $^{16}$C spectrum provides an energy calibration. The 14 events lying in a 1 MeV interval at high energy in fig. 2c are assigned to the ground state transition. Their centroid corresponds to a 24.82 ± 0.3 MeV mass excess for $^{18}$C and their laboratory cross section is 40 nb $sr^{-1}$.

The mass measured agrees with the value 24.91 ± 0.15 MeV obtained from the $^{18}$O($^7$Li, $^8$Be)$^{18}$C reaction and the predictions from the Garvey-Kelson formula, calculated with the most recent values of the $^{17}$C and $^{19}$N masses.

The ($^{18}$O, $^{18}$C) reaction is the first double charge exchange nuclear reaction observed which increases T. The difference between the ($^{14}$O,$^{14}$Be) and ($^{18}$O,$^{18}$C) cross sections should be due to the difference between the reaction Q-values, -33.68 MeV and -31.33 MeV, respectively.

5. $^{19}$N

The energy spectrum (fig. 3) of the $^{18}$O($^{18}$O,$^{18}$N)$^{17}$F reaction confirms the occurrence of a 0.57% ± 0.025% MeV excited state in $^{18}$N, reported in ref. 1. The $^{18}$N mass measured is 15.207 ± 0.035 MeV, in agreement with previous values 1,5).

6. $^{19}$N

The complex rearrangement reaction $^{18}$O($^{18}$O,$^{18}$N)$^{17}$F was used to study $^{18}$N. The $^{19}$N energy spectrum is shown in fig. 4. Two unknown excited states of $^{18}$N appear at 1.12 ± 0.04 and 1.59 ± 0.04 MeV. The $^{18}$N mass excess is measured as 15.856 ± 0.05 MeV in agreement with more accurately than previous reported values 7,8). The laboratory cross section for the ground state transition is 4.9 nb $sr^{-1}$.

Fig. 3

Counts

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<tr>
<th>Q (MeV)</th>
<th>150</th>
<th>170</th>
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Fig. 4

Counts

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<th>190</th>
<th>210</th>
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<tbody>
<tr>
<td>Count</td>
<td>100</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

Références

1) F. Naulin et al., J. de Phys. Lettres, 41 (1980) 179
2) F. Boussei et al., Nucl. Instr. Meth. 153 (1978) 111
5) G.C. Ball et al. Phys. Rev. Lett. 31 (1973) 395
8) G.C. Ball et al. F.A.P.S. 22 (1977) 552
Abstract

The decay of neutron rich light nuclei in the region N = 28, Z = 20, has been investigated at the ISOLDE facility with the 600 MeV proton beam, using a uranium target and different ion sources to select Cl, Ar or K, Ca and Sc isotopes. The subsequent transitions have been studied via delayed γ, β and, when necessary, m measurements in single and coincident modes. The paper summarizes the information obtained for the nuclei 41\textsuperscript{43}Cl, 45\textsuperscript{47,48,50,51,52}K, 51\textsuperscript{52}Ca, 52\textsuperscript{53}Sc and presents a survey of some systematic trends in the decay properties of these neutron rich isotopes.

1. Introduction

Recent experiments at ISOLDE have shown that detailed nuclear spectroscopy measurements can be performed for different isotopic chains of light nuclei and extended far from stability. This opportunity is provided by the balance of fragmentation of heavy targets with 600 MeV protons and the availability of ion sources which allow to select elements like Ar, Cl or K, Ca and Sc. A region of interest in the study of exotic light nuclei is that located near the doubly-magic 48\textsuperscript{Ca} as useful informations for shell model studies can be provided by the investigation of nuclides with only a few particles or holes related to a closed core. We have reported in Fig.1 the part of the chart which displays the nuclei for which beta decay has been studied in our experiments at ISOLDE and which are centered around A = 48.5 For the heaviest chlorine isotope reported, 44\textsuperscript{Cl}, we expect only two holes in the f shell while for 52\textsuperscript{Sc} which correspond to the highest T value (T\textsubscript{Z} = 7), an excess of five neutrons with regard to the same shell is assumed. The present investigation is an attempt to extend the knowledge on particle-hole configurations to several nuclei (Cl, Ar, K, Ca, Sc) which include the heaviest isotopes observed so far. The decay of heavy Ar isotopes has been reported earlier 1-3).

2. Experimental procedures

The studied isotopes are produced by bombarding a uranium target with the 600 MeV protons of the CERN synchrocyclotron. Different ion sources 4-5) ensure the selectivity.

Mass separated ions were collected on a thin Mylar tape allowing either a fast transport (tenths of a second) of the sources to the detectors or only evacuation of the daughter activities in the case of measurements at the collection point.

Gamma-ray spectroscopy is done with high efficiency Ge(Li) counters in the multi-spectrum mode or in three dimensional γ-γ-t measurements. The registration of singles is gated by the outputs of a nearly 4π plastic beta counter in order to minimize the gamma background. The γ-γ coincidences from the Ge(Li) counters are currently observed with a time resolution of 5 to 6 nanoseconds.

A scintillation telescope is used to measure beta energy distributions: the ΔE and E plastics are respectively 0.2 and 120 mm thick. Generally the β events are stored in coincidence with the subsequent γ rays.

Accurate half-life determinations are done with a 200 channel multiscalar advanced by a precise quartz crystal oscillator.

Delayed neutron time of flight measurements were carried out with a scintillation counter (10 cm diameter, 1.5 cm thick) over a one meter flight path, the start pulse being delivered by the 4π beta detector. Typical time resolution was one nanosecond. Neutron-gamma coincidences were stored in a biparametric, time of flight versus γ-energy, configuration to ascertain neutron branching.

A neutron counter has now been developed consisting of a 1.5 cm thick and 18 cm high curved scintillator of 160 cm long, viewed on both ends by a photomultiplier. With a radius of curvature equal to 1 meter it covers a solid angle of 27 msr. After compensation of transit time with a mean-timer a 1.5 nanosecond resolution is achieved. The efficiency is thus increased by a factor 40 compared to our previous time of flight device.

The data storage is performed by means of two Plurimat computer systems with respectively 32 and 48 K byte memories.

3. Results

We have reportec in Table I the list of the studied isotopes with indication of the measured half-life. These values have been obtained either from β multiscaling or γ multiospectreum measurements.

* Centre de Recherches Nucléaires, 67037 Strasbourg France
** IN2P3 Paris and CERN, Geneva, Switzerland
Fig. 2a: Decay scheme of $^{42}\text{Cl}$

Fig. 2b: Decay scheme of $^{40}\text{Cl}$
Table 1

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>T&lt;sub&gt;1/2&lt;/sub&gt;</th>
<th>T&lt;sub&gt;z&lt;/sub&gt;</th>
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<tr>
<td>41&lt;sup&gt;Cl&lt;/sup&gt;</td>
<td>38.4 (8) s</td>
<td>7/2</td>
</tr>
<tr>
<td>42&lt;sup&gt;Cl&lt;/sup&gt;</td>
<td>6.9 (3) s</td>
<td>4</td>
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<tr>
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<td>3.4 (3) s</td>
<td>9/2</td>
</tr>
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<td>11/2</td>
</tr>
<tr>
<td>52&lt;sup&gt;Ca&lt;/sup&gt;</td>
<td>3.2(10) s</td>
<td>6</td>
</tr>
<tr>
<td>52&lt;sup&gt;Sc&lt;/sup&gt;</td>
<td>8 (2) s</td>
<td>5</td>
</tr>
<tr>
<td>45&lt;sup&gt;K&lt;/sup&gt;</td>
<td>17.81(25) min</td>
<td>7/2</td>
</tr>
<tr>
<td>47&lt;sup&gt;K&lt;/sup&gt;</td>
<td>17.5 (4) s</td>
<td>9/2</td>
</tr>
<tr>
<td>48&lt;sup&gt;K&lt;/sup&gt;</td>
<td>6.9 (2) s</td>
<td>5</td>
</tr>
<tr>
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<td>1.27(8) s</td>
<td>11/2</td>
</tr>
<tr>
<td>50&lt;sup&gt;K&lt;/sup&gt;</td>
<td>0.47(2) s</td>
<td>6</td>
</tr>
<tr>
<td>51&lt;sup&gt;K&lt;/sup&gt;</td>
<td>0.38(3) s</td>
<td>13/2</td>
</tr>
<tr>
<td>52&lt;sup&gt;K&lt;/sup&gt;</td>
<td>0.11(3) s</td>
<td>7</td>
</tr>
</tbody>
</table>

3.1. Decay of chlorine isotopes

We would like to discuss first the results obtained in the study of the odd-odd isotope 42<sup>Cl</sup>, previously unreported. From γ-ray single and γ-γ techniques, a detailed study of the subsequent transitions in 42<sup>Cl</sup> has been made which complements the rather scarce information known from only the (t,p) reaction. A complex decay scheme has been established (Fig.2a) which accounts for transitions between 39 levels. From the intensity of beta branches to the 2414 keV (J<sup>+</sup> = 4<sup>+</sup>) and to the ground state (J<sup>+</sup> = 0<sup>+</sup>) of 42<sup>Ar</sup>, the value J<sup>+</sup> = 2<sup>+</sup> can be inferred for the ground state of 42<sup>Cl</sup>. On the decay scheme, it can be observed that allowed beta branches are found to populate only two levels (E<sub>x</sub> = 4045 and 4417 keV) at an excitation energy where there is a clustering of levels fed with log ft values around 7.

We have interpreted this feature as the population of negative parity levels arising from

\[ \left( \frac{d_{3/2}}{d_{3/2}'} \right)^{-3} \left( f_{7/2}' \right)^{15} J_z = 3 \]

configurations in 42<sup>Ar</sup>. The excitation energy for the centroids of such J<sup>+</sup> = (2-5)<sup>+</sup> states, evaluated with a Bansal-French particle-hole formula is precisely found equal to 4.5 MeV. A similar situation is observed in 40<sup>Ar</sup> at E<sub>x</sub> = 4.3 MeV and can be understood as resulting from the

\[ \left( \frac{d_{3/2}}{d_{3/2}'} \right)^{-3} \left( f_{7/2}' \right)^{3} \]

configuration. The decay scheme, 40<sup>Cl</sup> → 40<sup>Ar</sup> established in previous studies has been reported by Klotz et al.6) and Fig.2b allows the comparison. In 40<sup>Ar</sup>, the first 0<sup>+</sup> excited state (core excited state) can be described as

\[ \left( \frac{d_{3/2}}{d_{3/2}'} \right)^{-4} \left( f_{7/2}' \right)^{10} \]

with subscripts standing respectively for J and T.

The Bansal-French estimate gives an excitation energy, E<sub>x</sub> = 2.2 MeV (7), in excellent agreement with the experimental value (E<sub>x</sub> = 2.12 MeV). In 42<sup>Ar</sup>, the same evaluation yields E<sub>x</sub> = 1.84 MeV for the

\[ \left( \frac{d_{3/2}}{d_{3/2}'} \right)^{-4} \left( f_{7/2}' \right)^{6} \]

state as from our results the best candidate for J<sup>+</sup> = 0<sup>+</sup> is the level at 2511 keV on the basis of β and γ transitions.

For 41<sup>Cl</sup> → 41<sup>Ar</sup> e decay scheme has been established and is represented in Fig.3. The decay proceeds to many previously unreported levels in 41<sup>Ar</sup> up to 4.7 MeV in addition to the main branch (I<sub>B</sub> = 63 %) populating the 1/2<sup>+</sup> "hole" state at 1868 keV reported in the first study by Guruch et al.,8). On the other hand, the "hole" state at 1034 keV, J<sup>+</sup> = 3/2<sup>+</sup>, which should have a strong (d<sub>3/2</sub>)<sup>-3</sup>(f<sub>7/2</sub>)<sup>-4</sup> component, was found to be only weakly fed by the beta decay of 41<sup>Cl</sup> (I<sub>B</sub> < 8 %). The square of the matrix element was found to be

\[ M_{ST}^2 = 0.033 \]

in the first case (41<sup>Cl</sup> → 1/2<sup>+</sup>, 1.87 MeV, 41<sup>Ar</sup>), and

\[ M_{ST}^2 < 0.016 \]

in the second one (41<sup>Cl</sup> → 3/2<sup>+</sup>, 1.03 MeV, 41<sup>Ar</sup>). This observation suggests J<sup>+</sup> = 1/2<sup>+</sup> for the 41<sup>Cl</sup> ground state and an i*-forbidden transition 1/2<sup>+</sup> → 3/2<sup>+</sup>.

For 43<sup>Cl</sup> → 43<sup>Ar</sup>, a preliminary decay scheme has been built and is given in Fig.4. We found again a main branch (I<sub>B</sub> = 71 %) to a positive parity state at 1794 keV (J<sup>+</sup> = 1/2<sup>+</sup>, 3/2<sup>+</sup>). The γ decay of this state, only by cascade transitions to 43<sup>Ar</sup> ground state (J<sup>+</sup> = 3/2<sup>+</sup>) favours the lower spin value. In that case the excitation energy for the 1/2<sup>+</sup> "hole" state would remain constant when going from 41<sup>Ar</sup> to 43<sup>Ar</sup> while the ground state of heavy Cl isotopes with J<sup>+</sup> = 1<sup>+</sup> would present the same features as the heavy K nuclei (47<sup>K</sup>, J<sup>+</sup> = 1/2<sup>+</sup>).

![Fig.4: Preliminary decay scheme of 43<sup>Cl</sup>](image-url)
Fig. 3: Decay scheme of $^{41}\text{Cl}$

Fig. 5: Decay scheme of $^{45}\text{K}$
3.2. Decay of potassium isotopes

The high production yields measured at ISOLDE for K isotopes using a uranium target associated to a surface ionization source has allowed to perform two types of studies. First the reinvestigation, in much better conditions, of disintegrations previously reported (48K, 47K) and secondly the foremost detailed studies for the heaviest isotopes.

The decay of 45K, in spite of the possibility to reach this nucleus with low energy nuclear reactions, was very poorly known 9). In our study of γ rays subsequent to the β decay we can give 10 new beta branches and precise excitation energies and branching ratios for 16 levels in the N = 25, 42Ca nucleus. On the decay scheme reported in Fig.5 we note that the main part of the beta decay (84 %) corresponds to the feeding of four positive parity states (1880, 2354, 2392 and 2771 keV) which are assumed to have simple hole configurations. A more complete discussion of the level properties is given elsewhere9).

The 47K decay was previously reported by Warburton et al.11) the isotope being produced via the 48Ca(t, α) reaction. It is striking to note that despite the considerable improvement of experimental conditions (production yields, isotopic separation, detection efficiency) the resulting decay scheme, reported in Fig.6, is still in very good agreement. In particular no other beta branch could be found to upper lying levels in spite of the very high statistics. This feature indicates that the hole strength is almost exclusively concentrated in one level (Eγ = 2598 keV, Jπ = 1/2+). In our experiment, γ branching ratios for levels at 2598 and 2777 keV could be investigated and in the first case a weak E3 branch to the ground state has been observed.

\[
\begin{array}{c}
47K \\
17.5 s
\end{array}
\]

\[
\begin{array}{c}
\frac{1}{2}^+ \\
80% \\
20%
\end{array}
\]

\[
\begin{array}{c}
<9% \\
1.985 \\
2598 (1/2^+) \\
2577 (3/2^+) \\
277 (3/2^-) \\
2013 (3/2^-)
\end{array}
\]

\[
\begin{array}{c}
47Ca \\
0 \frac{1}{2}^-
\end{array}
\]

Fig.6 : Decay scheme of 47K

The 48K + 49Ca decay has been studied via delayed γ-ray singles and coincidences techniques. The high Qβ value (Qβ = 12.1 MeV) allows to investigate a large range of excitation energy in the doubly-magic 48Ca and to gain information on negative parity, low spin levels which are expected to be connected by GI transitions to the Jπ = 2+, 48K ground state. Thus a special effort has been made to investigate the radiative decay of 49Ca levels by means of γ-γ coincidences. These measurements were made in collaboration with the Mainz and the CERN ISOLDE groups who have determined the properties of the delayed neutron emission of heavy potassium nuclei and the results will be discussed in detail elsewhere12).

In a way similar to the one described in the study of 49K14) an estimate of the excitation energy of the favoured configurations reached by GI transitions is made. This evaluation takes into account the [({sd})-1f5]5/2 s = 4 and [({sd})-1f5]3/2 s = 4 configurations with the different intermediate couplings which can be consistent with the total isospin T = 4 (r stands for any of the p1/2 and f5/2 shells). The calculated excitation energies are found to fall into two groups : one near 7 MeV and the other at 11 MeV, in fair agreement with the experiment.

The study of the decay 50K → 50Ca was also the result of the collaboration of the different groups in an effort to complement the information given by high resolution 4He neutron spectrometers, gamma spectroscopy and γ–γ bidimensional analysis with time of flight and Ge(Li) measurements12). These combined techniques were well adapted to the intricate decay of 50K, where a strong delayed neutron emission was found (Pn = 29 %) (ref.14), a sizeable fraction (1/6) of which populating excited levels in 50Ca at 2023, 3354 and 4073 keV. The resulting decay scheme is reported in Fig.8.

\[
\begin{array}{c}
Q_{\beta,\text{calc}} = 13.88 \text{ MeV} \\
50K \\
T_{\pi} = 0, 2, 4, (5, 7, 11, 17)
\end{array}
\]

\[
\begin{array}{c}
E_\gamma (\text{MeV}) \\
E_\text{c} (\text{MeV})
\end{array}
\]

\[
\begin{array}{c}
29 \\
17 \\
5.9
\end{array}
\]

\[
\begin{array}{c}
4.88 \\
4.60 \\
1.56 \\
1.82
\end{array}
\]

\[
\begin{array}{c}
49Ca \text{ n} \\
50Ca
\end{array}
\]

\[
\begin{array}{c}
0 \frac{1}{2}^- \\
2 \\
3.880
\end{array}
\]

Fig.8 : Decay scheme of 50K

- 382 -
The $Q_{\beta}$ value ($Q_{\beta} = 13.88$ MeV) is evaluated from the Comay-Kelson mass formula. The uncertainty on the beta decay energy leads to unreliable log ft values. Nevertheless it can be deduced from the decay scheme that the $\beta$ strength function presents a structure with its maxima (6.5 and 9 MeV) in close analogy with the results observed in the $^{48}$K and $^{49}$K decay. Calculations have been performed by Povles to evaluate excitation energies for the $^{48}$K decay. These results are consistent with experiments, and the values observed in the $^{49}$K decay are also consistent with experiments, as in the case of the lighter isotopes.

The decay $^{51}$K to $^{51}$Ca was more difficult to investigate, the low production yield excluding detection of $\gamma$-ray coincidences. Four $\gamma$ transitions were found to decay with the $^{51}$K half-life ($T_{1/2} = 0.38 \pm 0.03$ s). From $\gamma$-ray measurements, two of these transitions (1026 and 1976 keV) were attributed to the decay of levels at 1.03 and...
3.00 MeV in $^{50}$Ca following delayed neutron emission. It is not clear whether the two other $\gamma$ transitions (3462 and 3530 keV) are emitted by $^{51}$Ca or $^{50}$Ca. Two-neutron emission from $^{51}$K, though allowed by the balance of masses, has not been observed and an upper limit on such a process could be evaluated ($P_{2n}/P_0 < 6.10^{-3}$) assuming $P_0 = 47 \pm 5 \%$ [14] for $^{51}$K. The heaviest potassium isotope observable in this work was $^{52}$K for which only the half-life value could be obtained: $T_{1/2} = 110 \pm 30$ ms.

3.3. Decay of calcium isotopes

A detailed study of the $^{51}$Ca decay ($^{51}$Ca produced as the daughter of $^{51}$K) has been possible at ISOLDE and has provided the first precise level diagram determination of $^{51}$Sc through $\gamma$ and $\gamma$-$\gamma$ measurements [17]. The deexcitation scheme which accounts for twenty two $\gamma$ transitions between eleven levels in $^{51}$Sc is reported in Fig.9. Two

![Fig.9: Decay scheme of $^{51}$Ca](image)

$^{51}$Sc states (3195 and 3039 keV) appear to be strongly populated in GT decays. If we assume for the $^{51}$Ca ground state a main $\nu(2p3/2)$ configuration, we expect strong transitions to $\pi(2p3/2)$ and $\nu(2p3/2)$ levels. The interpretation of the two levels at 3195 and 3039 keV by such configurations is supported by the features of the $^{49}$Ca decay, schematically reproduced in Fig.10, which clearly indicates the location of the one proton $2p3/2$-state.

![Fig.10: Partial decay scheme of $^{49}$Ca and $^{51}$Ca](image)

The heaviest known calcium isotope, $^{52}$Ca, was found to have a sufficiently long half-life ($T_{1/2} = 3.2 \pm 1.0$ s) to be extracted with reasonable yield from the uranium target connected to the surface ionization source operated at high temperature. The new isotopes $^{50}$Ca and $^{52}$Sc were simultaneously produced and a series of multispectrometers measurements was necessary to separate their two contributions in the $\gamma$ spectra. An example is given in Fig.11, where two time-bins (0-9 and 9-18 s) are displayed showing clear discrimination between Ca($E_\gamma = 1635$ keV) and Sc lines ($E_\gamma = 1047$ keV). A preliminary decay scheme for $^{52}$Ca has been established (Fig.12) and allows to identify the three first $J^\pi = 1^+$ states in $^{52}$Sc on the basis of the log ft values ($E_X = 1635$, 2468 and 2871 keV).

3.4. Decay of $^{52}$Sc

The $^{52}$Sc nucleus ($T_{1/2} = 8 + 2$ s) is produced in the $^{52}$Ca disintegration and can also be extracted directly from the source. In its decay we observe strong transitions to $J^\pi = 2^+$, $E_X = 1047$ keV level in $^{52}$Ti and $J^\pi = 4^+$, $E_X = 2314$ keV limiting the ground state spin of $^{52}$Sc to values lower than $J^\pi = 5^+$. This first result indicates that the low energy multiplet originating in the $(2p3/2)^{-1}(2p3/2)^{-1}$ coupling differs from the similar multiplet in $^{50}$Sc.

4. Conclusion

Nuclear spectroscopy techniques with mass separated radioactive sources (C, K, Ca, Sc) have permitted the determination of the level scheme of heavy Ar, K, Ca and Sc nuclei. Only a selection of the obtained informations has been given in order to present the main features observed in this mass region. The theoretical description of particle-hole levels in terms of the weak coupling-shell-model looks promising as well when particles and holes are distributed over two shells (heavy Ar for ex.) as when they belong to a higher number of shells (heavy Ca). Consequently further experimental investigations are planned in order to obtain and correlate more nuclear data in this mass region.
Fig. 11: γ-ray multispectrum from the decay of \(^{52}\text{Ca}\) in two time-bins. Identifications of the peaks are made by the symbol of the parent nucleus.

\(^{52}\text{Ca}\)  
\(Q^*\) est 6.3 MeV  
3.2 s

\(^{52}\text{Sc}\)  
\(Q^*\) est 10 MeV  
8 s

Fig. 12: Preliminary decay scheme of the \(A = 52\) chain.
References


4) H.L. Ravn, Phys.Reports 54 (1979) 201

5) H.L. Ravn and B. Vosicki, to be published


9) J.R. Beene, Nucl. Data Sheets 22 (1977) 1


15) A. Poves (private communication)

16) A.H. Wapstra and K. Bos, Nucl. Data Sheets 17 (1976) 474


DISCUSSION

E.A. Henry: We've seen this week the prediction that 52Ca may be a doubly magic nucleus. Does your data in this region give any information concerning this prediction?

A.C. Knipper: Not precisely. On the other hand, the effect might have a very sudden onset. Our hope is to look at levels in 49Ca, from the decay of 52K; this requires some technical development, but we have good hope.
THE $^{49}$K BETA DECAY


The ISOLDE Collaboration, CERN, Geneva, Switzerland.

Abstract

The decay of $^{49}$K has been studied through neutron and gamma spectroscopy techniques. The $^{49}$K activity was formed by 600 MeV proton fragmentation reactions in a uranium carbide target. The observed $\beta$-strength, in addition to the general behaviour expected from the gross theory of $\beta$-decay, displays two resonances centered at about 6.5 MeV and 9.5 MeV in $^{49}$Ca. This structure is discussed in simple shell-model terms.

1. Introduction

Recent experiments[1,2] using charge exchange (p,n) and (He³,t) reactions on $^{48}$Ca(T = T₃) have shown that the Gamow-Teller (GT) operator acting on a target with N > Z can populate a broad distribution of T₃ states and also the T₃ component of the giant GT resonance. All these states have positive parity and can be related to configurations with particles and holes mainly distributed in two shells. Very recently the excitation of "stretched" states, based on a proton-particle, neutron-hole configuration with both the particle and the hole in the same shell has been also reported with the (p,n) reaction on $^{48}$Ca[3].

The observation of the Gamow-Teller strength in the $\beta$ decay of K nucleus with large neutron excess clearly complements the previous informations, giving access to another class of particle-hole states. As the ground state of heavy ($A \geq 48$) K isotopes can be related to configurations with the proton hole in the $d_{3/2}$ or $s_{1/2}$ shell and the valence neutrons in $f_{7/2}$, $2p_{3/2}$ and/or $f_{5/2}$ shells, the GT $\beta$ decay of these isotopes will provide informations on negative parity particle-hole states in the daughter nuclei with particles and holes distributed in many shells. It is clear that a description of these states cannot at present be carried out in the complete sd-fp shell model basis, however simple estimates can be made to locate the centroids of p-h states.

The present paper describes a series of new results obtained in the investigation of the $\beta$-decay of $^{49}$K. The goal of this study was, by combining different techniques, to obtain a complete description of the $\beta$-strength and to attempt an interpretation of the observed structures in terms of shell model states.

A previous study of the $^{49}$K decay has been reported by Detraz et al.[4]. It has provided the first value of the half-life ($T_{1/2} = 1.1 \pm 0.35$ s) and the strongest gamma lines up to 4.2 MeV. The experimental possibilities to study the $^{49}$K beta decay have considerably increased due to new target-ion-source techniques[5] which allow production of heavy K isotopes out to mass 53.

2. Experimental Procedures and Results.

In the present experiments, $^{49}$K was produced at the on-line mass separator ISOLDE by bombarding a 12 g/cm² uranium carbide target heated to 2000°C, with 1.6 µA, 600 MeV proton beam from the CERN synchrocyclotron. After a fast diffusion from the target to a surface ionization source, the extracted beam was mass separated and deflected into different experimental areas in order to perform a set of spectroscopic measurements. The production yield of $^{49}$K was 10⁵ atoms/s. As $^{49}$K was found to be a very strong delayed neutron emitter, high resolution neutron and γ ray spectroscopy and n-γ coincidence techniques have been used in order to define the excitation spectrum of $^{49}$Ca.

The half-life of $^{49}$K was measured both by beta and neutron counting. The results obtained were $T_{1/2}(\beta) = 1.27 \pm 0.08$ and $T_{1/2}(n) = 1.25 \pm 0.05$ s. We adopt the value $1.26 \pm 0.05$ s in agreement with the previous result[4].

The neutron branching ratio was determined from simultaneous beta and neutron counting. The beta activity was detected in a 1 mm thick plastic scintillator located inside a neutron long-counter equipped with eight $\bar{\beta}$ proportional detectors. The relative beta to neutron efficiency was obtained from a comparison with the $^{9}$Li neutron branch which has been recently remeasured at ISOLDE and found to be $P_n = 50 \% \pm 6\%$. The $P_n$ values, measured with this method for $A = 48 - 51$ K nuclei, are reported in Table 1:

| $^{48}$K | 1.14 ± 0.15 | 2.0 |
| $^{49}$K | 86 ± 9 | 5.2 |
| $^{50}$K | 29 ± 3 | 7.6 |
| $^{51}$K | 47 ± 5 | 9.6 |

+ Institute of Physics, University of Aarhus, Denmark
++ Centre de Recherches Nucléaires, 67037 Strasbourg, Cedex, France
+++ ISOLDE Collaboration, CERN, Geneva, Switzerland
* Institute für Kernchemie, Universität Mainz, 6500 Mainz, Germany
** Department of Physics, Chalmers University of Technology, Göteborg, Sweden
*** Depto de Física Teórica C-XI, Universidad Autónoma, Madrid - 34, Spain
† IN2P3, Paris, France and CERN, Geneva, Switzerland
Fig. 1: Delayed neutron singles spectrum from $^{49}$K decay

Fig. 2: $\gamma$-ray spectrum registered in coincidence with $\beta$ rays from $^{49}$K.

Fig. 3: $\gamma$-ray spectrum in coincidence with $\beta$ delayed neutrons from $^{49}$K.
It is striking to note that, as the available energy window (Q\(_{\beta} - B_N\)) for beta delayed neutron emission increases regularly from A = 48 to A = 51, the total intensity of the delayed neutron branches shows a strong maximum for A = 49. The high \(I_B\) value observed in this case (\(I_B = 86.9\%\) ) is an indication that configurations favoured by the 49K beta decay are located above the neutron binding energy \(B_N = 5.147\) MeV.

The delayed neutrons were investigated first with high-resolution 3He ionization chambers. The neutron spectrum, corrected for detector efficiency and response, is shown in Fig. 1 where thirteen well separated lines are observed and can be related to the upper part of the 49K strength function.

Gamma ray measurements were made with a 109 cm\(^3\) Ge(Li) detector, in a multianalysis mode of 2 x 1.5 second after each ion collection and in coincidence with \(\beta\) rays detected with a plastic scintillator surrounding the collection point of a tape transport system. The spectrum registered during the first time bin is given in Fig. 2 where all the observed lines have been identified and originate from one of the three following processes:

- the decay of levels in 49Ca at 2027, 3585, 4272 and 4072 keV. The latter excitation energy corresponds to a previously unreported level almost at the same energy as the one in 49Sc, populated by the subsequent Ca \(\rightarrow\) Sc beta decay. The relative contribution of these two levels was evaluated from intensity and decay rate considerations.
- the inelastic 49K delayed neutron scattering in the germanium counter or in the surroundings. The high efficiency of this process is due to the fact that the excitation of \(0^+\) states in 70,74,76Ca is followed by emission of conversion electrons totally absorbed within the Ge crystal whereas the very strong line at 691 keV (72Ge) is suppressed in our case by the fact \(\beta\)-\gamma coincidence.
- the deexcitation of two levels in 46Ca: the first 2\(^+\) state at 3832 keV (3832 \(\rightarrow\) 0) and the second 0\(^+\) at 4284 keV (4284 \(\rightarrow\) 3832). This process was clearly related to the delayed neutron emission from the time dependence of the two lines in the multispectrum found in agreement with the half-life of 49K.

A time of flight measurement has been performed with a 10 cm diameter plastic scintillator and combined with the Ge(Li) \(\gamma\) analysis in a bidimensional experiment. The coincident gamma spectrum, shown in Fig. 3, is dominated by the 3832 keV line and at low energy by the radiation following \(\beta\) interaction. With a window set on the 3832 keV \(\gamma\) ray the coincident neutron spectrum indicates at least three neutron groups (0.12 + 0.03, 0.3 + 0.05 and 0.6 + 0.06 MeV) corresponding to the decay of highly excited levels in 49Ca feeding the 2\(^+\) state of 48Ca. It has not been possible to evaluate the energy of the neutron branch populating the 0\(^+\) level at 4284 keV as a consequence of the high background for low energy \(\gamma\) rays and of the weak intensity of the 452 keV line (I(452 keV)/I(3832 keV) = 0.06 + 0.01).

The ground state feeding of 49Ca was inferred from two independent evaluations: the comparison of the Ca \(\rightarrow\) Sc activity to the K \(\rightarrow\) Ca one and a direct measurement of the \(\beta\) and \(\gamma\) activities using two counters with known absolute efficiencies. This determination (\(I_B = 10\%\) ) makes possible the calculation of absolute values for all the \(\beta\) branches.

3. Discussion

Using for \(Q\_\beta\) an estimate obtained from mass formulae (\(Q\_\beta = 11.0\) MeV), the corresponding log ft values have been deduced and are listed in the decay scheme (figure 4) which shows the information from this comprehensive study. From the decay scheme it can be noted that most of the excited states in 49Ca observed in this work are not seen in the 48Ca (d,\(\alpha\))reaction which can be explained by the particle-hole nature of the states populated in the allowed beta decay.

Fig. 4: Decay scheme of 49K

The \(\beta^-\) strength function of 49K was derived and is shown in Fig. 5 quoted in terms of reduced Gamow Teller transition probabilities per 100 keV versus excitation energy. The influence on the measured strength distribution of an experimental analysing limit for \(\beta\)-feeding of \(I_\beta = 6 \times 10^{-3}\) is also indicated. The beta strength function reproduces the general increase with the energy which is predicted by the gross theory of beta decay 10 but gives also evident deviations due to nuclear structure effects with the appearance of two pronounced maxima around 4.5 MeV and 9.5 MeV excitation energy.
Fig. 5: $\beta$-strength function of $^{49}\text{K}$ decay in terms of reduced GT transition probabilities

In a shell model approach, the ground state of $^{49}\text{K}$ ($J = 1/2, 3/2$; $T = 11/2$) can be described as a $^{40}\text{Ca}$ core with the dominant configurations:

$$\{p_{3/2}^2, p_{1/2}^1, f_{5/2}^2\}0^+_{1,1} = (f_{7/2}^0/0,4)$$

for valence particles, and for holes:

$$\{p_{1/2}^2, d_{3/2}^1\}0^+_{1,2}/1,2$$

where subscripts stand for $J$ and $T$ values. The Gamow-Teller nuclear matrix element will allow to connect final states in $^{49}\text{Ca}$ with the same components coupled to $T' = T - 1$ and to $J' = J + 1$. The description of such states in $^{49}\text{Ca}$ is listed in Table 2 where the different intermediate couplings have been taken into account. In Table 2 any of the subshells $p_{3/2}^2$, $p_{1/2}^1$, and $f_{5/2}^2$ are denoted as $r$.

Table 2: $T = 9/2$ particle-hole states in $^{49}\text{Ca}$

<table>
<thead>
<tr>
<th>Configurations</th>
<th>$E_x$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a $[(sd)^{-1}l^8(T=4)]_{9/2}2^2(T=1)$</td>
<td>9.2</td>
</tr>
<tr>
<td>b $[(sd)^{-1}l^8(T=4)]_{9/2}2^2(T=0)$</td>
<td>9.2</td>
</tr>
<tr>
<td>c $[(sd)^{-1}l^8(T=4)]_{7/2}2^2(T=1)$</td>
<td>9.2</td>
</tr>
<tr>
<td>d $[(sd)^{-1}l^8(T=3)]_{7/2}2^2(T=1)$</td>
<td>11.7</td>
</tr>
<tr>
<td>e $[(sd)^{-1}l^9(T=7/2)]<em>{3/2}^1(T=1/2)</em>{1/2}$</td>
<td>6.2</td>
</tr>
</tbody>
</table>

The evaluation of the excitation energies for these configurations implies a knowledge of the interaction parameters for two particles in the different shells with $T = 0$ and $T = 1$. The adequate information is not yet complete and remains precisely the goal of our investigations on light nuclei far from stability. However, an estimate based on the Bansal-French formulae with parameters extracted from effective interactions has been done. The use of this formalism with the same parameters has besides proved to be successful in this mass region. The excitation energies expected for the centroids of states corresponding to the different configurations with $r = p 3/2$ are reported in Table 2 where different values can result from Coulomb splitting.

From this table it appears that the expected excitation energies fall into two groups, one at 5-6 MeV (states c and e) and the other above 9 MeV (states a, b and d). The observed structure in the $^{49}\text{K}$ strengths function has certainly its origin in these two groups. The occupation of $p_{3/2}^2$ and $f_{5/2}^2$ shells produces an increase of the excitation energy. For example in the case of state (c) where one particle is in the upper shells, the expected excitation energy would move from 6.2 MeV ($r = p_{3/2}^2$) to 8.2 MeV ($r = p_{1/2}^1$) and 9.7 MeV ($r = f_{5/2}^2$). This situation makes difficult the evaluation of the relative contribution of the different groups to the observed beta strengths.

It is important to note that the same approach with the same parameters give reasonable results for the p-h states of $^{40}\text{Ca}$ and $^{40}\text{Ca}$. Thus we can conclude that at present, with a simple model, the main features of the $\beta$-strength function of $^{49}\text{K}$ decay are understood semi-quantitatively. It would be rewarding to further improve our knowledge on p-h structures in neutron rich Ca isotopes. Both, experimental and theoretical work on the decay properties of the isotope sequence $47-52\text{K}$ is underway.

Acknowledgments

The authors would like to acknowledge fruitful discussions with J. Elmoqvist, S.G. Prussin and A. Zuker.

References

5. H. L. Ravn, Phys. Reports 54 (1979) 201
7. A. H. Wapstra and K. Bos, Nucl. Data Tables 19 (1977) 171
9. A. H. Wapstra and K. Bos, Nucl. Data Tables 17 (1976) 474
DEFORMED GROUND STATES AND DOUBLE BACKBENDING AT HIGH SPINS IN LIGHT Kr ISOTOPES

Physics Department, Vanderbilt University, Nashville, Tennessee, USA.

J. Roth, L. Cleemann, J. Eberth, T. Neck, W. Neumann, M. Nolte
Institut für Kernphysik der Universität zu Köln, D-5000 Köln 41, FRG.

R. L. Robinson and H. J. Kim
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

S. Frauendorf
Physics Department, University of Tennessee, Knoxville, Tennessee, USA.

J. Döring, L. Funke and G. Winter
Zentralinstitut für Kernforschung Rossendorf, 8051 Dresden, DDR.

J. C. Wells and J. Lin
Physics Department, Tennessee Technological University, Cookeville, Tennessee, USA.

A. C. Rester
Physics Department, University of Florida, Gainesville, Florida, USA.

H. K. Carter
UNISOR, Oak Ridge, Tennessee, USA.

Abstract

The energy levels in $^{74,76}$Kr have been studied with a range of in-beam, $\gamma$-spectroscopy techniques following heavy-ion reactions and in $^{76}$Kr via the radioactive decay of $^{76}$Rb. Breaks in the level energies and moments of inertia in $^{74,76}$Kr are observed at low spins. These data can be understood in terms of the crossing of bands built on near-spherical and deformed shapes with the ground states having very large deformation. In $^{76}$Kr the yrast cascade is observed to a tentative 20$^+$ level. Double backbending of $\gamma$ is observed at spins of 12$^+$ and 16$^+$. These changes are interpreted in terms of rotation-aligned structures.

1. Introduction

Two of the important frontiers in nuclear research are the extension of our knowledge of the structures of nuclei further from stability and to higher spins. The present paper reports on studies which extend our knowledge in both these directions in the light krypton isotopes. In both instances evidence for new structures are found, including large ground state deformation in $^{76}$Kr and double backbending of the moment of inertia in $^{74}$Kr above the 10$^+$ level. These latter data were obtained by using a new neutron multiplicity technique with $(n,n,\gamma)$ and $(n,\gamma,\gamma)$ coincidences.

The energies of the $0^+$ states have a deep minimum in $\text{N} = 40$ Ge and Se isotopes so that in $^{76,72}$Ge and $^{72,74}$Se they are very near or, in the case of $^{72}$Ge, below the energy of the first excited $2^+$ states (see review in Ref. 1). These and a variety of other data have been interpreted in terms of shape coexistence in these nuclei, where the low-lying $0^+$ states are more deformed than the ground states$^{(1)}$. The origin of this shape coexistence can be attributed to the gaps in the single particle spectrum seen in Fig. 1 at $\text{N} = 40$, $\delta = 0$ and $\text{N} = 40$, $\delta = 0.25$, that stabilize the nuclear shape. Evidence for the spherical subshell closure around $\text{N}(2) = 40$ is found when $2(2)$ is close or equal to 28 or 50, because the protons (neutrons) prefer a spherical shape, as seen for example in $^{68}$Ni(30Zr,60). However, as Z moves away from 28 or 50 the level density for a spherical shape becomes very high and the minimum of the proton deformation energy moves to deformed shapes as qualitatively indicated by the circles in Fig. 1. The same holds for the neutrons since the proton and neutron single particle levels are almost identical. Away from the Z(2) = 28 and 50 closed shells, maximal deformation is expected at N(2) = 38. However, the deformed state can coexist with a nearly spherical configuration in a delicate balance. Which one is lower depends on the proton number. For $^{70,72}$Ge and $^{72,74}$Se the coexistence of nearly spherical ground states with deformed

![Fig. 1. Nilsson diagram for the A = 76 region for protons.](image-url)
excited bands has been reported\(^{1-4}\). In \(^{72,74}\)Se, the deformed band becomes yrast at \(I = 2\rightarrow 4\) because of its lower rotational energy. For the Ge isotopes, the bands built on the two different shapes are less well developed because of the smaller deformations (two protons less than Se). In the Kr isotopes, the 36 protons favor deformation even more. Here we present evidence that the deformed minimum becomes the ground state and the lowest \(0^+\) states are the spherical ones in \(^{74,76}\)Kr.

2. Evidence for deformed ground states

To investigate the nature of the \(0^+\) states and the influence of the \(n = 40\) subshell closure farther from the proton magic numbers, levels in \(^{74,76}\)Kr were studied with in-beam gamma-ray spectroscopy techniques via, a) the reactions \(^{60}\)Ni(\(160\), \(2n\)) and \(^{60}\)Zn(\(170\), \(2n\)) with 45 MeV \(^{15}\)O and 39 MeV \(^{15}\)C ions from the Oak Ridge EN tandem, including angular distribution and \(\gamma-\gamma\) coincidence measurements with Ge(Li) detectors, and b) the reaction \(^{56}\)Ni(\(2\gamma\), \(2\gamma\)) with 68 MeV ions from the University of Kölln tandem (in that work an additional technique\(^{5}\) of measuring \((n,\gamma)\) and \((n,\gamma)\) coincidences was used), and the radioactive decay of \(^{70}\)Rb to \(^{76}\)Kr was studied with mass-separated samples at the UNISOR facility. The \(^{70}\)Rb was produced in the reaction \(^{88}\)N (\(2\gamma\)Ne, \(x\)) at 112 MeV. Mass separated samples were collected and then transported via a tape transport system to a position between two Ge(Li) detectors for \(\gamma-\gamma\) coincidence studies. As one sample was being counted, the next was being collected.

From the \(^{76}\)Kr in-beam and the \(^{76}\)Rb decay studies, a \(0^+\) state at 770 keV and a \(2^+\) state at 1688 keV that feeds only the \(0^+\) level were established in \(^{76}\)Kr (see Fig. 2). Thus, the energies of the \(0^+\) levels continue to drop sharply as one goes from \(^{80}\)Kr to \(^{76}\)Kr. The even-parity yrast cascades in \(^{76}\)Kr and \(^{76}\)Rb were established to \(10^+\) and \(12^+\), respectively, in the first studies. The moments of inertia for the low-spin members of the even-parity yrast bands in \(^{75,76}\)Kr (present work) and \(^{78,80}\)Kr\(^{6-9}\), Fig. 3, become larger when going from \(N = 44\) to \(N = 38\), except for \(^{74}\)Kr, where the point corresponding to the \(2^+\) energy in \(^{74}\)Kr strongly deviates. This trend can already be seen in \(^{76}\)Kr to a lesser degree. In \(^{72,74}\)Se\(^{39,40}\), \(^{1,4}\) as in \(^{186-188}\)Hf\(^{91}\) strong forward bends in the moments of inertia above the \(2^+\) states were interpreted in a shape coexistence picture, with bands built on the ground and excited \(0^+\) states with quite different deformations. The forward bend of \(\beta\) occurs\(^{1,4,9}\) when the deformed band crosses the sequence of states built on the nearly spherical minimum. Because of the larger proton number in the Kr isotopes, deformed shapes may have a slightly lower energy than the spherical ones. The observation that in \(^{76}\)Kr the \(0^+\) level is low but the \(2^+\) level, which feeds it, is 918 keV above it while the \(2^+\) state is only 425 keV above the ground state supports this. Thus we suggest that it is the ground state which is more deformed and the \(0^+\) level which is associated with a near-spherical shape in \(^{76}\)Kr, in contrast to the reverse situations in \(^{72,74}\)Se and \(^{186-188}\)Hf. A similar situation should be occurring in \(^{76}\)Kr.

The relative large \(2\rightarrow 0\) energies in \(^{74,76}\)Kr (which make these look less deformed than they really are) would arise from an interaction between the \(0^+\) deformed and \(0^+\) near-spherical states to push down the \(0^+\) energy. Since the \(2^+\) spherical state is quite high in energy, there will be little mixing of the \(2^+\) and higher spin states, since the

Fig. 2. Energy levels in \(^{76}\)Kr observed via in-beam spectroscopy.

Fig. 3. Analysis of the energies of the yrast levels in the even-mass Kr isotopes. The dashed lines show the Harris extrapolation of high spin levels. The frequency and the moment of inertia are defined in Ref. 10 as \(h\omega = 4\sqrt{2}/2\) and \(J^2/\hbar = (\gamma + 1)/\gamma\). The Harris extrapolation is given by \(J^2/\hbar = \gamma^2(J^2/\hbar)^2\), where \(\gamma = 12.5, 10.8, 7.3\) MeV\(^{-1}\) and \(J^2/\hbar^2 = 12.3, 5.0, 29.0\) MeV\(^{-1}\) for \(^{74}\)Kr, \(^{76}\)Kr and \(^{78}\)Kr, respectively. The dashed lines in the lower figure for the yrast levels are obtained by using the parameters \(\gamma\) and \(\gamma\), and fitting the energies of the \(6^+,7^+,8^+\) states in \(^{74,76}\)Kr and the \(4^+\) level in \(^{78}\)Kr, as in Ref. 10.
energies for the near-spherical structure grow much faster with I than in the deformed band. In $^{72,75}$Se there also is considerable mixing of the deformed and spherical configurations near the band crossing at I $\approx 2$-4 observed\(^1\).

Calculations described below indicate that for N = 38, the deformed structure is generated from the spherical one by promoting two pairs of neutrons from the f$_{5/2}$ to the g$_{9/2}$ shell. Correlations of the pairing type contain the multiple scattering of pairs from the f$_{5/2}$ to the g$_{9/2}$ shell (and vice-versa) and may be an important source for the coupling of the two structures.

In order to quantify the band mixing suggestion, we analyzed the Kr yrast bands in terms of a two-level model. For I $\geq$ 6 h one expects that the yrast levels are purely deformed. In Fig. 3 this region corresponds to the nearly linear part of $\gamma$. The up bands are related to the alignment of a g$_{9/2}$-proton pair\(^7\). The position of the unperturbed deformed levels were determined by extrapolating the linear part of $\gamma$ (o) down to $\omega = 0$. As discussed in Ref. 10 this corresponds to a Harris or VMI-parametrization of the deformed g-bands. The relation between the level energy E(I) and the Harris parameters $\beta_{0}$, $\gamma_{0}$ given in Fig. 3 may be found in Ref. 10. Figure 3 compares the extrapolated with the measured levels. The deviation is much larger in $^{76}$Kr than in $^{78}$Kr in accordance with the higher position of the known 0$^+_2$ level in the latter.

The shifts $\Delta E = E_{0}^{\gamma} - E_{0}^{1\gamma}$ can be found in Table 1. The difference between the unperturbed states in Kr isotopes.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$\Delta E$ (MeV)</th>
<th>$E_{0}^{1\gamma}$ (MeV)</th>
<th>$E_{0}^{1\gamma}$ (MeV)</th>
<th>$V$ (MeV)</th>
<th>BE(2-0) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Kr</td>
<td>0.250</td>
<td>0.624</td>
<td>0.160</td>
<td>0.330</td>
<td>0.62</td>
</tr>
<tr>
<td>$^{76}$Kr</td>
<td>0.187</td>
<td>0.770</td>
<td>0.396</td>
<td>0.530</td>
<td>0.74</td>
</tr>
<tr>
<td>$^{78}$Kr</td>
<td>0.102</td>
<td>1.017</td>
<td>0.813</td>
<td>0.305</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*The value $V$ is assumed and $E_{0}^{1\gamma}$ and $\Delta E_{0}$ calculated by using this value. The energies are in MeV.

Levels $\Delta E_{0} = E_{0}^{1\gamma} - E_{0}^{2\gamma}$ is equal $E_{0}^{1\gamma} - 24E_{0}^{2\gamma}$. The interaction V is equal to $(1/2)\Delta E_{0}^{2\gamma} - \Delta E_{0}^{1\gamma}$, where $\Delta E = E_{0}^{1\gamma} - E_{0}^{2\gamma}$. These quantities are also included in Table 1. The close values of V for $^{76}$Kr and $^{78}$Kr indicate that the smaller energy perturbations in $^{76}$Kr are related to the higher position of the (unperturbed) spherical state. One may suggest that the interaction V in $^{78}$Kr has a value similar to that of $^{76}$Kr. Adopting this value of 0.33 MeV, one may use $\Delta E$ to predict the $E_{0}^{1\gamma}$-level at 6.68 MeV. The extracted, unperturbed 2 $\rightarrow$ 0 energies in the deformed ground bands are 200 and 237 keV in $^{74,76}$Kr, respectively. By scaling the unperturbed 2 $\rightarrow$ 0 energy by $\frac{A_{2}}{A_{1}}$, one may compare the deformation of $^{76}$Kr to that of $^{238}$U. The 200 keV transition in $^{78}$Kr would correspond to 29 keV in $^{238}$U compared to the actual value of 45 keV. This is an unusually large ground state deformation, slightly larger than the 'super deformation' recently reported\(^11\) for $^{108}$Sr.

As further support for the importance of deformation effects, the lifetimes of several levels were measured by Doppler shift line shape analysis. The B(E2) strengths for the transitions between the yrast states in $^{76}$Kr are given in Table 2.

<table>
<thead>
<tr>
<th>E$_{1\gamma}$ (keV)</th>
<th>E$_{0}^{1\gamma}$ (keV)</th>
<th>I$^{1\gamma}$</th>
<th>t$_{mean}$ (ps)</th>
<th>B(E2) $^{1\gamma}$ sp</th>
<th>B(E2) $^{2\gamma}$ sp</th>
</tr>
</thead>
<tbody>
<tr>
<td>424</td>
<td>424</td>
<td>2$\rightarrow$ 0</td>
<td>53(7)</td>
<td>59(7)</td>
<td></td>
</tr>
<tr>
<td>1035</td>
<td>611</td>
<td>4$\rightarrow$ 2</td>
<td>5.0(20)</td>
<td>76(23)+2</td>
<td></td>
</tr>
<tr>
<td>1860</td>
<td>825</td>
<td>6$\rightarrow$ 4</td>
<td>1.25(12)</td>
<td>89(8)</td>
<td></td>
</tr>
<tr>
<td>2880</td>
<td>1020</td>
<td>8$\rightarrow$ 6</td>
<td>0.50(3)</td>
<td>129(13)</td>
<td></td>
</tr>
<tr>
<td>4068</td>
<td>1188</td>
<td>10$\rightarrow$ 8</td>
<td>0.14(2)</td>
<td>19(19)</td>
<td></td>
</tr>
<tr>
<td>5346</td>
<td>1278</td>
<td>12($\rightarrow$ 10)</td>
<td>0.24(5)*</td>
<td>52(11)*</td>
<td></td>
</tr>
</tbody>
</table>

*Composite lifetime and composite B(E2) compared to single particle values.

\(^1\)Nolte, et al. (Ref. 12).\(^1\)Based on an average ($\gamma = 6.6 \pm 1.5$) of the present data and that of Nolte et al. ($\gamma = 8.2 \pm 2.3$) (Ref. 12).

These values are highly collective; the most collective known for any nucleus in the A = 70 region. For comparison B(E2)$^{1\gamma}$sp/B(E2)$^{2\gamma}$sp are 10(4) and 12(4) for the 2 $\rightarrow$ 0 and 4 $\rightarrow$ 2 transitions, respectively, in $^{76}$Ge and $^{78}$Se for $^{75}$Se where mixing presumably occurs. However, from the 2$\rightarrow$0 to the 10$\rightarrow$0 state, the B(E2) values generally follow the gradual increase expected for a rotational nucleus in sharp contrast to the rapid increase in B(E2) values in a vibrational model.

In the two-level model, one also may calculate the square of the amplitude, C$^{1\gamma}$, of the deformed state in the perturbed ground state which is equal to $(1 + \Delta E^{1\gamma}/\Delta E^{2\gamma})$. Assuming that the E2 matrix elements between the bands is much smaller than the matrix element within the deformed band, the B(E2: 2$\rightarrow$0) value will be reduced by C$^{1\gamma}$ $(I = 0)$ x C$^{2\gamma}$ $(I = 2)$. This reduction factor is also included in Table 1. It represents an upper limit of the reduction, since one expects a finite matrix element between the bands. The data in Table 2 are consistent with the predicted reduction of B(E2: 2$\rightarrow$0).

In summary, these data extend our understanding of the coexistence of different nuclear shapes first proposed in $^{76}$Se. However, apparently in $^{74,76}$Kr the role of the near-spherical and deformed minima are reversed with the ground states strongly deformed and the excited 0$^+_2$ states associated with a near-spherical minima. This interpretation for the N = 38, 40 Kr nuclei supports the expectation that at these neutron numbers as the proton number approaches the middle between the N = 28 and 50 closed shells, the protons can drive a nucleus with a pair of g$_{9/2}$ neutrons toward deformation. It is not certain whether these deformed states are prolate or perhaps triaxial. The low level density on the oblate side ($\gamma = -0.25$) of Fig. 1 for N $\cong$ 38 indicates that the deformation energy could weakly depend on the $\gamma$-degree of freedom. The importance of the triaxial deformations in these nuclei is reflected by the observation of the $\gamma$-band at low energy.

The odd spin negative parity band seen to 15$^+$ in $^{76}$Kr has been interpreted in the interacting Boson approximation as arising from the coupling of octupole and quadrupole Bosons\(^3\). To further test our interpretation of this band in $^{76}$Kr and in $^{76}$Kr as arising from two quasiparticles with one in the g$_{9/2}$ orbital, G, and 10(2) and 45(2) quasiparticle-plus-rotor calculations for $^{76,78}$Kr in the Flamm-Cline approach\(^11\). For the negative parity states,
8 basic states close to the Fermi level were included. The assignment of even spin and odd parity to the experimental levels in $^{76}\text{Kr}$, as shown in Fig. 4, is based essentially on the close agreement of their energies with those from the calculations. All of the calculations are strongly supportive of the importance of the 2-quasiparticle structures in both the negative parity bands beginning at $5^-$ and the positive parity bands beginning at $8^+$. The yrast levels in $^{76}\text{Kr}$ were extended from $10^+$ to a proposed $20^+$ level and other side bands observed as shown in Fig. 5. This is the highest spin state reported in this region and is remarkably high for such a light nucleus. Spin assignments were made by $(n,\gamma)$ and $(n,n,\gamma)$ coincidence yield functions between 58 and 68 MeV and $\gamma$-angular distribution measurements.

As shown in Fig. 6, the plot of the angular momentum $I(\omega)$ as a function of $\omega$, where $\hbar \omega = E_V[(1 + 1) - (1 - 1)]/2$, clearly shows two distinct breaks -- double backbending in the moment of inertia. Coupled with the interaction of the deformed and near-spherical $0^+$ states, one has a record three crossings of the ground band! Only in $^{158}\text{Er}$ and $^{160}\text{Yb}$ [15,16] have double backbends been observed in yrast cascades. The break above the $10^+$ state is undoubtedly from a crossing of a $(8g/2)^2$ configuration. The observed $8^+$ and $10^+$ states are assigned as the low spin members of this band which carries about 3 units of angular momentum. Calculations in the approach by Bengtsson and Frauenfelder [10] indicate that the proton and neutron $(8g/2)^2$ configurations are close in energy so the character of these levels is not established yet. The next $(8^+_2)$ and $(10^+_2)$ states may be the aligned states of the other configuration. Magnetic moment measurements could help identify the character of these levels. Note $I(\omega)$ for the $8^+$ and $10^+$ levels are in line with those of the $12^+$ and $14^+$ levels.

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Fig. 4. Two-quasiproton levels in $^{76,70}\text{Kr}$. The experimental levels associated with the theoretical $6^-$, $8^-$, levels in $^{76}\text{Kr}$ have been assigned tentatively.

Fig. 5. Energy levels in $^{76}\text{Kr}$ observed in $(n,\gamma,\gamma)$ studies (see Ref. 5).
Fig. 6. A plot of the angular momentum \( I \) as a function of \( \omega = E_1/(1 + 1) - (1 - 1)/2 \) for \(^{78}\)Kr.

The second break above the 14° state has an aligned angular momentum compared to the ground state about double that of the first band to cross the ground state. Note in \(^{68}\)Ge where both proton and neutron \((q/2)^2\) 2 quasiparticle bands are reported to cross the ground band, each band has about the same 6 units of aligned angular momentum\(^1\). This larger alignment compared to the ground state suggests that this new band which crosses at 16° is a four-particle, aligned configuration which must be probably composed of two \((9/2)^2\) quasiprotons and two \((8/2)^2\) quasineutrons. Such an interpretation is in line with the double backbends in \(^{138}\)Kr and \(^{166}\)Og where the first two \(15/2\) neutrons align and then two \(11/2\) protons. Here both particles are in the same orbital. Note the high spin data for \(^{78}\)Kr do not show a second break in \( I \) at the tentatively proposed 16° level. If the first crossing is for two quasiprotons and the second for the addition of two quasineutrons to the 2p1 configuration in \(^{78}\)Kr, then this second crossing could be blocked by the presence of the four extra neutrons in \(^{78}\)Kr.

4. Acknowledgements

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DISCUSSION

W. Andraßschaff: I would like to mention here some preliminary thoughts on some delayed ground-state cascades in Se and Kr isotopes which we got as a by-product from lifetime measurements. The experiments were performed on the Rutgers tandem with the generalized centroid shift method (delayed coincidences). The first slide demonstrates a typical centroid diagram. Average delays are presented on the second figure. Delayed feeding of several hundreds of picoseconds in $^{74,76}$Se and maybe $^{76}$Kr indicate possible isomeric levels at high excitations.

J. H. Hamilton: We also observed long feeding time in $^{74,76}$Se and $^{82}$Kr. In $^{82}$Kr produced by a particle long feeding times were not observed. Then there seem to be more high spin isomers in this region.

H. Morinaga: 1) Sometimes odd nuclei like $^{77}$Kr show simpler rotational structure, free from complication due to co-existence. 2) As for anomaly in rotational structure, one should look at it comparing not only with the situation in heavy nuclei but also with light nuclei like $^{25}$Ne.

A. Galberg: How do the $B(E2)$'s in $^{76}$Kr compare with the leading-order theoretical values from the rotational model?

J. H. Hamilton: One expects a reduction in $B(E2, 2^+ \rightarrow 0^+)$ because of mixing of the two $0^+$ states. However, the high-spin data follow rotor predictions.
NEUTRON RICH NUCLEI STUDIED WITH THE \((^{14}\text{C}, ^{16}\text{O})\) REACTION

M. Bernas, Ph. Dessagne, J. De Boer*, M. Langevin, F. Pougheon, P. Roussel, C. Zaidins**
Institut de Physique Nucléaire, BP No 1, 91460 Orsay

Abstract

Measurements of the masses and excited state energies of neutron rich nuclei \(^{62}\text{Fe}, ^{68}\text{Ni}, ^{74}\text{Zn}\), and \(^{80}\text{Ge}\) have been performed with the \((^{14}\text{C}, ^{16}\text{O})\) reaction. The masses are compared with the Myers and Garvey-Pelson predicted values. The position of the first \(^2\) state is reviewed for the even-even isotopes of the four elements.

The acceleration of \(^{14}\text{C}\) beams opens new perspectives in nuclear spectroscopy. The \((^{14}\text{C}, ^{16}\text{O})\) reaction, a two proton pick-up process kinematically favored for its positive Q value, provides an adequate tool for studying proton pair correlations\(^3\). On neutron-rich targets, this pick-up leads to residual nuclei with still larger neutron excess. The \((^{18}\text{O}, ^{20}\text{Ne})\) reaction has already been investigated as an alternative to the obviously difficult \((n, ^3\text{He})\) reaction but the low lying states of \(^{20}\text{Ne}\) are strongly populated and they obscure the residual nuclei spectra. Moreover those low-lying states in \(^{20}\text{Ne}\) as well as the ones in \(^{18}\text{O}\) are strongly coupled to the ground-states introducing coupled-channel effects. The \((^{14}\text{C}, ^{16}\text{O})\) reaction does not suffer from those two inconveniences.

In this contribution we shall report on two proton pick-up on the most neutron rich isotopes \(^{64}\text{Ni}, ^{70}\text{Zn}, ^{76}\text{Ge}\), and \(^{82}\text{Se}\). With their large neutron excess - N-Z from 8 to 14 - these target nuclei lie isolated from the main part of the valley of stability. Due to the slope of this ridge \(\Delta Z/\Delta N = 1/2\) in the \((Z,N)\) diagram, the two-proton pick-up reaction leads to residual nuclei four neutron heavier than its last stable isotope. Such nuclei is out of the range for practical neutron stripping. Further more the final nuclei lie in a region of the chart of the nucleides far from the alkalies and not yet investigated by fission fragments spectroscopy.

EXPERIMENTAL SET-UP

The set-up (fig 1) was already described elsewhere. The ray tracing \(^2\) at the exit of the magnet is performed within an angular aperture of \(5^\circ\) lab, and with a 0.2° accuracy. The overall solid angle is 5 msr. The ion identification is unambiguously achieved with a \(\Delta E_1, \Delta E_2, E\) ionisation chamber \(^3\).

* From Universität München, Am Coulombwall 1, D 8046 Garching, West Germany
** On leave from the University of Colorado, U.S.A.

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Fig. 1 - Experimental set-up

A new device has been added in order to perform measurements at very small angles including 0°. The magnet vacuum chamber is equipped with two isolated systems of beam catchers and screens designed to eliminate background effects in the focal space. This system also provides a measurement of the beam intensity. In the experiment the ratio of the average magnetic rigidity of the analysed particles to the magnetic rigidity of the most abundant charge stated the incident beam was 0.76 and with optimized beam transport adjustments, we did not observe any significant increment of the background in the focal space, when the analyzer was set at 0°.

The targets were made of isotopically enriched elements evaporated on 20 \(\mu\text{g/cm}^2\) thick \(^{12}\text{C}\) backing and the \(^{70}\text{Zn}\) target deposit was covered with a \(10 \mu\text{g/cm}^2\) layer of carbon. The \(^{70}\text{Zn}\) targets were separated from enriched element at the CSNSM separator and collected on a 30 \(\mu\text{g/cm}^2\) \(^{12}\text{C}\) backing. The target thicknesses lie from 50 \(\mu\text{g/cm}^2\) for \(^{80}\text{Se}\) to 130 \(\mu\text{g/cm}^2\) for \(^{70}\text{Zn}\).

RESULTS

a) spectra

The \(^{16}\text{O}\) energy-spectra corrected for the kinematical effects are shown in fig.2 Wide peaks are observed for \(^{16}\text{O}\) and \(^{12}\text{C}\) contaminants, whose kinematical factors are...
larger than the heavy target ones. For all the targets, the ground state is the most excited level as expected, since on the neutron rich nuclei, the energy-matching occurs for negative excitation energy around $E_n=-10$ MeV. Excited states are observed for the first time in $^{62}$Fe and $^{74}$Zn spectra, however.

![Spectra](image)

**Fig. 2** - $B_p$ spectra measured for the exotic nuclei.

The unknown masses and excitation energies are determined using a calibration based on the $(^{14}$C, $^{16}$O) reaction itself, measured on $^{62}$Ni and $^{74}$Ge targets and on the $^{16}$O and $^{12}$C contaminants at different angles. The three-parameters calibration curve $E^2/E = f(P)$ where $P$ is the frequency of the magnetic resonance set in the spectrometer is fitted by a least square method. The larger deviation between the curve and the reference points (there are 9 of them) is $B_p < 10^{-4}$ which corresponds to an uncertainty of 20 keV in the mass measurement. The other sources of error are the channel determination connected with the statistics in the peak, the target thickness ($\sim 10$ keV) and the magnetic field stability ($\sim 10$ keV).

For $^{62}$Fe and $^{68}$Ni, the present measurements have been combined with previous results reducing the final error bars.

**b) Angular distributions**

The angular distributions have been plotted for the observed levels between $0^\circ$ and $13^\circ$ C.M. (fig. 3). Since the transfer takes place at the surface of the nucleus we observe a diffraction pattern, generated by the bright ring of nuclear surface oriented perpendicular to the incident beam. As in optics, there is a concentration of intensity in a very forward angular range. The first minimum is given by that for the function $J_0(R_R)$ which takes place at very small angles for heavy ion projectiles of low energy. The concentration of the cross-section is observed to be more effective for a $\Delta L=0$ transition. It can be

![Angular distributions](image)

**Fig. 3** - Angular distributions for $^{60}$Fe - reference nuclei - and for $^{62}$Fe with the results of the DWBA.
understood in the framework of the DWBA approximation where \( \Omega_2 \) is written as
\[
\sum_M M J^2 (i) ; \text{ where } J = \Delta L \text{ is the transferred angular momentum, equal to the spin of the final level here and }
\]
\[
\tau J^2 (\theta) = (-1)^M \sum_L L L L_f (M^0) \text{ as the entrance } L_f \text{ window is narrow), the diffraction shape is observed very clearly. But for } \Delta L \neq 0, \text{ the window is broadened (} L_f = L_i + \Delta L \text{). Furthermore, when increases, the other magnetic substates (} M \neq 0 \text{ enter in expression } ii) \text{ and } i) \text{ and smear on: the diffractive pattern. This makes the small angular range very significant for heavy ion transfers.}
\]

The characteristic shape of the \( L = 0 \) angular distribution is used for spin assignment. On the basis of a comparison between the angular distribution of \( ^{56}\text{Fe} \) and \( ^{62}\text{Fe} \) (fig 3) the spin value of 0 can be eliminated for the first \( ^{62}\text{Fe} \) excited state. A similar argument is applicable for the 2nd excited state of \( ^{62}\text{Fe} \) and the excited state of \( ^{74}\text{Zn} \). All these states are very likely to be \( 2^+ \) states.

In \( ^{68}\text{Ni} \) an excited states was reported previously with poor statistics\(^4\). In this experiment using a separated \( ^{70}\text{Zn} \) target, this state is hardly visible because of the inhomogeneity of the target.

DWBA calculations have been performed with the Saturn-Mars code using the optical potentials of ref. 1. Within the restrictive assumption of a cluster form factor the fits allow one to extract the product of spectroscopic factors \( CS_1^2 \times CS_2^2 \). The results are very similar (table I) although slowly increasing with the number of proton-pairs available in the \( f - p \) shell (except for the \( ^{70}\text{Zn} \) to \( ^{68}\text{Ni} \) transition). A systematic analysis of those spectroscopic factors will be published later.

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>( T = N - 2 )</th>
<th>Previous Measurements (MeV)</th>
<th>This work (MeV)</th>
<th>Predictions (MeV) Myers Garvey-Kelson Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{62}\text{Fe} )</td>
<td>5</td>
<td>58.87 ± 0.26(^6) 58.93 ± 0.067</td>
<td>58.83 ± 0.04</td>
<td>59.10</td>
</tr>
<tr>
<td>( ^{68}\text{Ni} )</td>
<td>6</td>
<td>63.47 ± 0.038</td>
<td>63.53 ± 0.03</td>
<td>64.78</td>
</tr>
<tr>
<td>( ^{74}\text{Zn} )</td>
<td>7</td>
<td>65.67 ± 0.149</td>
<td>65.57 ± 0.04</td>
<td>67.48</td>
</tr>
<tr>
<td>( ^{80}\text{Ge} )</td>
<td>8</td>
<td>69.38 ± 0.31C</td>
<td>69.38 ± 0.06</td>
<td>71.4C</td>
</tr>
</tbody>
</table>

Table II

\( c1 \) the masses

The masses of the residual nuclei are calculated with the conservation laws applied to a two-body reaction. They are shown in table I with the results of previous measurements \( 6,7,8 \). Except for the mass of \( ^{62}\text{Fe} \) from ref 8 for which the uncertainties may have been optimistically estimated. They are compatible with the previous values. The \( ^{62}\text{Fe} \) and \( ^{68}\text{Ni} \) spectra were measured with \(^{18O},^{20Ne} \) pick-up reaction. The nuclei of \( ^{74}\text{Zn} \) an \( ^{80}\text{Ge} \) are observed unambiguously for the first time and the error bar on their masses is clearly reduced.

In table I are the values predicted by the liquid drop model of Myers\(^11\) and the values calculated with the Garvey-Kelson\(^12\) formula. Those last values are in excellent agreement with our results.

On fig. 4, we have plotted the differences between the calculated and measured
masses versus the atomic number $A$. It is interesting to note that those differences are small and nearly constant for the full $f$ 7/2 proton shell Ni and for Zn isotopes. They increase with the distance to the bottom of the stability valley with negative sign for Fe and symmetrically for Ge isotopes.

In Myers model the shell corrections are included explicitly but Garvey-Kelson are not specially accounting for shell closure in their extrapolations and the optimum agreement obtained for $Z = 28$ may result from compensating terms on each side of the shell closure.

A simplified picture of the collectivity of even-even nuclei is given by the $2^+$ excitation energy. Whether one has vibrations or rotations, a lower energy indicates a softer nucleus or one with a greater permanent deformation.

It is worth to combine the systematic survey of the $2^+$ measured excitation energy (fig. 5) with the results of the collective Hartree-Fock Bogoliubov calculations, obtained by Giraud [12] with the D1 interaction of Gogny [14] shown on fig. 6. The Ni isotopes are found to be soft except the $68$ Ni
nuclei for which, with 40 neutrons, a defined rigidity occurs. With the same number of neutrons, the $^{70}$Zn also happens to be rigid. On fig.5 there is an indication for a change in the deformation when $N$ increases from 38 to 42 compatible with the H.F.B. results. In the Ge isotopes a similar change has been reported for this neutron number both experimentally (fig.5 and ref.15) and in H.F. calculations [16].

The Fe isotopes are all calculated to be soft, although the $2^+$ excitation energy of the $^{56}$Fe ($N=28$) isotope is larger than in the other isotopes.

A more detailed analysis of those results is under process.

SUMMARY

We have studied the $(^{14}$C,$^{16}$O) reaction on a few neutron rich targets of the f-p shell in order to measure masses and spectra of very neutron rich nuclei.

The analysis of the forward angular distributions have provided indications on the spin of the final levels.

The measured masses have been compared to different predictions. The location of the first $2^+$ has been discussed in connection with the H.F.B. results.

REFERENCES

2) P. Roussel et al, N.I.M. 153 (1978) 111
3) F. Naulin et al, N.I.M. 180 (1981) 647
4) F. Pougheon and P. Roussel, Phys. Rev. Lett. 30 (1973) 1223
5) M. Bernas et al, Phys. Rev. to be published
10) P. Del Marmol et al, Nucl. Phys. A 194 (1972) 140
11) Table of isotopes (7th edition) C.M. Lederer and U.S. Shirley eds NY (1978)
12) I. Kelson, Private communication
13) Girod, Private Communication
15) M. Vergnes in the proceedings of the VI European Physical Society Nuclear Division Conferences on the Structure of Medium-heavy Nuclei, Rhodes, Grèce, May 1979
16) Grammaticos and Ripka in D. Ardouin, PhD thesis UER Physique, Nantes

DISCUSSION

J.C. Hill: What is your estimate of typical cross-sections for the $(^{15}$C,$^{16}$O) and $(^{14}$C,$^{15}$O) reactions in this mass region?

M. Bernas: For $(^{15}$C,$^{16}$O) forward angular cross-sections we found a few mbs$^{-1}$. For the $(^{14}$C,$^{15}$O) (one charge exchange) a reduction by a factor of 5 may be expected, but it depends on the total Q value of the considered reaction.

P. Armbrecht: Are there HFB-calculations available in the mass region ($Z=28$, $N=40$) and do they indicate the onset of deformation your measurements indicate?

M. Bernas: On the last figure are shown results of calculations HFB performed with D1 force. A shape transition may be indicated for Zn isotopes on each side of $N=40$. One may note that these nuclei are all soft nuclei except $^{68}$Ni and $^{78}$Zn, for which the orbitals may be more apart as their deformation looks smaller and their shape more defined. It could explain why this overlap of their wavefunction is shown to be smaller (Table 1).

O.W.B. Schulte: Do you have an idea about the cross-section of a reaction where you effectively remove four protons from the target like e.g. in a $(^{14}$C,$^{14}$Ne) process?

M. Bernas: The worst situation is a reduction by a factor of 10 for each extra proton pick-up, but it could be tried first in the stability valley.
THE DECAY OF A NEW NUCLIDE: $^{71}$Br


Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

Abstract

The decay of mass-separated samples of the previously unknown nuclide $^{71}$Br have been investigated by means of the Chalk River on-line isotope separator. Eleven $\gamma$-transitions were assigned to the decay of this nuclide and its half-life was measured to be $21.4 \pm 0.6$ s. A simple decay scheme for $^{71}$Br has been constructed, incorporating six levels in its daughter, $^{71}$Se. The half-life of the first excited state in $^{71}$Se was measured to be $5.5 \pm 1.0$ ms and the transition from this state to the ground state was found to be highly converted. Systematic trends in the level schemes of $^{67}$Zn, $^{69}$Ge and $^{71}$Se are investigated.

I. Introduction

Nuclides close to the centre of the $28 < (N,Z) < 50$ shell have been found to be strongly deformed. The effects of the subshell closures at $Z=40$ and $N=38$, seen in the region of stable nuclei, vanish entirely for nuclides near $^{68}$Zr and instead strong collective effects are seen. Nuclides near the middle of the fp shell have therefore been the subject of many investigations. Here, collective phenomena, the coexistence of different shapes in the same nucleus have also evoked interest in such investigations. It is of considerable interest to study systematic trends in this region and to delineate more precisely the onset of deformation.

The nuclide $^{71}$Br is situated about half-way between the centre of the fp shell and its edge. The $\beta$-decay of this nuclide populates the $N=37$ nuclide $^{71}$Se and thus offers an opportunity to study the effect of the $N=38$ subshell closure in that region. The decay of $^{71}$Br has not yet been reported. The only previous indication of its existence was the observation of a deviation from pure exponential decay of $^{71}$Se, the $\beta$-decay daughter of $^{71}$Br. This effect was attributed to build-up from the decay of $^{71}$Br whose half-life was estimated to be 'somewhat less than 1 min'.

We wish to present here results for the decay of the $T_2=1/2$ nuclide $^{71}$Br. Eleven $\gamma$-rays were assigned to the decay of this nuclide and a simple scheme incorporating six levels in $^{71}$Se has been constructed. This level scheme is compared to those of the neighbouring $N=37$ isotones $^{67}$Zn and $^{69}$Ge and systematic trends are examined.

II. Experimental Procedure

Neutron deficient bromine isotopes were produced by bombarding a target of 2.5 mg/cm$^2$ natural calcium with a 132 MeV beam of $^{35}$Cl, the evaporation residues recoiling through a thin tantalum window into the porous graphite catcher of the FEBATD ion source of the Chalk River on-line isotope separator. Bromine isotopes are readily released from the catcher and ionized in the plasma region of the source. After acceleration and separation according to mass, a selected beam was directed into a beam transport line connecting the isotope separator with an experimental counting chamber. The beam was implanted into the tape of a small cassette tape transport system inside the experimental chamber.

Singles $\gamma$-rays from a saturated sample on the stationary tape were first detected in a 110 cm$^3$ Ge(Li) detector situated immediately behind the tape. Then, in a second arrangement the Ge(Li) detector was placed in a shielded counting position 76 mm away from the collection position. After a collection time of 40 s the separator beam was deflected and intercepted on a slit 5 m upstream from the experimental chamber. The collected sample on the tape was subsequently moved in front of the Ge(Li) detector and eight consecutive spectra were recorded, each for a 10 s counting period.

The absolute intensities of the $\gamma$-rays from the decay of $^{71}$Br were deduced from a third experiment in which the sample on the tape was stopped inside an aluminum block thick enough to stop and annihilate all positrons with less than 9 MeV energy. Eight consecutive $\gamma$ spectra were recorded with a Ge(Li) detector immediately behind the aluminum block, and the intensity of the strongest $\gamma$-ray from $^{71}$Br was determined relative to the component of the annihilation radiation peak that has the same half-life.

Coincidences between $\gamma$-rays and X-rays or low energy $\gamma$-rays were observed in a fourth experimental arrangement also situated along the path of the tape. Gamma rays were observed with the same Ge(Li) detector as used in the earlier experiment while a 200 mm$^2 \times 7$ mm intrinsic Ge detector was used for the low energy events. The two detectors were arranged 90$^\circ$ apart. Singles spectra of low energy events were also recorded with the intrinsic Ge detector.

III. Results

The $\gamma$-ray spectrum obtained with the first experimental arrangement from a saturated source collected from the mass 71 beam is shown in Fig. 1. Number of peaks originating from $^{71}$Se and $^{71}$As as well as peaks due to room background from activities belonging to the decay chains of $^{232}$Th and $^{238}$U can be seen in this spectrum. In

† Queen's University, Kingston and University of Toronto, Toronto, Ontario, Canada
‡‡ Queen's University, Kingston, Ontario, Canada
* DFG fellow on leave from University of Göttingen, Federal Republic of Germany
** University of Toronto, Toronto, Ontario, Canada
Fig. 1: The spectrum of γ-rays observed from a saturated source of activity from the mass 71 beam of the isotope separator. All peaks assigned to the decay of $^{71}$Sr are marked by arrows. The number above the arrow corresponds to the number given to each γ-transition in Table 1. Peaks due to coincident summing with annihilation radiation are denoted by SA.

Table 1

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>Energy (keV)</th>
<th>Relative γ-intensity$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.78 ± 0.05</td>
<td>17 ± 3</td>
</tr>
<tr>
<td>2</td>
<td>122.72 ± 0.05</td>
<td>64 ± 5</td>
</tr>
<tr>
<td>3</td>
<td>171.6 ± 0.1</td>
<td>77 ± 6</td>
</tr>
<tr>
<td>4</td>
<td>233.7 ± 0.1</td>
<td>81 ± 6</td>
</tr>
<tr>
<td>5</td>
<td>260.5 ± 0.1</td>
<td>100 ± 5</td>
</tr>
<tr>
<td>6</td>
<td>282.4 ± 0.1</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>7</td>
<td>387.4 ± 0.2</td>
<td>21 ± 3</td>
</tr>
<tr>
<td>8</td>
<td>474.6 ± 0.2</td>
<td>26 ± 4</td>
</tr>
<tr>
<td>9</td>
<td>647.6 ± 0.3</td>
<td>15 ± 3</td>
</tr>
<tr>
<td>10</td>
<td>756.9 ± 0.2</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>11</td>
<td>796.4 ± 0.4</td>
<td>56 ± 6</td>
</tr>
</tbody>
</table>

$^a$For absolute intensity per 100 decays of $^{71}$Sr divide by 12.1.

addition to these well-known γ-transitions, 14 previously unknown peaks are seen in the spectrum. Ten of these were intense enough that their (common) half-life could be determined. Another low energy γ-ray as well as Se X-rays were observed to decay with that same half-life in the spectra obtained with the intrinsic Ge detector (Fig. 2). This half-life was determined to be 21.4 ± 0.6 s from the measured decay curves of the four most intense γ-rays as well as the Se X-rays. The energies and relative intensities of the 11 γ-transitions exhibiting half lives consistent with this value are shown in Table 1.

The mass number 71, can be unambiguously assigned to the new activity owing to the use of mass separated samples. The element assignment is restricted to Kr, Br or Se from the target-projectile combination and the energy of the projectiles. The assignment of the γ-transitions listed
in Table 1 to the decay of $^{71}$Br is based on the following arguments.

(i) The half-life values of $^{71}$Kr and $^{71}$Se, known to be 97 ± 9 ms and 4.74 ± 0.05 min respectively, are not compatible with our measured value of 21.4 ± 0.6 s.

(ii) Se X-rays were observed with a 21.4 s half-life and, furthermore, the most intense γ-rays shown in Table 1 were also found to be coincident with Se X-rays.

(iii) A composite decay curve was established for the 147.5 keV γ-transition, which originates from the decay of $^{71}$Se (the β-daughter of $^{71}$Br). This decay curve was found to be compatible with a genetic relationship between two activities with half-lives of 21.4 s and 4.74 min.

(iv) The parameters chosen for the operation of the isotope separator ion source favoured the extraction of bromine ions. Tests performed with heavier (i.e., well-known) isotopes of the same elements showed that with the same ion source parameters no Kr was produced and only minute amounts of Se appeared.

The γ-γ coincidence measurements initially yielded no conclusive results and in particular those events that included the 48.78 keV γ-ray, the lowest energy transition assigned to $^{71}$Br, did not produce a prompt peak in the time spectrum even though the counting statistics should have been sufficient to have done so. It was concluded that the half-life of the state emitting this γ-ray was longer than our 1 μs sensitivity, and a separate two-parameter coincidence experiment was designed to measure it. In this case we used any event between 150 and 520 keV in the Ge detector as a start signal, and then recorded both the energy of any subsequent event in the intrinsic Ge detector and its time of occurrence after the start. In this experiment, delayed events were seen in time spectra for the 48.78 keV γ-transition and for Se X-rays. Statistically consistent half-lives were obtained from the decay curves of both types of delayed events. The weighted average for the half-life is 5.5 ± 1.0 μs.

The K-conversion coefficient for the 48.78 keV transition was deduced from the intensity ratio between delayed Se Kα X-rays and delayed 48.78 keV γ-rays observed in the two-parameter coincidence experiment. The result, $\alpha_k = 9.6 ± 2.1$, was determined with the values for the fluorescent yield and for the K/K ratio given in the Table of Isotopes.

The intensity of the 21.4 s component of the annihilation radiation relative to that of the 260.5 keV γ-transition from $^{71}$Br was determined with the annihilation set-up. The resulting value for the ratio between the number of positrons emitted in the decay of $^{71}$Br and the number of 260.5 keV γ-rays was deduced to be 12.1 ± 3.6.

**IV. Discussion**

A tentative decay scheme of $^{71}$Br is shown in fig. 3. It should be noted that the only proven coincidence relation in this decay scheme is the one between the 122.72 and 48.78 keV γ-rays depopulating an excited state at 171.53 keV. All other states proposed in $^{71}$Se are based on energy sums of γ-rays assigned to the decay of $^{71}$Br with the further requirement that at least two γ-ray channels must agree for each level assignment. According to the latter criteria one γ-transition, at 796.4 keV, could not be definitely placed in the decay scheme.

If the decay scheme shown in fig. 3 is accepted then our measured value of 12.1 ± 3.5 for the intensity ratio of decay positions to 260.5 keV γ-rays translates into a ground state β branch of (60 ± 15%). The intensities of the β-transitions populating the proposed excited states in $^{71}$Se can in principle be determined from a comparison of the total γ intensity depopulating each level to that seen feeding it. However, the resulting side-feeding would be comparable in intensity to those unknown γ-rays whose half-life could not be determined due to poor counting statistics and, consequently, could not definitely be assigned to the decay of $^{71}$Br. The uncertainties of the excited state β-branches...
would therefore be comparable to the branches themselves and no dependable conclusion could be based on the resulting log ft values. Consequently the only reliable log ft value that can be deduced from the present measurement is that for the strong ground state branch: viz., 5.17 ± 0.11.

The first excited state of $^{71}$Se has a half-life of 5.5 ± 1.0 μs, as is demonstrated by our measured decay curve for the 48.78 keV transition. The K conversion coefficient for the transition from this state to the ground state of $^{71}$Se, deduced to be 9.6 ± 2.1, agrees very well with a pure E2 assignment (theoretical 12) 9.2) and is not compatible with any other assignment.

The level scheme of $^{71}$Se is presented together with those of $^{67}$Zn and $^{69}$Ge, its closest n=37 isotones, in fig. 4. The levels shown for $^{67}$Zn and $^{69}$Ge have previously been identified2, 4, 13, 16 either as single particle states arising from the odd neutron, or as configurations originating from coupling the same single particle states to vibrational states in the neighbouring even-even nuclides. The three level schemes shown in fig. 4 are all quite similar and offer an opportunity to look for systematic trends.

Some specific remarks on some of the levels of $^{71}$Se are given below.

The ground state. The spin and parity of the ground state of $^{71}$Se is known10) to be $5/2^-$. The present log ft value of 5.17 for the $8$-transition to the ground state clearly indicates that this transition is allowed and hence the spin and parity of $^{71}$Br is $(3/2, 5/2, 7/2)^-$. The 48.78 keV state. Since the measured conversion coefficient for the 48.78 transition agrees very well with a pure E2 assignment, the spin of the first excited state in $^{71}$Se is presumably either 1/2 or 9/2 with negative parity. The first alternative is preferred from the systematic occurrence of a low-lying $p_1/2$ single particle state in the neighbouring isotones (fig. 4). The reduced transition probability of 1.7 ± 0.5 W.u., determined for the 48.78 keV transition, indicates the single particle nature of this state and lends further support for a $1/2^-$ assignment.

The 171.5 and 282.4 keV states. Both these states decay to the ground state and the first excited state by γ-transitions of comparable intensities. The same decay pattern has been found for the two lowest 3/2$^-$ states in $^{67}$Zn and $^{69}$Ge (fig. 4). Based on systematics one might then speculate that the 171.5 keV level found in $^{71}$Se has $\text{J}^\pi=3/2^-$ and originates from the coupling of the odd $f_5/2$ neutron to the $2^+$ first excited state $3^-$ in $^{70}$Se while the 282.4 keV level is the $3/2^-$ neutron hole state2, 4, 13, 16).

The 260.5 and 647.8 keV states. Apart from γ-ray branches feeding the $5/2^-$ ground state of $^{71}$Se neither of these two

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Fig. 4: The low energy level schemes of $^{67}$Zn, $^{69}$Ge and $^{71}$Se. The branching ratios shown for $^{67}$Zn were taken from Duffait et al.13) and from reference 11. The branching ratios for $^{69}$Ge were taken from Alexandrov et al.14).
states exhibit any branches to low-lying states in $^{71}\text{Se}$. However, there is a strong $\gamma$-branch connecting the two states. This fact together with systematics from $^{67}\text{Zn}$ and $^{69}\text{Ge}$ suggests that the two states have positive parity. The 260.5 keV level would then be the $g_{9/2}$ neutron single particle state and the 647.8 keV level would be the $5/2^+$ state arising from the coupling of the $g_{9/2}$ neutron to the $2^+$ first excited state in $^{70}\text{Se}$.

Without more detailed information on the decay of $^{71}\text{Br}$, it is not possible to obtain a measure of the deformation of $^{71}\text{Se}$. However, tentative conclusions can be made as to whether $^{71}\text{Se}$ is more or less deformed than its neighbours. A signature of increasing deformation for a $(f_{5/2})^{-1}$ configuration is a significant lowering of the $g_{9/2}$ state and, to some extent, of the $p_{1/2}$ state with respect to the $f_{5/2}$ ground state. If our speculation on the origins of the excited states in $^{71}\text{Se}$ are correct then such a trend of increasing deformation is indeed seen when going along the n=37 isotones from $^{67}\text{Zn}$ to $^{71}\text{Se}$. Irrespective of our interpretation of the origin of the excited states in $^{71}\text{Se}$, these states are generally found at a lower excitation energy than those of $^{67}\text{Zn}$ and $^{69}\text{Ge}$ indicating that $^{71}\text{Br}$ is continuing the trend to a region of deformation.

References

7) H. Schmeing, J.C. Hardy, E. Hagberg, W.L. Perry and J.S. Willis, accepted for publication in Nucl. Instr. and Methods
10) F. Kearnns and J.N. Mo, Nuclear Data Sheets 27 (1979) 517.
SPECTROSCOPIC AND DECAY ENERGY MEASUREMENTS FOR ISOTOPES WITH 79 ≤ A ≤ 84 AND N ≈ Z.

Brookhaven National Laboratory, Upton, NY 11973 USA

Abstract

Heavy-ion reactions induced by beams of 24, 25, 26Mg and 28Si on targets of 58Ni and 60Ni have been used to produce a number of new or poorly characterized radioactivities with 79 ≤ A ≤ 84 and N ≈ Z. The helium-jet recoil transfer technique was employed as a means of continuously preparing essentially massless sources of these radioactivities for extensive x-, γ-, and p-ray singles and multichannel coincidence spectroscopic measurements. The low lying level structure of 80Sr has been revealed for the first time by the decay of a new isotope 80y (T1/2 = 34 sec). These measurements have also resulted in a considerable clarification of the decay properties of 79Sr, and 81,82Y. Decay energies, Qdc, and nuclidic mass excesses deduced from them, both show progressively larger deviations from the predictions of currently available mass models for these isotopes, especially as the N = Z line is approached. Preliminary decay data are reported for 83Zr and 84Nb, which were both produced as evaporation residues from the 28Si + 58Ni reaction.

1. Introduction

The very neutron deficient isotopes of Rb, Sr, Y, Zr, and Nb constitute a group of nuclei whose predicted decay energies1,2 and reported spectroscopic properties3 suggest that they have been, at best, only partially characterized. Numerous conflicting reports3 have been made for a number of these radioactivities, e.g. 73Sr; others, like 78Sr, have reported half-lives which are decidedly at variance with the predicted decay energies and the half-life estimates derivable from the gross theory of beta decay.

This mass region, near 80Sr, which can be reached conveniently by heavy-ion reactions, is thought to be one of rapidly changing nuclear deformation. Excitation energies of the first 2+ levels in even-even nuclei in this region are known4 to vary strongly and systematically with both N and Z, indicative of the coupling of deformation to neutron and proton orbital occupancy in shells which are partially filled between the major shell closures at 28 and 50 nucleons.

A comprehensive program of spectroscopic investigations5,6 in this region has been underway at BNL for the past few years. The aims of this program are: 1) searches for new isotopes which lie on or near the N = Z line; 2) clarification of the decay properties of poorly characterized isotopes in this region; 3) decay energy, Qdc, measurements and the inference of nuclidic masses from these data to provide tests of mass models and aid in their refinement; and 4) comparison of energy level structures and γ-ray transition probabilities with predictions from theory, with special emphasis on the Interacting Boson Approximation model. This paper summarizes our more recent results.

2. Experimental

Most of the results given below were obtained from measurements using the BNL Tandem Van de Graaff facility and the helium-jet system7 shown in fig. 1. Optimization of the yields of

![Fig. 1 The BNL helium-jet system.](image)

the desired radioactive product(s) was obtained by careful selection of projectile-target combinations and beam energy. Evaporation calculations8 were performed to select optimal beam energies and in some cases "in-beam" γ-ray measurements were also made to check the predictions of the excitation functions from the evaporation calculations and as a cross confirmation of isotopic assignments in those cases where a particular γ-ray transition arose from both "out-of-beam" radioactive decays and from in-beam deexcitation of evaporation residues produced directly in the heavy-ion reaction. One off-line, radiochemical experiment designed to look for the reported5 31 min. 78Sr was also performed. Results5 were negative.

An important additional technique used to enhance the yield of particular products involved the "half-life tuning" of the shuttle time of the collection tape so that interferences from long-lived daughter activities could be effectively eliminated by periodic removal of the sources from the detector area after the collection and counting period of the short-lived isotope of interest ended. Decay curves were generated from a time-from-shuttle tag recorded with each counting event.

In addition to x- and γ-ray counting (singly and in coincidence mode), 8-ray spectra in coincidence with x or γ-rays were accumulated using an NE102 plastic detector. This detector was
calibrated using the shape function procedure of Davids et al. Representative positron calibration spectra are shown in fig. 2. The inset shows the linear behavior of the stretch factor, $a$, on the endpoint energy. Positron endpoint energies obtained for $^{79}$Sr, and $^{80-82}$Y were used to determine $Q_{\gamma\gamma}$ values for these activities. Errors attributed to measurements of this type were estimated from the nonlinear least squares shape fitting procedure, the statistical quality of both the calibration and "unknown" spectra and the linearity and reproducibility of the detector response. Where several different $(B,\gamma)$ gates were used in a particular decay, the error in the resultant endpoint reflects the composite of the individual determinations and their errors.

3. Results

3.1 New Isotope 34 sec $^{80Y}$

Early in the present series of studies of the neutron deficient nuclei produced in the $^{24}$Mg + $^{58}$Ni reaction, the presence of three $\gamma$ rays ($386$, $595$, and $783$ keV) was noted. Each decayed with $T_1/2 \approx 3$ sec and subsequent coincidence measurements established that these $\gamma$ rays formed a prompt cascade. Nolte et al. in an investigation of the yrast states of $^{80}$Sr via the $^{68}$Zn($^{16}$O,2$n$) reaction had placed $\gamma$ rays of the same energies as cascade transitions originating from the $6^+$ level of the $^{80}$Sr ground state band. The observation of these same transitions in the radioactivity spectra indicated the production of a new isotope, $^{80}$Y, from the $^{58}$Ni($^{24}$Mg,3$n$) $^{80}$Y reaction and its decay to $^{80}$Sr. The yield of $^{80}$Y was optimized with $55$-MeV $^{24}$Mg beams and extensive coincidence measurements, $(\gamma,\gamma)$, $(\gamma,\gamma)$, and $(\gamma,\gamma)$, were used to establish the decay scheme shown in fig. 3. The $Q_{\gamma\gamma}$ of $80\gamma$, $6952 \pm 152$ keV, Table 1, was determined from positron end point measurements of the 386- and 595-keV $\gamma$-ray gates, fig. 4.

![Fig. 2 Typical positron spectra used for calibrating the plastic detector. Spectrum A from $^{27}$Al(p,n)$^{28}$Si; spectrum B from $^{58}$Ni(p,n)$^{58}$Cu.](image)

![Fig. 3 Decay scheme of $^{80}$Y](image)

![Fig. 4 Positron spectra in coincidence with the 386- and 595-keV $\gamma$-rays in $^{80}$Sr.](image)

Discussion of the $^{80}$Sr level scheme and the $^{80}$Y $Q_{\gamma\gamma}$ can be found in section 4.

3.2 The decay of 1.3 min $^{79}$Sr

Conflicting reports have appeared on the decay of $^{79}$Sr. Bliige and Boswell reported
TABLE I. Measured positron end points and QEC values for $^{79}$Sr and 80–82Y

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Gating transition (keV)</th>
<th>$E_{\text{max}}$ (keV)</th>
<th>QEC (keV)</th>
<th>QEC adopted (keV)</th>
<th>QEC previously reported (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{79}$Sr</td>
<td>135</td>
<td>4065(120)</td>
<td>5621(120)</td>
<td>5258(104)</td>
<td>5259(78)</td>
</tr>
<tr>
<td></td>
<td>141</td>
<td>3952(104)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{80}$Y</td>
<td>386</td>
<td>5554(306)</td>
<td>6968(306)</td>
<td>6948(175)</td>
<td>6952(152)</td>
</tr>
<tr>
<td></td>
<td>595</td>
<td>4945(175)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{81}$Y</td>
<td>124</td>
<td>4235(112)</td>
<td>5460(112)</td>
<td>5333(135)</td>
<td>5408(86)</td>
</tr>
<tr>
<td></td>
<td>408</td>
<td>3701(135)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{82}$Y</td>
<td>573</td>
<td>6273(185)</td>
<td>7868(185)</td>
<td>7868(185)</td>
<td>7620(100)$^a$</td>
</tr>
</tbody>
</table>

$^a$Reference 14.

$T_{1/2} = 8.1$ min, whereas half-lives of 4.4 min and 1.9 min were reported by Ladenbauer-Bellis et al. $^{11}$ and Doran and Blann $^{12}$, respectively. Our reinvestigation of this decay using $^{79}$Sr sources from the reaction $^{58}$Ni($^{28}$Mg,p) at 90 MeV yielded a half-life of $2.3 \pm 0.1$ min. This result has been confirmed by other recent measurements of 2.52 min (Florida State University) $^{13}$ and 1.9 min (Oakley) $^{14}$. The $^{79}$Sr QEC was determined from positron spectra obtained from 135- and 141-keV γ-ray gating transitions. The 39-keV line reported $^{13}$ by the FSU group has been observed in our K-γ coincidence studies and it has been found $^{6}$ to result from the deexcitation of an isomeric level in $^{79}$Rb at that energy which has a lifetime of $23 \pm 1$ ns. The $^{79}$Sr decay scheme is shown in fig. 5.

Fig. 5 The decay scheme of $^{79}$Sr.

3.3 The decay of $^{81}$Y

Optimum production of $^{81}$Y, relative to other isotopes, was found to occur with the $^{58}$Ni($^{28}$Mg,p) $^{81}$Y reaction at 100 MeV. Three strong γ-ray transitions of $^{79}$, 124, and 408 keV were observed to decay with a half-life of 72.0 ± 1.5 sec. No evidence was found for the reported 5 min activity $^{3}$ attributed to $^{81}$Y. Coincidence measurements confirmed that the three γ-rays formed a cascade. However, ratios of their intensities were quite different in the singles and coincidence data. This fact, coupled with the observation of intense K X-rays of Rb in coincidence with the 79- and 124-keV lines, indicated the presence of one or more isomeric states in $^{79}$Sr. A lifetime of 370 ± 85 nsec was established for the 79-keV level from examination of the 79-124 keV TAC spectrum. Our data also suggest the presence of a second, highly converted transition (E < 50 keV). The $^{81}$Y decay scheme is shown in fig. 6.

Fig. 6 The decay scheme of $^{81}$Y.

QEC values for $^{81}$Y (Table I) were obtained from (8,γ) coincidence spectra gated by the 124- and 408-keV rays.

3.4 The decay of 9.5 sec $^{82}$Y

Gamma-ray transitions between low-lying levels in $^{82}$Sr reported $^{4,15}$ from in-beam experiments are not consistent with the decay properties attributed $^{3}$ to 10 min $^{82}$Y. When spectra were examined from sources produced from $^{28}$Mg beams on natural Ni targets, γ-ray transitions whose intensities decayed with $T_{1/2} = 9.520 \pm 0.4$ sec were observed. Some of these transitions matched in energy those placed in the $^{82}$Sr level scheme from the in-beam studies. Subsequent confirmation of their assignment to the $^{82}$Y decay came from the absence of these γ rays when enriched $^{58}$Ni targets were used, and the strong presence of these lines when using highly enriched $^{60}$Ni targets. Deprun et al. $^{14}$ report $T_{1/2} = 9.520 \pm 0.5$ sec for $^{82}$Y and Medsker et al. $^{16}$ reported $T_{1/2} \approx 9$ sec for
TABLE II. Decay scheme information for \( ^{82}\text{Y} \) \( \left( T_{1/2} = 9.5 \pm 0.4 \text{ sec} \right) \)

<table>
<thead>
<tr>
<th>( E_{\nu} ) (keV)</th>
<th>( E_y ) (keV)</th>
<th>( I_y ) (arb)</th>
<th>( J^p_1 )</th>
<th>( J^p_2 )</th>
<th>Multipolarity</th>
<th>Log ft</th>
<th>Coincident transitions (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>573.68 ( \pm 0.09 )</td>
<td>573.68 ( \pm 0.09 )</td>
<td>100</td>
<td>2(^+\rightarrow) 0(^+)</td>
<td>E2</td>
<td>5.14</td>
<td>602,737</td>
<td></td>
</tr>
<tr>
<td>1175.67 ( \pm 0.10 )</td>
<td>602.14 ( \pm 0.09 )</td>
<td>41 ( (2)_x^{+}\rightarrow 2^{+} )</td>
<td>E2/M1</td>
<td>4.98</td>
<td>573</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1311.03 ( \pm 0.14 )</td>
<td>737.35 ( \pm 0.10 )</td>
<td>9 ( 0^{+}\rightarrow 2^{+} )</td>
<td>E2</td>
<td>5.61</td>
<td>573</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE III. \( \gamma \)-rays observed in the decay of \( ^{83}\text{Zr} \) \( \left( T_{1/2} = 45 \pm 4 \text{ sec} \right) \)

<table>
<thead>
<tr>
<th>( E_y ) (keV)</th>
<th>( I_y ) (arb)</th>
<th>Coincident ( \gamma ) rays (keV)</th>
<th>( E_y ) previous work (^a) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>--</td>
<td>255,474,617</td>
<td>106</td>
</tr>
<tr>
<td>105</td>
<td>221</td>
<td>105,255,305</td>
<td>256</td>
</tr>
<tr>
<td>255</td>
<td>70</td>
<td>102,654,712</td>
<td>303</td>
</tr>
<tr>
<td>304</td>
<td>100</td>
<td>55,221</td>
<td>474</td>
</tr>
<tr>
<td>474</td>
<td>47</td>
<td>105,712</td>
<td>475</td>
</tr>
<tr>
<td>617</td>
<td>712</td>
<td>105,255</td>
<td>474</td>
</tr>
<tr>
<td>828</td>
<td>1133</td>
<td>105,255,304</td>
<td>55</td>
</tr>
<tr>
<td>1602</td>
<td>1664</td>
<td>255,304</td>
<td>474</td>
</tr>
<tr>
<td>1917</td>
<td>--</td>
<td>255,304</td>
<td>474</td>
</tr>
</tbody>
</table>

\(^a\)Reference 17.

this activity. Table II summarizes the features of the \( ^{82}\text{Y} \) decay. \( Q_{\text{EC}} \) for \( ^{82}\text{Y} \) was measured using the 574-keV ray (Table I).

3.5 The decays of 45 sec \( ^{83}\text{Zr} \) and 10 sec \( ^{84}\text{Nb} \)

The isotopes \( ^{83}\text{Zr} \) and \( ^{84}\text{Nb} \) were prepared with beams of 95-MeV \( {}^{28}\text{Si} \) on \( {}^{58}\text{Ni} \) via \( 2p \) and \( 3p \) evaporation channels respectively. Results for \( ^{83}\text{Zr} \) (Table III) confirm the earlier assignment of Kaba and Miyano. \(^{17}\) In addition, several more \( \gamma \)-rays have been assigned to this decay on the basis of half-life and/or coincidence relationships. A study of \( ^{83}\text{Y} \) levels by in-beam techniques is in progress to complement the \( ^{83}\text{Zr} \) decay data and to aid in the construction of the decay scheme. For \( ^{84}\text{Nb} \), \( \gamma \)-ray transitions of 549 and 580 keV were observed to be in coincidence and the intensity of the stronger 549-keV line exhibited a half-life of 10.0 \( \pm \) 0.7 sec. The 723-keV \( \gamma \) ray attributed to this decay by Korschinek et al. \(^{18}\) was not observed (\( \tau_{1/2} < 4 \times \tau_{1/2} \) \( ^{84}\text{Sr} \)).

4. Discussion

4.1 Comparison of \( ^{80}\text{Sr} \) levels to predictions of the Interacting Boson Approximation model (IBA-1)

The decay of \( ^{80}\text{Y} \) has revealed \(^{5,6}\) the low-lying, non-\( \text{yrast} \) states of \( ^{80}\text{Sr} \) for the first time. \( ^{80}\text{Sr} \), situated between the shell closures at \( N\geq 28 \) and \( N\geq 50 \), can be considered a nine boson system within the framework of the IBA model. Calculation of the \( ^{80}\text{Sr} \) level energies and \( \gamma \)-ray transition probabilities have been performed with the IBA-1 code PRINt. Three different calculations, whose results are summarized in fig. 7 and compared to experiment (leftmost column) were performed. These corresponded to 1) use of the IBA-1 parameters reported \(^{19}\) for \( ^{78}\text{Kr} \) (isotone of \( ^{80}\text{Sr} \)); 2) \( ^{80}\text{Sr} \) at the \( SU(3) \) limit; and 3) \( ^{80}\text{Sr} \) at the \( O(6) \) limit. The level scheme of \( ^{80}\text{Sr} \), like that of \( ^{78}\text{Kr} \), appears to correspond reasonably well to that predicted for the nine boson system at or near the \( O(6) \) limit. The branching ratio of the \( (4_2^+ \rightarrow 4_1^+) \) state at 1833 keV was calculated to be: Branching Ratio \( (4_2^+ \rightarrow 2_2^+) / (4_2^+ \rightarrow 4_1^+) = 1.05 \) in contrast to the experimental value of 0.37. However no \( 4_2^+ \rightarrow 4_1^+ \) branch was observed to a limit of \( < 5\% \), which conforms to the \( \Delta I = 2 \)
selection rule in the O(6) limit. Introduction of a Q\textsuperscript{0} breaking term to the O(6) limit, while reducing differences between predicted and experimental level energies, did not significantly improve the predictions of transition probabilities. Candidates for the states at 1571 and 1663 keV are J\textsuperscript{π} = 3\textsuperscript{−} and 3\textsuperscript{−} respectively.

4.2 Nuclidic masses

The Q\textsubscript{cc} measurements for 79Sr and 80–82Y are useful for delineation of features of the nuclidic mass surface at A \approx 80, and N \approx Z. Fig. 8 shows comparison of the differences, Δ,

![Fig. 8 Comparison of experimental Q\textsubscript{cc} values for 79Sr and 80–82Y (Table IV) with predictions from nuclidic mass models (see text).](image)

between measured and predicted Q\textsubscript{cc} values for these nuclides. Each numbered arrow in the figure corresponds to the Δ value obtained from different models for each isotope, e.g. (from reference 1): 1=Myers; 2=Groote et al.; 3=Seeger and Howard; 4=Liran and Zeldes; 5=Janczke, Garvey-Kelson; 6=Comay and Kelson; 7=Janczke and Eynon; (from reference 2) 8=Monahan and Serduke. A similar comparison of deduced and predicted mass excesses is illustrated in fig. 9. Table IV shows mass

![Fig. 9 Comparison of mass excesses for 79Sr and 80–82Y (Table IV) with predictions from nuclidic mass models (see text).](image)

Table IV. Computed mass excesses for 79Sr, 80Y, 81Y, and 82Y.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rb mass excess\textsuperscript{a} (MeV)</th>
<th>Strontium mass excess\textsuperscript{b} (MeV)</th>
<th>Yttrium mass excess\textsuperscript{c} (MeV)</th>
<th>Resultant mass excess\textsuperscript{d} (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>79Sr</td>
<td>-70.86(11) 5.26(8)\textsuperscript{b}</td>
<td>-65.60(13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80Y</td>
<td>-72.19(2) 1.91(3)\textsuperscript{c}</td>
<td>-63.33(16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81Y</td>
<td>-75.45(4) 4.00(3)\textsuperscript{c}</td>
<td>-51.4(19)</td>
<td></td>
<td>-66.04(10)</td>
</tr>
<tr>
<td>82Y</td>
<td>-76.21(2) 0.21(2)\textsuperscript{d}</td>
<td>7.87(19)</td>
<td></td>
<td>-68.13(20)</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Reference 20.  
\textsuperscript{b}Present work.  
\textsuperscript{c}Computed from data of Ref. 21.  
\textsuperscript{d}Reference 22.

excesses for 79Sr and 80–82Y that were calculated from the reported masses of 79–82Rb by addition of decay energy of 79Sr and the decay energies for Sr and Y isotopes for A = 80 to 82.

Fig. 8 exhibits several interesting features. For 79Sr and 80,81Y, model predictions of the Q\textsubscript{cc} values for these nuclides are within 1 MeV of the experimental values with more of the models indicating too high a decay energy rather than too low. The measured Q\textsubscript{cc} for 80Y differs from the predictions by as much as 3.5 MeV with all models predicting too high a decay energy. Fig. 9 shows similar trends in that Δ values are again nearly always large and negative, spanning an even greater range than those for Q\textsubscript{cc}. It is also noteworthy that there is some general self-consistency in these predictions. In both the Q\textsubscript{cc} and mass excess comparisons, the rank ordering of the models by sign and magnitude of Δ is generally the same for the four nuclides. At the extremes are the models\textsuperscript{1} of Myers (labeled 1) and of Liran and Zeldes (labeled 4).

The suggestion that the mass region around N=40, Z=40 is one characterized\textsuperscript{4} by rapid changes in nuclear deformation raises the question of the influence of this property on the masses of nuclides in this region. The neutron deficient Rb isotopes, whose masses have been determined\textsuperscript{20} down to A = 74, span part of this region of deformation, although the magnitude of the effects signaled by the 2\textsuperscript{+} = 0\textsuperscript{+} energy spacing in the neighboring Sr and Kr isotopes is smaller as one proceeds away from N = Z = 40. Comparison of the differences between experimental and predicted masses for the light Rb isotopes show trends similar to Figs. 8 and 9, although no single Rb case displays quite the same magnitude as seen for 80Y.

5. Acknowledgements

The authors wish to acknowledge the help of the BNL Tandem Van de Graaff laboratory staff for computer assistance, target preparation, and for providing the heavy-ion beams used in this investigation. We are indebted to L. Medsker and Y. Lehée for valuable information prior to publication from their radioactivity studies in the mass 80 region. Assistance from R. Casten in performing the IBA model calculations for 80Sr is gratefully acknowledged. This research has been performed under Contract No. DE-AC02-76 CH00016 with the Division of Basic Energy Sciences, U.S. Department of Energy.
References

* Present address: Shuster Laboratory, Department of Physics, University of Manchester, Manchester, M13 9PL, England.
3. See, for example; Table of Isotopes, seventh edition, ed. by C. M. Lederer and V. S. Shirley, J. Wiley and Sons, New York (1978).
16. L. Medsker, private communication.
DECAY PROPERTIES OF $^{81}$Ga AND $^{81}$Ge AND OBSERVATION OF ABNORMAL ENERGY SHIFT IN THE $^{1/2}$ STATE

P. Hoff, K. Aleklett, B. Fogelberg, E. Lund and G. Rudstam
The Studsvik Science Research Laboratory, S-611 82 Nyköping, Sweden

Abstract

$^{81}$Ga is efficiently produced in the isotope separator on-line facility OSIRIS at Studsvik, utilizing thermal fission of 235U. The fission products are extracted from a combined target/ion-source system and mass-separated. Gallium is one of the most favourable elements for this ion-source. The germanium isobar is studied as daughter products.

Investigations involving singles γ-ray spectroscopy, γγ-coincidences, βγ-coincidences and level half-life measurements have been performed. Detailed decay schemes for $^{81}$Ga (T1/2 = 1.23 s) and the two isomers of $^{81}$Ge (both with T1/2 = 7.6 s) are presented. The lowest lying states in $^{81}$Ge are interpreted within the framework of the collective model. Positive parity intruder states are observed and characterized. A shift of about 500 keV in the relative energy of the $^{1/2}$ state is observed, resulting in a 1/2$^+$ β-decaying isomeric state in $^{81}$Ge. In the decay of the high-spin isomer of $^{81}$Ge, selective population of a small number of states is observed.

On the basis of the level schemes and the $\beta\gamma$-coincidence measurements, total β-decay energies of both nuclides have been deduced.

1. Introduction

Although they are expected to possess interesting structural phenomena, the neutron-rich nuclei slightly below the closed neutron shell N=50 have not been subject to extensive investigations, mainly due to difficulties in obtaining source strengths sufficient for experimental studies. In this paper, we present experimental results obtained for the decay of $^{81}$Ga and $^{81}$Ge, as part of a more extensive survey of the nuclear properties in this region$^{1,2}$.

From recent studies of other nuclei in the same region, mainly of selenium isotopes$^{3,4}$, the presence of positive parity intruder states at relatively low energy has been clearly demonstrated. Although these states are not strongly populated via β-decay, neither directly nor indirectly$^4$, it is of interest to look for them also in germanium nuclei, whose structure are expected to be quite similar to the structure of isotonic selenium nuclei.

Additionally, there has been some ambiguity concerning the decay of $^{81}$Ge. In other even Z, odd N nuclei in this region, two β-decaying isomers are always present, arising from the close-lying configurations $^{1/2}$ and $^{9/2}$. The half-lives of these isomers are normally considerably different. However, preliminary investigations at this laboratory$^5$ have revealed that all γ-rays arising from the decay of $^{81}$Ge have similar half-lives.

2. Experimental techniques

The experiments were performed at the OSIRIS mass-separator at the R2-0 reactor at Studsvik. The separated isotopes were collected on an aluminium coated plastic tape which was used to transport the sources. At mass-number 81, the sources produced are almost exclusively gallium. These favourable conditions are achieved because the efficiency of the target/ion-source system at OSIRIS$^6$ is very low for the daughter products germanium, arsenic and selenium. The conditions for a detailed study of the decay of neutron-rich gallium isotopes and their germanium daughters are thus good.

Measurements of γ-rays and conversion coefficients were performed by means of two coaxial 80 cm$^3$ Ge(Li) detectors. We also used an X-ray detector to look for γ-rays down to 15 keV, but no transitions below 93 keV were observed at the mass number 81. Simultaneously, the conversion electrons were measured by means of a Si(Li) detector. The measurements of γγ-coincidences were performed in 180° geometry. Single γ-ray spectra were detected with different collection- and counting periods, in order to ensure the assignment of the transitions. Additionally, multispectra analysis was performed in an effort to look for isomers, in particular in $^{81}$Ge.

Tables containing the γ-ray energies and intensities, as well as the coincidence relations, have been published separately$^7$ and may be obtained from the laboratory at request.

The measurements of the $\beta\gamma$-coincidences used for the deduction of total decay energies were performed by means of a Si(Li) detector in coincidence with two multiplexed 80 cm$^3$ Ge(Li) detectors. The details of the experimental procedure for these measurements are given in ref.$^8$.

The measurements of level half-lives were performed with a method similar to the one applied by McDonald et al. in previous measurements at this laboratory$^9$. The results of their preliminary measurements were confirmed, and a value for the half-life of the second excited state in $^{81}$Ge was obtained.

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3. Results

On the basis of the measurements described above, we have obtained a detailed decay scheme for $^{81}$Ga and $^{81}$Ge, as well as values for their total decay energies, $Q_e$.

3.1 The $^{81}$Ga decay

The decay scheme for $^{81}$Ga is shown in Fig. 1. As expected from systematics an isomeric state at 679 keV, was observed in $^{81}$Ge. This isomer seems to decay entirely by $\gamma$-emission, the $\gamma$-ray branching was estimated to be less than 1%. From the multispectrum analysis of the $\gamma$-spectra, it was found that both isomers possess the same half-life, $7.6 \pm 0.6$ s.

Although it is impossible to investigate the states in $^{81}$Ge by means of nuclear reactions, most of the levels below 1.5 MeV are relatively easily interpreted by means of level systematics and

![Fig. 1 The decay scheme for $^{81}$Ga](image-url)
simple physical arguments. A level systematics for odd-mass \( N=49 \) isotopes is shown in Fig. 2. As seen from Fig. 2 the isomeric state is 1/2\( ^{+} \) in all other odd-mass \( N=49 \) nuclei. However, in \( ^{81}\text{Ge} \), the isomeric state at 679 keV is probably 1/2\( ^{+} \), while the 895 keV state is likely to be the 1/2\( ^{+} \) state. The 216 keV transition between the two levels has multipolarity E1 with 92 % confidence\(^1\). Thus, the two levels probably have different parity. For several reasons, the 1/2\( ^{+} \) assignment is preferred for the isomeric state; Firstly, there is no 679 keV \( \gamma \)-transition observed, as one should expect from systematics. Secondly, the characteristic phonon states are observed in all other odd-\( N \) nuclei in this region. These are strongly populated indirectly in \( \delta \)-decay and deexcite to the 1/2\( ^{+} \) state. Such states are also observed in \( ^{81}\text{Ge} \), and they deexcite mainly to the 896 keV level. The 679 keV state is weakly indirectly populated, except for the 216 keV transition, in analogy with other 1/2\( ^{+} \) intruder states. Additionally, its decay mode also indicates a different character (see next section).

The half-life of the 711 keV state was measured to 3.9±0.2 ns. If the multipolarity is assumed to be purely E2, this implies a hindrance factor \( F_{\text{m}} = 26.6 \pm 1.4 \). The half-life of the 583 keV state in the isotonic nucleus \( ^{83}\text{Se} \), which is known to be the 5/2\( ^{+} \) intruder state\(^3\), has been recently measured\(^4\) by means of the reaction \( ^{82}\text{Ge} (d,p) ^{83}\text{Se} \) to be about 5.5 ns, corresponding to a hindrance factor \( F_{\text{m}} \approx 14 \). From the similarity between the hindrance factors, as well as the decay properties of the states and expectations from level systematics, it is likely that the 711 keV state is the 5/2\( ^{+} \) intruder state.

Fig. 2 Level systematics for odd mass \( N=49 \) isotopes.

3.2 The \( ^{81}\text{Ge} \) decay

Although there are two \( \delta \)-decaying isomers in \( ^{81}\text{Ge} \), we only observe one half-life. It is thus necessary to make the isomeric assignments by means of physical arguments.

The decay of the two isomers of \( ^{81}\text{Ge} \) is shown in Fig. 3. Due to the similarity in half-life, the schemes must be considered tentative, but by making use of the large differences between the spins and comparing with the well-known decay of the isotonic nucleus \( ^{83}\text{Ge} \), where there is a considerable difference between the half-lives of the isomers, it is possible to assign most transitions to a specific isomer. This problem is discussed in more detail in ref.\(^1\).

Fig. 3 The decay of the two isomers of \( ^{81}\text{Se} \)

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A systematics of levels in odd-mass As-isotopes is shown in Fig. 4. The decay properties of $^{81}$As show$^4$) that the ground state is $3/2^-$. The 326 keV level is given the assignment $5/2^-$, from systematics as well as the strong indirect population from the decay of the 9/2$^+$ isomer of $^{81}$Ge. The states at 93 and 290 keV are either $1/2^-$ or $3/2^-$, but no firm assignment is possible. From systematics, the $3/2^-$ assignment is most likely for the 290 keV state.

The most characteristic feature of the $^{81}$Ge decay is the strong population of a few levels at about 2.6 MeV in the decay of the 9/2$^+$ isomer. This is probably due to the $\beta$-transition $99/2^- \rightarrow 79/2^-$, which is expected to occur at about this energy. The total reduced $\beta$-transition probability of the three strongly populated states is characteristic for this type of transition.

It is also noteworthy, that the 93 and 290 keV states are populated about equally strongly in the decay of the low-spin isomer. In all other odd-mass As-nuclei, the low-lying $1/2^-$ state is very weakly populated in the decay of the low-spin isomers of Ge-nuclei. This is an additional argument for the $1/2^-$ assignment of the isomeric state in $^{81}$Ge.

3.3 The measurements of total decay energies

In the decay of $^{81}$Ga 50 % of the $\beta$-particles feed levels between 3.0 and 4.5 MeV. Transitions depopulating the levels 2997, 3437, 3503, 4013, 4035, 4168, and 4470 keV were chosen for the experiment. The mean value of the determination is

$^{81}$Ga: $Q_\beta = 8.32 \pm 0.15$ MeV

For our investigation of both the isomers of $^{81}$Ge, we chose rather "strong" $\beta$-transitions depopulating the high lying levels between 2.86 and 3.56 MeV and 2.62 and 3.29 MeV respectively. As weighted mean we get the following $Q_\beta$-values:

$^{81}$Ge: 6.22 $\pm$ 0.13 MeV

$^{81}$mGe: 6.93 $\pm$ 0.28 MeV

The difference between the isomeric state is thus found to be 0.72$\pm$0.3 MeV which confirms the assumption in section 3.1 that the isomeric state lies 679 keV above the ground state in $^{81}$Ge.

The details of the determinations of the total $\beta$-decay energies of $^{81}$Ga and $^{81}$mGe are given in ref.$^8$).

4. Discussion

4.1 The structure of $^{81}$Ge

Two types of positive parity states occur at low energy in $^{81}$Ge, i.e. hole + phonon states at about 1.3 - 1.5 MeV and a pair of intruder states at about 0.7 MeV. Several other states observed below 2 MeV are probably also intruder states. A number of relatively low-lying 3/2$^+$ states may be expected, but a firm spin assignment is not possible.

The most extensive theoretical investigation of odd-mass $N=49$ nuclei has been performed by Heller and Friedman$^{11}$ who calculated theoretical energy spectra using a Coriolis coupling model with pairing included. Using different values for the deformation parameter, they calculated spectra for $^{85}$Kr and found that with $\beta \approx 0.2$, a pair of 1/2$^+$, 5/2$^+$ intruder states occur at about 600 keV, in fair agreement with the experimental findings for $^{83}$Se$^{31}$ and $^{81}$Ge.
For the odd-mass indium nuclei (Z=49), a greater amount of experimental material is available, as well as the amount of theoretical treatments.

In a rotational description, the positive parity intruder states are interpreted as members of the 1/2+ 431 rotational band, which is predicted to occur at low energies even at a relatively moderate deformation. In this model a fair reproduction of the position of the intruder states was obtained, but unrealistic values for the decoupling parameter had to be applied to reproduce the sequence of the levels.

A different and more successful approach has been used by Heyde et al. who performed unified model calculations of the odd-mass indium isotopes, taking into account single-hole as well as single particle/two-hole configurations. With this model they obtained a satisfactory reproduction of the energy spectra for a large number of the odd-mass indium nuclei. Calculations for N=49 have not yet been performed.

A number of 7/2- states observed at about 3 MeV in 82Ge are strongly populated in β-decay, and are believed to be states with a strong 3/2+, neutron-hole character, arising from the transition 7/2+ → 5/2+, which are expected at about this energy.

4.2 The structure of 81As

In an approach analogous to the one applied for N=49 nuclei, Scholtz and Malik have performed calculations of spectra for a number of odd-proton nuclei in the region slightly below the N=50 neutron shell, but the agreement with experiments is not as satisfactory as for the similar calculations in ref.[11]. In particular, the energy of the first excited 3/2- state is overestimated. The model has more success in predicting the position of the first positive parity states in this type of nuclei. A pair of states with spin 9/2+ and 5/2+ is predicted at relatively low energy. In 81As, however, the conditions do not allow an experimental identification of these states.

The decay of the 9/2+ isomer in 81Ge is characterized by a pronounced selectivity, populating only 3-4 states in 81As strongly. These states are believed to have a strong single-neutron character, arising from the transition 9/2+ → 9/2-.

Acknowledgements

This work has been supported by the Swedish Natural Science Research Council. One of us (P.H.) also acknowledges the financial support of the Norwegian Council for Science and Humanities.

References

1) P. Hoff and B. Fogelberg, accepted by Nucl. Phys.
5) L. and T. Matsushighe, unpublished work.
10) A. Bäcklin, A. Kavka and P. Hoff, preliminary result (1981).
IN-BEAM GAMMA SPECTROSCOPY OF $^{82}$Sr$^+$

Institut für Kernphysik der Universität zu Köln, D-5000 Köln 41, W.-Germany

Abstract

The excited levels of $^{82}$Sr have been investigated by means of in-beam gamma-ray spectroscopy via the reactions $^{72}$Ge($^{12}$C,2n), $^{66}$Zn($^{19}$F,p2n), and $^{74}$Br($^{6}$Li,3n). Lifetimes of excited states were measured by the recoil distance method. Excitation energies and B(E2) values have been compared with calculations using the Interacting Boson Model.

Introduction

The systematics of excited levels in even-even neutron deficient Sr isotopes shows a transition from particle to collective excitations taking place around the mass numbers $^{82-84}$Sr, which is 6 neutron holes away from the nearly doubly magic $^{84}$Sr has a rather rotational looking ground state band. On the other hand, particle-type excitations have been identified in $^{86}$Sr alongside of collective ones $^1$. Excited states in $^{86}$Sr have been described in a satisfactory way by Kitching $^2$ and Ogawa $^3$ by means of rather simple shell model calculations.

The question arises how well can we describe the properties of $^{82}$Sr by using a collective model, viz. the Interacting Boson Model (IBM), and to what extent collective states have particle-type admixtures.

Low spin states of $^{82}$Sr have already been studied by using the (p,t) reaction $^4$. The aim of this work was to investigate the high-spin states of $^{82}$Sr populated in the reactions $^{72}$Ge($^{12}$C,2n)$^{82}$Sr, $^{74}$Br($^{6}$Li,3n), and $^{66}$Zn($^{19}$F,p2n) and study the decay properties of excited levels.

Fig. 1: Gamma-ray singles spectrum of $^{79}$Br($^{6}$Li,3n)$^{82}$Sr at 2$\pi$ MeV taken at 55$^\circ$ relative to the beam axis. Energies are given in keV. The counting rate per channel is multiplied by the channel number as a rough correction for the detector efficiency.

Experiment and results

The conventional methods of gamma-ray spectroscopy have been used. Lifetimes of excited states have been measured by the Recoil Distance Doppler Shift (RDDS) technique. A summary of reactions, targets, and experiments is given in table 1. A gamma-ray singles spectrum from the $^{6}$Li reaction is given in fig. 1.

The level scheme was established on the basis of coincidence and intensity data (fig. 2). The spin parity assignments were made on the basis of gamma-ray angular distributions and excitation functions; several reliable

Table 1
List of experiments, reactions and targets

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Reaction</th>
<th>Beam-Energy (MeV)</th>
<th>Element compound</th>
<th>Enrichment (%)</th>
<th>Thickness (mg/cm$^2$)</th>
<th>Gold backing thickness (mg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-coincidence</td>
<td>($^{12}$C,2n)</td>
<td>46</td>
<td>$^{72}$Ge</td>
<td>58.2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$-coincidence</td>
<td>($^{19}$F,p2n)</td>
<td>65</td>
<td>$^{66}$Zn</td>
<td>90.4</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>$\gamma$-excitation</td>
<td>($^{12}$C,2n)</td>
<td>28</td>
<td>$^{74}$Br</td>
<td>58.6</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$-excitation</td>
<td>($^{19}$F,p2n)</td>
<td>39,42,45,48,52</td>
<td>$^{72}$Ge</td>
<td>58.2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$-excitation</td>
<td>($^{6}$Li,3n)</td>
<td>53,56,59,62,63,56</td>
<td>$^{66}$Zn</td>
<td>90.4</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>$\gamma$-angular distr.</td>
<td>($^{12}$C,2n)</td>
<td>65</td>
<td>$^{74}$Br</td>
<td>58.6</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$-angular distr.</td>
<td>($^{6}$Li,3n)</td>
<td>28</td>
<td>$^{66}$Zn</td>
<td>90.4</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>RDDS</td>
<td>($^{19}$F,p2n)</td>
<td>65</td>
<td>$^{74}$Br</td>
<td>98.6</td>
<td>2.6</td>
<td>0.1 + 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{66}$Zn</td>
<td>90.4</td>
<td>0.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

a) Sandwich
assignments from the (p, t) reaction and $\beta^-$ decay were used as a starting point.

Fig. 2: Level scheme of $\beta^2$Sr. The widths of the arrows represent the relative intensities of the transitions found in the $^{19}$F induced reaction.

The ground state band (gsb) was extended up to a $10^+$ state and the quasi gamma-band (qgb) up to $14^+$. Besides, we were able to identify negative parity states. The ordering of levels above the $7^+$ states is unclear. This is due to the 875 keV line in $\beta^2$Sr being a member of a doublet, which precludes an accurate intensity measurement.

Lifetimes were measured by RDDS in the $^{66}$Zn($^{19}$F, p2n)$\beta^2$Sr reaction. Since the odd-spin members of the qgb were populated only in the $^4$Li reaction, it was not possible to measure their lifetimes. The target to stopper distance was varied in the 0-6000 $\mu$m range. The stopper consisted of a 10 $\mu$m Ta foil. The gamma spectra were taken by two Ge(Li) detectors at 0° and 15°, respectively, against the beam axis. The target to stopper distance has been monitored throughout the experiment by measuring the plunger capacity; the conventional pulser technique has been used. The fluctuation of the distance during a one-hour run was 0.1 - 0.2 $\mu$m.

Decay curves for the lowest three gamma transitions of the gsb are shown in Fig. 3. Measured lifetimes as well as $B(E2)$ values are given in Table 2. Several lifetimes are as short as 1 ps, i.e. they lie at the lower limit measurable by our plunger'. Therefore their standard deviations are rather large.

---

**Fig. 3:** Decay curves of the three lowest members of the gsb.

**Table 2**
Lifetimes and $B(E2)$ values in the reaction $^{66}$Zn($^{19}$F, p2n)$\beta^2$Sr using the RDDS technique.

<table>
<thead>
<tr>
<th>State</th>
<th>$E_x$ (keV)</th>
<th>$t^\tau(\mu$s)</th>
<th>Transition $I_i \leftrightarrow I_f$</th>
<th>$B(E2)(e^2$fm$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>574</td>
<td>$2^+$</td>
<td>12.8 ± 0.5</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>1000 ± 50</td>
</tr>
<tr>
<td>1329</td>
<td>$4^+$</td>
<td>1.4 ± 0.3</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>2300 ± 500</td>
</tr>
<tr>
<td>2229</td>
<td>$6^+$</td>
<td>1.3 ± 0.2</td>
<td>$6^+ \rightarrow 4^+$</td>
<td>1100 ± 200</td>
</tr>
<tr>
<td>1176</td>
<td>$2^+$</td>
<td>10.8 ± 3.5</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>8.4 ± 3</td>
</tr>
<tr>
<td>1996</td>
<td>$4^+$</td>
<td>1.9 ± 0.5</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>800 ± 200</td>
</tr>
<tr>
<td>2836</td>
<td>$6^+$</td>
<td>0.9 ± 0.5</td>
<td>$6^+ \rightarrow 4^+$</td>
<td>1500 ± 800</td>
</tr>
<tr>
<td>3622</td>
<td>$8^+$</td>
<td>1.0 ± 0.5</td>
<td>$8^+ \rightarrow 6^+$</td>
<td>2000 ± 1000</td>
</tr>
<tr>
<td>4424</td>
<td>$10^+$</td>
<td>1.3 ± 0.3</td>
<td>$10^+ \rightarrow 8^+$</td>
<td>1900 ± 500</td>
</tr>
<tr>
<td>2818</td>
<td>$5^-$</td>
<td>4.4 ± 0.8</td>
<td>$5^- \rightarrow 4^-$</td>
<td>1469</td>
</tr>
</tbody>
</table>
A comparison of the level schemes of Sr nuclei with isotonic Kr nuclei shows striking similarities. Collective excitations in Kr isotopes have been successfully described by the Interacting Boson Model \(^1\). This constitutes an incentive to describe the properties of \(^{80-84}\)Sr by the same model.

Calculations were carried out with the proton-neutron variant of IBM \(^2\).

The Hamiltonian of IBM is

\[ H = \varepsilon (n_d + n_{\bar{d}}) + \kappa (\pi^0 \pi^0 - \pi^+ \pi^-) + a \mu \]

where the quadrupole operator \( Q \) is given by

\[ Q_\mu = (d^\pi s + s^\pi d)_\mu + \chi_\mu (d^\pi d^\pi)_\mu (2), \mu = \nu, \pi \]

and

\[ M = \sum_{\ell=1,3} (d^\pi \mu \pi \mu)_\ell (d^\pi \mu \pi \mu)_\ell (\ell) \]

\[ \text{MeV} \]

\[ 8^* \quad 7^* \quad 6^* \quad 5^* \]

\[ 0^* \quad 1^* \quad 2^* \quad 3^* \]

\[ \text{(p,t)} \quad \text{IBM-2} \quad \text{gsb} \quad \text{IBM-2} \quad \gamma\text{-band} \quad \text{IBM-2} \]

\[ B(E2, 1^- \rightarrow 0^+) \quad B(E2, 2^- \rightarrow 0^+) \]

\[ \times \quad \text{gsb} \quad \circ \quad \gamma\text{-band} \]

\[ \begin{array}{c|c|c|c}
\hline
I_1 & 0^+ & 0^+ & 0^+ \\
\hline
2^+ & 6^* & 6^* & 6^* \\
\hline
6^* & 6^* & 6^* & 6^* \\
\hline
10^* & 10^* & 10^* & 10^* \\
\hline
14^* & 14^* & 14^* & 14^* \\
\hline
\end{array} \]

Fig. 4: \(^{2}^{2}\)Sr: Comparison of IBM fits with experimental energies of the gsb, quasi-gamma-band and states found in a (p,t) reaction \(^3\). Parameters: \( \varepsilon = 1.05 \); \( \kappa = 0.175 \); \( \chi_\pi = -1.3 \); \( \chi_\nu = 0.71 \); \( a = 0.2 \).

The parameter \( a \) was kept constant for all Kr and Sr calculations. The parameter \( \chi_\nu \) has always been taken from the calculation of the Kr isotope, while \( \chi_\pi \) has been kept constant. Therefore the only really free parameters were \( \varepsilon \) and \( \kappa \).

d\( ^+ \) (d) and s\( ^+ \) (s) are creation (annihilation) operators of d and s bosons, respectively.

The comparison of the theoretical and experimental energy levels of \(^{2}^{2}\)Sr is given in fig. 4. The agreement is very good for the gsb and for states of the gsb up to 7\(^+\). A few 0\(^+\) and 2\(^+\) levels were populated only in the (p,t) reaction. Since the nature of these levels was uncertain, we did not take them into account during the fit. They came close to 0\(^+\) and 2\(^+\) levels predicted by IBM (fig. 4) and with which they can be identified.

Fig. 5: Comparison between experimental and theoretical E2 transition strengths for \(^{85}\)Sr. The B(E2)'s are normalized to the B(E2; 2\(^-\) \rightarrow 0\(^+\)) value. The dashed curve represents the fit for the gsb and the dashed-dotted curve that for the quasi gamma-band.

The comparison of the theoretical and experimental energy levels of \(^{90}\)Sr is given in fig. 4. The agreement is very good for the gsb and for states of the gsb up to 7\(^+\). A few 0\(^+\) and 2\(^+\) levels were populated only in the (p,t) reaction. Since the nature of these levels was uncertain, we did not take them into account during the fit. They came close to 0\(^+\) and 2\(^+\) levels predicted by IBM (fig. 4) and with which they can be identified.

If we examine the energy pattern of the gsb above 7\(^+\) we notice certain irregularities. The systematics of Kr and Sr isotopes shows that beside the collective states we can identify particle-type excitations. The most important of the latter is the \( \chi_\nu (2 \rightarrow 2) \) configuration, which has been observed in \(^{84}\)Sr and \(^{88}\)Sr. We could therefore assume that states of the type \( \chi_\nu (2 \rightarrow 2) ^{\omega} \) are mixed to the collective states of \(^{90}\)Sr, e.g., \( \omega = 2 \) to the states of the gsb starting with 1\(^+\) \( \rightarrow \) 8\(^+\).
Levels in the gsb and the qgb of $^{88}$Sr are taken from ir beam gamma-ray spectroscopy experiments reported previously). Further $0^+$ and $2^+$ states found in the (p,t) reaction can again be identified with states predicted by IBM though the agreement is not so good as in the case of $^{84}$Sr.

A characteristic feature of the IBM is a reduction of B(E2) values in the gsb compared to the rotational ones, due to the boson cut-off. The experimental B(E2)'s in $^{84}$Sr are even lower than required by the cut-off. This reduction could be due to an admixture of two-quasi-particle states.

We finally tried to compare the values of B(E2; $2^+ \rightarrow 0^+$) in even-even Sr and Kr isotopes with theoretical values given by IBM; the same effective charges were used throughout this calculation. Experimental data from lifetime measurements and Coulomb excitation, as well as theoretical values are shown in fig. 8. The agreement between theory and experiment is excellent.

Let us compare $^{82}$Sr to its neighbours $^{80}$Sr and $^{84}$Sr. Experimental as well as theoretical excited levels in these nuclei are given in figs. 6 and 7. The experimental data on $^{80}$Sr were taken from Nolte et al. 9,10; our own experiments with the $^{64}$Zn($^{19}$F, p2n)$^{80}$Sr reaction gave the same results. The $2^+$ and $4^+$ states were found by Lister et al. 11 in a $\beta$-decay experiment.

If we examine the energy spacings in the qgb above $^{88}$Sr and compare them with those of the gsb of $^{88}$Sr, we see that they are similar. On the other hand, B(E2; $8^+ \rightarrow 6^+$) in the qgb does not display the reduction one should expect in the case of a band crossing. It is therefore difficult to draw a conclusion on the origin of the irregularities of the qgb. Fig. 5 shows a comparison between experiment and theory for the B(E2) values normalized to the B(E2; $2^+ \rightarrow 0^+$). It would be difficult to carry out a relevant comparison with theory due to the rather large standard deviations of the experimental points.

Fig. 6: $^{88}$Sr: Comparison of IBM fits with experimental energies of the gsb, and the quasi-gamma-band.
Parameters: $\varepsilon = 0.975; \kappa = -0.175; \chi_m = -1.3; \chi_Y = 0.5; a = 0.2$.

Fig. 7: $^{84}$Sr: Comparison of IBM fits with experimental energies of the gsb, quasi gamma-band and levels found in a (p,t) reaction. 4)
Parameters: $\varepsilon = 1.1745; \chi_m = -1.3; \chi_Y = 0.92; a = 0.2$.

Conclusion

In contrast to $^{80}$Sr, where the interplay of collective and particle degrees of freedom is conspicuous, $^{82}$Sr displays a rather collective structure, with irregularities perhaps caused by particle admixtures. The collective states of $^{80,84}$Sr can be rather well described by the Interacting Boson Model.
Fig. 8: Comparison of B(E2; 2\(^+\) → 0\(^+\)) in even-even Sr and Kr isotopes with IBM fits. The same effective charge was used for Sr and Kr. The dotted curve represents the fit for Kr and the dashed dotted curve that for Sr.

Experimental point no.: 1 - ref. 12; 2 - ref. 13; 3 - ref. 14; 4 - ref. 15; 5 - ref. 16; 6 - ref. 17; 7 - ref. 10; 8 - ref. 18; 9 - ref. 1; 10 - ref. 19.

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References


11. C. J. Lister et al.: unpublished


15. L. Funke et al.: Annual Reports ZK-315, ZFK Rossendorf


18. J. Eberth: private communication

THE LEVEL SCHEMES OF Sr and Y ISOTOPES IN THE MASS CHAINS A = 95, 97 and 99


Abstract

The fission product separator Ostis at the Institut Laue-Langevin at Grenoble (France) was used for the investigation of the β-decays and the level schemes of short-lived Rb, Sr and Y isotopes with A = 95, 97 and 99.

The studies in the mass chains 95 and 97 were made using a surface ionization source to provide Rb isotopes whereas the mass chain 99 was investigated using an high temperature ion source.

The study of these nuclei close to $^{93}$Sr and $^{102}$Zr where a shape coexistence was evidenced is of great interest. Single γ-ray and conversion electron spectra, and prompt and delayed γ-γ and β-γ coincidences were measured. The level schemes of $^{93}$Sr, $^{95}$Sr, $^{97}$Sr and $^{99}$Y were established or extended and a preliminary level scheme is given for $^{99}$Y.

1. Introduction

Two transitional regions around A = 100 and A = 146 are accessible by the fission process. The spectroscopy of even-even nuclei reveals a different behaviour: whereas in the heavier group a smooth transition from spherical to deformed shapes is observed, the lighter one is characterized by an abrupt onset of large deformations and shape coexistence ($^{120}$Zr and $^{99}$Sr).

Up till now only few information is available for odd nuclei around A = 100. Recently the spins and moments of the ground states of Rubidium isotopes have been measured by new spectroscopic methods (12). The large quadrupole moment observed for $^{97}$Rb shows a large deformation comparable to the neighboring even-even nuclei. But these measurements do not allow an unique Nilsson assignment and more spectroscopic data are needed for a better understanding of this whole transitional region.

In this contribution, results concerning the level schemes of odd Strontium and Yttrium ranging in mass from A = 95 to A = 99 are presented.

2. Experimental Techniques

Samples of mass separated fission products were obtained from the isol-system Ostis installed at an external neutron beam of the high flux reactor of the Institute Laue-Langevin in Grenoble (13). The separator can be equipped with two kinds of ion sources: a thermionization source delivering nearly isotopically pure samples of Rb and Cs isotopes and a recently developed high-temperature source (14) which allows also Sr, Ba and rare earth elements to be ionized. The measurements in the mass chains A = 95 and A = 97 were performed with the first source whereas $^{99}$Y was studied with the later one. The mass separated ions were deposited on a moving tape installed between the detectors. By adjusting the speed of the tape the different elements of a β-decay chain could be enhanced. By performing γ and conversion electron singles, γ-γ coincidence as well as β-γ and β-e⁻ delayed coincidence measurements rather detailed decay schemes were established. Standard Ge(Li), Ge(HP) and Si(Li) detectors were used for these measurements.

3. Experimental Results

Whereas some information has been obtained on the level schemes of $^{93}$Y and $^{97}$Y from radio-activity and nuclear reactions very little is known about the schemes of odd Sr isotopes with mass A ≥ 95 and on $^{99}$Y. The new results of this work will be presented below isotopes by isotope.

3.1 $^{93}$Sr Level Scheme

The β decay of $^{97}$Rb has been reported by several groups. A mean value for the half-life $t_{1/2} = 377$ ms is obtained, but sparse and even contradictory informations have appeared in the literature on the level scheme of $^{93}$Sr. In the present work about 230 γ-lines could be attributed to the decay of $^{93}$Rb. The coincidence relationships allowed the construction of a scheme of 57 excited levels comprising about 97% of the activity.

The large number of transitions and the high density of levels cannot be discussed in detail in the frame of a conference. A discussion of the whole scheme will be given elsewhere. Only the characteristic features are displayed Fig.1. The intensity of the β branches has been determined from a fillation measurement assuming the absolute intensity $I_γ = 0.19 ± 0.02$ for the 954.2 keV γ-ray of $^{92}$Zr (ref.5) and $P_n = 8.9%$ (ref.5).

The scheme is characterized by the presence of many excited states up to 4660 keV, more than the neutron binding energy. Above 1439 keV one can distinguish three well separated groups of levels, two groups with rather low β feeding at about 2100 keV and 4200 keV and the third one at about 3500 keV with a strong β feeding (≈ 50% of the beta intensity). The logft calculated with a Qβ of 9260 keV indicate that the β branches feeding the levels of the groups at 2100 and 4200 keV are first forbidden whereas the levels at 3500 keV are fed by allowed ones. With the spin and parity assignment I, = 5/2⁻found for the ground state of $^{93}$Rb (ref.11) we have to admit the existence of a group of 13 negative parity states between 3366 and 3635 keV (the β strength function deduced from these feedings will be compared to a theoretical prediction in the contribution of Kratz et al. at this conference).

The measured K conversion coefficient for the 204 and 352 keV γ-lines are in agreement with a multipolarity E2 and M1, respectively. The half-life of the 204 keV γ-line was found to be

++) Centre d'Etudes Nucléaires de Grenoble, Département de Recherche Fondamentale/CPN, 85 X - 38041 GRENOBLE Cedex, France.

***) 11. Physikalisches Institut der J. Liebig Universität - 63 GIESSEN, Germany.

0) Member of CNRS.
T_{1/2} = 22 ± 3 ns in agreement with Fogelberg\(^4\). This value corresponds to the single particle Weisskopf estimate for an E2 transition. This E2-M2 sequence for the deexcitation of the two first excited states corresponds to the one found in the isotope \(^{97}\)Zr (ref.\(^9\)-\(^10\)). These levels are interpreted as arising from the neutron states \(1/2^+\), \(3/2^+\) and \(5/2^+\). The higher excited states up to 1439 keV may then be interpreted by the coupling of these neutron states with the first \(2^+\), \(4^+\) and \(2^+\) excited states of the neighbouring even Sr isotopes.

3.2 \(^{97}\)Sr Level Scheme

A mean value for the half-life of \(^{97}\)Rb

\[
T_{1/2} = 171 \text{ ms}
\]

is obtained by several groups but no decay scheme was proposed. In the decay scheme shown Fig. 2 nearly all the \(\gamma\)-lines observed were placed (about 94\% of the \(\gamma\) activity). Compared to the decay scheme of \(^{97}\)Sr we observe that the \(\beta\) decay feeds strongly levels at 650 keV instead of 3500 keV and that the feeding of states above 1.5 MeV seems to be negligible. Some very weak \(\gamma\)-lines were observed up to 2.5 MeV but could not be placed in the decay scheme. The intensity of the \(\beta\) branches deduced from a fission measurement assuming the absolute intensity

\[
I_\beta = 0.928 \text{ (ref.}^{11}\text{)}
\]

for the 743.4 keV \(\gamma\)-line of \(^{97}\)Nb and \(Pn = 25.2\% \text{ (ref.}^{12}\text{)}
\]

by delayed coincidence techniques several life-times greater than 1 ns were detected. The half-life \(T_{1/2} = 347 ± 12\) ns of the 141 keV transition (in good agreement with Clark et al.\(^{11}\)) fits into the systematic of E2 transition deexciting the \(7/2^-\) state in \(^{97}\)Sr and \(^{97}\)\(^{12}\)Zr (Fig. 6). This multipolarity was confirmed by the conversion electron measurements. The half-life of the 167.1 keV transition was found to be

\[
T_{1/2} = 1.5 ± 0.7 \text{ ns in the } \beta \text{-delayed neutron decay of } \text{\(^{97}\)Rb. The two levels at } 644.6 \text{ keV and } 713.8 \text{ keV have unexpected long half-lives of } 7.2 \text{ ns and } 1.7 \text{ ns, respectively. The level at } 644 \text{ keV may correspond to the level at } 667 \text{ keV } (T_{1/2} = 10.2 \text{ ns) in } \text{\(^{97}\)Zr (ref.}^{11}\text{)}
\]

(see Fig. 6). We can also remark that the scheme of these two isotopes are very similar. The long-lived level at 830.8 keV was only populated in the fission process and could be the \(11/2^-\) state\(^1\). For some intense \(\gamma\)-lines the \(\kappa\) conversion coefficient was measured. The values obtained indicated M1/E2 character. Due to the small difference of the theoretical \(\kappa\) for M1 and E2 transitions and poor statistics above 400 keV no value for the E2 admixtures can be given. A special case is the \(\gamma\)-line at 600.5 keV. Compared with the close intense \(\gamma\)-line at 585.2 keV of nearly pure M1 character the \(\kappa\) obtained for this line seems to indicate an E2 multipolarity. From these results a tentative spin and parity assignment could be made for some of the excited states.

The \(\log ft\) calculated with a \(Q_8\) of 10.325 keV (ref.\(^{13}\)) show that the \(\beta\) branches feeding the levels at about 650 keV are allowed and indicate a positive parity for the ground state of \(^{97}\)Rb. This new result combined with the spin \(I = 3/2^+\) and magnetic and quadrupole moments measured by Thibault et al.\(^2\) allows to fix an unique Nilsson orbital [\(\nu_3^1 l_3^2\)] for the ground state of \(^{97}\)Rb.

3.3 \(^{99}\)Y Level Scheme

The decay of \(^{99}\)Sr (\(T_{1/2} = 25.1\) s) has been studied by Herzog and Grimm\(^{16}\) who proposed a decay scheme mainly based on sum rule considerations. In the present work 85 \(\gamma\)-lines representing about 90\% of the \(\gamma\) activity were placed in a scheme of 34 excited states based on coincidence relationships (Fig. 3). The \(K\) conversion coefficient of the 260.6 keV \(\gamma\)-line indicate a M2 multiplicity. This \(\gamma\)-line has been observed in delayed \(\gamma\)-rays coincidence with fission fragments deexciting an isomeric level at 1087.4 keV (T\(_{1/2} = 57 ± 2\) ms)\(^17\). As the 826.8 keV level has \(I^\pi = 5/2^-\) (ref.\(^{18}\)) we can assign spin and parity \(I^\pi = 9/2^+\) to this isomeric level, in analogy with the odd \(Y\) isotopes. The intensity of the \(\beta\) branches was determined from the fission measurement used for the decay of \(^{99}\)Rb. The same \(\log ft\) is 6.0 (calculated with \(Q_8 = 6060\) keV)\(^1\) and we can attribute positive parity. A tentative spin and parity assignment is derived from the \(\log ft\) values and the \(\gamma\) deexcitation to the known first excited states.

3.4 \(^{97}\)Y Level Scheme

The decay of \(^{97}\)Sr (\(T_{1/2} = 435 ± 30\) ms) has already been studied with the separators Josef and Lohengrin\(^{19}\). In the present work the level scheme of \(^{97}\)Y was extended (Fig. 4). Some \(\gamma\)-lines in the energy range 2-3 MeV not seen in coincidence must deexcite higher levels to the ground state. This represents about 10\% of the \(\gamma\)-intensity arriving at the ground state and was taken into account in calculating the feeding of the levels. Contrary to the previous results\(^9\) no \(\beta\) feeding to the ground state was obtained. This can be explained by the different experimental conditions: whereas at Ostis all the elements of the mass chain 97 are obtained by \(\beta\) decay from \(^{97}\)Rb, at Josef and Lohengrin all the elements are collected according to their independent fission yield. This enters into the calculation and introduces additional errors. The levels above 1900 keV are characterized by strong \(\beta\) feeding and low \(\log ft\) values calculated with \(Q_8 = 7450\) keV (ref.\(^{19}\)). These levels with positive parity are depopulated by strong \(E1\) transitions to the \(1/2^-\) ground state and by \(\gamma\)-ray cascades via the 622.2 keV \(E2\) transition to the \(9/2^-\) isomeric state at 667.5 keV. In combining the \(\log ft\) values and the conversion electron measurements with the population of the \(1/2^-\) and \(9/2^-\) states a tentative spin and parity assignment can be proposed for several excited states.

3.5 \(^{99}\)Y Level Scheme

For the decay of \(^{99}\)Sr a half-life of

\[
T_{1/2} = 290 ± 40 \text{ ms (ref.}^{20}\text{)}
\]

was measured but no information on the decay scheme has been reported up till now. With the new high temperature ion source about 25 \(\gamma\)-lines could be attributed to the decay of this nucleus. The \(\gamma\)-\(\gamma\) coincidence measurements led to the establishment of the decay scheme shown Fig. 5. (A preliminary level scheme was given in\(^21\)). Contrary to the other odd \(Y\) isotopes we observe a considerable lowering of the excited states indicating a change in the structure of \(^{99}\)Y.

In a previous paper\(^1\) we proposed a spin and parity \(I^\pi = 1/2^-\) for the ground state of this nucleus and a possible \(9/2^-\) beta isomer from systematic of the odd \(Y\) isotopes. But all attempts to find this isomer failed. The new fission measurement performed at Ostis and assuming the absolute intensity \(I_\beta = 56\% \text{ (ref.}^{11}\text{)}\) for the 469.1 keV \(\gamma\)-line of \(^{99}\)Nb gives a stronger ground state \(\beta\) feeding of \(^{97}\)Zr (about 33\%) than in\(^1\). This indicates an allowed \(\beta\) branch to the \(1/2^-\). Therefore spin and parity \(I^\pi = 1/2^-\) or \(3/2^-\) have to be assigned to the ground state of \(^{99}\)Y. But by analogy with the isotope \(^{97}\)Rb the spin \(3/2^-\) seems the most reasonable choice.

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Fig. 3 Level scheme of $^{95}$Y
Fig. 4 Level scheme of $^{97}\text{Y}$
[a] from ref.19)
From the absolute intensity of the 125 keV $\gamma$-line found in the fission measurement ($\text{F}_{\gamma \gamma} = 0.19 \pm 0.03$) the ground state $\beta$ feeding of $^{99}\text{Y}$ is calculated as about 60%. This value is certainly overestimated due to the incomplete knowledge of the decay scheme but it must be rather strong. The log $t$ = 5.0 of this $\beta$ branch leads to the assignment $I^\pi = 3/2^+$ or $5/2^+$ for the ground state of $^{95}\text{Sr}$.

4.2 Odd proton nuclei $^{99}\text{Y}$, $^{97}\text{Y}$ and $^{95}\text{Y}$

The negative parity states below 1 MeV in $^{95}\text{Y}$ and $^{97}\text{Y}$ can be placed into the level systematics of the lighter odd mass Yttrium nuclei.

In $^{97}\text{Y}$ a positive parity system based on the $9/2^+$ is observed. The level spacing of these states at 667.5 keV (9/2$^+$), 1319.6 keV (5/2$^+$) and 1905.0 keV (1/2$^+$, 3/2$^+$) is characteristic of the weak coupling with a vibrational core.

By adding two neutrons a strong coupling of the $9g/2$ with the deformed core is observed in $^{97}\text{Rb}$. The positive parity found for the ground state fixes an unique Nilsson orbital assignment [451 5/2]. The large quadrupole moment measured by $\beta^+$ confirms the large deformation of the ground state of $^{97}\text{Rb}$.

Spin and parity assignment $I^\pi = 3/2^+$ to the ground state of $^{99}\text{Y}$ (ref. section 3.5) suggests that the structure of this state is analogous with the one of $^{97}\text{Rb}$. This then leads to the assignment of a comparable deformation for both nuclei. The deformation in $^{99}\text{Y}$ can be seen from the different features of its decay scheme compared to the lighter odd Yttrium isotopes (see Fig. 3, 4). The level spacing of the two first excited states as well as the mode of deexcitation of the level at 283 keV suggests the existence of a rotational band built on the ground state. In order to confirm this assumption we have calculated the ratio $K(g_\gamma - g_\text{p})/Q_\gamma$ from the branching ratio of the deexcitation of the level at 283 keV to the ground and first excited state in the framework of the rotational model. The obtained value of 0.44 is comparable with the number of 0.70 derived from the magnetic and quadrupole moments measured in $^{97}\text{Rb}$ (ref. 2). The last value of 0.70 was calculated under the assumption $g_\gamma = 2/ A$.

4.1 Odd neutron nuclei $^{95}\text{Sr}$ and $^{97}\text{Sr}$

The ground state and the two first excited states of $^{95}\text{Sr}$ and $^{97}\text{Sr}$ are analogous to the corresponding ones in $^{97}\text{Zr}$ (see Fig. 6), where they are interpreted as the shell model configurations $51/2^-$, $d_5/2$ and $g_7/2$ (ref. 1'). This systematic behaviour shows the rather spherical nature of these three states. In contrast, isomeric states at about 600 keV were observed in $^{95}\text{Sr}$ as well as in $^{97}\text{Zr}$ (ref. 1'). The strongly hindered deexcitation of these states to the low energy spherical ones shows these two groups of states are different in nature. In analogy with the even-even neighbouring nuclei $^{95}\text{Sr}$ and $^{97}\text{Zr}$ we could postulate these isomeric states have a different shape as the spherical ground state.

The abrupt change in the coupling mode of the orbit $9g/2$ with the core as a function of deformation is shown in Fig. 7.

406 ns

If our assumption is correct this would be the first rotational band observed in an odd mass nucleus in the $A \approx 120$ region. But more spectroscopic data would certainly be of great interest to confirm this result. Finally the spin and parity assignment $I^\pi = 3/2^+$ or $5/2^+$ for the ground state of $^{95}\text{Sr}$ (see section 3.5) may correspond to the Nilsson orbits [411 3/2] or [413 5/2] respectively.

Fig. 6 - Low lying excited states of $^{95}\text{Sr}$ and $^{97}\text{Sr}$ compared with those of $^{97}\text{Zr}$ and $^{97}\text{Zr}$.

Fig. 7 - Level scheme of $^{99}\text{Y}$.

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5. Conclusion

In this contribution new results on odd neutron and odd proton nuclei near $N = 60$ at the abrupt onset of deformation were presented. Although some of the results are preliminary a positive parity for the ground state of $^{133}$Rb and the existence of a rotational band in the corresponding nucleus $^{99}$Y could be suggested. It is a challenge for the future to extend detailed spectroscopic work further into the region $Z \leq 40$ and $N \geq 60$ with low fission yields.

List of References
8) B. Fogelberg, private communication.

DISCUSSION

W. Andrejacevofff:
1) Please elaborate on your statement about possible shape coexistence in $^{93}$Zr.
2) If the 125 keV level in $^{99}$Y is of rotational type it should have a lifetime in the region of 1 ns. The attempt to measure the lifetime might provide some useful information.

B. Pfeiffer:
1) By comparing the first excited states of $^{97}$Sr and $^{95}$Zr with those of $^{97}$Zr we concluded on a spheric-
THE STRONGLY DEFORMED NUCLEUS $^{100}$Sr

S. Mattsson\textsuperscript{a}, R.E. Azuma\textsuperscript{b}, H.A. Gustafsson\textsuperscript{c}, P.G. Hansen\textsuperscript{d}, B. Jonson\textsuperscript{c}, V. Lindfors\textsuperscript{e}, G. Nyman\textsuperscript{f}, I. Ragnarsson\textsuperscript{f}, H.L. Ravn\textsuperscript{g}, and D. Schardt\textsuperscript{c}

The ISOLDE Collaboration, CERN, Geneva, Switzerland.

Abstract

Experiments on the nucleus $^{100}$Sr are reviewed. The activity was produced by fission with 600 MeV protons on a uranium target and after mass separation studied by gamma-ray and conversion-electron spectroscopy and by nanosecond lifetime measurements.

The theoretical implications of these results are discussed on the basis of a Nilsson-Strutinsky calculation.

1. Introduction

The region of deformation near $(Z,N)= (40,60)$ was found by Cheifetz et al.\textsuperscript{1} in measurements of radiations from prompt de-excitation of fission fragments, and recent experiments at the mass separators JOSEF\textsuperscript{2} and OSTIS\textsuperscript{3} have greatly extended our knowledge of this region. The domain of interest is illustrated in Fig. 1, which shows the systematics of the first $2^+$ level in even-even nuclei of the elements around zirconium.

The proton number 40 has the character of representing a shell gap for spherical nuclei and at the same time also a shell gap for 2:1 prolate deformation\textsuperscript{4}. This character is clearly confirmed by the systematics in Fig. 1, which shows spherical shape for the 50 closed neutron shell and the 56 closed $d_{5/2}$ subshell, while on the sides the neutron numbers 40 and 60, which like $Z=40$ favour prolate deformation, lead to new regions of deformed nuclei. The behaviour of the $2^+$ energies for the nuclides with neutron number in the proximity of the mid-shell 1/2(50+82)=66 seems to be more smooth for molybdenum than for zirconium and strontium. Both strontium and zirconium exhibit a drastic drop in $2^+$ energies between 58 and 60 neutrons, with the strontium being lowest in energy. In $^{100}$Sr, the $2^+$ state comes as low as 129.2 keV and the ratio $E_{4^+}/E_{2^+}$ of 3.23, which is close to the

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{systematics.png}
\caption{Systematics of $2^+$ energies in the mass A=100 region as a function of proton and neutron number projected from the neutron-rich side. The data are taken from Ref. 1-6.}
\end{figure}

\textsuperscript{a,} Dept. of Physics, Chalmers Univ. of Technology, S-412 96 Göteborg, Sweden
\textsuperscript{b,} Dept. of Physics, Univ. of Toronto, Toronto Ontario M5S 1L7, Canada
\textsuperscript{c,} CERN-ISOLDE, CERN, CH-1211 Geneva, Switzerland
\textsuperscript{d,} Inst. of Physics, Univ. of Aarhus, DK-8000 Aarhus, Denmark
\textsuperscript{e,} Dept. of Physics, Univ. of Helsinki, SF-00170 Helsinki, Finland
\textsuperscript{f,} Dept. of Math. Physics, LTH, Sölvegatan 14, S-22007 Lund, Sverige
rigid rotor value of 10/3, is the highest yet found in this region.

2. Experimental procedures and results

The short-lived isotopes of rubidium were studied by γ-ray and conversion-electron spectroscopy and by nanosecond lifetime measurements. The radioactivity was produced by fission with 600 MeV protons impinging on a target of 46 g/cm² uranium carbide at a temperature of about 2000°C, and was separated on-line at the ISOLDE Facility at CERN. The yield of ¹⁰⁰Rb was about 10¹⁰ atoms per second.

The γ-ray spectrum observed in the β-decay of the 55 ms ¹⁰⁰Rb shows two γ-lines at 129.2±0.5 keV and 288.2±0.5 keV, interpreted as representing the lowest transitions in the ¹⁰⁰Sr ground-state rotational band³). From gamma-gamma coincidence and conversion electron measurements, the γ-lines were both found to be E2 transitions in coincidence. The E2 character of the 129.2 keV line could also be extracted from the K/L- ratio in the electron spectrum (Fig. 2). In the coincidence experiment, a new relatively strong transition of 120±1 keV was found to populate the 4⁺ level. The γ-line of 90.7±0.5 keV, which also decays with the 55 ms ¹⁰⁰Rb half-life²)²), was proved to belong to the delayed neutron daughter ⁹⁹Sr.

The lifetime of the 129.2 keV level has been determined by measuring delayed coincidences between β-particles and conversion electrons detected in 1 mm and 0.2 mm thick plastic scintillators.

The distribution of delayed coincidences shown in Fig. 3 reveals a single delayed component corresponding to a half-life of 5.15±0.20 ns. The period did not depend on the gate settings in the beta or electron energies.

Fig. 3 Time spectrum observed at ¹⁰⁰Sr from β-ray conversion electron coincidences measured by two thin plastic scintillators. The experimental resolution was 1.8 ns FWHM. The corresponding spectrum obtained for ⁹⁸Sr is shown in the inset.
Similar measurements were performed on $^{98}$Rb. The inset in Fig. 3 shows that in this case two delayed components are present. Our findings seem to be in excellent agreement with those of Schussler et al.\(^3\), who explained the longer component as the half-life of the first excited $0^+$ state in $^{98}$Sr.

3. Excited $0^+$ state

Part of the aim of the gamma and conversion electron experiments was to look for a possible low-lying excited $1^+=0^+$ state in $^{100}$Sr. As can be seen from Fig. 4, these $0^+$ levels are found at unexpectedly low energies in this mass region. In the present experiment, however, such a state, if it exists at low energy, was not possible to identify.

The systematics in Fig. 4 indicate that the low-lying $0^+$ levels in Mo tend to change between 60 and 62 neutrons. Molybdenum is known to have more smooth systematics of the energy levels than zirconium and strontium. Therefore, in $^{100}$Sr where the deformed shape is thought to be stabilized, the first excited $1^+=0^+$ level might be expected at higher energy than in $^{98}$Sr. It should be pointed out that any low-lying state could have escaped detection if it was fed at the percent level. This because the experiment was performed with a newly developed high-efficiency surface ionizer, which gave us a certain amount of directly produced strontium and thus larger background.

To observe a detectable signal from an excited $1^+=0^+$ state in $^{100}$Rb would require a low spin value of the $\beta$-decaying state in $^{100}$Rb. In the decay of $^{98}$Rb, two isomers with very small half-life difference were observed\(^9\). The fact that the first excited $0^+$ state in $^{98}$Sr is populated in a large amount, points to a $\beta$-decaying state of low spin value. Atomic hyperfine structure measurements\(^8\) give an uncertain spin I=0 as a result for $^{98}$Sr. Similar measurements\(^8\) on $^{99}$Rb point to $(431)3/2^+$ as the most likely proton-configuration (see contr. to this conf. by C. Ekström). For N=61 neutrons, the most likely neutron configuration for strong prolate deformation is $(411)3/2^+$. (See Fig. 5) The coupling of these single-particle configurations should, according to the empirical rule\(^9\), yield spin I=3 lowest in energy. An extrapolation of the two single-particle configurations coupling to $^{100}$Rb, gives for protons $(411)3/2^+$ and for N=63 neutrons either the same as for N=61 or $(532)5/2^+$.

4. Discussion

The results of the experiments point to $^{100}$Sr as a well-developed axial rotor. The B(E2) value for the $2^+\rightarrow 0^+$ transition translates\(^10\) into an intrinsic quadrupole moment of 3.3b. By assuming prolate spherical shape and using the relation between $\varepsilon$ and Q to second order $Q=4/5 \varepsilon^{2/3} + \varepsilon^{1/2}$, a deformation parameter $\varepsilon$ of 0.29 is derived. Note that the first order term in $\varepsilon$ alone would lead to an $\varepsilon$-value of 0.35.

We note that several theoretical calculations\(^11\) are able to explain the onset of permanent deformation around N=60. The "chameleon" character of the zirconium isotopes is explained by the proton number being a subshell gap for spherical shapes, while $Z=38$ emerges as a substantial gap in the Nilsson diagram for deformation $\varepsilon$=0.3 - 0.4 (see figure in contr. by C. Ekström). The calculations, however, have
difficulties in accounting for the suddenness of the transition from spherical shape at N=56 to the strong deformation encountered at N=60.

The calculation shown in Fig. 6 with parameters as given in the caption gives rise to a family of potential-energy curves that agree well with experiment: $^{94}$Sr with 56 neutrons comes out with a rather deep spherical minimum, $^{90}$Sr is soft, and $^{98,100}$Sr are deformed with the prolate minimum at $\epsilon=0.30$, that for $^{100}$Sr being deeper. The proton energy curve shown in the lower part of Fig. 6 for Z=38 explains why either very large or very small values of $\epsilon$ are favoured.

The role of the minima calculated for oblate deformation (Fig. 6) is not clear: they are almost as deep as the minima at prolate deformations, and they are certainly expected to connect with these via the gamma degree of freedom. Thus, our calculations would have the heavy strontium isotopes to be soft vibrators in the gamma directions, while the high experimental $E4^+/E2^+$ ratio excludes a strong triaxiality.

The moment of inertia of the $^{100}$Sr ground state rotational band is 67% of the prolate deformation rigid-body value, about the same as for $^{20}$Ne and well above the values of 50-55% (see Fig. 7) found in the rare earths and actinides. (If an oblate deformation were assumed, the moment of inertia would correspond to 82% of the rigid-body value). The high value of the moment of inertia, possibly due to weaker pairing correlations than in the heavier nuclei, may be associated with the Z=38 "deformed gap" mentioned above. Further indications for reduced pairing effects come from the mass measurements by Ephrêre et al.13), who find that the rubidium isotopes with N>50 have pairing energies much smaller than expected.

Attempts to explain the abrupt onset of deformation and occurrence of very low-lying excited $0^+$ states have been made re-

![Fig. 6](image)

The upper part of the figure shows potential-energy curves for Sr isotopes as a function of the deformation parameter $\epsilon$. The lower part shows the corresponding proton shell energy for Z=38 as calculated by the Strutinsky prescription. A modified oscillator potential has been used with the following parameters: $\hbar \omega_p = \hbar \omega_N = 0.08$, $\nu_p = 0.30$, $\nu_N = 0.22$. Only quadrupole deformation ($\epsilon$) has been considered, but it has been verified that the hexadecapole degree of freedom ($\epsilon_4$) is unimportant for these isotopes. The pairing strength parameter is taken as $G = (19/7)(N-Z)/A$ MeV,

![Fig. 7](image)

Plot of rotational-type $2^+$ energies for even-even nuclei over the entire mass region in logarithmic scales. A rotation on the basis of a rigid moment of inertia of any of the considered spheroidal shapes, with axis ratios of 4:1 prolate, 2:1 prolate and 1:2 oblate, corresponds to the three straight (dashed) lines drawn in the figure. The figure is taken from Ragnarsson et al.12)
cently by Federman and Pittel with calculations on proton-neutron interaction. In a purely independent particle picture, the 2r isotopes with Z=40 have the 1g9/2 proton orbital completely empty and the 1g7/2 neutron orbital begins to fill after N=62. This picture is modified by residual n-n and p-p interactions, which distribute nucleons over all active orbitals by configuration mixing. Neutrons and protons simultaneously filling selected partner orbitals can lead to strong n-p correlations and consequently to deformations. Mutual polarization of nucleons into the 1g9/2 proton and 1g7/2 neutron orbitals can occur if the gain in n-p interaction energy exceeds the loss in single-particle plus pairing energy.

The idea that n-p force favours large 1g9/2 proton and 1g7/2 neutron occupation probabilities and that this is closely related to the onset of deformation is consistent with the Nilsson model. By examining the relevant deformed proton orbitals, one finds that for sufficiently large prolate deformation, the two lowest Nilsson configurations beyond Z=38 correspond to 1g9/2, and not to 2p1/2 proton orbital.

In conclusion, a new region of strongly deformed nuclei is emerging. More experiments are needed, especially atomic hyperfine structure measurements that unambiguously can tie down the Nilsson assignments of the odd nucleons.

Acknowledgements

The authors are grateful to Dr C. Ekström for valuable comments on this paper.

References

5. T.A. Khan, W.-D. Lauppe, K. Sistemic, H. Lawin, H.A. Selîå

DISCUSSION

E.R. Flynn: I disagree with the interpretation that the first excited 0+ of 96Zr is related to the rotational states but is more related to a pairing vibration at the N=56 subshell closure. A similar situation may exist in Sr.

I. Ragnarsson: In another contribution to this conference (Bengtsson, Ragnarsson, Zhang and Aberg), it is demonstrated that the 0+ states of the spherical nuclei ..., 98Zr, 99Zr, can be considered to form one band while the 0+ states for the deformed 102Zr, 103Zr, ..., form another band (fig. 3 of the mentioned contribution). These bands then cross close to N=60. This suggests two coexistent close-lying 0+ states for 102Zr. Away from N=60 the two bands diverge rapidly. Thus, one could expect coexistent 0+ states with a spacing of 1-1.5 MeV for N=58 and N=62 while further away from N=60, the energy differences...
become larger and it becomes difficult to observe any coexistence. I would thus agree that the first excited $0^+$ state of $^{98}$Sr is probably not (or very little) connected with deformed shape. A similar situation as for the Zr isotopes is expected for the Sr-isotopes.

J.H. Wilhelm: Are the excited $0^+$ levels in $^{98}$Sr and $^{100}$Zr close to the calculated oblate minimum in the potential energy surface? Is there any experimental evidence for a rotational band built on these levels?

J. Ragnarsen: It is true that most potential-energy surface calculations in the neutron-rich Sr/Zr region give one oblate and one prolate minimum of about equal depth. However, in the $\gamma$-plane there is no or a very small barrier between the two minima. Furthermore, similar calculational results are obtained also in other regions of the nuclear chart while (to my knowledge) no firm experimental evidence for large oblate deformation (at low spin) has been presented for nuclei above the sd shell region. Thus it does not seem probable that the calculated oblate minima in $^{98}$Sr and $^{100}$Zr would show up as excited $0^+$ states.

P. Tondreau: I would like to make a comment about the theoretical prediction of a strongly oblate minimum in the region of $^{100}$Zr, $^{102}$Zr, $^{104}$Sr ... etc. The results I have obtained (Nucl.Phys. A359 (1981) 278 and this conference) suggest the existence of a very soft potential energy surface from $\epsilon = 0.3$ to $\epsilon = 0.1$, which is very different from your prediction, and which could be of some importance for the interpretation of the first $0^+$ excited state.
PHASE TRANSITION IN NUCLEAR SHAPE IN THE A = 100 REGION?

J. Stachel, N. Kaffrell, N. Trautmann, Institut für Kernchemie, Universität Mainz
H. Emili, H. Folger, E. Grosse, R. Kulesza, D. Schwalm, GSI Darmstadt
K. Brodén, G. Skarnemark, Department of Nuclear Chemistry, Chalmers University, Göteborg
D. Eriksen, Department of Nuclear Chemistry, University Oslo

Abstract

Two different types of experiments for the investigation of the neutron-rich Ru-isotopes are presented. A discussion of the neutron-rich isotopes of the A = 100 transitional region is given in the framework of the Interacting Boson Model.

1. Introduction

After the discovery of well-deformed nuclei in the middle of the neutron-shell N = 82-126 and around N = 140-150 nearly thirty years ago, very soon a region of deformation was predicted also around the middle of the N = 50-62 shell corresponding to a mass-number of A = 100. Subsequently various theoretical investigations have been concerned with this mass-region and the results of different microscopic calculations point to a phase transition in nuclear shape between vibrational nuclei near the shell-closure N = 50 and deformed shapes for the more neutron-rich nuclei. Following these calculations in the middle of the neutron-shell different types of deformation, prolate, oblate, triaxial or even shape coexistence between minima of different deformation seem to be possible.

To answer the question whether this predicted transition is realized in the nuclei of this mass-region, one has to investigate long isotope-chains starting from stable isotopes near N = 50 up to extremely unstable isotopes near the middle of the neutron-shell with \( \beta \)-half-lives of only a few seconds.

The following discussion will be concerned mainly with the Ru-isotopes, since these nuclei the experimental information covers now the whole region of interest.

Already the lever energy systematics of the lowest excited states give some evidence for an increasing deformation; so the excitation energy E(2\( ^+ \)) of the 2\( ^+ \)-state decreases continuously from \( E(2\^+\text{Ru}) = 250 \text{ keV} \) for 98\text{Ru} to 240 \text{ keV} for 102\text{Ru} to 100\text{Ru}. At the same time the ratio E(4\( ^+ \))/E(2\( ^+ \)) rises from 2.14 to 2.76 and the B(E2, 2\( ^+ \) + 0\( ^+ \))-value increases from 26 to 65 single particle units.

To obtain more detailed information about the heavier Ru-isotopes we have chosen two different experimental techniques. In section 2 Coulomb excitation experiments of the stable isotopes 102\text{Ru} and 104\text{Ru} will be discussed, which yielded besides excitation energies and spins also B(E2)-values and diagonal E2-matrix elements (i.e. electric quadrupole moments). The unstable isotopes 106\text{Ru} and 108\text{Ru} have been studied observing the \( \gamma \)-radiation following the \( \beta \)-decay of the short-lived precursors 36 s-106\text{C} and 5 s-108\text{C}. Measurements of \( \gamma \)-ray coincidences and \( \gamma \)-angular correlations allowed the construction of level schemes, the assignment of spins and the determination of E2/\( M1 \) mixing ratios. This will be discussed in section 3. Finally we will come back to the question, whether one can learn from the experimental information gathered so far with respect to the supposed shape transition in section 4. For this purpose experimental data will be compared to a schematic study in the framework of the Interacting Boson Model.

2. Multiple Coulomb excitation of 102\text{Ru} and 104\text{Ru}.

In previous Coulomb excitation experiments\(^9\) using light ions \((\alpha, f_{\alpha})\) the 4\( ^- \)-state in both 102\text{Ru} and 104\text{Ru} was reached. For the investigation of higher excited states and hence the identification of possible band-structures we used the 209\text{Pb}(4.6 MeV/u) beam of the GANIL at Caen to bombard thin targets of 102\text{Ru} and 104\text{Ru} \((500 \mu\text{g/cm}^2, 102\text{Ru} \text{ on } 35 \mu\text{g/cm}^2)\). The use of a special particle \( \gamma \)-ray coincidence set-up allowed for the correction of the strongly Doppler-broadened gamma-spectra observed with the Ge(Li)-detectors. Additional measurements of \( \gamma \)-coincidences using thick targets \((2 \text{ cm}^2, 102\text{Ru} \text{ on } 50 \text{ mg/cm}^2)\) were performed to place the observed transitions in the level schemes of 102\text{Ru}. Both ground state bands (gsb) and \( \gamma \)-band can be identified up to \( I = 8 \).

The measurement of \( \gamma \)-yields over a large range of scattering angles \(( 60^\circ < \theta_{\text{CM}} < 170^\circ)\) allowed the determination of E2-matrix elements (ME). For this purpose we used an iteration procedure\(^12\), which compares the experimental \( \gamma \)-yields with those obtained from a modified de Boer-Winterh Code starting from 2\( \text{E} \)-ME resulting from different collective models, namely the Generalised Collective Model (GCM)\(^13\), the Interacting Boson Model (IBM\(^{14})\), and the Asymmetric Rotov-VM Model (ARV\(^{15})\). To warrant model independent results one has to take into account all ME (mainly E2 but also M1, E1, E3, E4) connecting the observed states; especially the influence of the size and relative phase on the extracted E2-ME has to be tested carefully for all scattering angles.

It was shown\(^9\), that for the determination of B(E2)-values in a band it is useful to define yield ratios \( R_{I}\) \((=Y_{I})\) \((=Y_{I-I})\), where \( Y_{I-1} \) is the \( \gamma \)-intensity of the transition from the state with spin \( I \) to the state with spin \( I-1 \) at a scattering angle \( \theta \). These yield ratios are mainly determined by the B(E2)-value for the corresponding transition. For the gsb yields the influence of the other in-band transitions and the various interband transitions from the \( \gamma \)-band turns out to be roughly one order of magnitude weaker. Since most of these transitions are observed in the present experiment, these collective transitions ME can be fixed by fitting the corresponding yield ratios. Amongst the remaining unknown ME the influence of the diagonal E2-ME \( |2\text{E}| \) on the gsb yield ratios plays the dominant role. To demonstrate this we show in fig. 1 experimental \( \gamma \)-yields together with the fitting result for two different diagonal ME for the 6\( ^- \)-state. Note that their influence on the \( \gamma \)-yields is strong for small impact parameters, whereas for large impact parameters the \( \gamma \)-yields are especially sensitive to the corresponding E2-transition ME.

Therefore one can extract both the B(E2)-values and...
Fig. 1 γ-ray yields for the 6\(^+\)→4\(^+\) transition normalized to the 2\(^+\)→0\(^+\) transition as a function of the scattering angle \(\theta_{CM}\). The open circles (solid lines) correspond to events, where the γ-radiation is emitted along the recoil axis; for the closed circles (dashed lines) the relative angle between the γ-rays and the recoil axis was 60\(^0\). The curves represent the calculated yield-ratios assuming \(<6\|^2[E2]|E6]\> = -0.60 eb \(a\) and \(<6\|^2[E2]|E6]\> = -0.36 eb \(b\).

The electric quadrupole moments by fitting the experimental γ-yields. Note, that in order to reproduce the yields observed under different γ-angles deorientation effects have to be taken into account carefully. The deorientation coefficients were determined experimentally and were found to be rather strong especially for the 2\(^+\)-state, which has a lifetime of 81 ps.

The resulting B(E2)-values for the gsb are shown in Fig. 2a. For the 10\(^+\)→8\(^+\) transition no clear-cut assignment can be made. Nevertheless, one can estimate an upper limit for the E2-strength, connecting the 8\(^+\)-state with the next higher excited state(s); this estimate is based on the intensity and angular distribution of the 8\(^+\)→6\(^+\) transition assuming 960 keV for the 10\(^+\)→8\(^+\) transition energy. This is the value of the strongest unassigned γ-line in the spectrum; this energy is even above what one would expect from band systematics. Reducing this transition energy drastically (<100 keV) the corresponding 10\(^+\)→8\(^+\) B(E2)-value reduces to about 40 % (lower limit of the error bar in fig. 2a). The B(E2, 8\(^+\)→6\(^+\)) value is the mean-value resulting from previous experiments\(^{10}\); for the 4\(^+\)→2\(^+\) transition the corresponding mean values shows to be in rather good agreement with our value. Also shown in fig. 2a are the gsb B(E2)-values as predicted by different collective nuclear models; For all these models the over-all agreement with the experiment is about the same.

Fig. 2b shows the corresponding diagonal E2-ME of the levels of the gsb. The rather strong decrease between the 2\(^+\)- and 4\(^+\)-value is the most striking feature, which can be reproduced quite well by the rigid triaxial rotor model (AR) using \(\gamma = 275\) and \(\gamma = 25\)\(^0\) whereby the model parameters have been adjusted to the excitation energy and transition probabilities only. All other collectiv models predict a rather steep increase of the diagonal ME with increasing spin; also the 0(6)-limit of the Interacting Boson Model\(^{23}\), which is equivalent to the Jean-Kiels γ-unstable Rotor Model\(^{25}\) can predict only a rather steep increase in the currently used form of the model. Indeed it is the spin-dependence of the quadrupole moments, which allows to distinguish clearly between the stiff-triaxial\(^{16}\) and the γ-unstable Rotor Model. The error bar for the 8\(^+\) diagonal ME blows up in decreasing direction due to the large uncertainty of the B(E2, 10\(^+\)→8\(^+\))-value in direction to lower values.

3. Excited states in 106\(^{\text{m}}\)108Ru

Since the neutron-rich isotopes 106\(^{\text{m}}\)108Ru are unstable against β-decay they cannot be investigated by Coulomb excitation. So we have chosen the β-decay of their shortlived precursors 36 s - 106Tc and 5 s - 106Tc to feed excited states in these nuclei. The activity was produced by thermal neutron
induced fission of $^{239}$Pu in the Mainz TRIGA reactor. For a rapid on-line isolation of the Tc-activity from the fission product mixture we used the continuously working chemical separation system SISAK-II. This method consists of several mixer-centrifuge units and is based on a liquid-liquid extraction chemistry (for details see the contribution of N. Trautmann et al. to this conference or ref. 25).

In a first experiment the timing was optimized to measure the $\gamma$-radiation following the 36 s $^{106}$Tc $\rightarrow$ $^{108}$Ru $\beta^-$-decay. The activity reached the measuring position ~7 s after fission with a continuous flux of ~10 m/s.

In order to keep the measuring cell small enough a 4 cm$^3$ polyethylene cell was filled with an anion-exchanger (DOWEX 1 x 4), which kept the Tc-activity for about 30 s in this measuring position. With 2 Ge(Li)-detectors both in a distance of 5 cm from the middle of the measuring cell $\gamma\gamma$(t) coincidences have been measured for 5 different angles. Due to the finite source dimensions and solid angles remarkable corrections were necessary; nevertheless, we obtain reliable results as can be demonstrated for the $\gamma^- \rightarrow Z^- \rightarrow \gamma £ £ 0^+$ cascade, where the experimental coefficients $A_{22} = 0.34$ (9) and $A_{44} = 1.20$ (16) are in rather good agreement with the theoretical ones (0.3571 and 1.1429).

To obtain similar information about $^{108}$Ru with a 5 s half-life precursor, the SISAK system was reduced to 2 mixer-centrifuge units; this enabled the study of measurements ~5 s after fission. To suppress longer-lived activities the measuring time was shortened to about 1 s; the Tc-activity flushed with ~2 ml/s through a polyethylene cell (diameter 2 cm, length 4 cm). So we could measure comparable activities of $^{106+107+108}$Tc with 3 Ge(Li)-detectors.

The level schemes of $^{106}$Ru and $^{108}$Ru have been studied previously by measurements of $\gamma\gamma$-coincidences using the same separation technique). The case of $^{108}$Ru the much better statistics allowed us, to construct numerous additional excited levels. As is the case for $^{106}$Ru and $^{108}$Ru also for $^{106+108}$Ru the head of a gsb (0, 2, 4) and a $\gamma$-band (2, 3, 4) can be identified. Levels with higher spin values are not fed in allowed $\beta^-$-decay since the precursors $^{106+107}$Tc have relatively low ground state spins (I$^g$ = 2, 3$^+$).

Fig. 3a shows a typical $\gamma\gamma$-angular correlation. Via a $\chi^2$-minimization procedure we can make spin assignments for most of the observed levels and determine multipole mixing ratios for the stronger transitions. For an example see fig. 3b. In $^{106}$Ru most of the excited states above 2 MeV have spin values of I = 1 and presumable negative parity, since their decay to the $2^+$-state is predominantly dipole radiation; the nature of these states is still unclear. The until now missing first excited $0^+$-state in $^{108}$Ru could be located only ~1 keV above the $3^-$-state through a 20 % admixture of its characteristic 0-2-0 angular correlation to the $3^+ \rightarrow 2^+ \rightarrow 0^+$ cascade.

Some of the resulting E2/M1 mixing ratios are shown in table 1 together with the corresponding values for $^{102+104}$Ru. As is expected for transitions between collective bands the transitions between gsb and $\gamma$-band show a predominant E2-character with rather weak M1-contributions (<10 %). On the other hand the $2^+$-state decays mainly by M1-radiation, which does not fit in the collective picture and hence cannot be reproduced by the used collective

<table>
<thead>
<tr>
<th>$^{102}$Ru</th>
<th>$^{104}$Ru</th>
<th>$^{106}$Ru</th>
<th>$^{108}$Ru</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$^+\rightarrow 1^+$</td>
<td>-114$^{+8}_{-9}$</td>
<td>-81$^{+31}_{-121}$</td>
<td>17.9$^{+4.9}_{-2.2}$</td>
</tr>
<tr>
<td>3$^-\rightarrow 2^+$</td>
<td>-8.4$^{+0.7}_{-4.3}$</td>
<td>-6.3$^{+0.5}_{-1.8}$</td>
<td>-6.2$^{+1.6}_{-1.8}$</td>
</tr>
<tr>
<td>4$^-\rightarrow 4^+$</td>
<td>-4.1$^{+6.6}_{-1.8}$</td>
<td>-4.1$^{+6.6}_{-1.8}$</td>
<td>-4.1$^{+6.6}_{-1.8}$</td>
</tr>
<tr>
<td>2$^+\rightarrow 2^+$</td>
<td>0.27$^{+0.03}_{-0.45}$</td>
<td>0.45$^{+0.12}_{-0.45}$</td>
<td>0.28$^{+0.15}_{-0.45}$</td>
</tr>
</tbody>
</table>
models. As will be discussed in section 4 also the interpretation of the 0+\textsuperscript{\textit{f}}-state, which is connected to this 2\textsuperscript{\textit{f}}-state, is difficult within these models.

4. Discussion of the A \approx 100 region in the framework of the IBA-1

In the following the A \approx 100 transitional region will be discussed in the Interacting Boson Model\textsuperscript{(31)} (here in its simplest form, which does not distinguish between proton and neutron bosons, the so-called IBA-1). Its three dynamical symmetries \textsuperscript{32-34}, the SU(5)-, SU(3)- and O(6)-limit correspond to the three geometrical descriptions of nuclei as anharmonic vibrators, rigid axial symmetric rotors \textsuperscript{18} and soft triaxial rotors\textsuperscript{29}). Moreover the full IBA-1 Hamilton operator describes all direct and complex transitions between these limiting cases in a consistent and relatively simple way. The symmetry triangle in fig. 4 shows this in a symbolic way.

![Symmetry triangle symbolizing the three dynamical symmetries of the IBA-1 and the possible transitions between them. The transition SU(5) = SU(3) is realized in the NdSm-nuclei\textsuperscript{28}), the transition SU(3) = O(6) in the PtOs-nuclei\textsuperscript{29}).](image)

Now the question arises, where on this triangle can the A \approx 100 transitional region be located. As already mentioned, in the Ru-isotopes the energy ratio E(\textit{4}\textit{f})/E(2\textit{f}) increases continuously with increasing neutron number starting from a vibrational value near the shell closure at N = 50, but it stays clearly below the rotational value of 3.3 also for the heaviest of the known isotopes. For the Zr,Mo- and Pd-isotopes (Z = 40, 42, 46) a similar trend is observed. The increase is rather steep between N = 58 and 60 for the Zr- and Mo nuclei and rather moderate for the Pd-isotopes. In fig. 5 the B(E2, 2\textit{f} \rightarrow 0\textit{f})-values for Ru/Pd-isotopes are shown in comparison to those of NdSm-isotopes, representing a transition from vibrational to rotational SU(5) \rightarrow SU(3)\textsuperscript{28}) and of Os-isotopes, representing a transition from rotational to \gamma-unstable nuclei (SU(3) \rightarrow O(6)\textsuperscript{29}). Although two different shells are compared, for the A \approx 100 region a transition between SU(5)- and O(6)-nuclei is suggested; a comparison of some experimental B(E2)-ratios with the model predictions for the three limits confirms this suggestion (table 2); in any case a transition towards the SU(3)-limit can be excluded. For this transition one would expect also a rather sudden onset of deformation connected to discontinuities for the SU(5) \rightarrow SU(3) transition\textsuperscript{30}).

\begin{equation}
\text{H} = c_{\text{Q}_{\text{Q}}} \text{e}^{\text{P} + \text{d}} \text{L} \cdot \text{L} \cdot \text{e}^{\text{Q} + \text{a}_{\text{D}} + \text{e}_{\text{A}} + \text{e}_{\text{T}_{\text{T}}} + \text{e}_{\text{T}_{\text{T}}} + \text{e}_{\text{T}_{\text{T}}}}
\end{equation}

Since, until now, no examples are known for the SU(5) \rightarrow O(6) transition, a more detailed discussion seems to be worthwhile. In the following we will briefly outline a schematic study of this transition. It is convenient to write the IBA-1 Hamiltonian for this purpose in a multipole expansion of s- and d-boson creation and annihilation operators\textsuperscript{31}).

For the SU(5)-limit the monopole term \textit{c}_{\text{Q}_{\text{Q}}} is dominant, while for the O(6)-limit the p-wave term \textit{c}_{\text{Q}_{\text{Q}}} is the most important. Thus for a study of the SU(5) \rightarrow O(6) transition one should vary the ratio of these two terms systematically. Neglecting the other terms in the Hamiltonian, the corresponding simipli-

\begin{table}[h!]
\centering
\caption{B(E2)-ratios for low-lying excited states resulting from the three IBA-1 limits; in comparison the corresponding experimental values for \textsuperscript{102-108}Ru are shown\textsuperscript{7-9,10,14,2-4,5}).}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
B(E2)- & 2\textit{f}\rightarrow0\textit{f} & 2\textit{f}\rightarrow2\textit{f} & 3\textit{f}\rightarrow2\textit{f} & 4\textit{f}\rightarrow3\textit{f} & 4\textit{f}\rightarrow4\textit{f} \\
ratios & 2\textit{f}\rightarrow2\textit{f} & 3\textit{f}\rightarrow0\textit{f} & 4\textit{f}\rightarrow3\textit{f} & 4\textit{f}\rightarrow4\textit{f} & 4\textit{f}\rightarrow4\textit{f} \\
\hline
SU(5) & .011 & 1.40 & .06 & .72 & 1.0 \\
SU(3) & .70 & .32 & 2.50 & .03 & 6.93 \\
O(6) & .07 & .79 & .12 & .75 & 1.84 \\
\hline
\textsuperscript{102}Ru & .036(3) & .71(7) & .18(2) & .51 & 1.62(21) \\
\textsuperscript{104}Ru & .045(4) & .36(7) & .10(2) & .54(5) & 1.57(17) \\
\textsuperscript{106}Ru & .087(11) & -- & .16(7) & -- & -- \\
\textsuperscript{108}Ru & .103(11) & -- & .21(6) & -- & -- \\
\hline
\end{tabular}
\end{table}

- 439 -
fied Hamiltonian can be written as
\[ H = \epsilon (d^4d^0 + d^3d^2s^2 + d^2ss_d) \] (2)

This formalism was also chosen by Dieperink et al.\(^{38}\) in their investigation of the changes in ground-state properties connected with the shape phase transitions in the interacting Boson Model. The treatment of the SU(3) = O(6) transition using only one free parameter $\epsilon$ is certainly a rather drastic simplification, but the characteristic features of the phase transition are expected\(^{10}\) to be contained in this description.

In fig. 6a, b we compare the experimental excitation energies for several low-lying excited states ($4^+, 2^+, 6^+, 4^+$) with the theoretical ones resulting from these BBA-I calculations. This is done for different total boson numbers $N(N=5, 6, 14)$ as a function of $\xi = n/1n$ with $n = 4\epsilon/c (N=1)^{30}$. In this parametrization the phase transition occurs exactly at $\xi = 0.5$ for $N = m$, but is smeared out for smaller boson numbers. The comparison of theory and experiment gives $\xi$-values of $0.5 \pm 0.0$ for the Ru- and Pd-isotopes. In the case of Pd, only the energy of the $4^+$-state was considered, as the $2^+$-state is not at the same energy experimentally in contradicetion to this simplified BBA-description.

The decay properties only depend partly on $\xi$. The ratio $B(E2, 4^+ \rightarrow 2^+)/B(E2, 2^+ \rightarrow 0^+)$ e.g. does not change characteristicly between the two limits under consideration; therefore it does not help for the localization of the Ru/Pd-isotopes in the SU(3) = O(6) transitional region. On the other hand some transitions which are forbidden in the SU(3)-limit as cross-over transitions, increase by several orders of magnitude with increasing $\xi$ and reach the observed experimental values for the $2^+ \rightarrow 0^+$, $3^+ \rightarrow 2^+$ and $4^+ \rightarrow 2^+$-transition at $\xi = 0.5 \pm 1.0$. Again for Ru, rises with the neutron number, while for Pd this trend is not so clear, and even is in the opposite direction for some cases.

Thus as far as excitation energies and $B(E2)$-ratios are concerned in the Ru-isotopes we seem to observe a continuous development from nearly vibrational nuclei ($^{96,98}_{96,98}$Ru) to nuclei with a well pronounced $0(6)$-character ($^{100,102}_{100,102}$Ru). The known Pd-isotopes can be located clearly on the $0(6)$-side of this phase transition.

There are two distinct deviations from this simple picture. For the SU(3) = O(6) transition a very characteristic feature is the change in the decay mode of the $0^+$-state, since the SU(3)-limit allows an $E2$-decay only to the $2^+$-state, whereas in the O(6)-limit only a transition to the $2^+$-state is possible. The experimental situation in the $A = 100$ region appears to be rather complex: on the one hand the $0^+$-states in the Ru/Pd-nuclei are rather low in energy, more resembling a two-phonon triplet, and no decay to the $2^+$-state is observed; on the other hand the experimental ratio $B(E2, 0^+ \rightarrow 2^+)/B(E2, 2^+ \rightarrow 0^+) = 10^{\pm 0.5, 3}\%$ is about a factor of 2-3 smaller than the SU(3)-prediction. Moreover these $0^+$-states are populated in $(t,p)$ reactions leading to $^{104,106}_{104,106}$Ru\(^{46}\) with $\pm 20\%$ of the ground-state population, while this is forbidden in the SU(3)- as well as in the O(6)-limit\(^{39}\).

As mentioned above, also the predominant $M1$-decay of the $2^+$-state rules out the interpretation of the $0^+$, $2^+$-sequence in a simple collective picture. This leads to the conclusion, that the experimental $0^+$-states in the Ru/Pd-nuclei may not be the IBA $0^+$-states. In fact in some cases ($^{106,108,110}_{106,108,110}$Pd, $^{102}_{102}$Ru) second excited $0^+$-states are known\(^{50}\), which show the dominant ground decay to the $2^+$-state of the $2^+$-state\(^{27,43}\).

Concerning the real origin of the experimental $0^+$-states, different suggestions have been made: phenomena such as shape coexistence between minima of different deformation or large $Z=2/2$ admixtures (protons as neutrons) have been discussed already for Cd-, Sn- and Zr- isotopes\(^{24,57}\) as well as for $^{104,106}_{104,106}$Pd\(^{58,59}\). The enhancement observed in two neutron transfer reactions\(^{24,40}\) would favour the latter interpretation (two neutron correlated states).

The other discrepancy occurs in the spin-depen-
dence of the quadrupole moments as discussed in section 2. The experimental results are surprisingly well reproduced by the rigid triaxial rotor model. IBA-calculations performed so far (this investigation and ref. 15) are in disagreement with the experiment in this point. On the one hand the case of a rigid triaxial rotor is not contained in an IBA Hamiltonian limited to one- and two-body terms. On the other hand, a rigid triaxial rotor cannot explain the 0+ properties.

References:

24) L. Wilets, M. Jean, Phys. Rev. 102, 788 (1956)
39) P.H. Stelson, L. Grodzins, Nucl. Data A, 21 (1965)
44) A. Bockisch, M. Miller, A.M. Kleinfeld, Z. Physik A292, 265 (1979)
45) J. Stachel, N. Kaffrell, N. Trautmann, K. Brodén, G. Skarnemark, D. Eriksen, to be published
46) H. Bohn, priv. communication

DISCUSSION

A. Gelberg: While I consider the evidence for a shape transition as convincing, one should be rather prudent as far as the SU(5) = O(6) transition is concerned. 1) It is not easy to distinguish between the two limits, at least for the lowest bands. 2) Can there be an SU(5) symmetry in a nucleus with 6-holes and 4-ve particles? 3) In this situation it is generally difficult to assign a definite symmetry.

J. Stachel: 1) I agree that in general it is not easy to distinguish between the SU(5) and the O(6) limit. But as I showed, some properties change in a very characteristic way, even if there is no such a transition as between SU(5) and SU(3). 2) A comparison of the experimental data in Ru isotopes with the schematic study of the SU(5) → O(6) transition shows that there are no purely vibrational nuclides, the lightest isotopes (96-98Ru) seem to be placed around γ = 0.5, which is just the region of the so-called phase transition (onset of deformation). The Pd isotopes seem all to be located on the O(6) side of this transitional region and no clear neutron-number dependence is observed.

C. Baktash: From your quadrupole moment values, it seems that the data prefers a rigid-γ core. From our experience in the Os-Pt region, the matrix elements of the quasi-gamma band are also very sensitive to the softness of the core with respect to the γ vibrations. Could you comment if these matrix elements in your data prefer soft- or rigid-γ cores?

J. Stachel: As far as E2-matrix elements determined from our Coulomb excitation experiment (transition between the even members of the γ-band and interband transitions between these states and the ground state band) are concerned, there is no significant difference between γ-soft calculations (IBA) and γ-rigid ones (Toki-Paessler). This might have to do with the fact that in the γ-rigid calculations γ was chosen 25°, which gives the best fit to excitation energies and transition probabilities; in the γ-unstable limit of the IBA (O(6)) γ has a dynamical mean value of about 30°. This mean that from our data one cannot distinguish between a static and a dynamic deformation around 25-30°, except if one takes into consideration the quadrupole moments.
EXTENSION OF SYSTEMATICS FOR EVEN-EVEN Zr ISOTOPES TO A = 102

John C. Hill
Kernforschungsanlage Jülich, Germany and Ames Laboratory USDOE, Iowa State University, Ames, Iowa 50011 USA
Kernforschungsanlage Jülich, Germany

Abstract

The $^\beta$ decay of $^{102}$Y to levels in $^{102}$Zr was investigated using the gas-filled recoil separator JOSEF. The singles $\gamma$ spectrum, $\gamma-\gamma$ and $X-\gamma$ coincidences, and half-life were measured. Preliminary results from these measurements are reported. Only one isomer was observed with a $T_{1/2} = 0.27 \pm 0.07$ s. The $^\beta$ decay populated excited states in $^{102}$Zr at 151.9(2$^+$), 478.4(4$^+$), 730.7 and 1242.1 keV. No evidence was found for the population of a low-lying $^0$ state of the type seen in $^{100}$Zr. The results are compared with earlier fission fragment studies, and implications for the systematics of even-even Zr nuclides are discussed.

1. Introduction

The neutron-rich Zr isotopes are of special interest as they appear to exhibit a very rapid transition from a spherical to a deformed shape. The level structure for $^{98}$Zr shows magic properties in accordance with the spherical shell model[1,2], while $^{100}$Zr appears to be deformed[3]. The nucleus $^{98}$Zr appears to be of a transitional character[3] but more vibrational than rotational in nature. The energy of the $2^+$ state decreases by a factor of 6 in going from $^{98}$Zr to $^{102}$Zr indicating a sudden change to rotational behaviour similar to that occurring in the Sr isotopes but more drastic than the change observed in the Sm isotopes between $^{154}$Sm and $^{152}$Sm. The energy ratio $E_{2+}/E_{2+}^{100}$ is 1.6 for $^{100}$Zr but rises to 2.66 for $^{102}$Zr and at $^{102}$Zr the ratio is 3.14 approaches the rigid rotor value.

In order to gain a more detailed picture of the structure of $^{102}$Zr and the change from a spherical to a deformed structure in the Zr isotopes, an investigation of levels in $^{102}$Zr populated in the $^\beta$ decay of $^{102}$Y was undertaken. This nucleus cannot be reached by conventional reaction experiments and is most readily accessible through fission.

The only information presently available on the structure of $^{102}$Zr was obtained through observation of the prompt electromagnetic decay of $^{102}$Zr fission fragments[4,5]. The YRAST band up to $^6$ was observed. The only information available[6] on $^{102}$Y is a half-life of 0.9 sec. The JOSEF separator was well suited for a study of short-lived $^{102}$Y due to the very short separation time inherent in the system, but the low fission yield of $^{102}$Y is a limiting factor.

2. Experimental Techniques

2.1 The JOSEF separator

The gasfilled separator JOSEF provides a beam of fission products from the $^{235}\text{U}(n,f)$ reaction. The separation occurs according to the mass and its nuclear charge along the path in the gas-filled magnet and is essentially independent of the primary ionic charges and kinetic energies of identical fission products. The JOSEF separator is described in detail elsewhere[5]. The fission product beam impinged on a 3 cm wide tape of a tape transport device and measurements were carried out at the beam collection position. The tape was periodically moved to reduce interference from long-lived products. The data were accumulated in the megachannel computer analyser system MECC[7].

2.2 Identification of $^{102}$Y

Early experiments on $\gamma$ rays from fission fragments[8,9] established that the $2^+$ state in $^{102}$Zr occurred at 152 keV. In initial experiments at JOSEF a search was made for this $\gamma$ ray using a He-jet system without success. Subsequent measurements at the in-beam position revealed the presence of the 152 keV $\gamma$ ray with a very short half-life. In all subsequent measurements the fission product beam was collected and counted simultaneously. The tape was moved every 2 seconds to minimize buildup of long-lived products with a tape transfer time of 0.4 seconds.

The identification of the nuclide from which the 152 keV line emanated was carried out by measuring the intensity distribution of the $\gamma$ ray as a function of the magnetic rigidity $B_0$ of the gas filled magnet. The position of the $B_0$ maximum was that expected for 152 keV. In this measurement a 30 cc intrinsic Ge detector with a resolution FWHM of about 0.8 keV at 160 keV was used. Other lines observed in the decay of $^{102}$Y were too weak and complex to give unambiguous $B_0$ maxima in a singles $\gamma$ ray measurement. $B_0$ coincidence measurements are in progress to establish more firmly the origin of these $\gamma$ rays.

The fission products $^{105}$Mo, $^{106}$Nb, and $^{103}$Zr have $B_0$ maxima very close to that for $^{102}$Y. In order to eliminate these nuclides as sources of the 152 keV $\gamma$ ray a $X-\gamma$ coincidence measurement, which is described in detail below, was carried out. Definite coincidences were observed between the $Zr$ Ka $X$ ray and $\gamma$ lines from $^{102}$Y decay at 152 and 326 keV.

2.3 $\gamma$ ray singles measurements

$\gamma$ ray singles measurements were carried out both with the 30 cc intrinsic Ge(Li) detector and a large volume 150 cc Ge(Li) detector with a resolution of 2.0 keV for the 1332 keV $\gamma$ ray in $^{60}$Co. Also $B_0$ measurements were made for both detectors. The fission yield for $^{102}$Y is quite low for experiments at JOSEF and the resulting $\gamma$ spectra are complex. $\gamma$ ray intensities for $^{102}$Y are being determined by comparing results from several $B_0$ measurements. $\gamma$ ray energies were determined in coincidence measurements and are discussed below.

2.4 The half-life of $^{102}$Y

A crude half-life for $^{102}$Y was determined using the 150 cc Ge(Li) detector. Because of the very short half-life for $^{102}$Y it was necessary to install a "chopper" to interrupt the fission product beam at appropriate intervals. The fission product beam is concentrated at the entrance to the separator magnet by a guide consisting of a wire at a negative potential of from 5 to 20 kV. A second guide concentrates the beam coming out from the magnet at the tape...
collector. The "chopper" alternatively applied a negative and a positive potential to the second guide in order to interrupt the fission product beam.

For the half-life measurement the analyzer was operated in the multiscale mode. The activity was collected for 0.6 seconds and the decay followed for 1.0 seconds. After movement of the tape the cycle was repeated. Analysis of the time structure for the 152 keV $\gamma$ ray resulted in a preliminary half-life for $^{102}$Y of 0.27 ± 0.07 seconds. No evidence was seen for two different half-lives, thus it appears that unlike $^{98}$Y and $^{100}$Y only one isomer of $^{102}$Y undergoes $\beta^-$ decay (the case of two isomers with very similar half-lives cannot absolutely be ruled out). Measurements will be carried out with the high resolution 30 cc intrinsic Ge detector to obtain a more accurate half-life for $^{102}$Y.

2.5 $\gamma$-$\gamma$ coincidence measurements

Two sets of coincidence measurements were carried out both using the 150 cc Ge(Li) detector. For the X-$\gamma$ coincidences the 30 cc intrinsic Ge detector was used and for the $\gamma$-$\gamma$ coincidences a 60 cc Ge(Li). The detectors were at about 90° to each other. Two energy and one time descriptor were recorded in buffer tape mode.

In the $\gamma$-$\gamma$ coincidence experiment events were accumulated over a period of about 170 hours. The results of this measurement are given in Table 1.

<table>
<thead>
<tr>
<th>Gating transition (keV)</th>
<th>Definitely coincident $\gamma$ rays (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>326, 579, 1090</td>
</tr>
<tr>
<td>326</td>
<td>152</td>
</tr>
<tr>
<td>579</td>
<td>152</td>
</tr>
<tr>
<td>1090</td>
<td>152</td>
</tr>
</tbody>
</table>

No coincidences were observed with a $\gamma$ ray at 486 keV that would be the $6^+ \rightarrow 4^+$ transition in $^{102}$Zr.

In the X-$\gamma$ coincidence experiment events were accumulated over a period of about 230 hours. The range of the 30 cc detector was set from 0 to 220 keV to take advantage of its excellent resolution. $\gamma$ rays at 152 and 326 keV were observed in coincidence with the Kα X ray from Zr. A gate on the 152 keV line in the 30 cc detector spectrum revealed coincidences with $\gamma$ rays at 326, 579, and 1090 keV but the background was lower due to the smaller Compton distribution under the 152 keV peak. This spectrum is shown in Fig. 1

![Fig. 1: Spectrum of $\gamma$ rays in coincidence with the 152 keV $\gamma$ ray from $^{102}$Y decay.](image)
Because of the complexity of the γ ray singles spectra, the energies for the $^{102}$Y γ rays were measured in the coincidence mode. A $^{152}$Eu source was placed in front of the detectors and the $^{152}$Eu and fission product spectra were measured simultaneously. By choosing suitable gates and in some cases developing secondary standards it was possible to determine the $^{102}$Y γ ray energies which are given in Table 2. The results are compared with those from earlier fission fragment experiments$^5$).

Table 2: γ-ray energies observed in $^{102}$Y decay

<table>
<thead>
<tr>
<th>$E_γ$ (keV)</th>
<th>$E_γ$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{102}$Y</td>
<td>Ref.4</td>
</tr>
<tr>
<td>151.9 ± 0.1</td>
<td>151.9</td>
</tr>
<tr>
<td>326.5 ± 0.2</td>
<td>326.6</td>
</tr>
<tr>
<td>578.8 ± 0.2</td>
<td>485.5</td>
</tr>
<tr>
<td>1090.2 ± 0.2</td>
<td></td>
</tr>
</tbody>
</table>

3. Decay scheme and discussion

3.1 The decay scheme of $^{102}$Y

The measurements described above have been used to construct a preliminary first decay scheme for $^{102}$Y. The measured half-life of 0.27 ± 0.07 sec is in poor agreement with a range of values from about 0.9 to 3 sec predicted by the Gross-Theory of B decay$^6$. Theoretical predictions were systematically too large for other lower mass odd-odd Y isotopes. The decay scheme is shown in Fig. 2 and the levels in $^{102}$Zr are compared with results from fission fragment studies$^7$).

The level energies of 151.9 ($^2_2^*$) and 478.4 ($^4_1^*$) keV are in good agreement with values of 151.9 and 478.5 keV obtained in fission fragment studies$^7$). The 6$^*$ and 8$^*$ members of the YRAST band in $^{102}$Zr were not observed. This implies that J for $^{102}$Y is probably less than 5. In addition to the 4$^*_1^*$, 2$^*_1^*$, 0$^*_2^*$ cascade new levels in $^{102}$Zr at 730.7 and 1242.1 were confirmed by coincidence measurements.

Due to the complexity of the singles γ ray spectra analysis of relative γ ray intensities is still in progress, but preliminary results indicate significant 0$^*$ feeding to both the 4$^*_1^*$ and 2$^*_1^*$ levels in $^{102}$Y. Thus log fts indicate a transition from the above levels to the 0$^*$ state. This favours a J$^*$ assignment of 3$^*$ for the $^{102}$Y ground state.

Although isomerism is well established for $^{96}$Y, $^{98}$Y, and $^{102}$Y we were unable to detect an isomer for $^{102}$Y. The reason for this is not clear. Unfortunately it is a low-lying 0$^*$ state exists in $^{102}$Zr it would be difficult to populate by 0$^*$ decay from the 3$^*$ ground state. We see no evidence for population of a 0$^*$ state.

3.2 Systematics of even-even Zr isotopes

The level scheme for $^{102}$Zr is compared to that for $^{102}$Zr obtained in a study$^8$ of the decay of $^{102}$Y. The most obvious feature is the lowering in energy of the YRAST band from A = 130 to 102. This feeding and decay patterns for the 878.5 and 1408.2 keV levels in $^{102}$Zr are correspondingly similar to those of the 730.7 and 1242.1 keV levels in $^{102}$Zr. If these levels prove to

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Fig. 2: Decay scheme for $^{102}$Y from this work (left), and $^{102}$Zr levels from fission fragment studies (right).

Fig. 3: Comparison of the level structure of $^{102}$Zr and $^{102}$Zr.
be similar in structure then an appealing pattern emerges in which all the low-lying levels in $^{102}$Zr are systematically lowered relative to those in $^{100}$Zr. This is also true for the 6$^+_1$ and 8$^+_1$ members of the YRAST bands not observed in this study.

The 730.7 keV level in $^{102}$Zr is especially interesting. It could correspond to the 878.5 keV level in $^{100}$Zr which seems to have the characteristics of the bandhead of a $\gamma$-vibrational band\(^2\) as far as its decay pattern to the 0$^+_1$, 2$^+_1$, and 4$^+_1$ states is concerned. If the 730.7 keV level in $^{102}$Zr is actually a $\gamma$-vibrational bandhead, then both $^{100}$Zr and $^{102}$Zr would be axially asymmetric with softness in the $\gamma$ direction.

3.3 Conclusion

A first attempt has been made to study the structure of levels in $^{102}$Zr populated in the $\beta^-$ decay of $^{102}$Y. No low-lying 0$^+_1$ state was observed probably due to the J$^\pi$ for $^{102}$Y. Experiments are continuing in an effort to obtain accurate relative $\gamma$ ray intensities and search for new levels. Although only a few states in $^{102}$Zr were observed due to the short half-life and low fission yield of $^{102}$Y it is evident that $^{102}$Zr is well deformed but probably not axially symmetric.

References

STUDY OF THE PRODUCTION AND DECAY OF $^{89}\text{Mo}$ ISOMERS AND $^{96}\text{Pd}$

N. K. Aras*, P. W. Gallagher†, E. W. Schneider‡‡ and W. B. Walters

Department of Chemistry and Cyclotron Laboratory
University of Maryland, College Park, MD 20742, USA

Abstract

The production and decay of 190-ms $^{89}\text{Mo}$, 2.15-min $^{89}\text{Mo}$, 8.2-min $^{88}\text{Mo}$, and 2.0-min $^{96}\text{Pd}$ have been studied using sources produced at the Maryland Cyclotron. The resulting $\gamma$-ray spectra have extended the systematics of the N=47 and 48 isotones to higher Z and revealed sharp differences between the N=47 isotones and Z=47 isotopes. The low-lying $1^+$ states identified in $^{96}\text{Pd}$ following the decay of $^{96}\text{Pd}$ further supports the hypothesis of strong interaction between protons and neutrons with identical $\lambda$ values.

1. Experimental Procedures

The neutron deficient nuclides 8.2-min $^{88}\text{Mo}$, 2.15-min $^{89}\text{Mo}$, and 190 ms $^{89}\text{Mo}$ were produced at the Maryland Cyclotron in proton irradiations of enriched $^{92}\text{Mo}$ at beam energies ranging from 40 to 75 MeV. The study of activities with half lives greater than 1.5 min was done by manually transferring the target from the irradiation station to a high resolution large volume Ge detector in a low-background area. For the study of shorter-lived activities, a fixed target and detector setup was used and the

![Decay Scheme](image)

Fig. 1 Decay Scheme of 190-ms $^{89}\text{Mo}$ and the systematics of the low-lying $9/2^+$, $7/2^+$ and $1/2^-$ levels and E3 hindrances in the N=47 isotones.

*) On leave from the Middle East Technical University, Ankara, Turkey
†) Present address: Harvard Medical School, Boston, Massachusetts, USA
‡‡) Present address: General Motors Technical Center, Warren, Michigan, USA
irradiation and counting periods determined by a variable-speed rotating mechanical beam chopper (wheel). The wheel was designed to provide a 3:1 ratio between counting and irradiation time by the presence of four 22.5° slots in a 5 cm thick Al disc. The wheel could be rotated continuously from 2 rpm to ~200 rpm and could also be controlled by a switch to provide longer irradiation and/or counting periods. The position of the slots in the wheel was monitored by an optical sensor whose output was coupled to the Cyclotron Computer to gate the storage of γ rays into twelve 8192 channel spectra as a function of time-after-irradiation. A manual start was used for this data collection system for the longer-lived activity studies.

Four 3 mg/cm² 92Mo foils enriched to 96% were used in both studies to minimize the buildup of longer-lived activities, particularly 5.9-h 90Mo and 14.6-h 90Nb. Strong activities were also observed from the Nb isotopes produced in the 92Mo(p,αn) reactions.

2. 89Mo Studies

As the study of the 92Mo(3He,6He)89Mo reaction revealed the presence of 7/2⁺ and 1/2⁻ levels in the low-lying level structure of 89Mo and a Q value of 5.6 MeV for 89Mo decay, it was possible to estimate a half life for the E3 transition of a few hundred milliseconds for 1/2⁻ 89Mo and a half life of 15 sec or greater for the 8⁺/EC decay of 9/2⁺ 89Mo. Thus, the rotating wheel setup was used to make the initial studies for both isotopes. The wheel was rotated to give a 50 ms irradiations and 1050 ms counting periods in the initial measurement of 89Mo decay. For the initial study of 89Mo, the wheel was manually operated to give 45-sec irradiations and 300 sec counting periods. Subsequent studies of 89Mo decay were done using the manual target transfer procedure when the half life was found to be ~2 min.

2.1 89Mo Studies

The results of our study of 89Mo decay are shown in Fig. 1 along with the data for other N=47 isotopes. These studies reveal a sharply decreasing hindrance factor for the 1/2⁻→1/2⁺ E3 transition as 2 increases and a 7/2⁻→9/2⁺ difference that peaks in 89Sr. The hindrance was calculated as the ratio t1/2 (radiative)/tw where the theoretical E3 half life tw was calculated by the formula $t_w = 0.693/35A^{-1/2}$. Extensive calculations of the level energies and transition rates of the N and E=47 nuclides by Paar using a cluster-vibration model.

![Decay scheme of 89Mo decay](image)

Fig. 2 Decay scheme of 2.15-min 89Mo and levels of 89Nb observed in the 89Y(3He,3nγ) and 92Mo(p,α) reactions.
have successfully accounted for many of the observed features of these nuclides particularly for the \( Z=47 \) isotopes. The \( 7/2^+ - 9/2^+ \) difference in the \( N=47 \) isotones, however, shows a very different behavior that reflects the strong interaction between the three-neutron \( g_9/2 \) hole cluster and the occupancy of the \( g_9/2 \) proton orbital which becomes significant for \( Z > 38 \). This phenomenon is not important for the \((g_9/2)^3\) proton cluster in the \( Ag \) nuclides as the \( g_9/2 \) neutron shell is fully occupied throughout the \( Ag \) isotopes. The filling of the \( g_9/2 \) neutron orbitals in the \( Z=47 \) isotopes does not appear to play a significant role in the general properties of those nuclides.

2.2 \(^{89}\text{Mo}\) Studies

Our results\(^6\) from the study of the decay of \(^{89}\text{Mo}\) are shown in Fig. 2 for \(^{89}\text{Nb}\) along with the levels observed in the study of the \(^{89}\gamma(3\text{He},3\gamma\text{y})\) reaction\(^7\) and the \(^{92}\text{Mo}(p,\alpha)\) reaction.\(^8\) These data show very little change in the overall structure of \(^{89}\text{Nb}\) relative to \(^{87}\gamma\) except for the 658-keV level, as shown in Fig. 3. If that \( 7/2^+ \) assignment is correct, then the presence of two additional \( g_9/2 \) protons to the \(^{87}\gamma\) core permits the formation of a \((g_9/2)^3\) cluster and the sharp drop in the position of the \( 7/2^+ \) level because of the substantial \((g_9/2)^3\) admixture in its wavefunction. The study of the level structure of \(^{91}\text{Y}\) would particularly important to further observe how additional protons affect the position of this \( 7/2^+ \) level in nuclides where no \( g_9/2 \) neutrons are present. The behavior of the \( 7/2^+ \) state in the \( N=52 \) isotones with increasing \( Z \) is well established, as shown in Fig. 4.

2.3 \(^{88}\text{Mo}\) Studies

In seeking to confirm the identity of the 2.15-min activity associated with the 658.6-keV \( \gamma \) ray, we studied its yield at 40, 50, 70 and 75 keV. The threshold was found to lie between 40 and 50 MeV and the peak yield below 70 MeV. We also observed the 80-, 131-, and 171-keV \( \gamma \) rays attributed to 8.6-min \(^{88}\text{Mo}\) decay by Doron and Blann.\(^9\) We did not observe these \( \gamma \) rays at 50 MeV and only very small peaks were seen at 60 MeV. Significant peaks were observed at 75 MeV and a half life of 8±1 min determined. As all three of these \( \gamma \) rays are parts of complex structures, substantial uncertainty is associated with the half life measurement.

<table>
<thead>
<tr>
<th>ODD Z N=48 ISOTONES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1227 ( 9/2^+ )</td>
</tr>
<tr>
<td>1203 ( 11/2^+ )</td>
</tr>
<tr>
<td>1182 ( 3/2^- )</td>
</tr>
<tr>
<td>1077 ( 1/2^+ )</td>
</tr>
<tr>
<td>1024 ( 13/2^+ )</td>
</tr>
<tr>
<td>1023 ( 7/2^+ )</td>
</tr>
<tr>
<td>772 ( 5/2^+ )</td>
</tr>
<tr>
<td>793 ( 5/2^- )</td>
</tr>
<tr>
<td>658 ( 7/2^+ )</td>
</tr>
<tr>
<td>1272 ( 9/2^+ )</td>
</tr>
<tr>
<td>1155 ( 3/2^-, 5/2^-, 9/2^+ )</td>
</tr>
<tr>
<td>1057 ( 13/2^+ )</td>
</tr>
<tr>
<td>1003 ( 3/2^- )</td>
</tr>
<tr>
<td>830 ( 5/2^- )</td>
</tr>
</tbody>
</table>

Fig. 3 Comparison of \(^{87}\gamma\) and \(^{89}\text{Nb}\) levels.

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3. \textbf{\textit{\textit{96Pd Studies}}} \hspace{1cm}

These same facilities were also utilized to identify the closed shell nuclide $^{96}\text{Pd}$ and study its decay. As the earlier identification of the "further-from-stability" nuclides\textsuperscript{11,12} 15-sec $^{97}\text{Ag}$ and 8-sec $^{98}\text{Cd}$ permitted an estimate of 2-4 min for the half life of $^{96}\text{Pd}$, the initial experiments utilized the manual transfer of the enriched $^{96}\text{Ru}$ target to the detector area following irradiation of the target with 60-MeV $^4\text{He}$ ions. Two strong \(\gamma\) rays at 125 and 500 keV were observed and placed as feeding the well established $2^+$ isomer in $^{96}\text{Rh}$, as shown in Fig. 5.

The positions of these two $1^+$ levels are of particular interest as they confirm a continued trend of $1^+$ states in the odd-odd $N=51$ isotones that lie well below the odd $N=52$ states in the adjacent odd $N$ core. The odd $Z$ isotones with $Z>40$ and $N=52$ are characterized by the presence of low-lying $9/2^+$ and $1/2^-$ states as shown in Fig. 4. In Fig. 6 we show the odd $N$ nuclides with $51$ neutrons. They are characterized by a $d_5/2$ ground state and an excited $g_7/2$ state whose position is lowered with increasing $Z$ by both the increased size of the nucleus and the increased occupancy of its spin-orbit partner $99/2$ protons. The significant feature of these odd-odd $N=51$ isotones that include a single $d_5/2$ or $g_7/2$ neutron coupled to an increasing number of $99/2$ protons lies in the very much lower $1^+ - 2^+$ energy gap compared to the $5/2^- - 7/2^+$ neutron gap responsible for these states. This lower gap likely arises from the much stronger interaction between the $99/2$ protons and the $g_7/2$ neutron relative to the interaction between the $99/2$ protons and the $d_5/2$ neutron. It appears that the size of this interaction ($\sim 1$ MeV) is large and not very dependent on the occupancy of the proton orbitals. The importance of neutron-proton interactions where $\Lambda = 0$ has been recently discussed by Federman and Pittel\textsuperscript{13}) and these studies serve as a source of a quantitative measure of that interaction.

Extrapolation of the trends observed here suggest that the $1^+$ level will lie below the $2^+$ level in $^{98}\text{Ag}$ and possibly $^{100}\text{In}$ as well.

\[
\begin{array}{cccc}
\text{ODD Z N=52 ISOTONES} & \frac{1290}{3/2^-} & \frac{1213}{9/2^+} \\
1024 & 9/2^+ & 925 & 11/2^+ \\
1082 & 1/2^- & 978 & 13/2^+ \\
749 & 5/2^- & 834 & 5/2^- \\
949 & 2^+ & 808 & 3/2^- \\
652 & 7/2^- & 809 & 5/2^- \\
336 & 7/2^- \\
\end{array}
\]

Fig. 4 Comparison of the level structure of the \textit{N}=52 isotones.
4. Acknowledgements

We wish to acknowledge the support of the University of Maryland Cyclotron staff in the design and construction of the mechanical beam chopper system, and the assistance of the late Professor N.S. Wall and Dr. M.D. Glasscock in the implementation of the data collection system. The support of the U.S. National Science Foundation and the U.S. Department of Energy through its predecessor agencies the Atomic Energy Commission and the Energy Research and Development Administration is gratefully acknowledged.

References


Fig. 5 Decay scheme of 2.0-min $^{96}$Pd.


The $7/2^+ - 5/2^+$ and $2^+-1^+$ Differences in $N=51$ Isotones

$$\begin{array}{cccccc}
2^+ & 7/2^+ & 7/2^+ \\
2186 & 7/2^+ & 2201 \\
1872 & & \\
\downarrow & & \\
887 \text{ keV} & \begin{array}{c}2^+ \\
1350 \end{array} & \begin{array}{c}7/2^+ \\
1520 \end{array} & \begin{array}{c}2^+ \\
1495 \end{array} \text{ (7/2$^+$)} \\
\downarrow & \downarrow & \downarrow & \downarrow \\
1^+ & 892 & 906 \text{ keV} & \begin{array}{c}7/2^+ \\
942 \end{array} & \begin{array}{c}1^+ \\
686 \end{array} \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
1^+ & 367 & 500 & 125 & \begin{array}{c}5/2^+ \\
90 \text{ Zr} \end{array} & \begin{array}{c}5/2^+ \\
91 \text{ Zr} \end{array} & \begin{array}{c}2^+ \\
92 \text{ Nb} \end{array} & \begin{array}{c}2^+ \\
92 \text{ Mo} \end{array} & \begin{array}{c}5/2^+ \\
93 \text{ Mo} \end{array} & \begin{array}{c}5/2^+ \\
94 \text{ Tc} \end{array} & \begin{array}{c}0^+ \\
94 \text{ Ru} \end{array} & \begin{array}{c}0^+ \\
95 \text{ Ru} \end{array} & \begin{array}{c}2^+ \\
95 \text{ Rh} \end{array} & \begin{array}{c}0^+ \\
96 \text{ Pd} \end{array} & \begin{array}{c}5/2^+ \\
97 \text{ Pd} \end{array} \\
\end{array}$$

Fig. 6 The $5/2^+$, $7/2^+$, $1^+$ and $2^+$ levels in the $N=51$ Zr, Nd, Mo, Tc, Ru, Rh and Pd isotones along with the $2^+$ level in the adjacent $N=50$ core.
NANOSECOND ISOMERISM FOLLOWING HEAVY ION REACTIONS

and R. Levy
Department of Physics & Astronomy, Rutgers University***, New Brunswick, NJ 08903, USA

Abstract

Nanosecond isomeric investigations in \(^{199}\) reactions (E = 56 and 64 MeV) using the generalized centroid shift method with germanium counters are presented. Several lifetimes in \(^{166}\)Cd, \(^{71}\)As and \(^{103}\)Pd in the range 0.6 - 2.1 ns have been measured for the first time. Puzzling evidence for possible delay of yrast cascades (< 300 ps) in some even-even nuclei has been found.

1. Introduction

The study of possible isomerism during the deexcitation of the compound nucleus is necessary for understanding the structure of the energy levels as well as the deexcitation mechanism itself. In the region of investigated discrete states, information on nuclear lifetimes, i.e. on electromagnetic transition probabilities is of vital importance to determine the validity as well as the refinement of any nuclear model.

The spectrum of \(\gamma\)-radiation following a heavy-ion induced reaction is very complex: numerous transitions with energies and intensities varying over a broad range occur. The selection of a method for isomeric investigations is therefore determined mainly by two requirements: (i) to obtain time information simultaneously on as many \(\gamma\)-rays as possible in one experiment, and (ii) the capability of the system to detect the shortest possible lifetimes.

In this paper, we present first results from the application of an advanced variant of the delayed coincidence method in HI reactions. This method may be called the generalized centroid shift method (see below). It allows direct multidimensional time measurements down to a few hundred picoseconds. It should be mentioned that the region between \(\approx 0.1\) and \(\approx 5\) ns is of special interest in HI reactions because of possible delayed feeding in this time range and because it is somewhat poorly covered by other methods in the light of the requirements (i) and (ii). Useful information on all the methods presently in use for different time regions is given by Possan and Warburton in their review\(^7\).

2. Experimental method and techniques

Time distributions from delayed coincidences are analyzed according to their slope or to the shift of their centroids (first moments) relative to that of a prompt time distribution. By means of the centroid shift method, lifetimes can be measured which are much shorter (10-100 times) than the FWHM \((2\sigma)\) of the instrumental time resolution curve.

The high \(\gamma\)-ray peak-density following HI reactions requires the application of germanium detectors. Utilizing such a detector and the slope method it is relatively easy today to measure lifetimes down to 4-5 ns at \(E_{\gamma} \approx 200\) keV. Below that, difficulties with the time resolution arise. The application of the centroid shift method is beset with several problems, one of which is to find a "prompt" reference time distribution at the energy of interest \(E_{\gamma}\). In reactions with low-energy particles, White et al.\(^4\) used a rotating target system containing two targets: the one producing the state of unknown lifetime, and the other a prompt \(\gamma\)-rays. Applying pulse-shape selection filters they were able to measure some lifetimes below 100 ps. This is a nice demonstration of the capability of the centroid shift method. However, the general application of the rotating target system for time measurements in HI reactions is difficult.

Some years ago, in Rossendorf we started to compare delayed time distributions with "faster" ones obtained in the same experiment from windows close to the energy peak in question\(^5\). The contribution of the Compton background to the time curve was found by interpolation from two neighboring windows and subtracted so that the time distribution of the photopeak could be extracted\(^6\). By the transition to the centroid shift method it was noticed that the time distributions of the Compton background are somewhat delayed compared with those of prompt photopeaks. Besides the influence of higher lying isomers, this effect is understood to be due to the charge collection process in the Ge diode\(^5\). It became clear that lifetime information could be extracted from a centroid plot versus the \(\gamma\)-ray energy\(^5\) but only after eliminating the influence of the Compton background and determination of the zero-time line\(^5\). The procedure worked out in this way was later applied on decay measurements of short-lived isotopes in Dubna\(^11\).

The present investigations were performed on the Rutgers FN tandem. Thick targets (5-8 mg/cm\(^2\)) of Fe, \(^{59}\)Co, \(^{89}\)Y,
$^{93}$Nb, $^{60}$Ni, $^{63}$Cu, $^{90}$Zr were irradiated by 56 and 64 MeV $^{16}$O ions. In-beam delayed coincidences between two 7.5 x 7.5 cm Pilot B plastic scintillators (START) and a germanium counter (intrinsic Ge, planar, 10 cc) or true coaxial 50 cc Ge (Li) (STOP) were performed. The discriminator threshold for the scintillators was set at ~150 keV, that for the Ge detector at ~70 keV (small detector) or ~200 keV (large detector). With this set up the FWHM of the integral time curve is $2\tau_p \approx 6.5$ ns. A triple event is formed by coincident pulses from the two energy tracks and the TAC. The events are recorded on tape via our on-line computer SIGMA 2. The spectra are sorted and analyzed on the off-line PDP 11/55 computer. By sorting, usually two types of spectra arise: (i) prompt and delayed energy spectra (2048 channels) from the Ge counter (windows in the time curve) as well as (ii) time distributions (512 channels) with windows in the energy spectrum. The analysis of the time spectra includes subtraction of an interpolated "background" time curve.

From a plot of the centroid positions versus energy, delayed and prompt transitions are identified. Thereby, the centroids from the Compton background windows (fig. 1) form a smooth curve. The zero-group is not always easy to recognize. A possible fluctuation of the centroids due to statistics and other effects (e.g. delayed transitions recorded by the start detector) should be additionally considered. Further, it was found that some lines obviously due to ($n,n'$) reactions (e.g. 846 keV in $^{16}$Fe) appear as delayed ($\sim$1.2 ns) probably being excited in secondary neutron reactions with the time of flight of the neutron much longer than that of the photon.

Most of the results reported here were observed in two independent measurements with the two germanium detectors. Often, the same final nucleus appears in different exit channels of reactions on different targets. A final decision on whether a transition has a certain delay is made after checking all the related energy and time spectra upon consistency.

Practically all the transitions deexciting known isomers produced in the reactions we investigated were observed as delayed. For the 443 keV $\gamma$-rays deexciting the 1307 keV state in $^{138}$Ba with $T_{1/2} = 1.35 \pm 0.04$ ns [ref.] we obtain $T_{1/2} = 0.8 \pm 0.3$ ns (low statistics). For the 131 keV level in $^{109}$Cd with $T_{1/2} = 1.75 \pm 0.10$ ns [ref.], a half-life $T_{1/2} = 1.3 \pm 0.3$ ns results from our centroid diagram. It is possible that the downward deviation of both our half-lives is due to the somewhat ambiguous location of the zero-time line.
3. Results and discussion

3.1 The reaction $^{97}$Nb($^{16}$O,p2n)$^{186}$Cd

The level scheme of $^{186}$Cd has been very carefully investigated by Samuelson et al. (11). Above 1.5 MeV they proposed several 2qp states and some bandlike structures with collective features. Possible isomerism in this nucleus was expected to reflect the suggested strong competition between collective and non-collective phenomena. From the energy spectra and the centroid diagram (fig. 1) it is evident that several transitions are delayed. However, some of them appear delayed only because of the delayed feeding from a higher lying isomer. After taking into account this delayed feeding, the following half-lives were determined in $^{186}$Cd:

- $T_{1/2}(5^+,23;0.7 \text{ keV}) = 0.6 \pm 0.2 \text{ ns};$
- $T_{1/2}(6^+,25(3.1 \text{ keV}) = 1.0 \pm 0.3 \text{ ns};$
- $T_{1/2}(8^-,350(7.9 \text{ keV}) = 1.2 \pm 0.4 \text{ ns};$
- $T_{1/2}(9^-,3679.0 \text{ keV}) = 0.7 \pm 0.2 \text{ ns};$
- $T_{1/2}(10^+,4436.1 \text{ keV}) = 2.1 \pm 0.6 \text{ ns}.$

Fig. 2 shows a part of the level scheme with all the measured lifetimes.

The values $B(E2,2^+\rightarrow0^+)$ = $0.076e^2b^2$ and $B(E2,4^+\rightarrow2^+)$ = $0.13e^2b^2$ in the ground band are representative of the collectivity in this nucleus. On the other hand, for

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Fig. 2 Partial level scheme of $^{186}$Cd according to refs. (12,13) and the present work. The framed half-lives were measured in this work.

- 455 -
transitions from the 4qp isomer (12+) at 4659.8 keV, B(E2, 12+→10+) = 8.1×10^{-4}e^2b^2
and B(E1,12+→11-) = 8.6×10^{-10}e^2b result. These are clearly non-collective transitions.
Comparing our new results with the above values, conclusions on the degree of
collectivity can be drawn.

All five new isomers are suggested\textsuperscript{11}) to have predominantly 2qp character.
Collective contributions are present in the 9+-7-, 8--6- and 5+-4+ E2 transitions
(B(E2) = 0.016, 0.11 and 0.026 e^2b^2, respectively). Obviously, the corresponding
final states contain strong 2qp components of the same type as the initial ones.
This is not the case e.g. for the 10+-8+ E2 transition (E\gamma = 1068.8 keV, B(E2) = 1.4×10^{-5}e^2b^2). The corresponding 10+
state at 4436.1 keV is supposed to be
mainly a two-quasineutron [h_{11/2}^2]
configuration decaying to an 8+- rotational state of the two-quasineutron [d_{5/2}g_{7/2}^2]
configuration. Somewhat surprising is the
low value B(E2,6+-4') = 5.4×10^{-6}e^2b^2
(E\gamma = 1009.3 keV). The final state is a
0qp configuration of the ground band.
The initial state is considered as the two-quasineutron state [d_{5/2}g_{7/2}^2] and a low
transition rate might be expected in first
approximation. However, the initial level is only 11 keV away from the 6+- state of
the ground state band, which may give rise
to some configuration mixing and enhance-
ment of the 1009.3 keV transition. This
enhancement is not evident in the
B(E2) value.

3.2 The nuclei 71As and 101Pd

Some transitions in 71As were observed as a result of the reaction 88Ni (14O, p\gamma) 71As, among them the 147.5 keV
3/2--5/2 ground state M1 transition.
From the corresponding centroid shift, a half-life

T_{1/2} = 1.1±0.3 ns

has been determined. From this value, a
reduced transition probability
B(M1) = 0.011 \mu_C^2 follows. The main components of the initial and final states characterize this M1 transition as
P_{3/2} → f_5/2, i.e. \gamma-forbidden. The B(M1)
value is similar to those of other known transitions of this type. Within the
Alaga-Paar model, T_{1/2} = 0.6 ns was predicted\textsuperscript{44) for the 147.5 keV level in reasonable agreement with the experiment.

The 667 and 670 keV transition in
101Pd are evident in the \gamma-ray spectra
from the reactions 92Sr (14O,αn), and
probably also 89Y (14O,p3n). Both delayed gamma values, conclusions from the centroid diagram reveal
the 670 keV transition from the 1337.4 keV level as delayed with

T_{1/2} = 1.6±0.3 ns.

Using Carolis mixing between negative
parity Nilsson states with h_{11/2} parentage
as well as positive parity Nilsson states from the 81/2(+), 51/2(−) shells, Popli
et al.\textsuperscript{11}) predicted for this level
T\textsubscript{1/2} = 0.25 ns. Again, the consistency with the present experiment is reasonable
for this type of data.

Several delayed transitions in other
final nuclei were found and are now under
investigation.

3.3 Delayed yrast cascades in some
even-even nuclei?

In fig. 1, the centroid shift of 632.7 keV Z=80 ground state transition in 116Cd
indicates this transition as delayed. In a similar way, the 861.2 keV 4+-2+
transition and the 6+-4+ 997.9 keV transition appear delayed. The delay of the ground state
cascade in this nucleus is not surprising
because of the many isomers which feed into
this cascade.

Generally, we expected that E2 transitions in the ground state cascades of even-
even nuclei with lifetimes known to be
in the picosecond region would conveniently
provide points on the zero-time line. How-
ever, this is not always the case. Measurements in the reactions \textsuperscript{61}Zn (14O,p2n)
\textsuperscript{78},\textsuperscript{78}Kr and \textsuperscript{59}Co (14O,p2n)\textsuperscript{78}Se revealed the transitions in the yrast cascades of the
final nuclei as prompt. In the same
eperiment, after the \textsuperscript{59}Co target we measured a \textsuperscript{64}Ni target which via the 2p
exit channel produces \textsuperscript{78}Se, where no dis-
crete isomer has been located so far. All
transitions of the yrast cascade in \textsuperscript{78}Se observable up to the 12+-10+ transition appear as delayed with ΔT ≈ 300-400 ps
(fig. 3). Preliminary results concerning
several nuclei are summarized in fig. 4
where an average delay of the yrast transition
is given.

We realize that experimental findings
on delayed yrast cascades might provide
very important information on non-collective
high-spin states—a topic of high current interest. To our knowledge, such
long feeding times have not been reported so far. Therefore, we tried to consider
carefully the possible experimental effects
which could cause a centroid shift simu-
tating delayed transitions. It was not
possible thus far to find such effects
which can not be ruled by our unambiguously.
In spite of the somewhat puzzling character
of this finding, it seemed worthwhile to
present it here.

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Fig. 3 Centroid diagram. Transitions in $^{72,76}$Se are labeled with their energies and spins of the states involved. Both targets $^{59}$Co and $^{60}$Ni were measured in the same run. Yrast transitions in $^{72}$Se are prompt, those in $^{76}$Se appear delayed.

Fig. 4 Preliminary information on average delay of yrast cascades in some nuclei. For the nuclei $^{59,60}$Se only estimates concerning the $2^+\rightarrow0^+$ transitions were available.
4. Summary and conclusions

The present work reports new results from nanosecond isomeric investigations with germanium detectors using the centroid shift method with the Rutgers tandem. The lifetimes of several 2p states in $^{154}$Cd, that of the bandhead of a $\frac{11}{2}$ bandlike structure in $^{151}$pd and that of the $p_{3/2}$ state in $^{71}$As decaying via an $\epsilon$-forbidden M1 transition were measured for the first time. Of special interest are the experimental hints on possible delayed feeding (2300 ps) of the yrast cascades in some even-even nuclei.

These investigations reveal the generalized centroid shift method as a promising tool for in-beam studies of nuclear structure.

We would like to thank G. M. Temmer for his support and interest in this work. Further, fruitful discussions with P. Simms, E. Warburton and D. Fossan are greatly appreciated.

References

12. C. M. Lederer and V.S. Shirley, Table of Isotopes, J. Wiley & Sons (1978)
HIGH SPIN STATES IN NEUTRON DEFICIENT $^{102}$Cd


*Institut des Sciences Nucléaires (et IN2P3) 53, avenue des Martyrs, 38026 Grenoble-Cedex, France
+Institut de Physique Nucléaire (et IN2P3) Lyon-1 43, Boulevard du 11 novembre 1918, 69622 Villeurbanne-Cedex France

Up to now, a very little information has been available on Cadmium isotopes with $A < 103$, and only the half-life on the ground state of $^{102}$Cd was known. Recently, the new isotope $^{102}$In (T\(1/2\) = 24 + 4 s) which feeds the first levels of $^{102}$Cd by \(\beta\)-decay has been identified using an on-line mass isotopic separator. This work has been carried out by the Lyon-Grenoble collaboration. This study has allowed us to extract the high spin level structure of $^{102}$Cd, from the in-beam experiments, observed in the $^{92}$Mo($^{12}$C,2n) reaction.

An isomeric state was found at 2.718 MeV energy. Its half-life was measured by γ-γ coincidence and estimated to be approximately 25 ns. The uncertainty in this value is due to the weak feeding of this isomeric level (\(<10\)%). Moreover the 157.4 and 487.5 keV transitions are strongly mixed with lines belonging to other reaction products.

![Level scheme of $^{102}$Cd](image)

**Fig. 1**: Level scheme of $^{102}$Cd deduced from $^{92}$Mo($^{12}$C,2n)$^{102}$ reaction, * indicates composite lines.

The $^{102}$Cd nucleus has been investigated at 50 MeV bombarding energy with the $^{12}$C beam of the Grenoble variable energy cyclotron. The level scheme shown in fig. 1 has been established by using data from γ ray single and γ-γ-t coincidence experiments. Angular distribution measurements were performed at several angles including 0° and 90° relative to the incident beam.

![Systematics of light even Cadmium nuclei](image)

**Fig. 2**: Systematics of light even Cadmium nuclei

The 923 keV line with an $A_2 = \pm 0.19 \pm 0.09$ seems to be a pure $E_0$ transition. Thus the spin of the 2560.8 keV level is probably $6^+$. It should also be noted that in $^{104,106,108}$Cd (fig. 2) a second $6^+$ state is excited from the nuclear reaction. The energy spacing between $6^+$ levels is minimum at $A = 106$. The second $6^+$ state can be interpreted as a two quasi-particle excitation (γγ 7/2)$^+_2$.

**REFERENCE**

0+ - STATES IN $^{102}$Pd AND $^{108}$Cd.

K. Cornelis, E. Coenen, M. Huyse, G. Lhersonneau and J. Verplarcke
K.U. LEUVEN, Celestijnenlaan 200D, 3030 Leuven, Belgium.

Abstract

A presentation is made of an angular correlation experiment by which we could identify the two phonon 0+ - states in $^{102}$Pd and $^{108}$Cd. In the case of Pd a comparison is shown with IBA calculations and a level structure calculated with an asymmetric rotor vibrator model.

1. Introduction

The even-even Pd and Cd-nuclei have for many years been interpreted as having an anharmonic vibrational structure. A two phonon multiplet can be seen from $N=60$ for Cd-nuclei and from $N=58$ for Pd-nuclei (fig. 3.4.). In order to extend the systematics in the behaviour on those multiplet states we looked for the 0+ - states in $^{102}$Pd and $^{108}$Cd.

fig.1. Angular correlation pattern of some $x^{n^{+}}_{2^{+}}$. 0+ cascades.
Therefor we performed a $\gamma$-$\gamma$ angular correlation experiment on the $(\delta^+ + EC)^-$ decays of 102$^m$Ag and 108$^m$In nuclei. In 102 Pd we found a $0^+$ state very close to the long living anomalous $0^+$ on which we reported earlier 1). The electromagnetic features of the new $0^+$ state are more in agreement with a two phonon description whereas the other $0^+$ state seems to be some kind of intruder which can not be accounted for in a normal collective (IBA, triaxial rotor vibrator etc.) model. The $0^+$ state in 108Cd is lower in energy than the expected trend, but seems to have normal electromagnetic properties.

2. The angular correlation experiment.

The produced radio activity and the available measuring time for a ISOL setup at a cyclotron are normally not sufficient to perform a decent $\gamma$-$\gamma$ angular correlation experiment. However, the huge anisotropy of a $0^+\rightarrow 2^+$- cascade makes it possible to distinguish it from other $x^\gamma \rightarrow 0^+$ cascades, even with poor statistics as can be seen in fig.1. This means that the angular correlation technique can still be a usefull tool when looking for $0^+$ states in low activity- and short living sources.

In our experiment we only measured the correlation at the three crucial angles $0^\circ$, $50^\circ$ and $90^\circ$. The 102$^m$Ag and 108$^m$In sources were produced with a nat$^4$Mo($^{14}$N(90MeV), xyn) reaction and mass-separated using the LISOL facility at Louvain-la-Neuve 2). An example of the resulting spectra gated on the $2^+\rightarrow 0^+_g$ transition is shown in fig.2. The spectrum at $180^\circ$ shows the $(1101.7 \pm 0.5)$ keV gamma which proved to have the good anisotropy for a $0^+\rightarrow 2^+$- cascade. From the coincidences we could also deduce that the $0^+$ level at 1658 keV is almost completely fed by a 729 keV gamma coming from a known level at 2390 keV ($J^\pi 1,2^2$)

In the same way we observed a $0^+$ state at $(1375.0 \pm 0.9)$ keV which is mainly fed by 1244, 1306 and 827- keV transitions depopulating known levels in 108Cd 3). Also mini-orange spectra were taken from both sources in order to measure the $EO(0^+\rightarrow 0^+_g)$ transition strength. From these spectra only an upper limit could be deduced for the parameter.

$$X = \frac{B(E2, 0^+ \rightarrow 2^+)}{B(E2, 0^+ \rightarrow 2^+)}$$

For 102Pd we have $X \leq 2.7 \cdot 10^{-1}$ and for 108Cd $X \leq 4$.

fig 2. Spectra at 50° and 180° gated on the $2^+\rightarrow 0^+_g$ transition
3. Discussion.

In fig. 3 we can see that the $^{0+}$- state in $^{102}$Pd is following the systematical trend of rising when going to lesser neutrons. The $2^+$ and $4^+_1$ do not go up as fast and in $^{102}$Pd the two phonon triplet is completely broken. The same systematical behaviour can be reproduced by IBA-2 calculations 4) as shown in fig. 4.

In table 1 a comparison is shown of the low energy levels in $^{102}$Pd and a theoretical calculation with an anharmonic vibrator model 5).

Table 1.

<table>
<thead>
<tr>
<th>$I^+$</th>
<th>Exp. (keV)</th>
<th>Theory: E</th>
<th>INn</th>
<th>INn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>0</td>
<td>0</td>
<td>011</td>
<td></td>
</tr>
<tr>
<td>$2^+$</td>
<td>556</td>
<td>552</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td>$4^+$</td>
<td>1275</td>
<td>1333</td>
<td>411</td>
<td></td>
</tr>
<tr>
<td>$2^+$</td>
<td>1534</td>
<td>1492</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td>$0^+$</td>
<td>1658</td>
<td>1658</td>
<td>012</td>
<td></td>
</tr>
<tr>
<td>$6^+$</td>
<td>2111</td>
<td>2119</td>
<td>611</td>
<td></td>
</tr>
<tr>
<td>$4^+$</td>
<td>2138</td>
<td>2177</td>
<td>421</td>
<td></td>
</tr>
</tbody>
</table>

In this calculation the experimental energy of the $^{0+}$- state was not used in fitting the model parameters, however, the agreement with experiment is excellent.

The first excited $^{0+}$-state in $^{108}$Cd (fig. 5) does not seem to follow this systematical trend of rising when going more neutrondeficient. In this case it would be interesting to find the second excited $^{0+}$-state which appears to be low in the heavier Cd isotopes. These $^{0+}$- states can probably be explained in terms of 2-proton particle - 2 hole excitations through the $Z=50$ shell closure as in the case of the even Sn isotopes 6).

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In fig. 3 Positive parity states in even Pd nuclei.

- 462 -
fig. 4 IBA-2 calculation of the Pd isotopes.
Fig. 5  Positive parity states in even Cd nuclei.

References

1) K. Cornelis, et al., Z. Physik A 292 (1979), 403
2) G. Dumont, et al., Nucl. Inst. and Meth. 153 (1978), 81
3) I.N. Wischnewski, et al., Z. Physik A 298 (1980), 21

Discussion

J. Kantele: I have some complementary information to give: within the Jyväskylä-Uppsala collaboration, we have studied $^{152}$Pd low-spin states using $(p,d)$ and double Coulomb excitation. The 1648 keV state is seen in the latter reaction which indicates a collective character for this state; it probably contains some two-phonon strength. The 1592 keV level does not seem to be connected to the $2^+_1$ state, which yields the largest known $X$-value, over 400. Thus the 1592 keV $2^+_1$ state has a structure completely different from that of the $2^+_1$ one at 1648 keV; the wave function is probably dominated by some two-quasiparticle component.

V. Paar: How many parameters do you have in fitting spectra in your figure? Do you fit to each nucleus parameters separately?

K. Cornelis: The parameters in this fit were allowed to vary in the fit.

J. Stachel: In principle the full IBA-2 Hamiltonian has $\approx 12$ free parameters. The calculations referred to here (P. Van Isacker, G. Puddu, Nucl. Phys. 1980) are a simultaneous fit to all neutron-rich (N = 50-66) Pd- and Cd-isotopes. Some of the parameters were set to 0 in this fit, all parameters involving only protons were kept constant over the whole isotope chain, some were taken equal for Ru- and Pd-isotopes. So it is essentially the change in three parameters describing the change in excitation energies and decay properties along each isotope chain.

D.S. Brenner: In your IBA-2 calculations which parameters did you vary to obtain your fits to the Pd and Cd isotopes? What criteria were used to determine the "best" fit to these data?

K. Cornelis: For this question I refer to P. Van Isacker, for he has been doing the calculations. He certainly can tell you more about the details.
SEARCH FOR FIRST O+ EXCITED STATES IN 108Cd AND 106Cd

B. Roussière, P. Kilcher, J. Sauvage-Letessier and ISOCELE Collaboration
Institut de Physique Nucléaire (IN2P3), 91406 Orsay, France
R. Béraud, R. Duffaut, M. Meyer
Institut de Physique Nucléaire (IN2P3), Université Lyon-1, 69622 Villeurbanne Cedex, France
J. Genevey-Rivière, J. Tréherne
Institut des Sciences Nucléaires (IN2P3), 38044 Grenoble, France

Abstract
The 108Cd and 106Cd isotopes have been studied from the $\beta^+$/EC decay of 108In and 106In, with the on-line ISOCELE separator facilities. $\gamma$-rays, conversion electrons, $\gamma$-$\gamma$-t and $e^-$-$\gamma$-t coincidence measurements have been performed. Level schemes of 108Cd and 106Cd have been deduced from our results. A O+ level has been unambiguously established at 1.913 MeV in 108Cd and a new O+ level proposed at 2.035 MeV in 106Cd. The energies and branching ratios are discussed in terms of vibrator + particles approach, interacting boson approximation and rotor + quasi-particles model.

1. Introduction
The cadmium nuclei (Z = 48) belong to the transitional region situated between the semi-magic tin nuclei and the more deformed zirconium ones. With only two protons from the closed shell (Z = 50) they are analogous to the mercury nuclei with respect to lead.

![Deformation energy curves of even-even Hg and Cd nuclei obtained from HF calculations using the SIII effective interaction with the 5 constant pairing prescription.](image)

Shape coexistences have been clearly established in the mercury nuclei $^{102,104}$Hg. Furthermore, deformation energy curves obtained for the Hg and Cd isotopes $^{102,104}$Cd (fig. 1) exhibit some similitudes. Except the semi-magic $^{100}$Cd, expected spherical, the Cd and Hg nuclei are found to be quite soft and a common feature of all these potential energy surfaces in the existence of two minima closed in energy, one oblate and the other prolate. The even-even Cd nuclei are however predicted prolate in fairly good agreement with the experimental O+ values $^3$. So we searched for a low-lying energy O+ excited state corresponding to an oblate shape in both 108Cd and 106Cd nuclei.

2. Experimental Procedure
The 108Cd and 106Cd nuclei have been studied from the $\beta^+$/EC decay of 108In and 106In. The In isotopes have been produced by the Orsay synchrocyclotron through the reactions Sn($^{13}$He,70 MeV,3pxn)In, Sn($^{20}$Ne,3pxn)In and Sn($^{20}$Ne,2pxn)In reactions (fig. 2). The $^{3}$He, p beams maximum intensities are 1 $\mu$A, 1 $\mu$A and 2 $\mu$A respectively, so we choose to use the $^{3}$He beam for the 108Cd study and the p beam for the 106Cd one.

![Yields (in atoms per second) of In nuclei from molten Ag and Sn targets.](image)

The In isotopes, produced in the target, are extracted by evaporation, then mass separated with the on-line ISOCELE II separator $^8$L The mass separated activities are transported on a tape from the collecting point to the counting one, using a mechanical tape transport system. Single $\gamma$ and coincident three dimensional $\gamma$-$\gamma$-t spectra have been measured by means of two Ge (HP) detectors. The conversion electrons have been performed with a Si(Li) detector and $e^-$-$\gamma$-t coincidence events have also been recorded.
3. Experimental Results

3.1 Level schemes

The $^{108}$Cd and $^{106}$Cd nuclei have already studied from $^{108}$In and $^{106}$In decay (7-9). The level schemes built from our results is in agreement with the previous ones. However, many new levels have been observed, especially in the 3.3 MeV-5 MeV energy range. Figure 3 shows partial level schemes. In both nuclei, we can notice:

- a collective ($O_{1+}$, $2_{1+}$, $4_{1+}$, $6_{1+}$) built on the ground state
- a $2_{2+}$ state lying closed to the $4_{1+}$ one
- $4_{2+}$ and $6_{3+}$ states, the nature of which is probably the same in both nuclei (table 1)
- the existence of a $O_{3+}$ state: in $^{108}$Cd, the $O_{3+}$ state at 1913.2 keV of energy decays to $2_{1+}$ and $2_{2+}$ states and to the ground state by an E0 transition. In order to establish unambiguously the E0 character of this transition, we have estimated the lower value of the conversion coefficient: $g_{\text{exp}} > 10$ aU(M4). In $^{106}$Cd, we propose an excited $O_{3+}$ state at an energy of 2034.8 keV. This $O_{3+}$ state decays to the $2_{1+}$ state but not to the $2_{2+}$ one (table 1).
- two $5^-$ states which are weakly fed
- a $6_{2+}$ level strongly populated in the decay of $^{108}$In
- a $8_{1+}$ level in $^{106}$Cd this level has the most intensity feeding.

<table>
<thead>
<tr>
<th>B(E2) ratios</th>
<th>$^{108}$Cd</th>
<th>$^{106}$Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4_{2+} + 4_{1+}$</td>
<td>1.9</td>
<td>1.1</td>
</tr>
<tr>
<td>$4_{2+} + 2_{2+}$</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>$6_{3+} + 4_{1+}$</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>$0_{2+} + 2_{2+}$</td>
<td>1070</td>
<td>&lt; 500</td>
</tr>
</tbody>
</table>

Table 1 - Transition probabilities ratios of the $4_{2+}, 6_{3+}, 0_{2+}$ states in $^{108}$Cd and $^{106}$Cd

![Graph showing level schemes](image)

3.2 Isomeric states spins of $^{108}$In and $^{106}$In

Isomeric states spins of $^{108}$In and $^{106}$In have already discussed by several authors (7-10). The present work leads to propose $7^+$ as spin and parity for the high spin isomeric state of $^{108}$In and $^{106}$In. More than 95% of the intensity has been placed in both decay schemes and the log ft values have been deduced. In $^{108}$Cd, the $6^+$ level at 2807.5 keV exhausts 40% of the total feeding. The log ft value is only consistent with $\Delta J = 0, 1$ and $\Delta T = +$. In contradiction with S. Flanagan et al. (1), the $5^-$ level at 2601.5 keV is not significantly fed in our experiment. Thus we prefer the $7^+$ assignment for the isomeric state of $^{108}$In.
In $^{106}_{\text{Cd}}$, three states are preferentially populated by the $^{+}_{\text{EC}}$ decay of $^{106}_{\text{In}}$; the 8$^+$ state at 3044.4 keV ($\approx 30\%$) and the two 6$^+$ states at 2503.3 keV and 2491.8 keV ($\approx 10\%$). For these three levels, the log ft values are only consistent with $\Delta J = 0,1$ and $\Delta I = \pm 1$. We deduced that the isomeric state of $^{106}_{\text{In}}$ has a $^7$ spin and parity. However, the positive parity is assigned taking into account the only two possible configurations $\nu g_7/2 \pi g_9/2$ and $\nu d_5/2 \pi g_9/2$ for this state.

4. Discussion

In order to understand the nature of the $0^+$ excited states observed in the $^{108}_{\text{Cd}}$ and $^{106}_{\text{Cd}}$ nuclei, let us compare their low-lying states to those observed in some neighbouring even-even isotopes (fig. 4). The first excited state $0_{2+}$ energy shifts slowly from $^{116}_{\text{Cd}}$ to $^{110}_{\text{Cd}}$ but there is a sudden rise in energy from $^{110}_{\text{Cd}}$ to $^{108}_{\text{Cd}}$. $^{110,112,114,116}_{\text{Cd}}$ nuclei have long been regarded as vibrational nuclei with their typical triplet $0_{2+}, 2_{1+}, 4_{1+}$ at around 1.3 MeV excitation energy. In $^{108}_{\text{Cd}}$ and $^{106}_{\text{Cd}}$, the observed $0_{2+}$ states are too high in energy to belong to such a triplet. Neither can they be interpreted as head states of a collective band corresponding to another shape than that of the ground state (as in Hg nuclei), since no state decays to them.

Within the framework of the particle vibrator coupling model, V. Lopac$^{11,12}$ calculated the low-lying states of $^{108}_{\text{Cd}}$. The level energies and the transition probabilities of the $2_{1+}, 4_{1+}$ and $2_{3+}$ levels have been rather well reproduced in this model. Theoretically, the $0_{2+}$ state decays mainly to the first $2^+$ level and weakly to the second $2^+$ one in contrast with experiment (fig. 5 and table 2).

The IBA2 model of Iachello and Arima$^{13}$ has been applied to the Ru and Pd nuclei$^{14}$. This model could describe the evolution of the low-lying levels of Cd nuclei. Figure 6 shows that the evolution in energy of the $2_{1+}, 4_{1+}$ and $6_{1+}$ levels is consistent with an extrapolation of theoretical curves from Ru and Pd to Cd. Concerning the $0_{2+}$ level, the IBA2 model provides a sudden rise in energy between $N = 60$ and $N = 58$ in Ru and Pd nuclei. Experimentally in Cd isotopes, this feature is observed between $N = 62$ and $N = 60$. Unfortunately, the decay mode of this $0_{2+}$ state has not been studied in the IBA2 model applied to Ru and Pd nuclei. However, it would be surprising that this model could reproduce such a sudden change in the $0_{2+}$ decay mode between $^{108}_{\text{Cd}}$ and $^{106}_{\text{Cd}}$ since the model parameters follow a smooth variation with the nucleon number.

In conclusion, we have observed $0^+$ excited states in $^{108}_{\text{Cd}}$ and $^{106}_{\text{Cd}}$ which cannot be understood in terms of shape coexistence. These states seem to have rather a particle nature (neutron excitations). To interpret high spin states, observed in HI reactions, L.E. Samuelson et al.$^{15}$ have suggested the axial rotor + two quasi-particles model. It would be fruitful to extend this model to low spin states. The decay mode of these "intruder" $0^+$ states would make up a stringent test of its validity.

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**Fig. 4** - Systematics of first excited levels in Cadmium isotopes.
**108Cd**

*Fig. 5* - Comparison between experimental level scheme of $^{108}$Cd and the theoretical one calculated in the vibrator + particles model [12].

*Fig. 6* - Comparison between experimental (points) and calculated energies for the lowest states in the Ru, Pd and Cd isotopes within the IBA2 model [14].

<table>
<thead>
<tr>
<th>Transition</th>
<th>B(E2) \text{exp}</th>
<th>B(E2) \text{th}</th>
<th>Ratio</th>
<th>Exp</th>
<th>th</th>
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<tr>
<td>$2^+ \rightarrow 0^+_1$</td>
<td>0.082</td>
<td>0.088</td>
<td>$0^+_2 \rightarrow 2^+_1$</td>
<td>1070</td>
<td>0.05</td>
</tr>
<tr>
<td>$2^+ \rightarrow 0^+_1$</td>
<td>0.0059</td>
<td>0.003</td>
<td>$2^+_2 \rightarrow 2^+_1$</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>$4^+_1 \rightarrow 2^+_1$</td>
<td>0.122</td>
<td>0.130</td>
<td>$2^+_2 \rightarrow 0^+_1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2* - Absolute and relative values of transition probabilities (in $e^2b^2$) in $^{108}$Cd.

**REFERENCES**

6) J.C. Pataux et al., EMIS Conference, Sinal, Sept. 1980
Q-VALUE FOR THE POSITRON DECAY OF $^{109}$Sn AND THE LEVEL STRUCTURE OF $^{109}$Sn

M.G. Johnston, J.S. Grant, P. Misaelides,
Schuster Laboratory, University of Manchester, Manchester M13 9PL, U.K.,
P.J. Nolan,
Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, U.K.,
P. Peuser,
Institut für Kernchemie der Universität Mainz, Mainz, Federal Republic of Germany,
R. Kirchner, O. Klepper, E. Roeckl and P. Tidemand-Petersson,
GSI Darmstadt, 6100 Darmstadt, Federal Republic of Germany.

Abstract

The QEC value for the decay of $^{109}$Sn was determined to be $6380\pm16$ keV from the analysis of mass-$109$ $\gamma$-ray coincidence data accumulated using the on-line mass separator at GSI. Positron end-points were measured with a plastic scintillator telescope for the spectra in coincidence with $\gamma$-transitions to the ground state of $^{109}$Sn. The decay scheme of $^{109}$Sn has been established, and additional information about the level structure of $^{109}$Sn obtained from in-beam measurements using the $^{109}$Cd$($α,n$)$ reaction.

1. Introduction

The mass differences between $^{109}$Sn and a number of other neutron-deficient nuclei in the tin region are known from observations on $\alpha$-decays and $\beta$-delayed protons$. To link the mass differences of these nuclei to the known mass of $^{109}$Sn, and thus to determine their absolute masses, the QEC-value for the decay of $^{109}$Sn is required. In this paper we report on studies of the decay scheme of $^{109}$Sn, and on measurements of positron spectra, which in conjunction with the decay scheme, lead to a value for QEC.

The decay scheme turns out to be well-suited to the Q-value determination. The strongest $\gamma$-lines in the decay spectrum are ground-state transitions from levels at 664, 925 and 1062 keV which are populated directly in the $\beta$-decay and which have little or no feeding from higher levels. The positron spectra taken with a plastic scintillator in coincidence with these $\gamma$-lines lie in the energy range where the response of the scintillator is linear, and the endpoint energies can be accurately measured by comparison with known standards.

The low-lying levels in $^{109}$Sn populated in the $\beta$-decay are of interest in themselves, since $^{109}$Sn is the lightest odd-A tin nucleus yet studied, and its level structure below 1 keV excitation was not previously known. In order to obtain more information about these levels, we have also studied in-beam $\gamma$-transitions in the $^{109}$Cd($\alpha,n$)$^{109}$Sn reaction, measuring angular distributions, $\gamma-\gamma$ and $\gamma-\gamma$ coincidence spectra.

2. The Decay Scheme of $^{109}$Sn

Sources of $^{109}$Sn were produced in the $^{92}$Mo $+$ $^{6}$Ne reaction at the Manchester heavy ion linear accelerator, and in the $^{58}$Ni $+$ $^{58}$Ni reaction at GSI. At Manchester, the reaction products were transported by a helium jet system to a target which moved at 40 second intervals to the counting position. Singles spectra were accumulated in multiscattering mode, and $\gamma-\gamma$ and $\gamma-\gamma$ events recorded. Those $\gamma$-transitions which were in coincidence with tin X-rays, and were also later observed in a mass-separated A = 109 spectrum at GSI, have been assigned to transitions in $^{109}$Sn. The energies of these transitions and their relative intensities are listed in Table I. Part of the mass-separated spectrum is shown in figure 1, with energies labelling the $^{109}$Sn lines; many of the other lines are transitions in $^{107}$In.

Table I

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>246.7</td>
<td>1.9 (2)</td>
</tr>
<tr>
<td>261.0</td>
<td>2.0 (2)</td>
</tr>
<tr>
<td>544.8</td>
<td>10.6 (5)</td>
</tr>
<tr>
<td>664.5</td>
<td>63 (4)</td>
</tr>
<tr>
<td>678.6</td>
<td>19 (1)</td>
</tr>
<tr>
<td>925.4</td>
<td>100</td>
</tr>
<tr>
<td>950.6</td>
<td>2.0 (1)</td>
</tr>
<tr>
<td>1061.7</td>
<td>75 (5)</td>
</tr>
<tr>
<td>1078.0</td>
<td>3.9 (2)</td>
</tr>
<tr>
<td>1343.5</td>
<td>2.2 (2)</td>
</tr>
<tr>
<td>1495.8</td>
<td>30 (2)</td>
</tr>
</tbody>
</table>

The lines at 246.7, 261.0 and 950.6 keV are in coincidence with the ground-state transitions at 678.6, 664.5 and 544.8 keV respectively. All the other lines in Table I are ground-state transitions with no measurable feeding from higher levels. In particular, the intense lines at 925 and 1062 keV are populated only by the $\beta$-decay. The positron spectrum in coincidence with 64 keV $\gamma$-rays does include a component of feeding from the 925 keV level, but this is only 3% of the total intensity. The decay scheme deduced for $^{109}$Sn is illustrated in figure 6.

Analysing the multispectrum intensities of $^{109}$Sn in terms of a single exponential leads to a half-life of 16.67 ±0.15 s. This result is taken from the helium jet measurement, for which production of the $^{109}$Te precursor is expected to be small (about 3% of the $^{109}$Sn) and which used a longer cycle time. The 16.67 values shown in figure 6 are derived from this half-life in conjunction with the branching ratios corresponding to the relative intensities in Table I and the ground state branching ratio of 2:1$^2$ found by fitting the positron spectrum.

3. Positron End-points

Positrons were detected with the plastic scintillator telescope shown in figure 2, which is described in detail elsewhere). The energy calibration of the telescope was established using conversion electron lines from $^{137}$Cs, $^{207}$Bi and $^{208}$Pb sources, and continuous $\beta$-decay spectra from $^{90}$Y,

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Fig. 1 Part of the mass-separated $\alpha = 109$ $\gamma$-spectrum from the $^{58}$Ni + $^{58}$Ni reaction at a bombarding energy of 5.0 MeV. The peaks labelled in keV are assigned to transitions in $^{109}$Sn.

Fig. 2 The beta-gamma detector system. (1) $E$ scintillator; (2) $E\Delta E$ scintillator; (3) Ge(Li) detector; (4a,b) photomultipliers; (5a,b) photomultiplier bases; (6) vacuum chamber of the tape transport system at the mass separator; (7) source position.

The beta-gamma detector system. (1) $E$ scintillator; (2) $E\Delta E$ scintillator; (3) Ge(Li) detector; (4a,b) photomultipliers; (5a,b) photomultiplier bases; (6) vacuum chamber of the tape transport system at the mass separator; (7) source position.

The response of the $E$-detector scintillator to positrons is not the same as to negative electrons because of the possibility of an additional signal from one or both of the annihilation photons. In the plastic scintillator, photo-electric absorption is negligible for annihilation photons, and Compton scattering is the only important process leading to additional signals. The response function of the scintillator has been modified for positrons as follows. The average additional signal due to annihilation photons is assumed to be independent of positron energy. The response function is represented by the sum of three Gaussians: (i) the unmodified electron response function, with a variance increasing linearly with energy; (ii) a Gaussian at an energy increased by 230 keV, and a variance increased by 8300 keV$^2$, the values corresponding to a triangular approximation to the Compton scattered signal for annihilation photons; (iii) a Gaussian at an energy increased by 460 keV, and variance increased by 16000 keV$^2$, representing events in which both annihilation photons are Compton scattered.

Positron spectra from $^{66}$Ga sources were fitted...
with this response function, using the probability of Compton scattering by a single annihilation photon as a parameter. The end-point energy obtained from this procedure agrees with the known 66Ga end point when the probability of Compton scattering is 10.5%, corresponding to an average additional energy of 53 keV deposited by annihilation radiation for each positron stopped in the scintillator. It must be emphasised that the additional energy is the important quantity, and that this is rather well-known, since the end-point is very insensitive to the detailed shape of the response function. However, it lends confidence to the method of analysis that the value of $\chi^2$ for the fit to the positron spectrum has a minimum at the same value of additional energy as is required to bring agreement with the $\gamma$-energy calibration.

The positron spectrum fitting procedure was tested on-line with mass-separated $^{112}$Sn sources. A positron spectrum was collected in coincidence with the 1257 keV $\gamma$-transition following $^{112}$Sb decay. This transition has a significant amount of feeding from higher levels. The intensity of $^{112}$Sn $\gamma$-lines in the singles spectrum was in agreement with the published decay scheme for $^{112}$Sb. The relative intensities of $\gamma$-transitions feeding the 1257 keV $\gamma$-line were taken from reference 3 in generating the $\gamma$-spectrum, assuming that all these transitions have an allowed spectrum shape. The fitting procedure for $^{112}$Sb leads to a value for $Q_{\gamma}$ of 7.062±0.016 MeV in agreement with the previously measured value of 7.030±0.050 MeV).

Fits to the positron spectra in coincidence with the 925 and 1062 keV $\gamma$-lines in $^{109}$Sb decay are shown in figure 3. The end-points of these spectra, and of the spectrum in coincidence with the 664 keV transition, all lie between the 66Ga end-point and the end-point of the 112Sb end-point in coincidence with the 1257 keV line. The values of the end-points, directly from the fit, and converted to $Q_{\gamma}$ for the ground state transition by adding the $\gamma$-energy, are given in Table II.

### Table II

<table>
<thead>
<tr>
<th>$E_{\gamma}$ (keV)</th>
<th>End-point (keV)</th>
<th>$Q_{\gamma}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>664</td>
<td>4674±22</td>
<td>5338±22</td>
</tr>
<tr>
<td>925</td>
<td>4416±21</td>
<td>5341±21</td>
</tr>
<tr>
<td>1062</td>
<td>4352±24</td>
<td>5392±24</td>
</tr>
</tbody>
</table>

The errors in Table II are statistical, derived from the goodness of fit. Since the annihilation photon correction has been taken from the 66Ga spectrum, the end-points are referred to the 66Ga end-point and in addition to the statistical errors there are the following sources of error: (i) uncertainty in the 66Ga end-point (=8 keV). (ii) Uncertainty in the keV/Channel for the scintillator. This is 3%, but since the extrapolation from 66Ga is from 180.7 to 523 keV, this error is smaller than the statistical error, (iii) A change in the average energy deposited by annihilation photons between 66Ga and 112Sb. Since the total energy deposited is estimated to be 53 keV, any change must be only a few keV, and this source of uncertainty has been neglected. Combining these errors leads to a final result $Q_{\gamma}$ = 5358±16 keV or $Q_{\gamma}C$ = 6380±16 keV.

An upper limit to the branching ratio for decay of $^{109}$Sb to the ground state of $^{109}$Sn has been obtained by analysing the singles positron spectrum. Assuming that all positrons above 4.8 MeV are due to $^{109}$Sb decays with the end-point of 5358 keV derived above, the branching ratio is found to be 2±1%. The upper limit of 6.1 for the log ft value for the ground state shown in figure 6 corresponds to a 3% branch.

![925 keV coincidence spectrum experiment a theory.](image1)

![1062 keV coincidence spectrum experiment a theory.](image2)

Fig. 3 Positron spectra in coincidence with transitions in $^{109}$Sn. The dotted lines indicate the range over which the theoretical spectrum shapes were fitted to the data.

4. In-beam Measurements on $^{109}$Sn Transitions

Transitions in $^{109}$Sn have already been studied using the $^{106}$Cd(a,n)$^{107}$Cd and $^{106}$Cd(a,3n)$^{104}$Cd reactions. Maduene et al. measured conversion coefficients as well as $\gamma$-spectra, but were unable to deduce the low-lying level structure of $^{109}$Sn. Hashimoto et al. were primarily interested in high-spin states; they found a number of high-spin bands, but did not observe transitions from level 5 below 1 MeV.

To obtain further information about the $^{109}$Sn levels populated in $^{109}$Sb $\beta$-decay, we studied $\gamma$-spectra in the $^{106}$Cd(a,n) reaction, using n-$\gamma$ coincidences as a signature for $^{109}$Sn transitions. At bombarding energies below 17 MeV, (a,n) is the only compound nuclear reaction for which neutron emission is energetically possible. Using the tandem accelerators at Liverpool and Oxford, we have accumulated n-$\gamma$ and $\gamma$-single spectra at energies from 12.5 to 18.0 MeV and have measured angular distributions at 14.0 and 18.0 MeV.

The enriched $^{106}$Cd target foil was mounted on a 208Pb backing just thick enough to stop recoil Sn nuclei at the highest bombarding energy. A Compton-suppressed Ge(Li) detector rotated in a horizontal plane about the target. Coincidence events were...
collected between this detector and a second, unsuppressed Ge(li) detector in a fixed position. The second detector served as a monitor for the angular distributions. Below the threshold for direct $^{109}$Sn production, all the $^{129}$Sn lines are from the decay of $^{109}$Sn, and hence have isotropic angular distributions. These lines checked that there was no significant anisotropy arising from absorption or beam misalignment. Two liquid scintillators, with rise-time discrimination between neutrons and gammas, were used to select neutron coincidences in the Compton-suppressed detector. Singles and neutron coincidence spectra are compared in figure 4, in which the peaks labelled in the coincidence spectrum are assigned to $^{109}$Sn. The peaks which are not strongly attenuated, but have not been labelled, are due to ($\alpha$,n) contamination from cadmium isotopes other than $^{109}$Cd in the target. All of the $\gamma$-lines observed in $^{109}$Sn decay are also seen in-beam. On the basis of all the single and coincident data from the in-beam and decay studies, we have built up the level scheme shown in figure 6.

A preliminary analysis has been made of part of the angular distribution data and Legendre polynomial coefficients extracted for some prominent $\gamma$-lines. Examples of the angular distribution data and fits are shown in figure 5. The values of the coefficients $A_2$ and $A_4$ in the Legendre polynomial expansion are listed in Table III, together with the multipolarity for transitions for which conversion coefficients are given in reference 6. The spin of the ground state of $^{109}$Sn is known from atomic beam measurements to be $\frac{5}{2}^+$, and for transitions from higher levels to this state the spin of the upper level is in several cases uniquely determined by the angular distribution. We have made theoretical estimates of the angular distributions using optical model parameters taken from reference 9. Upper level spins which can yield the observed angular distributions are given in the last column of Table III. The spins in brackets are spins which give angular distributions of the right general shape, but outside the statistical range of the fits to the data.

Table III

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$A_2$</th>
<th>$A_4$</th>
<th>Multipolarity</th>
<th>$J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>545</td>
<td>-0.17(2)</td>
<td>0.03(2)</td>
<td>5/2, 9/2</td>
<td></td>
</tr>
<tr>
<td>665</td>
<td>-0.33(2)</td>
<td>0.05(2)</td>
<td>5/2, 9/2</td>
<td></td>
</tr>
<tr>
<td>679</td>
<td>0.05(3)</td>
<td>0.01(3)</td>
<td>3/2, 5/2, 7/2, 9/2</td>
<td></td>
</tr>
<tr>
<td>891</td>
<td>-0.19(2)</td>
<td>0.21(2)</td>
<td>9/2</td>
<td></td>
</tr>
<tr>
<td>925</td>
<td>-0.03(1)</td>
<td>0.01(1)</td>
<td>5/2</td>
<td>3/2</td>
</tr>
<tr>
<td>992</td>
<td>-0.20(2)</td>
<td>0.02(2)</td>
<td>5/2, 9/2</td>
<td></td>
</tr>
<tr>
<td>1062</td>
<td>-0.36(3)</td>
<td>0.10(3)</td>
<td>6/2, 9/2</td>
<td></td>
</tr>
<tr>
<td>1078</td>
<td>-0.02(5)</td>
<td>0.22(5)</td>
<td>9/2</td>
<td></td>
</tr>
<tr>
<td>1240</td>
<td>0.24(3)</td>
<td>-0.19(3)</td>
<td>7/2</td>
<td>11/2</td>
</tr>
<tr>
<td>1244</td>
<td>-0.02(3)</td>
<td>-0.18(3)</td>
<td>E2(M1)</td>
<td>7/2 , 11/2</td>
</tr>
<tr>
<td>1256</td>
<td>0.15(3)</td>
<td>-0.20(3)</td>
<td>M2, E3</td>
<td>7/2 , 11/2</td>
</tr>
<tr>
<td>1343</td>
<td>-0.23(3)</td>
<td>-0.02(3)</td>
<td>5/2, 9/2</td>
<td></td>
</tr>
</tbody>
</table>

No Doppler shifts are observed in any of the $\gamma$-lines below 1500 keV. At 1200 keV, roughly the energy of the first $2^+$ vibrational states in the neighbouring $^{108}$Sn and $^{110}$Sn, the full Doppler shift at a bombarding energy of 14.0 MeV is 3.6 keV. The failure to observe a Doppler shift for the $\gamma$-lines near 1200 keV implies that their lifetimes are greater than 1 ps, or that the strength of an E2 transition is less than 5 Weisskopf units.

5. The Structure of the Low-lying Levels in $^{109}$Sn

The combination of in-beam and decay measurements has led to information about a number of previously unknown levels at low excitation in $^{109}$Sn. This information is summarized in figure 6. The ground state, which has spin $\frac{5}{2}^+$, is no doubt the $\frac{7}{2}^+$ state, and has been labelled with positive parity. Presumably all the states below the 1256 keV level have positive parity (the 1256 keV level is shown to be the $\frac{11}{2}^+$ state by the E3 multipolarity of the ground state transition). Most of the spin values consistent with the angular distributions are acceptable, and all the mixed M1, E2 transitions are required to be predominantly E2, with the exception of the $\frac{5}{2}^+$ option for the 992 keV transition, which must be nearly pure M1. This is odd, since $\frac{5}{2}^+$ seems an unlikely assignment for this state, as it is not populated in the $\beta$-decay.

There are some other unresolved puzzles.

(i) No spin $\frac{5}{2}^+$ state is observed. The $\frac{7}{2}^+$ state is the ground state in $^{111}$Sn and $^{113}$Sn, and is at 255 keV in $^{115}$Sn. It may well have moved to a somewhat higher excitation in $^{109}$Sn, and be by-passed in the decay of all other levels.

(ii) No state has the preferred assignment to M1 from the angular distributions, although in $^{111}$Sn, $^{113}$Sn and $^{115}$Sn the lowest log ft value is for the transi-
tion to a $3/2^+$ state$^\dagger$). In $^{109}$Sb decay the strongest transition is to the 925 keV level. The in-beam angular distribution of the 925 keV transition is essentially isotropic, and we recommend a $3/2^+$ assignment for this state, although the predicted $A_2$ is then 0.06, outside the limits of the data.

(iii) The 1078 keV transition has a strong anisotropy, which demands a $5/2^+$ assignment, inconsistent with the observation of this state in $\beta$-decay. The only explanation at present is a chance coincidence of two levels.

(iv) Hashimoto et al. propose $11/2^+$ for the 1244 keV state, which is strongly populated in the decay of high-spin bands. We accept this assignment, although the expected values of $A_2$ and $A_4$ (0.38 and -0.13 for $11/2^+\rightarrow 7/2^+$ transitions) are outside the limits of the data. The 1240 keV transition has the same angular distribution, suggesting that it is also pure E2. Yet it is difficult to understand two $11/2^+$ states at this excitation.

(v) The 1256 keV transition must be an E3, M2 mixture because of its conversion coefficient. A predominantly E3 transition has a broadly angular distribution, but a statistically acceptable fit cannot be found.

The lower limit to the lifetime found for the states at about 1200 keV is a few times greater than the measured $2^+\rightarrow 0^+$ lifetimes in the even tin isotopes$^\ddagger$. The limit is not high enough to test whether there are states weakly coupled to the case excitation or whether the quasiparticle character of the states is largely retained at this excitation. It would be interesting to measure actual values for their lifetimes. Of course, the lowest states in $^{109}$Sn will be rather pure quasiparticles; as in the other odd-A isotopes, the $\beta$-decay to the $7/2^+$ state has a high log ft value because $\Delta \text{I} = 2$ in the $d7/2 + g7/2$ transition.

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**Acknowledgements**

We should like to thank Prof. W.D. Schmidt-Ott for preparing $^{66}$Ga sources at the Göttingen cyclotron. The first experiments in this work were done at the Manchester and Liverpool accelerators just before they closed down, and we wish to thank the operators and the UNILAC, and the members of the GSI mass separator group who kept the separator running reliably during the short beam time available.

Four of us (M.C.J., I.S.G., P.M., P.J.N.) wish to express our appreciation to the U.K. Science Research Council for a grant which enabled us to join the GSI group.

**References**

1. A. Plochociki et al, "Nuclear Masses Close to the Proton Drin Line in the Tin Region". This Conference.
7. O. Hashimoto, Y. Shida, G. Ch. Madueme, 
8. W. Hagervorst, C. Ekstrom, S. Inkelman, 
9. C.M. Perrey and F.G. Perrey, Atomic Data and 
  Nuclear Data Tables 17, 1 (1976)
  (1980).
PARTICULAR RELATIVE POSITIONS OF LOW ENERGY LEVELS IN THE $h_{11/2}$ BAND STRUCTURE OF $^{119}\text{Xe}$: EXPERIMENT AND IBPA CALCULATIONS

J. Gizon, V. Barci, A. Gizon and J. Crawford
Institut des Sciences Nucléaires (IN2P3, USM6), Grenoble, France
M.A. Cunningham
Wright Nuclear Structure Laboratory, Yale University, New Haven, Ct. 06511, USA

Abstract

The level ordering of the lowest members in the $h_{11/2}$ band structure of $^{119}\text{Xe}$ is discussed and compared with those of xenon isotopes and isotones. A description is given in terms of the interacting boson fermion model.

1. Introduction

Intensive studies on nuclei of the intermediate transitional region located between tin and well-deformed rare-earths have been carried out. A special effort has been made to establish the level structure of very neutron-deficient barium isotopes $^{133}\text{Ba}$. The systematics of the $h_{11/2}$ negative parity levels in nuclei from $^{133}\text{Ba}$ to $^{129}\text{Ba}$, i.e., nuclei with a neutron number between 77 and 67 show some typical trends of level orderings and level spacings.

Properties of these nuclei can be directly deduced from this $h_{11/2}$ structure and understood within the framework of geometrical models, from the position of the Fermi energy. The heaviest barium, $^{133}\text{Ba}$, has a Fermi energy $E_F$, situated between the $11/2^-$ and $9/2^-$ orbitals and the $h_{11/2}$ band is based on an $11/2^-$ state. Then, $E_F$ penetrates more deeply into the shell and the $9/2^-$ and $7/2^-$ levels appear successively, in $^{131}\text{Ba}$ and $^{129}\text{Ba}$, as base states. For the $^{129}\text{Ba}$ nucleus, $E_F$ is located between the $7/2^-$ and $5/2^-$ orbitals.

The situation is similar in other even-Z nuclei of this region but the systematics were less complete for $Md$, $Ce$ and $Xe$ isotopes. Recently, the level scheme of $^{123}\text{Xe}$ $^{3}$ and data on odd-A $^{117-121}\text{Xe}$ were published. In the preceding communication to this conference, a complete study of $^{119,121}\text{Xe}$ is given $^{5}$.

Thus, the information on negative parity $h_{11/2}$ levels in the xenons is now more extensive. It is particularly interesting to know how the positions of the $7/2^-$, $9/2^-$, ... levels evolve as a function of the neutron number. Our experimental study place in this context. Its aim was to carefully establish level energies, spins, multipolarity of transitions, branching and mixing ratios in the level structure for which preliminary data had been given by Chowdhury et al. $^{4}$. In this short communication, the case of the $h_{11/2}$ band in $^{119}\text{Xe}$, which presents special features, is discussed in detail.

2. Experimental results

The description of the experimental techniques is given in another communication $^{5}$ to this conference. We concentrate here only on some typical points of the $h_{11/2}$ band.

One of these interesting features is the special ordering of the $7/2^-$, $9/2^-$ and $11/2^-$ levels. Indeed, in heavier $\text{Ba}$ and $\text{Xe}$ isotopes with 69 and 67 neutrons these three levels are ordered by increasing energy while the $9/2^-$ state in $^{119}\text{Xe}$ is placed above the two others. Such relative positions are firmly established by the $E2$ and $M1+E2$ multipolarities of the $67.3$ and $70.3$ keV transitions respectively, the $A_{22}$ angular distribution coefficients being $(0.29 \pm 0.05)$ for the former and $-(0.64 \pm 0.16)$ for the latter. Figure 1 shows the experimental $h_{11/2}$ band, the energy of the $11/2^-$ state being set to zero.

$$
\begin{array}{ccc}
(25/2^-) & 27/2^- & 29/2^- \\
21/2^- & 23/2^- & 25/2^- \\
17/2^- & 19/2^- & 21/2^- \\
15/2^- & 17/2^- & 19/2^- \\
9/2^- & 11/2^- & 13/2^- \\
7/2^- & 9/2^- & 11/2^- \\
119\text{Xe} &
\end{array}
$$

Fig. 1: The $h_{11/2}$ band in $^{119}\text{Xe}$

The second point which must be mentioned concerns the half-life of the $11/2^-$ level. Indeed, since the $9/2^-$ level is $4$ keV above this $11/2^-$ state, the latter can only decay by an $E2$ transition to the $7/2^-$ base state. In spite of difficulties of in-beam measurements at low energy a $\sim 27$ ns half-life is observed for the $11/2^-$ level. This is deduced from coincidences between the $67$ keV $\gamma$-ray and the radio-frequency signal of the cyclotron. This value of $27$ ns corresponds to a half-life of 30 times shorter than the Weisskopf estimate.

3. Discussion of the $h_{11/2}$ level pattern

Though the ordering of the lowest levels in $^{119}\text{Xe}$ is peculiar, it could be foreseen from comparisons of this band structure in the isotones and in the xenon isotopes.

3.1. Comparison of $h_{11/2}$ bands

The negative parity levels of $N = 69$ and 67 $\text{Te}$, $\text{Xe}$ and $\text{Ba}$ nuclei have been plotted in figure 2. The data are from J. Gizon and A. Gizon $^{1}$ for $^{129}\text{Ba}$, A. Luukko et al. $^{3}$ for $^{123}\text{Xe}$, U. Hagenmann et al. $^{6}$ for $^{119}$, $^{121}\text{Te}$, N. Yoshikawa et al. $^{1}$ for $^{129}\text{Ba}$ and V. Barci et al. $^{5}$ for $^{121}\text{Xe}$. One sees that all the levels go up, relative to the $11/2^-$ state in passing from $8a$ to $\text{Te}$. The $h_{11/2}$ band in the $N=69,67$ barium

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* On leave from McGill University, Montreal, Canada.
and xenon isotopes have the same level ordering but different spacings. Thus, in $^{120}\text{Ba}$ and $^{121}\text{Xe}$, the $7/2^-$ level is still the base state but there is a strong diminution of the spacings between the $7/2^-$, $9/2^-$ and $11/2^-$ levels, the $13/2^-$ and $15/2^-$ ones...

If this tendency were maintained in lighter isotopes, one should observe changes of level orderings in $^{119}\text{Xe}$. This was foreseen by Chowdhury et al. who have suggested that the $9/2^-$, $17/2^-$ and $21/2^-$ levels cross the $11/2^-$, $19/2^-$ and $23/2^-$ ones, respectively.

![Fig. 2](image)

The $n_{1/2}$ level structure in $N = 67$ and $N = 69$ isotopes.

The systematics in figure 3 can also give some insight on the $h_{11/2}$ band in $^{119}\text{Xe}$. The curve has been plotted mainly with results from ref. 7 for $^{132}\text{Xe}$, ref. 8 for $^{129,131}\text{Xe}$, ref. 9, 10 for $^{125}\text{Xe}$, ref. 3 for $^{123}\text{Xe}$, ref. 4, 5 for $^{119,121}\text{Xe}$ and ref. 4, 11 for $^{117}\text{Xe}$. In this figure, one observes that the $9/2^-$ is decreasing in energy from $A = 133$ until $A = 125$ and 123 and starts to go up at $A = 121$. One expects to have this $9/2^-$ state very close to the $11/2^-$ one in $^{119}\text{Xe}$. This is what we have found (it is placed 3 keV above). Such a tendency in the raising of the $9/2^-$ level in $^{119}\text{Xe}$ agrees with its position in $^{117}\text{Xe}$ where it lies 83 keV above the $11/2^-$ state $4,11$.

The variations of the $7/2^-$ state are more difficult to appreciate and foresee. It is at 78,1 and 68.7 keV below the $11/2^-$ level in $^{123}\text{Xe}$ and $^{125}\text{Xe}$, respectively and we do not expect to see it cross the $9/2^-$ and $11/2^-$ levels in $^{119}\text{Xe}$. In fact, it only starts to go up in $^{119}\text{Xe}$.

3.2. The origin in the change of the $h_{11/2}$ level structure

The evolution of the level structure when passing from the heavier xenons to $^{119}\text{Xe}$ is the sign that a change will appear in the structure of the lighter isotopes ($A > 119$). Indeed, the odd-$A$, even-$Z$ nuclei of this region with at least 67 neutrons have a level pattern of the $\DeltaI = 1$ type which is explained in the rotor-plus-particle model $[12]$ by the coupling of an $h_{11/2}$ quasi-neutron-hole to a prolate core. The nucleus $^{119}\text{Xe}$ has a level pattern which one must find in light xenons, bariums,

Indeed, compared to the $^{121}\text{Xe}$ case (fig.3), the increase in the energy of the $9/2^-$ level is associated with a similar raising of the $13/2^-$ energy which is only 4 keV below the $15/2^-$ one. It must also be pointed out that the $17/2^-$ level has crossed over the $19/2^-$ one. The light xenons, bariums... will have a half-empty $h_{11/2}$ shell with a Fermi surface

![Fig. 3](image)

Systematics of the $h_{11/2}$ band in odd-$A$ Xe isotopes on or below the $5/2^-$ orbital. The level structure will then be governed by the quasi-particle mode which will generate an $h_{11/2}$ decoupled band based on the $11/2^-$ state.

The two well known level patterns, i.e. the $\DeltaI = 1$ rotational-like type and the decoupled $\DeltaI = 2$ band, which correspond to the extreme situations of transitional nuclei: have been well studied and analyzed. They appear in prolate nuclei where the Fermi surface is in the upper and lower part of a shell, respectively. Up to now the intermediate situation corresponding to a Fermi energy placed in the middle of a shell has not been experimentally explored. Our experimental results on $^{119}\text{Xe}$ concern just this region.

The triaxial-rotor-plus-particle model $[13]$ could be used to illustrate the situation schematically. Though we are not sure about the validity of this model when using a large number of quasi-particles (or holes), the level ordering and level energies of the $h_{11/2}$ band in $^{119}\text{Xe}$ are correctly reproduced when the Fermi energy is set between the $7/2^-$ and the $5/2^-$ orbitals i.e. lower than the middle of the shell.

4. IBM calculations

A quantitative analysis of $^{119}\text{Xe}$ and more generally of the xenon isotopes has been made using the interacting boson-fermion model $[14]$. Indeed it has been shown that the coupling of boson pairs with fermions $[15]$ can reproduce the properties of odd-$A$ nuclei. The results presented here on levels of the $h_{11/2}$ band are obtained by the coupling of an $h_{11/2}$ neutron to the $^{118}\text{Xe}$ core.

The boson-fermion interaction used in the calculation included only monopole, quadrupole and exchange terms; hence there were three independent
parameters. The results of the calculation are shown at right in figure 4. The important feature to note is the correct ordering of the levels $9/2^+$, $11/2^+$, $13/2^+$, $15/2^+$, etc. This is particularly significant since this ordering does not originate from a weak coupling limit, but rather from a strong coupling regime. (Note that the multiplet based on coupling the $h_{11/2}$ neutron to the $2^+$ state in $^{118}$Xe is split by 406 + 67 ≈ 473 keV.) The calculation fails, however, to reproduce the position of the first $7/2^+$ state, placing it above, rather than below the $11/2^+$ base state. Since this is a strong coupling situation, moving the position of the $7/2^+$ level will necessarily destroy the ordering of the higher levels. This suggests that some other degrees-of-freedom are required to fully describe the low-lying spectrum. Indeed, it is likely that the $f_{7/2}$ and $h_{9/2}$ single particle levels play an important role in determining the properties of these negative parity states. Of singular importance in these studies will be the placement of other, non-yраст states in the spectrum.

5. Conclusions

The $h_{11/2}$ band in $^{119}$Xe which has a special level ordering has been presented. It has been compared to the same band in Xe isotopes and isotones. The observed level ordering indicates that the structure of the xenon isotopes is changing near $^{118}$Xe and that the lighter ones will be governed by the coupling of quasi-particles ($h_{11/2}$ neutrons) to the core i.e. will exhibit $h_{11/2}$ decoupled bands. A quantitative analysis has been made in terms of the Interacting Boson- Fermion Approximation. This nucleus $^{119}$Xe is described by the coupling of an $h_{11/2}$ neutron to the even core: more extensive calculations, taking into account the mixing of the $h_{11/2}$, $h_{9/2}$ and $f_{7/2}$ configurations, are in progress.

References


2) C.F. Liang, A. Peghira, F. Paris, B. Weiss, A. Gizon, communication to this conference.


5) V. Barci, A. Gizon, J. Crawford, J. Genevey, J. Gizon, A. Plascocki, Communication to this conference


10) H. Helppi, J. Hattula, A. Luukko, Nucl. Phys., A332 (1979) 183


14) M.A. Cunningham, Int. Conf. on Nuclear Physics, Berkeley, 1980, p. 786

Abstract

Band structures in $^{119,121}$Xe produced by $^{110,112}$Cd ($^{12}$C, 3$n$) reaction have been investigated using in-beam $\gamma$ spectroscopic techniques. Details of the structures of the h11/2 and g9/2 bands are presented. A new d3/2 decoupled band has been observed in $^{121}$Xe and a possible g9/2 band in $^{119}$Xe. These collective features are discussed in the framework of the triaxial-rotor-plus-particle model, and the IBFA model.

1. Introduction

In recent years, a number of experimental studies have been carried out to establish the collective features of odd-A isotopes, ranging from those in the vicinity of the N = 82 shell closure to those more deficient in neutrons. The aim of such studies is to follow systematics of such common features as the structure of the strongly excited negative parity h11/2 band and of a series of positive parity bands (e.g. g9/2) and to investigate the applicability of a nuclear model which has shown promise for the description of these transitional nuclei. For example, the triaxial-rotor-plus-particle model has been particularly useful for the description of bands built on unique parity states in odd-A barium isotopes, especially for cases involving nearly empty or nearly complete pure shells. Following precise in-beam measurements done on $^{123}$Xe, the same particle-rotor model was shown to be successful for the interpretation of the h11/2 level structure for odd-A xenon isotopes between $^{123}$Xe and $^{133}$Xe. There was a clear need for a continuation of such studies for $^{125}$Xe and lighter xenon isotopes in which the Fermi level should lie near or below the middle of the h11/2 shell. Preliminary work at Grenoble on $^{121}$Xe and $^{119}$Xe indicated the necessity of very careful measurement of low energy $\gamma$ transitions; the h11/2 band structure in this region is characterized by a series of close doublets.

2. Experimental techniques

The $^{110,112}$Cd ($^{12}$C, 3$n$) reaction was used to produce the xenon isotopes studied. For $^{119}$Xe the $^{12}$C beam from the Grenoble variable energy cyclotron was set to 65 MeV, and $^{110}$Cd targets of thickness 5.7 mg/cm$^2$ or 3.0 mg/cm$^2$ were used for the $^{121}$Xe production beams were 60 or 63 MeV and the $^{112}$Cd target thickness was 5.2 mg/cm$^2$. Angular distribution measurements and 4-parameter coincidences ($E_{\gamma}^{1}$, $E_{\gamma}^{2}$, $t_{\gamma1-\gamma2}$, $t_{\gamma1-\beta}$) were performed.

3. Experimental results

3.1. The base states

In all the odd-A, even-Z nuclei of this transitional region, the h11/2 band is strongly excited. Its level pattern, which is known in detail, is used as a starting point to establish the level scheme of nuclei excited by heavy ion induced reactions. Thus we will start from the 7/2$^-$ base state of the h11/2 band in $^{119,121}$Xe to fix the base state of both nuclei.

The most intense $\gamma$-rays (196.1 keV in $^{121}$Xe and 176.1 keV in $^{119}$Xe) have negative A2 angular distribution coefficients (-0.34(3) and -0.23(4), respectively) typical of D1 = 1 transitions. These lines, which coincide with all the lines of the h11/2 band, are delayed relative to the beam as shown in figures 1 and 2, as depopulate long-lived states (5.5 ± 0.5 ns in $^{121}$Xe and 20 ± 4 ns in $^{119}$Xe). These 196 and 176 keV lines are E1 transitions depopulating the 7/2$^-$ level to a 5/2$^-$ state. The E1 assignments are associated with hindrance factors of 1.1 x 10$^5$ in $^{121}$Xe and 3.3 x 10$^5$ in $^{119}$Xe which are present work is made in another contribution to this conference 111.

Fig. 1: Timing distribution for transitions in $^{121}$Xe
The second strongest low-energy line (179.3 keV) in $^{121}$Xe which coincides with a whole band structure is also placed at the bottom of the scheme. It has a large negative $A_{22}$ angular distribution coefficient ($A_{22} = -0.68 \pm 0.06$) compatible only with an $\text{H}1 + \text{E}2$ admixture. Thus, the 179.3 keV level has spin $I = 7/2^-$. Similar reasoning can be applied to $^{119}$Xe where the 225.1 keV γ-ray which depopulates a band has an $A_{22}$ value equal to $-0.69 \pm 0.11$. From coincidence and energy relationships, a weakly fed level is established at 239.8 keV in $^{121}$Xe. It supports a decoupled band similar to the one based on the 97.4 keV level in $^{121}$Xe to which an $I = 3/2^+$ is assigned. It is shown by decay studies that it is a 3/2$^+$ level.

A sequence of four E2 transitions (414, 531, 630 and 703 keV) with moderate intensities is in coincidence with a 257.9 keV gamma, which is a cross-over transition of the 88.6 and 169.3 keV lines. Because of the composite character of the 257.9 keV gamma and of the weakness of the 88.6 keV one, the spin and parity of the 258 keV level cannot be assigned in the in-beam study. However it is proposed as $I^\pi = (9/2^+)$ on the basis of cascade decay studies.

### 3.2. The $h_{11/2}$ level structures

The negative parity levels are the most excited in these $^{12}$C induced reactions. Several criteria are used to fix the $h_{11/2}$ band (and more generally the whole structure) in both $^{119, 121}$Xe (fig. 3 and 4). First of all, the coincidence relationships indicate the relative position of the transitions. Gamma-gamma coincidence experiments have been performed using a planar germanium detector in order to detect low energy γ-lines which give, in fact, the crucial part of the scheme i.e. the low spin levels on which the whole band structure lies. Secondly, the multipolarities of the transitions are assigned on the basis of angular distribution mea-

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Fig. 2: Timing distribution for transitions in $^{119}$Xe

Fig. 3: Level scheme of $^{119}$Xe deduced from the $^{110}$Cd($^{12}$C,3n) reaction
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Fig. 2: Timing distribution for transitions in $^{119}$Xe

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measurements. The energy relationships are of little use in establishing bands where the levels are grouped in very narrow doublets.

3.2.1. The nucleus $^{121}\text{Xe}$

The $h_{11/2}$ band in $^{121}\text{Xe}$ has been established from the doublet observed in the strong composite 423 keV $\gamma$-line. Indeed the lower part of the level structure is deduced from the existence of the 422.3 and 423.5 keV gammas. Thus the whole level pattern is characterized by $\Delta I = 1$ level spacings and by $13/2^- - 15/2^-$, $17/2^- - 19/2^- \ldots$ doublets. Higher than the 196 keV state, the relative order of the levels is reversed compared to the situation in $A > 123$ xenons.

The base state is a $7/2^-$ one as expected from heavier Xe isotopes $^{3-6}$) and from the isotope $^{123}\text{Ba}$ $^{12}$). The positions of the $9/2^-$ and $7/2^-$ levels are fixed by the E2 and M1 + E2 character of the 68.7 and 38.4 keV $\gamma$-lines, respectively.

Compared to previous results $^7$), our data determine the low spin part of the band, the existence of new levels and unambiguous assignments of several states.

In addition to typical levels which are always excited in this kind of heavy ion induced reaction i.e. levels with spin $I = j = 11/2, j + 1, j + 2, \ldots$, one knows that there are other excited states (for example a second $13/2^-$, a second $15/2^- \ldots$). These have been observed here at 677.6 and 1045.6 keV above the $11/2^-$ state, respectively.

3.2.2. The nucleus $^{119}\text{Xe}$

The $h_{11/2}$ bands in $^{119}\text{Xe}$ and in $^{121}\text{Xe}$ have similar features: they exhibit $\Delta I = 1$ spacings with very narrow doublets (the $9/2^-$ and $11/2^-$ are separated by only 3 keV and the $13/2^-$ and $15/2^-$ by only 4 keV) and the $7/2^-$ level is still the base level. In contrast to the $^{121}\text{Xe}$ case, the $19/2^-$ level has crossed the $17/2^-$ one.

An interesting and unique feature appears which involves a special ordering of the $7/2^-$, $9/2^-$ and $11/2^-$ levels. While these three levels are always ordered by increasing energy in the heavier xenon nuclei, the $9/2^-$ state in $^{119}\text{Xe}$ is placed above the other two. The level sequence is unambiguously established by the E2 and M1 + E2 multiplicities of the 67.3 and 70.3 keV lines, their $A_{22}$ angular distribution coefficients being $+(0.29 \pm 0.05)$ and $-0.64 \pm 0.16$, respectively.

The existence of the $7/2^-$ level had not been established in a previous study $^7$) in both $^{119,121}\text{Xe}$. We have also found new levels and have firmly assigned their spins.

Fig. 4: Level scheme of $^{121}\text{Xe}$ deduced from the $^{112}\text{Cd} (^{12}C, 3n)$ reaction
3.2.3. Half-lives of the 11/2⁻ states

The 11/2⁻ states in both nuclei have long half-lives: 6 ± 1 ns in 121Ixe and 27 ± 5 ns in 119Ixe. They have been obtained by coincidences between γ-rays and the radiofrequency signal of the cyclotron. Such values are difficult to establish because of the low energy of the transitions. Figures 1 and 2 illustrate our experimental results. Comparisons between prompt and delayed lines assure the delayed character of the 11/2⁻ states.

3.3. The g7/2 bands

An even-parity band with regular level spacings based on the 7/2⁻ states exists in both nuclei. The strong M1 + E2, 179.3 and 225.1 keV lines in 121Ixe and 119Ixe, respectively, are in coincidence with a complete level structure which is of the \(\Delta I = 1\) type. This results in the pile-up of M1 + E2 transitions, having E2 cross-overs.

This 7/2⁻ band is less excited than the h11/2 one. It drains only roughly 20% of the total excitation in each nucleus, with the rest appearing in the h11/2 band.

3.4. A d5/2 band in 121Ixe

A sequence of prompt stretched E2 transitions of 321.0, 460.7, 568.7 and 655 keV coincides with the 86.1 and 239.8 keV lines deexciting the (3/2⁻) state. This band is determined up to the (19/2⁻) level at 2245 keV. It is weakly fed, which explains the impossibility of detecting lines coming from the unfavored states.

3.5. A level sequence built on the (9/2⁺) state in 119Ixe

A 9/2⁺ state very likely exists at 257.9 keV in 119Ixe as mentioned in section 3.1. It is fed, at least partly, by a stretched E2, 414 keV transition which coincides with three other E2 lines. These four cascading γ-rays have relatively large intensities compared to those in the h11/2 band. This is due to the fact that they arise from yrast states (the 25/2⁺, 21/2⁻ and 17/2⁻).

4. Discussion of the experimental results

The existence and the relative positions of intrinsic states are directly related to the deformation of the nuclei and the position of the Fermi energy. The nuclei 121Ixe and 119Ixe have 67 and 65 neutrons, respectively; this places their Fermi energy approximately in the middle of the h11/2 shell, in the upper part of the g9/2 one, near the m11/2 level and in the vicinity of the d3/2 and d5/2 ones. From a Nilsson diagram one could also expect states with positive parity generated from the g9/2 shell and with negative parity from the f7/2 one.

4.1. Odd-parity h11/2, shell

In the transitional region we are dealing with, this h11/2 band is always the most excited in heavy-ion induced reactions because its levels are yrast states. Before speaking of theoretical interpretations, one can look at the evolution of the level patterns, transition intensities, mixing ratios... in the systematics of xenon isotopes (see fig. 3 of ref. 11) and also of several series of isotones.

The level schemes of 129, 127, 125, and 123Ixe have been carefully studied and their properties established. All the trends observed in the A > 123 xenon isotopes are found in 119, 121Ixe. A detailed analysis of the relative level positions is given in another communication 11) where a discussion is also made. Thus, only a few important points are considered here.

The I = j - 1 = 11/2⁻ - 1 = 9/2⁻ and I = j = 11/2⁻ I = j + 1 = 13/2⁻ and I = j + 2 = 15/2⁺ levels are very close to each other. The states that we can call "unfavorable" such as the I = j = 1, j + 3, j + 5 i.e. 9/2⁻, 17/2⁻, 21/2⁻... lie even above the favored ones I = j, j + 4, j + 6... in 119Ixe. This change in the level pattern of both 119,121Ixe relative to that in the heavier isotopes is the sign that a change is appearing in the structure of the nuclei.

Indeed these two nuclei are just between two typical and extreme well known situations: the prolate nucleus with a full shell and those with an empty shell which generate a \(\Delta I = 1\) rotational-like level pattern and \(\Delta I = 2\) decoupled bands, respectively. In 119, 121Ixe, the Fermi energy has dropped to the middle of the h11/2 shell. Thus, the \(\Delta I = 1\) rotational-like pattern of the A > 123 isotopes tends to be shaded off and the decoupled structure begins to emerge 11).

The h11/2 band in both xenons can be explained in the triaxial-rotor-plus-particle model 8) by coupling a quasi-neutron hole to the proton core when the Fermi surface is set between the 7/2⁻ and 5/2⁻ orbitals, with \(\beta = 0.2\) and \(\gamma = 16°\).

Calculations have also been undertaken on xenons 10) in the interacting boson-fermion model 9) by coupling the h11/2 single particle level to core states. The treatment has been improved by including the coupling of further degrees-of-freedom beyond the h11/2 level. Calculations are in progress with the introduction of h9/2 and f7/2 odd-parity levels. First results on 119,121Ixe are given in another communication 11) and will be discussed later in detail 11).

The half-lives of the 11/2⁻ levels in both 119,121Ixe which results in the low energy deexciting transitions are more difficult to explain quantitatively.

4.2. The g9/2 bands

A g9/2 band is common in the nuclei of this region. It has been found for the first time in 125Ba 2) and its properties are well understood if one couples a g9/2 neutron-hole to \(\beta\) and \(\gamma\) deformed core states. The level pattern is of the \(\Delta I = 1\) rotational type and the inertia parameter \(\kappa^{2/3}\) exhibits a weak staggering (fig. 5).

The spin and parity assignments are clear, but we must make some comments about the identification and the nature of the states. In 121Ixe, there is a g9/2 band decaying by the 179.3 keV, 7/2⁻ → 5/2⁺ transition to the 5/2⁺ level which is the 5/2⁺ [404], 9/2⁻ or the 5/2⁻ [413], 5/2⁻ state. In 119Ixe, the energy of the lowest line is such (225.1 keV) that it could be a 9/2⁻ → 7/2⁻ transition. This would give variations of the \(\delta E/2I\) ratio versus I(I+1) (curve number 3 in fig. 5) opposite to those in 121Ixe. Thus, on the basis of the inertia parameter we assign an I = 7/2⁻ spin to the 225.1 keV level (curve number 2). This does not indicate whether we have

(1) a 7/2⁻ band based on the 225.1 keV, 7/2⁻[404] state and decaying to the 5/2⁻[402], 9/2⁻ or 5/2⁻[413], 5/2⁻ state.

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4.3. The $d_{3/2}$ decoupled band in $^{121}\text{Xe}$

A set of $3/2^+$, $7/2^+$, $11/2^+$, $15/2^+$ and $19/2^+$ levels exists in $^{121}\text{Xe}$. They are separated by energies close to those in the ground band of neighbouring $^{122}\text{Xe}$ and $^{120}\text{Xe}$ (fig. 6) which is typical of a decoupled band. The unfavorable states are unobserved because they are weakly fed, as usual.

Since the band is based on a $3/2^+$ state, it is generated from the $d_3/2$ neutron shell. It can be explained in the rotor-plus-particle model by the coupling of a $d_3/2$ quasi-neutron to the prolate even core states.

4.4. Possibility of a $g_{9/2}$ band in $^{119}\text{Xe}$

The level structure based on the $(9/2^+)$ state is made of four stretched $E2$ lines which deexcite successively the $25/2^+$, $21/2^+$, $17/2^+$ and $13/2^+$ states. These lines have energies similar to those of the $E2$ transitions between the favored states in the $h_{11/2}$ band i.e. 414.2 keV to compare with 406.0 keV, 531.3 with 575.1, and 629.9 with 706.4. Thus this $g_{9/2}$ band is not a decoupled one.

The $g_{9/2}$ band is very likely the result of the coupling of a $g_{9/2}$ neutron hole to the prolate core. It could be built in a similar way to the $h_{11/2}$ band which has weakly populated unfavorable states. Indeed, no other level has been found in the $g_{9/2}$ structure of $^{119}\text{Xe}$. In the $h_{11/2}$ band, the lines deexciting the unfavorable states are 8 or 19 times weaker than the $E2$ transitions from the favored ones. They would be too small in the singles and coincidence spectra and would escape our analysis. The existence of such a band with a $\Delta I = 1$ character is very likely because the Fermi energy of $^{119}\text{Xe}$ is near the upper orbital of the $g_{9/2}$ neutron shell.

References

11. J. Gizon, V. Barci, A. Gizon, J. Crawford, M.A. Cunningham, communication to this conference
13. M. A. Cunningham, to be published.

![Fig. 5](image)

Variations of the moment of inertia in the $g_{7/2}$ bands. Curves 1 and 2 are obtained with a base state $7/2^+$ at 179.3 keV in $^{121}\text{Xe}$ (curve 1) and at 225.1 keV in $^{119}\text{Xe}$ (curve 2).

or (ii) a $5/2^+$ band lying on the $5/2^+[402]$, $g_{7/2}$ or $5/2^+[413]$, $d_{5/2}$ ground state. Since the $g_{7/2}$ and $d_{5/2}$ orbitals are very near each other in this region, the nature of the intrinsic states cannot be fixed from this experiment alone. Calculations according to several theoretical approaches could clarify this situation.

![Fig. 6](image)

Comparison of the ground bands in even cores with the $\Delta I=2$ band observed in $^{121}\text{Xe}$ and based on a $(3/2^7)$ level at 239.8 keV.
THE DECAY OF NEUTRON DEFICIENT $^{117,119m++g}$, $^{121m++g}$Cs. LOW LYING LEVEL STRUCTURE IN $^{117,119,121}$Xe NUCLEI

J. Genevey
Institut des Sciences Nucléaires, Grenoble, France

G. Margueri, A. Charvet,
Institut de Physique Nucléaire, Lyon, France

C. Richard-Serre,
IN2P3/CERN, Genève, Suisse

A. Knipper,
Centre de Recherches Nucléaires, Strasbourg, France

J. Crawford*,
Mc Gill University, Montreal, Canada

and the ISOLDE Collaboration

Abstract

The decays of neutron-deficient $^{117}$Cs, $^{119m++g}$Cs, $^{121m++g}$Cs have been investigated at the Isolde facility. Systematics of low-lying energy levels, both in cesium and xenon nuclei are presented.

1. Introduction

The decays of even-mass cesium isotopes from $A = 124$ to $A = 116$ have already been studied by our group $^1$ at the Isolde facility. Until recently, little was known about the decay of odd-A cesium nuclei with $A < 125$.

Earlier this year our study of the decay of $^{123m++g}$Cs was published $^2$ and here, we present preliminary results concerning the $\beta$-decay of neutron deficient $^{117,119m++g}$, $^{121m++g}$ Cs to the related xenon levels. Systematics of low-lying energy levels in odd-A cesium and xenon nuclei are presented, including our own data and published results.

2. Experimental procedure

Cesium isotopes were produced at the Isolde separator using the target of molten lanthanum $^3$ bombarded by the 600 MeV proton beam of the CERN synchrocyclotron. The on-line mass separated cesium sources were collected and carried in front of the detectors using a tape transport system. They were analyzed through a complete set of spectroscopic on-line measurements including studies with high resolution Ge(Li) and Si(Li) detectors, a 4×8 plastic scintillator, γ-γ coincidence, an e-γ multipolemeter experiment, and multianalysis of the gamma-rays. The data were recorded with a Pluri-mat 20 computer.

3. $^{121m}$Cs decay and odd-A Cs level structure

Preliminary results have been published previously $^4$. The half-lives of $^{121m}$Cs($T_{1/2}=122\pm3$s), $^{121}$Cs($T_{1/2}=155\pm4$s), $^{119m}$Cs($T_{1/2}=29\pm2$s), and $^{119}$Cs($T_{1/2}=44\pm2$s) were measured with better accuracy. The e-γ multipolemeter experiment for $A = 121$, a 68.5 keV line was found, with $\alpha_5$ and $\alpha_7$ values which indicated a $\Delta l = 3$ character. The presence of X- (Cs) X-rays does not allow us to measure its $\alpha_5$ value nor to distinguish between K3 and M3 multipolarity for this transition. However, it may be pointed out that the Weiskopf estimate for the lifetime of a 68.5 keV M3 line is in agreement with the measured half-life of $^{121m}$Cs; hence this line probably represents the isomeric transition between the $9/2^+$ level and the ground state.

![Figure 1](image_url)
Fig. 1 shows the systematics of odd-A cesium nuclei. It includes spin measurements from Ekström et al. 5), Fisher et al. 6) and data from Garg et al. 7), d'Auria et al. 8) as well as the present results. The (9/2⁻) spin and parity for 117Cs was tentatively proposed according to the ½-decay of this nucleus (see section 4). No half-life greater than ½ belonging to a hypothetical isomeric state, has been found in 117Cs.

4. Level structure in 117,119,121Xe

Decay schemes for 117,119m⁺,121m⁺9Cs have been built from available experimental data. From these, we conclude spin 5/2⁻ for the ground state of 119Xe and 121Xe. A few details of the level structure at low excitation are shown in figs. 2 and 3, which present the systematics of the series of odd-A Xe isotopes. It may be seen that the 1/2⁺ state, which was the ground state for nuclei with A > 123 lies at an excitation energy of 153.9 keV in 121Xe and 246.9 keV in 119Xe. It decays to the ground state by an E2 transition. The half-life of this line was found to be ≈ 80 ns in both nuclei, in agreement with the Weisskopf estimate. As in heavier isotopes, the 3/2⁻ level lies ≈ 90 keV above the 1/2⁺. The first members of ΔI = 2 bands built on these levels (clearly seen in 123,125Xe, 9,10) are found in 121Xe with energy spacings close to those in the 120Xe core. The 7/2⁻ state (972⁻) was also identified, and a ΔI = 1 sequence built on it was observed.

For the negative parity states (h11/2 system) in odd-A 123-125Xe a level pattern was proposed by Gizon and Gizon [11], and Luukko et al. 9,10]. In 121Xe the same arrangement was established in our decay study and from in-beam experiments 12). The tendency for the 9/2⁻ level to rise in energy and for the 11/2⁻ level to fall as A is decreased is confirmed by their relative position in 119Xe (our measurements) and 117Xe [13].

In this last nucleus, two E2 transitions are observed in the decay studies. The first (E₂ = 205 keV) which de-excites the 11/2⁻ level was also observed by Chowdhury et al. [13], although the second, from the 7/2⁻ level (E₂ = 245 keV) was not observed in that in-beam experiment. This permits us to establish the excitation energy of the 7/2⁻ level and to propose, tentatively, 97/2⁻ for the spin and parity of the ground state of 117Xe. This ground state is strongly fed by an allowed 8 transition from 119Cs, which may also have J⁺ = 9/2⁻.

A complete report on this study will soon be published.

References

14. V. Barci, A. Gizon, J. Crawford, J. Genevey, J. Gizon, A. Plöchcki, communication to this conference
A NEW 6.3 SECONDS ISOMER IN $^{124}$Cs

C.F. Liang 1), P. Paris 1), A. Pégahine 1), B. Weiss 2), A. Gizon 2),

1) CSNOM Orsay, France
2) Université de Nice, France
3) ISN, Grenoble, France

Abstract

A new isomer [T1/2 = (6.3 ± 0.3) s] has been identified in $^{124}$Cs. Its 1+ decay has been studied by gamma- and electron - spectroscopy on mass separated samples.

1. Introduction

To get more detailed information about low-spin levels in the neutron-deficient transitional nuclei of the 54 $< A <$ 58 region, a systematic search for isomeric levels and their decay has been undertaken with the mass separator Isocel II operating on-line to the Orsay synchrocyclotron.

In the cesium isotopes (Z = 55) a large number of ground states and isomeric states have been already identified at CERN and their spins have been known 1). For the odd-odd nuclei, two different half-lives have been reported for $^{124}$Cs and $^{130}$Cs but only one has been observed for $^{124,126,128}$Cs.

Looking at the intrinsic states already identified in odd-A xenon (odd neutron) and in odd-A cesium (odd proton) isotopes 2), the 1+ ground state of odd-odd cesium nuclei can be explained from A = 130 to A = 122 but the absence of isomer in $^{128,126,124}$Cs is surprising and suggests new systematic investigations in a large range of half-lives.

2. Experimental techniques

The mass-separated samples were produced by bombardment of a molten cesium metallic target 3) with a 280 MeV $^4$He beam or a 200 MeV proton beam. The cesium activities were carried out from the collecting point of the isotope separator to the detectors, using a rapid tape driver system. Different techniques have been used to study these activities, mainly based on $γ$, $X$ and $e^-$ singles measurements at very low-energy. A multispectrum analysis has been performed on the $γ$-ray singles and the conversion electron spectra. $γ-γ$, $γ-X$, $γ-e^-$ and $X-e^-$ three parameters coincidences have also been recorded.

3. Preliminary experimental results

Up to now, the data are not completely analysed, but several results are clearly extracted. In addition to the transitions previously observed in the decay of $^{124}$Cs $→^{124}$Xe 4), four new gamma lines at 53.7, 58.0, 89.3 and 96.3 keV have been found in the low-energy part of the $γ$-ray singles spectra of $^{124}$Cs samples.

From the multispectrum analysis (eight time groups per spectrum) of the $γ$-ray singles spectra, the decay curves (reproduced in figure 1) have been determined. So, in addition to the previous 31 seconds activity already measured in $^{124}$Cs, a new half-life of (6.3 ± 0.3) seconds has been clearly detected.

In the electron spectra recorded with the magnetic selector associated with a silicon detector 5), the K, L and M lines corresponding to the internal conversion in cesium of these $γ$-rays have been observed (figure 2). Moreover, two other transitions at (64.7 ± 0.1) keV and (161.0 ± 0.2) keV have also been detected by their conversion electrons in cesium (figure 2). These electron lines have the 6.3 seconds half-life.

All these new transitions have not been observed in samples collected at a mass (124 + 19) and corresponding to Ba$^+$ ions of the "fluorine technique" developed at Isocel II 6). Moreover, in the $γ$-$X$ and $e^-$-$X$ coincidence spectra they are in coincidence with the Cs $X$-rays and they can be unambiguously assigned to $^{124}$Cs. Multipolarities have been deduced from the relative 1e$^-$/1 $γ$ intensities. A first normalisation has been made for the stronger, medium energy $γ$-rays (96.3 and 89.3 keV) with the 533.9 keV E2 transition, 2$^+ → 0^+$ of the $^{124}$Xe ground band. From this estimation the 89.3 keV appears as a pure E1 transition and has been used to normalize the $γ$ conversion coefficients of the very low energy lines (Table 1).

Fig. 1 Decay curves for low energy $γ$-rays observed in $^{124}$Cs.
Fig. 2 Conversion electron spectrum measured with $^{134}$Cs samples.

Due to the large variations of the efficiency of both the magnetic selector and the gamma detector, the uncertainties on $\alpha_K$ and $\alpha_l$ are important but the K/L ratios give supplementary values, useful to determine the multipolarities.

Table 1. Characteristics of the transitions

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$</th>
<th>$I(e^-K)/I_\gamma$ (norm.)</th>
<th>K/L</th>
<th>Multipolarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.7</td>
<td>7.1</td>
<td>~ 3.2</td>
<td>6.6</td>
<td>M1, E2</td>
</tr>
<tr>
<td>58.0</td>
<td>20.9</td>
<td>~ 1.1</td>
<td>8</td>
<td>E1</td>
</tr>
<tr>
<td>64.7</td>
<td>26.6</td>
<td>~ 28</td>
<td>3.6</td>
<td>M2</td>
</tr>
<tr>
<td>89.3</td>
<td>52.5</td>
<td>0.26</td>
<td>6.9</td>
<td>E1</td>
</tr>
<tr>
<td>96.3</td>
<td>51.9</td>
<td>0.98</td>
<td>7.7</td>
<td>M1(E2)</td>
</tr>
<tr>
<td>161.0</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>(E3)</td>
</tr>
<tr>
<td>169.3</td>
<td>5.8</td>
<td>0.14</td>
<td>M1, E2</td>
<td></td>
</tr>
<tr>
<td>188.8</td>
<td>27.6</td>
<td>0.14</td>
<td>6.2</td>
<td>M1, E2</td>
</tr>
<tr>
<td>211.6</td>
<td>56.2</td>
<td>0.12</td>
<td>4.8</td>
<td>E2, M1</td>
</tr>
</tbody>
</table>

Before a complete analysis of the data, it is impossible to place unambiguously the low-energy levels of $^{124}$Cs.

Recent $\gamma-\gamma$, $\gamma-X-\gamma$ and $\gamma-e^--\gamma$ coincidence experiments have been performed with $^{124}$Ba samples to precise the same part of the level scheme.

Nevertheless, mainly from the $\gamma-\gamma$ coincidences, it appears that the $^{124}$mCs isomeric level is deexcited by two different paths. The first one corresponds to a cascade of four transitions 64.7 keV (M2), 96.3 keV (M1), 89.3 keV (E1) and 211.6 keV (E2, M1) (Figure 3 and 4). The second cascade contains the 161.0 keV transition (probably E3) followed by the 58.0 keV (E1), 53.7 keV (M1,E2) and 188.8 keV (M1, E2) transitions.

The 161.0 keV transition, observed on the electron singles spectra appears very likely as the cross-over of the 64.7 keV * 96.3 keV lines of the main cascade. So, the two different paths could feed the same level at (300.8 ± 0.2) keV established by the two different sums 89.3 + 211.5 = 300.8 ± 0.2 keV and 58.0 + 53.7 + 188.8 = 300.5 ± 0.3 keV. This 300.8 keV level, which is deexcited by E1 transitions would also present a weak half-life and it is a candidate for a second low-energy isomeric level in $^{124}$Cs. The ground state of $^{124}$Cs has spin and parity $^1$D$^1$. From the multipolarities of the transition and the $\gamma-\gamma$ coincidence relationships established in the decay of $^{124}$mCs, the 6.3 seconds isomeric level at 461.8 keV could very likely support a (77) assignment while the level at 300.8 keV could be a (47) state. Up to now, the partial analysis of the data does not permit to determine unambiguously the neutron and proton orbitals involved in the description of the low-energy states of this odd-odd $^{124}$Cs nucleus.

References
2) J. Genevey et al., communication to this Conference and references in.
4) A. Charvet et al., J. de Phys. 38. (1977), L 242
NEW ISOMER AND LOW-ENERGY INTRINSIC STATES IN $^{127}$Ba

C.F. Liang$, P. Paris$, A. Peghaire$, B. Weiss$$, A. Gizon$$$

$+$ CSNSM, Orsay, France
$+$+ Université de Nice, France
$$++$ ISN, Grenoble, France

Abstract

A new isomer (T$_{1/2}$ = 1.9 ± 0.2 seconds) has been identified in $^{127}$Ba. A 7/2$^-$ spin and parity assignment has been deduced. The ground state of $^{127}$Ba is established as a 1/2$^+$ state. New positive parity band structures have been observed.

1. Introduction

From in-beam experiments performed with the $^{118}$Sn(12C, 3n) reaction, collective band structures have been easily identified in $^{127}$Ba 1). An odd-parity rotational-like band developed on a 9/2$^+$ base state has been explained in terms of an h$_{11/2}$ neutron-hole coupled to a triaxial core. An even-parity band based upon a 7/2$^+$ state has also been associated with the coupling of a g$_{9/2}$ neutron-hole to the core with the Fermi energy located in the highest orbital of the shell. More generally, the experimental collective level patterns excited by heavy ion reactions in the odd-A neutron-deficient bariums (N=67 to N=77) have established prolate-type nuclear shapes for these nuclei by a treatment in the framework of the triaxial rotor-plus-particle model 2). Nevertheless, the experimental systematics on high spin states excited via heavy ions reactions give only a partial knowledge of these isotopes. Indeed, transitional nuclei of this region are known to be rather soft and both prolate and oblate nuclear shapes have been theoretically predicted 3).

In the special case of $^{127}$Ba, the information about low-spin, low-energy states is very poor. In previous experiments the half-life was not well determined. Two different values were proposed by d'Auria et al 4), one associated with a high spin state, $T_{1/2}$ = 10 minutes and another one corresponding to a low-spin state, $T_{1/2}$ = 18 minutes. In a more recent measurement, only one half-life has been reported ($T_{1/2}$ = 13.0 ± 0.5 minutes) by Pathak and Preis 5).

From the in-beam experiment performed at Grenoble with the $^{118}$Sn(12C, 3n) reaction on lead-backed targets, the lowest state observed was a 9/2$^+$, identified by systematics with the heavier odd-A isotopes. In this work, it was impossible to decide if this 9/2$^+$ state is an isomeric level or eventually the ground state of the $^{127}$Ba nucleus.

Such a complicated situation has suggested to include the study of the $^{127}$Ba isotope in the syste-

![Fig. 2: Part of a multispectrum analysis on the conversion electrons of $^{127}$Ba. The collection time was 5 seconds. Each spectrum was recorded during 1 second. The spectra shown have a time separation of 2 seconds. Lines labelled with a point belong to $^{127}$Ba($T_{1/2}$ = 13 minutes).](image-url)

Fig. 1: Comparison between gamma singles spectra for samples collected at A = 129 + 19 (BaF$_2$ ions) and at A = 129 + 38 (LaF$_3$ ions)
magnetic search on low-energy isomeric states undertaken at Isotope II, using the new extraction possibilities of barium and lanthanum nuclei.

2. Experimental techniques

The isotopes studied in the present paper have been produced by bombardment of molten cerium metallic targets with a 200 MeV $^3$He beam or a 200 MeV proton beam. The barium and lanthanum isotopes have been extracted at Isotope II, using the new fluorination technique based on the volatility differences of the fluorides $^5$. The efficiency of the method is demonstrated in figure 1.

The mass separated samples were collected on a tape driver and transported in front of the detectors. The identification of the nuclei was mainly based upon singles measurements carried out with high resolution Ge(Li), X-ray intrinsic Ge and Si(Li) detectors. Conversion electron spectra have been recorded with a magnetic selector $^7$. The multispectrum analysis was performed on the y-ray singles and the conversion electron spectra (8 time groups per spectrum).

3. Experimental results

In y-ray singles spectra recorded with Ge(Li) detectors on $^{127}$Ba$^+$ samples collected at a mass A = 146, one new line at 56.2 keV and Ba X-rays have been identified with a new half-life of 1.9 ± 0.2 seconds. From a multispectrum analysis (8 groups of 1 second) of conversion electron spectra on samples collected during 5 seconds (figure 2), the same half-life has been observed for the strongly converted transitions at 24.2, 56.2 and 80.2 keV (figure 3). The multipolarities of these low-energy transitions have been determined. From y-X and y- coincidences the (80.2 ± 0.2) keV (E2) transition appears as the cross-over of the two (24.2±0.1) keV, (M2) and (56.2±0.1) keV, (M1,E2) transitions.

With the $^{127}$La $^{2+}$ samples collected at a mass A = 165, the y-ray singles spectra show a lot of new transitions. Indeed, as the ground state of $^{127}$La has spin and parity 11/2 $^-$, its decay feeds levels at relatively high spins in $^{127}$Ba. The partial level scheme established mainly from y-y coincidences is reproduced in figure 4. Several points have to be mentioned to show the complement between the decay and in-beam measurements. The negative parity band already observed in the $^{118}$Sn(12C,3n) reaction $^1$ is fed up to the 15/2$^+$ level at 777 keV. In addition to the previously identified states 9/2$^+$, 11/2$^+$, 13/2$^+$, 15/2$^+$, a lower energy level is established at 79.4 keV below the 9/2$^+$ state mainly by prompt y-y coincidences (figure 5). This level can be identified as a 7/2$^-$, by analogy with the h11/2 negative parity structures detected in lighter odd-A barium isotopes $^9$. This assignment is very important to establish the decay of $^{127}$Ba$^+$ (T1/2=1.9 seconds). Indeed, from the systematics, the lower levels in odd-A bariums are 1/2$^+$ and 3/2$^+$, the first one being the ground state. The (M1, E2) 56.2 keV transition is located between these states and the isomeric transition, 24.2 keV (M2) is placed between the 7/2$^-$ and the 3/2$^+$ states. The place of the 56.2 keV transition is confirmed by different other y-y coincidences and by the intensity balance.

Three positive-parity bands are fed from the $^{127}$La decay. The one based on the 7/2$^+$ level at 195.6 keV is the regular g7/2 band structure observed in the $^{118}$Sn(12C,3n) reaction. This structure is strongly connected with the one based on a level at 83.3 keV and deexcited by a 25.1 keV transition to the lower 3/2$^+$ state (figure 6). As the multipolarity of the 114.3 keV transition has not been determined in the present work, the (5/2$^+$) assignment made for the level at 83.3 keV (figure 4) is only tentative. The strong connexion between the two rotational bands suggests that the base states 7/2$^+$ and (5/2$^+$) are both originating from the same g7/2

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**Fig. 3**: Decay curves of low energy transitions observed in $^{127}$Ba. The open circles show measurements taken with a Ge(Li) detector while the diamonds show the Si(Li) measurements and the squares the measurements with the electron selector.

**Fig. 4**: Partial level scheme of $^{127}$Ba fed by the $^{127}$La decay.
shell. The third positive parity band is based on the $1/2^+$ state, but, as no multipolarities have been established up to now, the nature of this band cannot be discussed in detail.

4. Discussion

From the present work several points are well established in $^{127}\text{Ba}$. Two different half-lives have been identified. The first one ($T_{1/2} = 13$ minutes) is associated to the $1/2^+$ ground state while the second one ($T_{1/2} = 1.9$ seconds) corresponds to the $7/2^+$ isomeric state. The systematics of the lower energy states in odd-bariums with $127 \leq A \leq 133$ is now well established and reported in figure 7.

![Figure 5 - $\gamma$-$\gamma$ coincidence spectra which show the lower part of the negative parity band.](image)

![Figure 6 - $\gamma$-$\gamma$ coincidence spectra which show the decay of the positive parity structure to the lower levels of $^{127}\text{Ba}$.](image)

References

BOSONIC VARIABLES IN NUCLEAR MATTER

K. Bleuler
Institut für Theoretische Kernphysik der Universität Bonn, W-Germany

Abstract

It is shown that the boson theoretical interpretation of nuclear forces necessitates the introduction of bosonic variables within the state function of nuclear matter. In this framework the 2-boson exchange plays a decisive role and calls for the introduction of special selfenergy diagrams. This generalized scheme is discussed with the help of a solvable field theoretical model.

1. Introduction

Microscopic nuclear theory was in a first attempt based on phenomenological two-body potentials which were determined from a detailed comparison with the empirical nucleon-nucleon scattering phases. These potentials are given by special analytical expressions which contain a large number of parameters adapted to the experimental data. These expressions are then taken over - without any change - into the well-known approximation schemes for nuclear matter. In an earlier stage the two different methods, i.e. the Brueckner theory and the variational methods (in particular the Fermi Hypernetted Chain Approximation) were in characteristic disagreement, but the introduction of the terms in Brueckner's approximation led to a satisfactory agreement between the two theoretical schemes. Having thus reached some confidence with respect to these approximation schemes it turned out, however, that all results based on phenomenological potentials were in disagreement with empirical values. (In the case of the well-known Reid-potential the density is too high and there is also a slight overbinding). The situation appears to be unsatisfactory also from more general viewpoints: It turns out that various phase equivalent but different phenomenological potentials inserted in the same approximation scheme for nuclear matter may produce results which differ in an essential way. This means that the properties of nuclear matter yield an interesting test for different explicit expressions for nuclear forces. Unfortunately, all these theoretical results disagree with the experiment, i.e. they lie outside the empirical point in the well-known density binding diagram (so-called Coester-line, compare Fig. 1). It thus appears to be impossible to make a definite choice among the different phenomenological potentials. Apart from the fact that these potentials are determined by large numbers (up to 40) of unphysical parameters, it thus turns out that this phenomenological approach leads to a characteristic contradiction between the free nucleon-nucleon scattering (which determines the parameters) and the properties of nuclear matter.

Fig. 1 Nuclear matter binding energy per particle E/A as function of the Fermi momentum k_F. The solid curves show the results for different "Bonn potentials" with and without intermediate Δ-isobars and for different cut-off masses Λ (in MeV) for the transition potentials. The saturation points (crosses) do not leave the Coester-line. The crosses at RSC and BS give the saturation points obtained with the Reid soft-core and the Bryan-Scott potentials and the box presents the empirical result.
2. The One Boson Exchange Potential

This situation will by now be improved step by step with the help of the boson theoretical viewpoint, in particular with the help of the introduction of bosonic variables within the structure of nuclear matter. In the framework of a first step, the so-called One-Boson-Exchange-Potential (OBEP) has to be discussed\(^5\): The exchange of a pair of bare interaction bosons is treated with help of the so-called ladder approximation (Lippmann-Schwinger equation). The corresponding coupling constants and the rather important form factors of the boson-nucleon vertices are partly determined through a comparison with the empirical scattering phases. In the framework of this approximation it was, however, of capital importance to replace all 2-pion (more generally 2-boson) exchange terms which, as we will see, play a rather important role in the middle range part of the potential by the introduction of the unphysical $\sigma$-boson which, in turn, is treated again through the simple ladder approximation. The corresponding mass, coupling constant and form factors are for the moment treated parameters to be fitted to the experimental data. In spite of all these strong simplifications it turned out that this scheme is rather successful: The empirical phase shifts are perfectly reproduced with the help of a relatively limited number of parameters (coupling constants and form factors) which are - as far as they are directly measurable - in reasonable agreement with values obtained from particle physics. A great advantage with respect to the various phenomenological potentials, mentioned above, is a certain unicity and the fact that the parameters to be adapted are very much reduced in number and have to some extent a physical meaning. At the same time, this meson theoretical expression of the nucleon-nucleon potential yields a natural interpretation of the various terms: The long range tail of the potential exchange, the middle range attractive part, which plays a decisive role in nuclear matter, comes from the $\sigma$-boson and the repulsive core is due to the exchange of the vector bosons $\omega$ and $\rho$. In spite of this success it turns out, however, that the insertion of this boson theoretical expression into the approximation schemes for nuclear matter yields nearly the former result with its characteristic disagreement: The density appears to be too high and the binding too large. (These values correspond, in fact, more or less to the results from the phenomenological Reid-potential).

3. Bosonic Variables

In view of this failure it is of decisive importance to observe that the boson theoretical viewpoint leads in a natural way to an understanding of this problem: If our potential is determined from a boson theory, it is clear that the effect of the boson exchange depends - via the Pauli principle - on the surrounding of the nucleons in question. In other words, the interaction between two nucleons embedded into nuclear matter differs in a characteristic way from the one between free nucleons. In order to obtain a handle on this effect, a natural enlargement of the description of nuclear matter is legitimate: The state function has to contain not only the variables of the nucleons but also the occupation number of the various boson states. In other words, the boson variables have to be introduced explicitly. This leads to the problem of treating the following field theoretical Hamiltonian: $H = H_0 + H_1$ where $H_0$ is the Hamiltonian of the $\text{the fF}ee$ (nonrelativistic) boson field (the relativistic bosons (treated both as quantized fields) and $H_1$ describes the interaction between the nucleon and the various boson fields (containing thus all the parameters which are again determined from an adjustment to the scattering problem). It has now been shown by D. Schütte\(^6\) that this Hamiltonian may be used in the framework of a generalized Brueckner theory (though speaking, this amounts to replace within the hole-line expansion the lines which correspond to the potential by the various boson lines and to change the characteristic density dependence. This turns the experimental data automatically to the enlarged state function, mentioned above. In a first step this scheme - including the same bosons as before - is again applied to nuclear matter: In spite of the huge number of parameters, contained in the calculation the old discrepancy remains: The result is again a point on the "Coester-line", i.e. in disagreement with the experimental values. On the other hand, the new state function yields a clear indication about the origin of this problem. The unphysical $\sigma$-boson which so far was still included in this analysis plays by far the most important role within this comprehensive state: The corresponding amplitudes exceed the ones of the other bosons by an enormous factor (comp.Fig.2). One might thus say that nuclear binding is due to a locally dominant exchange of $\sigma$-exchange. This fact strongly suggests to introduce the 2-pion exchange explicitly, i.e. to replace this hypothetical $\sigma$-exchange through the underlying physical processes. In order to do so in a systematic way, it is of great importance to use the bosonic variables explicitly. (The introduction of these additional variables is needed anyhow in a systematic treatment of the so-called meson currents as well and as an explicit representation of the boson condensation).

4. The 2-Boson Exchange

In the framework of this program it is, first of all, of greatest interest to calculate the nucleon-nucleon scattering through this detailed description of the 2-pion exchange\(^6\). ($\text{rt}$ is in this connection of the most importance not to use the well-known method of dispersion theory because it will be seen that this detailed determination leads to the strong and characteristic changes of the binding energies which otherwise would be lost). This program amounts to treat explicitly a large
Fig. 2 Probability distribution $K(p)$ for different mesons of the standard OBE-scheme in nuclear matter as function of the mesonic momentum. $k_F = 1.7 \text{ fm}^{-1}$ is the saturation density obtained with the non-covariant "Bonn potential" without box diagrams which was used for this calculation. From "The mesonic degrees of freedom and nuclear wave function" W. Perchländer, K. Kotthoff and D. Schütte (to be published)

number of diagrams (comp. Fig. 3). First of all, we have to deal with the crossed $\pi - \pi$ and $\pi - \rho$-terms. The main contributions come, however, from the so-called block diagrams in which the nucleon suffers a virtual excitation of the $\Delta$-resonance state. These extremely long calculations indicate that the effect of the unphysical $\omega$ can be, to a large extent, replaced, leading thus to a complete boson theoretical interpretation of nuclear forces $^{77}$. A remaining part which is due to the direct $\pi - \pi$-interaction $^{76}$ has, however, still to be estimated. The results of these consideration suggest, at the same time, a natural interpretation of an im-

portant part of the nuclear interaction: The scattering process of two nucleons is strongly influenced by their polarization, i.e. virtual excitation of a resonance state. (Effects of this kind are well-known in the theory of chemical forces). Within the bound state this excitation might have - via the Pauli-principle - a characteristic effect on the single particle states of conventional shell structure.

5. Nuclear matter from the Bosonic Viewpoint

The decisive problem consists now in the introduction of these 2-boson exchange diagrams in the approximation scheme for nuclear matter $^{78}$. In order to carry through this calculation, it is important to introduce explicitly the bosonic variables. This represents an extremely tedious and lengthy numerical calculation. As to be expected, the results for binding and density differ strongly from those obtained by the simplifying introduction of the $\sigma$-boson. The fact that the Pauli principle acts, so to speak, on the additional nucleon lines in the characteristic 2-pion diagrams (i.e. in all block diagrams with one nucleon line or the diagrams with crossed pion lines) has as a consequence that the binding energy is strongly reduced with respect to the simplified case. This repulsion is much stronger than the values obtained in first estimates, because there is also an essential contribution

Fig. 3 Box diagrams with intermediate nucleons and $\Delta$-isobars. The dotted lines represent the exchanged bosons especially $\tau$- and $\rho$-mesons
from the introduction of bosonic variables. At first sight there is thus a definite lack of binding energy, whereas the density appears to be quite reasonable. On the other hand, these calculations do not contain the higher terms of the hole-line expansion. A rough estimate through the introduction of the so-called "continuous choice" for the energy of the particle states in the Brueckner scheme leads to a definite increase of the binding energy; nevertheless there is still an appreciable amount of binding lacking. A detailed analysis of this situation shows, however, that the boson propagator within nuclear matter has also to be changed with respect to the case of the exchange between free nucleons. In fact, the bosons within nuclear matter experience a characteristic change of their self energy through the typical bubble diagrams introduced also in the theory of boson condensation. It might be foreseen that this effect contributes in an essential way to the binding energy. It is thus realized that the introduction of the 2-boson exchange into the theory of nuclear matter leads to appreciable modifications which might, in eventually, bring the saturation point within the energy density diagram to the right position. On the other hand, the calculations have still to be completed with respect to the boson self-energy and the higher terms in the hole-line expansion.

6. A Solvable Model

In view of the formal complications of the boson theoretical method, it might be worth while to check this approximation scheme with the help of so-called solvable models. This corresponds to the introduction of a simplified field theoretical fermion-boson system which allows a rigorous solution. Applying then a given approximation scheme to this same model, one might expect errors with respect to the exact values can be directly determined. Models of this kind generalizing the well-known Lee-model from field theory were introduced and discussed by D. Schütte and J. da Providencia. In this framework it turned out that the terms changing the boson propagators are definitely needed in order to improve the convergence of the approximation scheme. The same model was also used in order to give an explicit representation of the boson condensation: It is, in fact, seen that a classical boson field is being generated as soon as the critical point has been passed. It is thus realized that the boson theory of nuclear matter leads to a rather extended research which is far from being solved completely. It should be stressed that the main part of nuclear binding is due to the virtual excitation of the nucleons and the characteristic change of the self energy of the bosons. In this respect it must be mentioned that the change of the bosonic self energy of the nucleons embedded into nuclear matter should also be taken into account. The corresponding terms appear, in fact, automatically in our enlarged boson theoretical scheme. (Calculations are under way).

7. Quark Theoretical Viewpoints

Eventually the phenomenological input to this theory should be discussed: The whole scheme is based on the properties of the various boson-nucleon vertices (including the J-resonance). This amounts to assume a reasonably that the quark coupling constants and form factors to be determined for the moment from experimental particle physics and to a large extent from a comparison with the empirical nucleon-nucleon scattering phases. In particular it should be stressed that the numerical values of the various form factors play a rather important role in the numerical results. In view of the enormous success of the quark-gluon structure of nucleons and bosons in the framework of modern particle physics, the question arises whether it might be possible to determine the various parameters of these vertices from this more fundamental viewpoint. Some first attempts of obtaining some coupling constants were already made. The main problem which remains, however, is the fact that present day quark models (so-called bags) lead to form factors which appear too large with respect to the values which were introduced in the boson theory discussed here. We have the impression that the quark models of nucleons need an important refinement and readjusting to the problems of nuclear physics. As the radii of some conventional bags are of the order of the relative distances of nucleons, it was also suggested that the nucleons were to some extent dissolved into their constituents within nuclear matter forming a kind of a quark sea or quark bag. This assumption might correspond in a certain way to the fact that in conventional theory the nucleons are strongly excited and that the bosons change their properties in an essential way. Although it has been checked that this number of coupling constant could also be obtained from these large quark bags, it remains to be shown that a relatively strong clustering into 3-quark subsystems (surrounded by a sea of quark-antiquarks representing the boson cloud of the nucleons) should occur, at least on the surface of the nucleus, in order to understand the characteristic single particle levels of nuclear shell structure. In any case it seems to be clear that present day boson theory represents by no means the final step in our understanding of nuclear forces and nuclear matter but rather an important intermediate step.

References

1) cp. as an example: R.V. Reid, Ann.Phys. 50 (1968) p. 411
schaftsverlag, Mannheim (1980) p. 58
3) B.D. Day, Rev.Mod.Phys. 50 (1978) p.495
N.P. A328 (1979) p. 1 and
Conf.Report Bad Honnef "The Meson Theory of Nuclear Forces and Nuclear Matter"

4) K. Holinde and R. Machleidt, N.P.A247 (1975) p. 495 and
N.P. A256 (1976) p. 479

5) D. Schütte, N.P. A221 (1974) p. 396

6) K. Holinde, R. Machleidt, M.R.Anastasio, A. Fässler and H. Mütter,
P.R. C18 (1978) p. 870

7) X. Bagnoud, K. Holinde and R. Machleidt,
to be published in P.R. C

8) cp. for ex. W. Ferchländer and
D. Schütte, P.R. C22 (1980) p. 2536

9) R. Machleidt and K. Holinde,
N.P. A350 (1980) p. 396 and
H. Mütter, A. Fässler, M.R.Anastasio
K. Holinde and R. Machleidt
P.R. C22 (1980) p. 21

10) J. Jeucken, A. Lejeune and C. Mahaux,
N.P. A245 (1975) p. 411

11) W.M. Alberico, M. Ericson and

12) D. Schütte and J. da Providencia,
N.P.A202 (1977) p.518,
N.P.A338 (1980) p.463 and
B.I. Wissenschaftsverlag
Mannheim (1980) p.287

13) G.E. Brown, M. Rho and V. Vento,
Phys.Lett. 82B (1979) p.177 and
84B (1979) p. 338
I. Duck, Phys.Lett. 77B (1978) p.223

14) A. Chodos, R.L. Jaffe, K. Johnson and
G.B. Thorn, P.R. 10 (1974) p. 2599

15) H.R. Petry, to be published
INTRODUCTION

The study of nuclei far from stability has been a field of nuclear physics for a long time. Progress has been made by developing techniques to study nuclei. The shorter and shorter lifetimes which correspond to greater distances from the stability line. Also, an expansion to greater distances from the line of stability has become possible as new techniques have been developed for producing these exotic nuclei.

The new development in recent years aiding the production of nuclides at greater distances from stability involves the use of heavy ion accelerators. Fragmentation of the heavy ion or deep inelastic scattering produces a very broad range of masses for a given element so that many new isotopes both neutron rich and neutron deficient have been identified in the last few years. The use of high energy protons as projectiles on heavy targets is also used to produce high yields of neutron rich and deficient isotopes by spallation and fission. In some regions essentially all possible nuclides have been produced out to the proton and neutron drip lines. Farther yet from the stability line, the nuclei would be unstable against proton or neutron emission in their ground states, and would be difficult to identify because of their extremely short lifetimes. The drip lines are usually considered to be the limit of possible observation.

There are at least three reasons for interest in studying nuclei far from stability. First, the high decay energy can lead to exotic decay modes which do not occur at all for nuclei nearer to stability. Such modes can thus only be studied for the highly unstable nuclei. Second, it is of interest to find new regions of the N,Z plane with nuclear characteristics familiar from studies nearer stability. One may look for new regions of deformation, new double magic nuclei, new islands of isomers. This will furnish new sample nuclei on which to test theoretical ideas which are also applicable to more stable nuclei. Finally, even without new phenomena or new distinct regions of the N,Z plane, it is useful to extend the region of known nuclear properties away from the stability line so that the full two dimensional N and Z dependence of various nuclear properties is clearly exposed. This is important both for a clear understanding of the long range, smooth liquid drop properties related to the saturation of the nuclear forces and to their symmetry properties; and also for a sure understanding of the individual particle shell structure aspects, which can govern collective effects as well.

If nuclear properties are known only in the neighborhood of the stability line, a substantial change in one of the variables N,Z can only be made by changing the other variable as well. Thus it is difficult to pin down the separate dependence on N and Z of a property which changes relatively slowly with N or Z, unless large N,Z regions are measured.

For example, the liquid drop effects are smooth and slowly varying. Thus accurate masses are needed over a large N,Z area in order to determine accurately such details as a separate volume and surface symmetry energy, effects of a finite surface thickness etc. On the other hand many of the shell effects change rapidly with N and Z. The ground state spin of successive odd mass isotopes may change several times within a range of only five to seven neutrons added. The change from a spherical to deformed shape may take place with the addition of four to six particles. Thus the fermi surface part of the shell structure for neutrons and protons can be determined and tested from relatively local data in the N,Z plane.

SHIFTS OF SINGLE PARTICLE LEVELS

However, there are also expected to be slow shifts of the single particle level order and spacing as N and Z are changed. This is suggested from the fact that the size of magic gaps, the existence of sub shells, and even level orders are not exactly the same for neutrons and protons at the same particle number. To determine the direction and magnitude of these shifts one must either have data on the nuclear levels far from stability, or one must have a theoretical basis for calculating these shifts.

Knowledge of these single particle shifts is crucial for predicting or explaining the properties such as masses, deformations, magic numbers, ground state spins et c. for nuclei far from stability. An accurate extrapolation of the nuclear masses is needed to determine the limits of particle emission stability or the onset of new decay modes. The shell effects are an important part of the nuclear mass so all mass formulas which could be used for extrapolation must have a way of incorporating such effects from the known nuclear masses.

Most of the mass formulas used for extrapolation parameterize the liquid drop contributions and then assume that the magic shell gaps are the same throughout the N,Z plane as those determined from data nearer to stability. While a parameterization of the shell effects in terms of these gaps is appropriate near the stability line, it might be completely misleading if used for extrapolation.

The qualitative features of the sequence and spacing of the spherical single particle levels depend on the radial shape of the nucleus and thus on the saturation characteristics of the nucleon-nucleon interaction rather than on the details of the force. The exception to this is the one-body spin orbit splitting which does depend on specific components of the force.

However, the determination of the shifts of these spherical proton and neutron single particle levels as a function of N and Z does require a more detailed model for the interaction. An average over the orbits is not useful in this case and the interactions between particles in specific orbits must be correctly given by the force in order to obtain agreement between calculation and experiment.

SPHERICAL HFB

In this paper we shall use the Brueckner G matrix appropriate for medium weight nuclei derived from the Reid soft-core nucleon-nucleon potential. The G matrix is derived by summing the Brueckner-Bethe-Goldstone ladder series suitable to the core of N=40 nucleons (50 particles) and a valence nucleon-nucleon interaction rather than on the details of the force. The exception to this is the one-body spin orbit splitting which does depend on specific components of the force.

However, the determination of the shifts of these spherical proton and neutron single particle levels as a function of N and Z does require a more detailed model for the interaction. An average over the orbits is not useful in this case and the interactions between particles in specific orbits must be correctly given by the force in order to obtain agreement between calculation and experiment.
calculation in the valence space, and contains no free parameters. 2

The inert core of 40 neutrons and protons will contribute to the one-body force. This is taken into account in terms of single particle energies $e_i$ in the valence space due to the core. The Hamiltonian is thus:

$$H = \sum_i e_i c_i^\dagger c_i + 4^{-1}\sum_{ij} [v_{ij} d_i^\dagger d_j + c_i^\dagger c_i c_j^\dagger c_j]$$

(1)

where $v_{ij}$ is the antisymmetrized effective interaction. The energies $e_i$ are a single set of free parameters chosen once and for all to give reasonable results in the Pb and Sn regions.

Some of the nuclei in the valence region will be spherical and some deformed. But to make a uniform description over the whole region we present only spherical Hartree Fock Bogolyubov (HFB) calculations. Our purpose in this exercise is to show how the spherical single particle energies due both to the inert core and to the filling valence levels shift with N and Z over the whole region of medium to heavy nuclei including nuclei far from the line of stability. Of particular interest is the possibility of changes in the major energy gaps between levels and thus in magic numbers, which in turn can have strong effects on nuclear masses and all other nuclear properties as well.

The HFB equations may be written

$$\begin{pmatrix}
H - \lambda & \Delta \\
-\Delta^* & -\lambda
\end{pmatrix}
\begin{pmatrix}
u \\
v^*
\end{pmatrix} =
\begin{pmatrix}
u_E \\
v^*_E
\end{pmatrix}$$

(2)

With no radial mixing and with spherical symmetry, both the HFB potential and the pair potential are diagonal in the $|njm\ell>$ basis where $\ell$ means proton or neutron. The energies plotted are the HFB energies, $H = \epsilon_j$, where

$$\epsilon_j = \epsilon_j^t + (2\ell+1)^{-1}L_j^T L_j^t, V^2$$

$$L_j = \frac{\sqrt{2}}{2} \frac{(2\ell+1)^{-1/2}}{\sqrt{2\ell+1} \sqrt{\ell+1}}^{1/2}$$

(3)

$$\epsilon_j^t = \frac{\sqrt{2}}{2} \frac{(2\ell+1)^{-1/2}}{\sqrt{2\ell+1} \sqrt{\ell+1}}^{1/2}$$

(4)

The same G matrix elements $v_{ij}$ are used in calculating $\epsilon$ and $\Delta$ of the HFB equations, so the only parameters of the calculation are the core energies $\epsilon$ which are held fixed for all the nuclei. The Fermi energy parameters $\lambda_0$ and $\lambda_N$ are chosen to set the expectation values for Z and N to the desired values. 

RESULTS

Figures 1-6 show the neutron and proton spherical single particle levels $\epsilon_i$ relative to the Fermi energy $\lambda$ for a large number of nuclei. Since the plotted quantity is $\epsilon_i - \lambda$, the zero on the energy scale is really the Fermi energy. Levels below zero are less than half full while those above are more than half full. In some cases, where the gap is particularly large between the lowest levels above and below zero, the gap parameters will vanish, there will be no pairing, and the levels below will be full and those above empty. Such is the case for a magic or semi-magic nucleus.

It is clear from the figures that the spacing sequence of levels changes from nucleus to nucleus, in some cases enough to shift completely the location of magic numbers.

Proton levels for N=90

The dependence of the proton levels on N is striking for the heavy nuclei, as seen in Fig. 1, showing the 96Ru nuclei. For Z = 86 the protons are filling the $h_9/2$ level just above the lead magic gap at Z = 82. But notice that while the gap is large at N = 134 it gets much smaller with decreasing N and essentially vanishes at N = 114. For the very light Rn nuclei far from stability, the gap is above the $h_9/2$ level rather than below and the magic number has shifted from Z = 82 to Z = 92.

The cause of this change of magic number is that as N increases from 134 to 134 the low spin $s, p, d,$ and f proton levels drop in energy relative to the higher spin $g, h$ and $i$ proton levels. The magnitude of this relative shift is between two and one MeV for the N=110 and 126, or a shift of about 200 keV per neutron added.

Fig. 2 shows the Pt levels as a function of N. In is seen from this figure that there is a sharp reversal of the trend of the proton levels below N=112 and that the gap, which is a good magic number for N=112, returns and is also a good magic number for N=104. For 90<N<114 the high spin $g$ and $h$ and i levels drop in energy by 1.5 to 2.5 MeV relative to the low spin $s, p$, and d proton levels, with increasing neutron number, a relative shift of about 100 keV per neutron added.

Similar results occur for Pb. This disappearance of the Z = 82 gap in the region of N = 114 and reappearance at still smaller N values has clearly observable consequences and is a real effect. 2, 3

For example, for the 171Fm nuclei the 9/2- level appears below 500 keV in the spectrum for N = 104 to N = 114. The level is lowest for N = 110 rather than for N = 114 as in the calculation, but the rising trend toward a magic Z = 82 for either increasing or decreasing N values is just as in the calculation. The 9/2- also appears as a low level in several 79Au nuclei in this same neutron region.

Another consequence of these shifts seen also from Fig. 3 of the Yb isotopes is that the disappearance of the Z = 82 magic number at N = 114 is associated with a nearly magic gap at Z = 76 for these same neutron numbers. While the 76Os nuclei do not look semi-magic, the isotope 769190,192 are not very deformed having the first 2+ state at 200 keV, a suggestion of a small gap at Z = 76. The gap at Z = 76 is large enough to inhibit the pairing correlation, and the Z pairing parameters $\lambda_0$ for Os are still quite large.

Proton levels for N=90

From Fig. 3 on Yb and Fig. 4 on the Sm isotopes it is seen that the direction of the proton level shifts with N changes once again; for N = 72 to N = 90 the low spin proton levels s, p, d move down relative to the high spin levels g, h, i. The relative shift is large, about 5 MeV with a change of 18 neutrons or 350 keV per added neutron. Figs. 5 and 6 on the 54Xe and 46Pd isotopes show a less simple picture. As N goes from 50 to 70 there is a drop in the s, d, and h proton levels relative to the p, e, and i levels by about 2 MeV or 100 keV per added neutron.

These shifts do not lead to any new magic numbers and, for example, Z = 50 is predicted to be a good magic number for all N values. The relative shifts predicted for the proton 9/2- and 7/2+ levels in this region are, however, clearly seen in the 54Xe data. For these nuclei the calculated 3/2- level is above both 5/2- and 3/2+ with the 5/2+ lowest for the light nuclei and the 7/2+ lowest for heavy ones in agreement with the experimental trend.
Figure 1. Proton and Neutron Single Particle Energies for Rn isotopes as a Function of N.

Figure 2. Proton and Neutron Single Particle Energies for Pt isotopes as a Function of N.
Figure 3. Proton and Neutron Single Particle Energies for Yb Isotopes as a Function of N.

Figure 4. Proton and Neutron Single Particle Energies for Sm Isotopes as a Function of N.
Explanation of the proton level shifts with N

The origin of the pattern of shifts discussed so far is remarkably simple. In each neutron region discussed, the proton levels falling with increasing N are those which are similar (high or low orbital angular momentum k) to the levels being filled with the neutrons as shown in Table 1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Falling P Levels</th>
<th>Filling N Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>N &gt; 114</td>
<td>s,p,d,f</td>
<td>P_{1/2}^{1/2},P_{3/2}^{1/2},P_{5/2}^{1/2}</td>
</tr>
<tr>
<td>90 &lt; N &lt; 114</td>
<td>g,h,i</td>
<td>f_{7/2}^{1/2},h_{9/2}^{1/2},i_{13/2}^{1/2}</td>
</tr>
<tr>
<td>72 &lt; N &lt; 90</td>
<td>s,p,d,f</td>
<td>g_{9/2}^{1/2},f_{25/2}^{1/2},f_{27/2}^{1/2}</td>
</tr>
<tr>
<td>N &lt; 72</td>
<td>s,d,h</td>
<td>s_{1/2}^{1/2},h_{11/2}^{1/2}</td>
</tr>
</tbody>
</table>

The filling neutron levels can be determined from the position of the Fermi level on the neutron level plots. In each region the falling proton levels are of the same nature as the filling neutron levels. If the neutrons are filling large k levels, the high k proton levels will drop. It need not be exactly the same k values; for example, for N>114 p and f low spin levels are filling causing low spin proton levels including s_{1/2} to fall.

The shifts of levels are large with many level crossings. However, in some regions the high spin levels go up and low spins go down. In other regions it is the reverse. The effect over the very long range of the isotope chart is that the general level order and spacing of the proton levels at low N is not so different from that at high N.

Neutron levels as a function of N

The shifts of neutron single particle levels with N is much the same as that of the proton levels. For N>114, as seen in Figs. 1 and 2, the low spin s,p,d levels go down relative to the high spin g, h, and i levels with increasing N. The effect is not so large and corresponds to a relative shift of about 100 keV per added neutron. The main effect on magic numbers is the development of an energy gap above the i_{13/2} level which corresponds to a nearly magic number at N = 114. This gap is present for Pt and Os nuclei, but only for N values close to N = 114. It is large enough that for these nuclei the neutron pairing parameters \( \Delta \) almost vanish for N = 114. This is consistent with the relatively small deformations observed for the corresponding Os, Pt, and Hg nuclei, but the calculated gap probably exaggerates the actual effect.

From Figs. 2 and 3 it can be seen that for 90<N<114 the high spin g, h, and i levels fall relative to the s, p, d, and f levels with increasing N, by about 100 keV per added neutron. One effect of these shifts is that the large N = 82 magic gap maintains its existence up to about N = 106, but for larger N values it becomes much smaller.

For 72<N<90 the low spin s,p,d,f levels fall significantly relative to the g, h, and i levels with increasing N, by about 150 keV per added neutron. Figs. 5, 4, and 5 show that the calculation suggests that N = 76 should develop as a magic number. This does not appear to be the case, N = 82 being the only strong magic number for these N values. A calculation with the core neutron h_{11/2} level raised by an MeV or so would probably fix it up, but no attempt was made to optimize the fit to all data.

For N<72 no clear pattern is seen for the level shifts in Figs. 5 and 6. The figures do suggest that in addition to the magic number N = 50, N = 56 might be a sub shell closing for Xe88. There is a little evidence for this effect from the even Mo isotopes since the energy of the 2^+ level in 42Mo^{98} is a little higher than those of either 96Mo or 100Mo suggesting a very weak subshell effect there.

A recent paper by Tondeur^4 shows that this subshell at N = 56 becomes an important effect for lighter nuclei with 32<Z<40.

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Figure 5. Proton and Neutron Single Particle Energies for Xe Isotopes as a Function of \( \kappa \).
Figure 6. Proton and Neutron Single Particle Energies for Pd Isotopes as a Function of N.

Table 2. P and N Level Shifts

<table>
<thead>
<tr>
<th>Region</th>
<th>Falling P and N Levels</th>
<th>Filling P Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z &gt; 82</td>
<td>h,i</td>
<td>h_{9/2}</td>
</tr>
<tr>
<td>70 &lt; Z &lt; 82</td>
<td>s,p,d,f</td>
<td>s_{1/2},d_{3/2}</td>
</tr>
<tr>
<td>60 &lt; Z &lt; 70</td>
<td>g,h,i</td>
<td>g_{9/2},h_{11/2}</td>
</tr>
<tr>
<td>N = 84 all Z</td>
<td>no shifts</td>
<td>s_{7/2},d_{5/2},h_{11/2}</td>
</tr>
<tr>
<td>N &lt; 82 all Z</td>
<td>g,h,i</td>
<td>s_{7/2},d_{5/2},h_{11/2}</td>
</tr>
</tbody>
</table>

The pattern is clearly the same as before. As protons are added, the binding increases particularly for the P or N orbits which are similar to the filling levels. The magnitudes of the shifts also follow the same pattern. The N level shifts are at rates from 150 to 250 keV per added proton while the P level shifts are from 100 to 200 keV per added proton. Once again the unlike particle NP force is stronger than the like particle PP force.

One change of subshell closures is clearly seen as Z changes. The neutron subshell at N = 64, seen in the Sn region of Fig. 5 due to the near degeneracy of the d_{5/2} and g_{7/2} levels, disappears for Z less than 46. For the smaller Z values of Fig. 6 the subshell closure is at N = 56 as noted earlier. There is good evidence for both of these subshells in their respective regions. The effect is shown in Fig. 7 which shows the levels of N = 68 nuclei as a function of Z.

- 503 -
Figure 7. Proton and Neutron Single Particle Energies for the N = 68 Isotones as a Function of Z.

Shifts of the spin orbit splitting

The mass dependence of the spin-orbit splitting has been discussed by Goodman and Borysowicz. The change in spin-orbit splitting is much less than the relative shifts of orbits with different orbital angular momentum. In other words, the two-body force has a relatively weak spin dependence in its one-body effects. For example, from Fig. 2 we see a relative shift of 3 MeV between the h_{9/2} and d_{5/2} proton levels as N goes from 96 to 114. In this same range the h_{9/2} - h_{11/2} proton spin orbit splitting decreases by only a little over 1 MeV and the d_{5/2} - d_{5/2} splitting is nearly constant. Likewise in the Sn region of Fig. 4, while the high l - low l relative shifts of proton levels are 4 to 5 MeV over the N range plotted, the h and d spin orbit splittings shift by only a small fraction of an MeV.

EFFECT OF SUBSHELL SHIFTS ON MASS FORMULAS

The resulting locations for major magic numbers and subshell closures is shown on Fig. 8. Such a diagram contains less information on shell closures than Figs. 1 - 6 since it cannot show the N dependence of a gap in the N levels, for example. It does, however, show the major magic numbers and subshells as they are seen at the fermi surface.

Most of the mass formulas in use today for purposes of interpolation and extrapolation from the measured masses use a liquid drop formula with a few parameters and a shell correction with more parameters in each region between the assumed magic numbers. Altogether there are many shell correction parameters since there are many regions each of which is treated separately. Typical mass formulas of this type are those of Myers and Swiatecki and Zeldes, et al.
The quartet mass formula

A new and very interesting mass formula is being discussed by Michael Danos. In this formula a new treatment is made of the symmetry energy and the odd-even mass difference term in the liquid drop formula. The usual Weissacker forms are

\[ \text{Sym} = aT^2/A \]  \hspace{1cm} (5)  
\[ \text{odd-even} = b\delta A^{1/2} \]  \hspace{1cm} (6)

where \( T = |N - Z| \) and \( \delta \) is ±1 or 0 when the nucleus is odd-odd, even-even, or odd mass, respectively, and \( a, b \) are two independent parameters. Danos' formula which is based on quartetting and the group SU(4) is

\[ \text{Sym} = aT(T + 4)/A^{1.5} \]  \hspace{1cm} (7)  
\[ \text{odd-even} = a d/A^n \]  \hspace{1cm} (8)

where \( d \) is 0, 3/2, 3 for even-even, odd mass, odd-odd nuclei for \( T \neq 0 \) and \( d \) is 0, 5 for even-even, and odd-odd nuclei for \( T = 0 \). The \( a \) and \( n \) coefficients are common for the two terms. The least square fit gives rather consistent results in the different regions with \( a = 27 \) and \( n = 0.79 \).

Danos argues that the good fit he gets - as good or better than the usual Weissacker results - is strong evidence that the odd-even so called pairing term is really due very little to pairing, but due more to the quartet structure. A weak point of the argument is the fact that the specific form of the symmetry energy term, \( T(T + 4) \) as compared to \( T^2 \), cannot really be proved from the fit because it is completely obscured by the shell correction terms which, of course, must also be included to obtain the good quality fit.

The shell correction terms in each region between the assumed magic numbers are taken as linear and quadratic terms in \( N \) and \( Z \) plus a constant, five adjustable coefficients in each region. Extrapolation of the masses to determine the limits of particle stability is cependent on the validity of the shell corrections. It is clear that subshells like those of Fig. 8 have real physical effects in the regions of known nuclei. For reliable extrapolation, the disappearance of some magic numbers and the appearance of others at greater distance from the region of stability must be properly taken into account. Without this more careful treatment of shell effects any long-range extrapolation must be suspect.

There is no simple solution to this problem. Something like the self-consistent calculation reported here is necessary to obtain the qualitative shifts of level orderings and spacings needed to get the changing magic numbers. To get the required few hundred keV accuracy needed to fit masses, some additional least squares fit of the two-body force parameters to the many-body data would clearly be required.

Figure 8. Chart of Magic and Quasi-Magic Numbers for \( N \) and \( Z \).
The mass formula of Garvey, et al.

The only widely used mass formula which avoids the problem of determining magic numbers is that of Garvey, et al. This formula is based on an observed pattern in the mass data. A certain sum and difference of six neighboring masses is seen to vanish with moderately good precision. This suggests that all the masses may be well described by the formula

\[ M(n, Z) = g_1(n) + g_2(Z) + g_3(n + Z) \]  \hspace{1cm} (9)

where the three sets of parameters \( g_1, g_2, \) and \( g_3 \) are chosen by a least squares fit to the data. The number of fitting parameters is thus equal to the number of \( N \) values plus the number of \( Z \) values plus the number of \( N + Z \) values contained in the region of the fit. The fit made ten years ago to 1272 nuclides had 477 parameters -- 145 \( N \) values, 94 \( Z \) values, and 238 \( N + Z \) values.

The authors argue that this mass formula is consistent in some way with the interacting shell model picture. However, we have shown that Eq. (9) is inconsistent with the long range behavior of the mass dependence on \( N \) and \( Z \) expected from the symmetry and coulomb terms of the liquid drop formula. Also, the pairing of Eq. (6) or the quartetting of Eqs. (7) and (8) cannot be satisfied by the Garvey form of Eq. (9). The discrepancy between quartetting and Eq. (9) is particularly large at the \( N = Z \) line and makes extrapolation across the \( N = Z \) line with Eq. (9) useless, as recognized by Garvey, et al.

Our suggestion for avoiding this difficulty was to apply a liquid drop formula with its parameters, and then to use the Garvey formula to fit the remaining shell discrepancies. A method was described for doing this without repeating the lengthy least squares fit made by Garvey, et al., and results were presented as in Fig. 9 showing corrections to be made to Garvey's masses to recover the long range \( N, Z \) behavior corresponding to the liquid drop equation of Seeger. The result is a reduction of the mass by about 8 MeV at the neutron drip line from that predicted by the Garvey formula, thus suggesting increased stability for these nuclei. The effects are smaller on the proton excess side.

The formula of Eq. (9) is a natural form for shell effects if they arise from stable magic numbers in \( N \) and \( Z \) since such effects would be incorporated into \( g_1 \) and \( g_2 \). But if, for example, a \( Z \) magic number depends on the value of \( N \), such an effect could only be accommodated by \( g_3 \) which implies a specific relation between changed magic \( Z \)’s and changed magic \( N \)’s. We have seen that these effects can be described in terms of attractions between particles in similar (high spin or low spin) levels. The like particle attractions can be accommodated by \( g_1 \) and \( g_2 \), but there is a problem with the \( NP \) pairs.

If the \( NP \) force were the same between all pairs of levels so that the effect on the mass was proportional to the number of \( NP \) pairs the Garvey formula would work, since

\[ \text{No. of Pairs} = N Z = 1/2(N + Z)^2 - N^2 - Z^2 \]  \hspace{1cm} (10)

showing the specific separation into \( g_1, g_2, \) and \( g_3 \). However, we have demonstrated that there are large differences in the \( NP \) attraction depending on the specific pairs of levels involved. It is easy to show in that case that the form of Eq. (9) cannot be correct even for describing the one-body part of the shell effects with its shifting magic numbers as described earlier in this paper. Thus Eq. (9) is incorrect in reflecting the long-range \( N \) and \( Z \) dependence both of the liquid drop and shell effects.

Since Eq. (9) contains many parameters and is fit in a rather uniform way from all the data, it remains a good fit to the masses and is probably good for interpolation and short-range extrapolation, but it should not be trusted for longer range extrapolations.

**FINAL COMMENTS**

In this study of medium to heavy nuclei, we have shown the shifts of the spherical single particle levels. Not all these nuclei are spherical, but the spherical levels may be used as the basis for a self consistent calculation to determine which should be deformed. In particular, those with \( N \) or \( Z \) near a magic or semi-magic number are expected to be spherical, or less deformed, while those with a large level density near the fermi surface will be more deformed.

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**Figure 9.** The Quantity \( \delta M \) to be Added to the Garvey Mass Table of Ref. (9) to Produce the Long Range Liquid Drop Behavior of Ref. (11).
Not only masses and deformations, but also other nuclear properties as well are dependent on the single particle levels. This includes not only the low lying levels of odd mass nuclei, which are a direct reflection of those levels, but also the collective level spacing and transition rates, the structure of giant resonances, the beta decay strength function, etc.

Any microscopic calculation must either start with an assumed set of levels or calculate them. The classical procedure for shell model calculations is to use actual nuclear levels for $N = 1$ and $Z = 1$ nuclei (for $N$ and $Z$ magic) to define the single particle levels, which are then used in the calculation. This method is useful for nuclei far from the original magic numbers only if effects causing the level shifts, as discussed above, are properly taken into account.

One of the methods widely discussed in recent years for calculating nuclear spectra is the Interacting Boson Approximation (IBA) of Arima and Iachello. This method is based on the existence of magic numbers and the finite number of particles which will fill the levels between two adjacent magic numbers. Pairs of these particles are described as a boson. There are two types of these bosons, the $s$ boson of spin zero and the $d$ boson of spin two. The total number of bosons in a particular nucleus is fixed and equal to the number of pairs of protons or neutrons away from the magic number. In the IBA the behavior of the level structure with $N$ and $Z$ depends first on this charge in number of bosons, and also the boson interaction is assumed to depend on $N$ and $Z$. The IBA is useful for a systematic study from nucleus to nucleus because the boson interaction is found empirically to depend on $N$ and $Z$ in a rather regular way as the number of particles changes over a major shell.

It should be clear from this discussion, however, that the IBA is probably not going to be useful for extrapolation away from the known nuclei toward the limits of particle stability. Even if the magic numbers, and thus the numbers of bosons in the theory, do not change over the range of the extrapolation, the subshell effects will change enough to make very uncertain the reliability of the assumed $N, Z$ dependence of the boson interaction. This criticism applies not only to IBA, but to any microscopic nuclear calculation in which the single particle level shifts are not properly taken into account.

The theorist can do a good job calculating the properties of a nucleus based on the measured characteristics of its neighbors, but with relative single particle level shifts of 200 - 300 keV per added nucleon, it is clear that long-range extrapolations are not to be trusted.

REFERENCES


DISCUSSION

N. Zeldes: In your transparency showing the proton levels of Rn there is no maximum of the gap at $Z = 82$ when $N = 126$. Thus in this case the experimental mutual support of magicities is not reproduced by the calculation. Could this be due to a neglect to consider the neutron-proton interaction beyond the H.F. approximation, as is done for identical nucleon by addition pairing in H.F.B.?

R.A. Sorensen: The "mutual support of magicities" almost works in our calculation. In Fig. 1 the $Z = 82$ gap grows rapidly as $N$ increases from 114 to 126. For $N > 126$ it grows more slowly. In fact it would actually get smaller again, as it should, if the proton $1f_7/2$ level had been taken about 1 MeV higher in energy. Such a choice would also improve the proton levels for lighter nuclei, for example making $Z = 64$ a better sub-shell, in agreement with experiment, and improving the double magic $^{132}$Sn spectrum.

N. Zeldes: Gillet et al. consider only nuclei beyond the $2f_5/2$ shell. When lighter shell regions with nuclei on both sides of the $Z = N$ line are considered, the $T(4+)$ description is definitely superior to $T^2$.

R.A. Sorensen: I agree with the comment.

J.R. Nix: At least some of the effects that you discuss are included in many mass formulas, where the single-particle levels are calculated for nuclei in different regions of the periodic table with appropriate single-particle potentials.

R.A. Sorensen: This is true only if the potential parameters are fit to data at several points in the $Z,N$ plane including points far from stability as well as points near the stability line. In particular, the disappearance of a magic number could not be "predicted", but only "observed". It seems unlikely to me that extrapolations away from the known region could be reliable.

F. Tondeur: Results of self-consistent Skyrme-type calculations and Woods-Saxon potential for the variations of the shell effects from stability show more common features with your results, but also striking differences. Your figure about the proton levels in Rn shows, for example, a lowering of low-spin levels (compared to high-spin levels) when the neutron number is increased, whereas the reverse effect is obtained (due to the increase of the radius) in HF or WS results. This could be due to the differences of the model for a) the mean field, b) pairing. Could you give your opinion about this point, and about the possibility of studying this problem with Skyrme-type HF models?
R.A. Sorensen: As neutrons are added in low-spin levels, the low-spin proton levels fall relative to high-spin proton levels. As neutrons are added in high-spin levels, the high-spin proton levels fall relative to the low-spin proton levels. In either case the radius is increasing. Thus it is not just a radius effect, but must depend on the detailed radial shape of the self-consistent one-body potential for the protons. I would imagine that any two-body force which is primarily short range and attractive would behave this way.

E. Hylf: We have studied [Int. Workshop on Gross Properties and Nuclear Excitations III (1975)] the smoother trends of the single-particle levels close to the Fermi surface as a function of N and Z, using the Woods-Saxon potentials, generated from the Droplet-model density distributions. As a result, the gaps, for example, of the protons of a magic proton nucleus do depend smoothly on N, in the way that the gap closes with n-excess if the p-gap bordering proton levels differ in angular momentum, in that the level above the gap has the higher \( \Delta E \sim \alpha \Delta k + \beta (N - Z/A) \) with \( \alpha = 1 \) and \( \beta = 2 \). Neither our study nor any other I know of, does explain however the strong exp. observed mutual support of magicities. For this the residual interactions have to be taken into account beyond the HFB scheme.

R.A. Sorensen: Our results in the HFB approximation (with no additional correlations) will tend to show this "mutual support of magicity" if each magic gap has the same general arrangement of high and low spin levels above and below the gap. For example, at \( Z = N = N \) approaching magic from below, the neutrons will be filling levels which will draw down the \( Z \) levels below the gap, increasing the \( Z \) gap size. As more neutrons are added above the \( N \) magic number, the \( Z \) levels above the gap will be pulled down reducing the \( Z \) gap again.

K. Bleuler: Did you compare the calculated single-particle levels to experimental data? A similar but simplified calculation we worked out several years ago was relatively successful in this respect.

R.A. Sorensen: We have not compared to the data in great detail, but for the major shifts of levels, new subshells, or disappearance of magic numbers, we have looked at the data to see if the calculated effects are real. Comments on specific cases appear in the paper.

W.J. Swiatecki: I was fascinated by your finding that low/high angular momentum proton states tend to pull down low/high angular momentum neutron states and vice versa. I guess this must be another manifestation of the "matching energy" (the extra interaction between particles in identical or similar orbits) that seems to be responsible for the "Wigner term" in the nuclear mass formula (see W.D. Myers, Droplet Model of Atomic Masses®, Plenum, New York, 1977).
ON THE INTERPLAY BETWEEN ROTATION, DEFORMATION AND PAIRING

Ragnar Bengtsson, Ingemar Ragnarsson
Department of Mathematical Physics, Lund Institute of Technology, Box 725, S-220 07 Lund 7, Sweden.

Jing-ye Zhang*
Niels-Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

and

Sven Åberg**
NORDITA, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Abstract

The influence of angular momentum on the extension of deformed regions is studied. Techniques based on the similarity between pairing rotational bands and ordinary rotational bands are used. Indications for an increase of deformation with increasing spin is obtained for rare-earth nuclei with neutron numbers N = 88–90. The yrast states of odd and even nuclei and of positive and negative parity are compared on an absolute scale. It is found that, in the rare-earth region, the odd-even energy difference has almost disappeared for I ≥ 14. However, by considering both positive- and negative-parity yrast states, it is concluded that a substantial pairing gap exists also at higher spins.

1. Introduction

In the study of nuclei far from stability, different regions of deformation have attached a great interest. However, these investigations have mainly been limited to the ground state or the low-spin states. Recently, it has been possible to follow a large number of nuclei up to quite high-spin states, I = 20–30 or even higher. In the words of Bohr and Mottelson\(^1\), this opens a new dimension in our study of nuclei and it becomes possible to map out the regions of deformation, not only as functions of neutron and proton number but also as functions of angular momentum. Recent theoretical studies suggest that at very high angular momenta, almost all nuclei become strongly deformed. This is simply a consequence of the centrifugal forces as was first quantitatively accounted for in ref. \(^1\). In the present study, we will consider lower spins where the macroscopic centrifugal forces are of minor importance. For such spins, say I = 10–30 for nuclei with \(A \approx 150\), it is mainly single-particle effects which are important. Our studies are thus strongly related to the change of the shell effects with angular momentum. Are there any new structures which can be observed at these angular momenta? Another question is what happens to the pairing energies with increasing spin. At which spin do the pairing correlations disappear\(^1\)? Is it possible to observe any odd-even mass difference also at high spin?

Let us start by a more qualitative discussion in an attempt to clarify and relate some of the methods we will use (see also ref. \(^1\)). In the rare-earth region, pairing is of great importance and in analogy with the quadrupole degree of freedom, one may say that the rare-earth region is well-deformed with respect to pairing. One then also talks about pairing-rotational bands (rotational bands in gauge space). Such a band is essentially the energy of a series of isotopes or isotones as illustrated schematically in fig. 1. For

![Diagram](image)

Neutron number

Fig. 1. Schematic illustration of pairing-rotational bands for spherical and deformed shape. With typical energy spacings, the deformed region appears to become larger with increasing spin. The inset shows that the shape transition is expected to manifest itself as a back-bend in an \(N\) vs. \(\lambda\) diagram. The Fermi energy \(\lambda\) is obtained as \(\lambda = \frac{3N}{\pi^2}\).

For a pairing-rotational band, the energy \(E\) varies as \(N^2\), \(N\) being the number of particles, in a similar way as the variation with \(I^2\) for an ordinary rotational band. When the pairing correlations are strong, the local fluctuations are smeared out and the Fermi energy \(\lambda\) is proportional to \(N\). Furthermore, \(\lambda\) is defined as \(\lambda = \frac{3N}{\pi^2}\). Thus, \(\frac{3N}{\pi^2} = N\) which leads to \(E = N^2\) as stated above. The particle number \(N\) can be referred to as angular momentum in gauge space. The Fermi energy \(\lambda\) then corresponds to the rotational frequency in ordinary space, \(\omega\). The analogy can be put on a mathematically firm basis (see e.g. refs. \(^{5\text{th}}\)) and has consequences for example on two-particle transfer which have been experimentally tested.

In fig. 1 is illustrated schematically how one pairing-rotational band is formed for spherical shape and another for deformed shape. If the transition was as sudden as

* On leave of absence from Modern Physics Institute, Lanchow, China.
** On leave of absence from Department of Mathematical Physics, Lund.
shown in the figure, it would lead to an abrupt change in the derivative $\frac{dE}{dN} = \lambda$. In a plot of $N$ vs. $\lambda$, this would show up as a very pronounced back-bend at the critical particle number, $N_C$, where the transition occurs (see fig. 1, inset). The analogy to conventional back-bending plots, which can for example be drawn as $I=I(\omega)$, is obvious. It should also be mentioned that plots of $\lambda$ as a function of $N$ are often used to identify ground-state shapes by transitions. However, $\lambda$ or rather $2\lambda$ is then generally referred to as the two-particle separation energy.

Pairing-rotational bands can also be drawn for non-zero angular momenta. In the spherical region, the low-angular momentum states are generally obtained from vibrational excitations of the nucleus. These are approximately equally spaced in energy with a typical spacing of 600 keV in the rare-earth region. In the well-deformed region, rotational motion takes over and the excitation energies follow the $A(\hbar^2 I)$ systematics with $A \approx 15$ keV. This means that for the excited pairing-rotational bands in fig. 1 a gradual decrease of $N_C$ with increasing spin is observed. From these oversimplified but general arguments one may expect an increase of the deformed regions with increasing spin. In practice, this may be seen for a transitional nucleus, being mainly vibrational at low spins and becoming more rotational at higher spins.

In sect. 2, we study the experimental shell energy vs. neutron number in realistic cases using plots similar to fig. 1. However, the evaluation of the shell energy requires that a macroscopic liquid-drop energy is subtracted and thus involves some arbitrariness. The model-independent method of the inset in fig. 1 is therefore employed as an alternative in sect. 3. This method furthermore has the advantage to magnify the irregularities at a shape transition. The results obtained in sects. 2 and 3 may be put together in diagrams showing the different systematics defined by shape, particle alignment etc., which nuclei undergo with varying particle number and spin (sect. 4). In sect. 5 we concentrate on the single-particle excitations. The quasi-particle energies in the rotating frame are studied both as functions of rotational frequency in ordinary space ($\omega$) and in gauge space ($\lambda$). One important purpose of these single-particle studies is to find out what the observed spectra could tell about the disappearance of pairing at high spin. In this connection we also study the odd-even mass-difference as a function of spin.

Shell energies from experimental masses and excitation energies

For the Dy-nuclei, both masses and spectra up to high spins are known for a long chain of nuclei down to the very neutron deficient ones. Furthermore, the lightest isotopes with $N$ around 82 are clearly spherical, those with $N = 88-90$ are transitional and the heaviest ones with $N = 98-100$ are strongly deformed. In fig. 2 we plot the energy in a similar way as in fig. 1. However, to make the variation anticipated in fig. 1 visible, the liquid-drop energy for spherical shape has been subtracted leaving what is generally referred to as the experimental shell correction. The yrst-spectra up to the maximum spin of 38 are then also plotted on top of the experimental shell corrections. For the liquid-drop energy, we have used the recent formula of Möller and Nilsson' which seems to describe the nuclei far from stability with a high accuracy. However, other formula would lead to the same general appearance of the figure which thus can be considered as arising primarily from experimental data.

The curve for the ground state in fig. 2 is well-known. For $N = 82$, the nucleus is spherical with a negative shell energy. With increasing neutron number away from $N = 82$, the shell energy then increases and becomes positive. If the nuclei had stayed spherical, the shell energy would increase to a maximum somewhere in the middle between the magic numbers $N = 116$ and $N = 126$ and then decrease to a new minimum at $N = 126$. However, long before this maximum is reached, it becomes more favourable for the nuclei to go deformed; a band-crossing in the language of fig. 1. The shell energy then either stays out or generally even begins to decrease because of shell effects for the deformed shape. For the Dy-isotopes, the maximum in the spin-zero curve is observed at $N = 90$ which is thus the transition point from spherical to deformed shape.

The way we plot the yrst bands in fig. 2 makes it possible to see, in a similar way as for the ground state, the transition point from spherical to deformed shape also for the higher spin states. One observes that with increasing spin, the maximum moves towards a smaller neutron number. Thus, for $^{122}$Dy, the low-spin states are expected to be of vibrational type but a transition to rotational motion appears to occur somewhere around $I = 6$. As was discussed in the introduction (see fig. 1) the enlargement of the deformed region is easy to understand from the lower excitation energies in the rotational than in the vibrational bands. It is, however, only up to spins 10-14 expected. Higher spins are for all nuclei formed from configurations involving p-h excitations in which case no systematic difference between spherical and deformed nuclei is expected. This is also what comes out from the Dy-isotopes where for spins between 10 and 20 the maximum stays between $N = 87$ and 88. The small fluctuations are mainly due to irregular structure of the yrst spectrum of $^{152}$Dy which is known to be built from p-h excitations. Let us also mention that at somewhat higher spins we expect another enlargement of the deformed regions. The mechanism behind is, however, different and can be understood from the classical centrifugal forces as mentioned in the introduction.

The overall impression from fig. 2 is that the general structure is very stable with increasing spin. Thus for spins up to at least 20 the shell effects appear to be very similar to those of the ground state. Away from the critical neutron number $N_C$, the transition from the ground to the S-band
Fig. 2. The yrast levels for $I=0-18$ of $^{66}$Dy plotted relative to the liquid-drop energy for spherical shape. The experimental masses are taken from refs. 8,9 and the excitation energies from ref. 10. The arrows indicate the maxima, which should roughly correspond to the shape transition. For odd nuclei, we indicate the ground-state energies by filled circles and some higher spin states by open circles. The energy of for example $I=10$ for an odd nucleus is obtained as the mean value of the $I=19/2$ and $I=21/2$ yrast energies. The fact that almost no odd-even mass difference is observed for $I \geq 14$ does not imply that the pairing gap is zero.

is seen only as a small disturbance on the character of the yrast spectra. This disturbance is far from changing the fact that, at least for $N \geq 90$, the nuclei are deformed and rotate in a collective way, while for $N \leq 86$ the spin is built from $p-h$ excitations at no or small deformation. In the transitional region, however, such small disturbances might have a rather drastic effect on the yrast spectra. Note also that for spins $I = 10-20$, the nucleus $^{112}$Dy is energetically very close to getting deformed with collective rotation.

The experimental shell energies for some odd nuclei are also shown in fig. 2. For the ground states, the odd-even mass differences are clearly seen. The excitation energies of the higher spin states are plotted as the mean values of the $I = 1/2$ and $I + 1/2$ yrast energies where $I = \ldots, 10, 12, 14, 16, \ldots$. This makes the comparison to the even nuclei straightforward. It is interesting to observe that at spin 10, most of the odd-even mass difference has disappeared and that very little of this difference is left for higher spins. This seems rather natural, because when the even nucleus begins to break pairs it should be similar to an odd nucleus (cf. sect. 5 below). It is also consistent with the fact that for $N \geq 85$, the odd-even mass difference disappears at even lower spins because for the surrounding even nuclei, already the low-spin states are more or less pure particle-hole excitations. Observe, however, that even if the odd-even mass difference disappears at a rather low spin, it does not mean that the pairing gap, $\Delta$, is zero for this spin.

The ground-state experimental shell energies of the $^{192}$Ir-isotopes are exhibited in fig. 3. Also shown are the known excitation energies of the yrast $2^+$ and $4^+$ states. The mass for $^{192}$Ir is not known so here we have used a calculated value 7). This mass is however not important for our discussion below but makes the figure somewhat more clear.

For the ground state we observe in addition to the expected shell-energy minimum at $N=50$ also a second irregularity at $N=56$. For this latter neutron number, the shell energy is 500-600 keV lower than would be
expected from the trend of neighbouring even nuclei. The low value for $^{92}$Zr has earlier been discussed (see e.g. [1]) and is clearly associated with the sub-shell closure at $N=56$. It is, however, interesting to observe that for the $2^+$ state, the irregularity at $N=56$ has disappeared and a smooth trend is observed. Thus, in $^{92}$Zr it seems more appropriate to state that the $0^+$ state is unusually low than that the $2^+$ state is unusually high. Going away from the $^{92}$Zr ground state, not in spin but instead in neutron number, one notes again that the strong binding at $N=56$ disappears. The strong binding of $^{92}$Zr thus seems to be associated with the combination of the subshell closure at $Z=40$ and $N=56$. As soon as one of these subshells is broken, either from particle-hole excitations or from addition or removal of particles, the extra binding disappears.

In fig. 3, one also observes how the Zr-isotopes get deformed around $N=60$. If only the measured masses ($N<60$) are considered this does not show up for the ground state but quite clearly for the $2^+$ states. This is so because, in a similar way as for the Dy-isotopes, the transition to deformed shapes seems to occur at a lower neutron number for the $2^+$ states than for the ground states.

3. Back-bending in gauge space

The analogy between the three-dimensional ordinary space and the two-dimensional gauge space was pointed out in the introduction. For the study of shape transitions, one may therefore directly adopt the experience obtained from the study of irregularities in ordinary rotational bands. Such irregularities are conventionally magnified in back-bending plots showing the angular momentum (or moment of inertia) as a function of the rotational frequency. The analogous plot in gauge space is the particle number $N$ versus the Fermi energy $\lambda$ as discussed in the introduction.

In fig. 4, we exhibit a plot of calculated $N$-values vs. $\lambda$ for two fixed deformations, $\varepsilon=0$ and $\varepsilon=0.25$, respectively. The $\lambda$-values have been obtained from the BCS-equations which were applied to the Nilsson model orbitals. One observes that around $N=82$, the marginal energy cost to add one additional neutron, $\Delta\lambda = \lambda_n$, is about equal for spherical and deformed shape while for higher particle numbers the energy cost is largest for spherical shape. However, it is first for $N=88$ that the total energy becomes lower for deformed than for spherical shape. With the reasonable assumption that $^{152}$Dy is spherical, $^{154}$Dy is transitional and $^{156}$Dy is clearly deformed, the back-bend would show up as indicated by the dashed line in fig. 4.

\[ \Delta=0.12\hbar\omega, \quad \varepsilon=0.25 \]

\[ \lambda = (N-88)/2 \]

\[ \Delta\lambda = \lambda_n - \omega_\chi \]

\[ H' = H_0 - \alpha Q - \Delta(\hat{\mathbf{P}}^2+\hat{\mathbf{F}}) - \lambda N - \omega \hat{\mathbf{I}}_\chi \]

(1)

The notation used in this equation should be self-explanatory. In a similar way as the quadrupole field may break the spherical symmetry in ordinary space, the pair field may break this symmetry in gauge space. Thus the two Lagrangian multipliers, $\lambda$ and $\omega$, enter on the same footing. They can both be derived from experimental energies, namely

\[ \lambda_p(Z,N,I,\nu) = \frac{\beta E(Z,N,I,\nu)}{E(Z+1,N,I,\nu)-E(Z-1,N,I,\nu)} \]

(2)

\[ \lambda_n(Z,N,I,\nu) = \frac{\beta E(Z,N,I,\nu)}{E(Z+1,N,I,\nu)-E(Z-1,N,I,\nu)} \]

(3)
\[ \omega(Z,N,I,\nu) = \frac{\delta E(Z,N,I,\nu)}{\delta I_X} \]

where we have distinguished between the neutron and the proton Fermi energies. The nuclear energy of a state with angular momentum \( I \) and the additional quantum numbers \( \nu \) is defined as

\[ E(Z,N,I,\nu) = -E_B(Z,N) + E_{\text{ex}}(Z,N,I,\nu) \]

where \( E_B(Z,N) \) is the ground state binding energy and \( E_{\text{ex}}(Z,N,I,\nu) \) is the excitation energy relative to the ground state.

We have applied the equations above to the yrast states of the Dy-isotopes. Thus, \( \nu \) is plotted as a function of \( \lambda_n \) in fig. 5. In agreement with fig. 2, a strong irregularity appears around neutron number 88 at spin zero. For higher spins we observe a similar irregularity but now at lower neutron numbers. As was discussed above, this irregularity is connected with a shape transition from near-spherical shape at lower \( N \)-values to well-deformed shape at higher \( N \)-values. The curve corresponding to the spherical liquid drop is also shown in fig. 5.

The experimental shell-correction energy in fig. 2 was defined as

\[ E_{\text{shell}}(Z,N,I,\nu) = E_{\text{exp}}(Z,N,I,\nu) - E_{\text{sph}}(Z,N) \]

At the maximum points in fig. 2

\[ \frac{\delta E_{\text{shell}}(Z,N,I,\nu)}{\delta N} = 0. \]

It therefore follows immediately that the maxima in fig. 2 correspond to the points where the experimental curves are crossed by the liquid-drop curve in fig. 5. It is obvious that the crossing point with the liquid-drop curve does not exactly coincide with the inflexion point in the experimental \( N(\lambda_n) \)-curve. This is consistent with our general understanding of a shape transition as a smooth process with no really well-defined transition point.

Fig. 5. Neutron number \( N \) vs. Fermi energy \( \lambda \) for even Dy-isotopes. The values for angular momentum \( I = 0-14 \) are calculated from experimental masses and yrast spectra. It is indicated that, in analogy with angular momentum alignment, one can define a particle number alignment of \( \Delta N = 3.5 \) for the Dy-isotopes. The figure also shows the behaviour of the spherical liquid drop\(^{17}\). The short-dashed line and the crosses give theoretical values of \( \lambda \) calculated in a similar way as in fig. 4. The inflexion points, defining the \( N \)-values, \( N_C(\lambda) \), are indicated by arrows.
4. Phase diagrams

The critical neutron numbers, $N_C$, determined from the inflexion points in the $N(\lambda_n)$-diagram can be summarized together with the critical angular momentum, $I_C$, determined from the $I(\lambda)$ diagrams, in a phase diagram (fig. 6). Such a diagram, as introduced in refs. 15,16, shows the different phases nuclei undergo with increasing angular momentum in ordinary space and in gage space (the latter being the neutron number $N$). The interplay between these two types of "angular moments" is thus nicely illustrated. In particular, one can read out at what neutron number the transition from near spherical to deformed shapes takes place. Thus for Dy we see a gradual decrease of $N_C$ (transition spherical-deformed), when going from $I=0$ to $I \sim 6$, as discussed in the introduction and in sect. 2.

Comparing the phase diagrams of $^{64}$Gd, $^{64}$Dy and $^{68}$Er (fig. 6), we observe the tendency that the $N_C$ values increase and the $I_C$ values (transition g-band - s-band) decrease when going from Gd to Er. The increase of $N_C$ indicates that the Gd-isotopes (in the region $N \geq 88$) are softer towards deformation than the Er-isotopes (cf. ref. 15). The suggested smaller deformation in Er makes the orbitals easier to align (a larger slope in a plot like fig. 9) and thus leads to a decrease of $I_C$.

As shown in these phase diagrams, the shape of some special nuclei (e.g. $N=88$) will change from near spherical to well deformed along the yrast line. Such a shape transition may play an important role in causing back bending in ordinary space (see e.g. 16).

A support for an increase of the deformation along the yrast line was recently obtained by a Riso-Oslo collaboration 17. At low spins for the nucleus $^{150}$Ho, they observed a fairly large signature splitting. As the odd proton is in the orbital [523 7/2], originating from h11/2, this requires a quite small deformation. Above the backbending, caused by the alignment of two i13/2 neutrons, no signature splitting was observed in this 7/2+ band. A possible explanation is that the deformation has increased 17. This interpretation of the data is consistent with the fact that when the same band is observed in heavier isotopes (with a large deformation), it does not show any signature splitting.

5. The pair field at high angular momentum

In sect. 2 we observed that most of the odd-even energy difference disappeared at angular momentum $I \sim 14$ when we compared energies of positive-parity states in Dy-isotopes. The high-spin yrast states of the odd-N isotopes belong to the i13/2-band. In CHFB-calculations (sect. 3) of the quasiparticle levels as functions of the rotational frequency $\omega$ 18, the levels of the i13/2 high-j intruder shell penetrate into the pair gap already at low rotational frequencies. This explains why the energy of the i13/2 bands do not reveal the existence of a pair field at high angular momentum. However, if we had plotted the energy of the negative-parity yrast states of the odd isotopes in fig. 4, we would have seen a significant odd-even energy difference up to the highest spins.

To illustrate the difference between the two parities, fig. 7 was prepared. We have considered the Yb-isotopes, which to
Fig. 7. Positive- and negative-parity yrast states for $^{70}$Yb drawn in a similar way as for $^{68}$Er in fig. 2. For I=10, 14, 18 and 22 the lowest positive- (solid lines) as well as negative- (dashed lines) parity states are exhibited. For odd nuclei, the energy for even spin is defined from interpolations in the favoured band. This is also the case for negative parity in even nuclei if a band with odd spins is favoured. The high-spin spectrum is known also for lighter isotopes but the masses are not. Indeed, the mass for N=94 has been extrapolated from the heavier isotopes. Note that above spin 14, it is only the negative-parity states which reveal the existence of a pairing gap.

Fig. 8. Theoretical quasi-particle levels for Er at $\omega=0$. The deformation and the pairing gap has been varied as a function of N as calculated for the ground states of the Er-isotopes. Experimental band-head energies for a number - as we believe - relatively pure quasi-particle configurations in the odd-N isotopes are also included. The position of the experimental points has been adjusted in such a way that the ground state coincides with the corresponding theoretical level.

...good agreement between theory and experiment shows that these calculations can be considered as quite reliable...

The energies $E_1$ of fig. 8 are obtained from the simple BCS-equations. When the nucleus rotates, the more involved CHFB-equation (sect. 3) must be used instead. The quasi-particle levels in the intrinsic system can then be calculated as functions of the rotational frequency, $\omega$. Such a figure is provided in fig. 5. In contrast to fig. 8, the time-reversal symmetry is broken for $\omega=0$ and each quasi-particle level splits up into two branches which can be distinguished by a new quantum number, the signature, which takes the values $\alpha = 1/2$ and $\alpha = -1/2$. At $\omega=0$, the energies of fig. 5 should, except for small parameter differences, coincide with the $N=94$ ($\lambda = 6.4\,\hbar\omega$) energies of fig. 8. With increasing $\omega$, we then see how the large pair gap gradually disappears when the quasi-particle levels dive down into the gap. There is, however, a clear difference between the (high-j) positive- and (low-j) negative-parity levels. Thus, the positive-parity levels ([6/2, 5/2] at $\omega=0$ in fig. 9),...
reach the middle of the gap at $\omega/\omega_0 \approx 0.03$ and then give rise to a back-bend when the two-quasiparticle state becomes yrast. However, no negative-parity quasiparticle energy comes close to zero in the frequency interval displayed in fig. 9 (the highest frequency $\omega/\omega_0 = 0.05$ corresponds roughly to angular momentum 30). Since the energy of the quasiparticle level occupied by the odd quasiparticle is equal to the excitation energy relative to the even-even vacuum, we can easily understand why the positive-parity yrast states in the odd-$N$ nuclei do not show any significant energy difference as compared to the even-even yrast states above $\omega/\omega_0 \approx 0.03$ ($I \approx 14$), while the opposite is true for the negative-parity yrast states. This understanding is obtained with a fixed pairing gap and without considering blocking effects.

We are now prepared to investigate the quasiparticle energies for a fixed value of 

Fig. 10. Theoretical and experimental quasineutron energies for Yb-isotopes at a fixed rotational frequency, $\omega/\omega_0 = 0.03$ drawn as functions of the Fermi energy, $\lambda$ (i.e. the rotational frequency in gauge space). The positive-parity levels are drawn with solid (signature, $\alpha=1/2$) and short-dashed ($\alpha=1/2$) lines, the negative-parity levels with dot-dashed ($\alpha=1/2$) and long-dashed ($\alpha=-1/2$) lines. If a level has reasonably pure Nilsson labels, these are shown in square brackets [$N\alpha\Omega\lambda$]; other levels are only labelled [$\nu\pi\alpha$] where $\nu$ indicates the number of a level within its symmetry group, ($N\alpha\lambda$), counted from the Fermi surface and $\pi$ is the parity. In some cases, Nilsson quantum numbers are given in round parenthesis, indicating the dominating component in the wave-function. The dominating component of the $13/2^-$ levels lying inside the gap is also indicated (for example $[633/2^+]$ in the region 6.53 $< \lambda/\hbar\omega_0 < 6.66$). The thin lines show the non-interacting $11/2^+$-levels. They are indicated with thin lines also in fig. 9. For odd nuclei, due to the blocking effect described in the text, it is these non-interacting levels which should be compared to experiment. The deformation has been varied in a similar way as in fig. 8 while the pairing gap is reduced by 20% relative to the experimental odd-even mass differences. This reduced pairing gap varies in the interval 0.10-0.12 $\hbar\omega_0$ for neutron numbers $N=91-99$ and decreases for larger neutron numbers to reach a value of $\sim 0.06 \hbar\omega_0$ for $N=105$. The neutron numbers are given in the bottom of the figure. The experimental energies are extracted from the observed bands and interpolated to $\omega/\omega_0 = 0.03$ (corresponding to $I=10-14$). Encircled symbols are used for the even isotopes. When it is not obvious with which theoretical level an experimental point should be compared, this is shown by an arrow. The good agreement between theory and experiment suggests that the chosen pairing gap is approximately correct.
\( \omega \) and drawn as functions of the Fermi energy \( \lambda \). Such a diagram for \( \omega = 0.03 \omega_0 \), roughly corresponding to the frequency of the first back-bend, is exhibited in fig. 10, where it is evident that the single-particle levels are mixed in a much more complicated way than in the non-rotating case (fig. 8). However, also for \( \omega/\omega_0 = 0.03 \), one clearly observes a pairing gap, which survives for all particle numbers shown. It is only the high-\( j \) 113/2 levels, denoted by \([1^{+}, -1/2] \) and \([1^{+}, 1/2] \), which penetrate deeply into this gap, whereas orbitals like \([3/2] \) and \([5/2] 1/2 \) which come from lower-\( j \) shells behave roughly as in the \( \omega=0 \) case (fig. 8).

It is interesting to observe that the difference in energy between the single-particle levels through all the particle numbers of fig. 10. However, with the Fermi level in the upper part of the 113/2-shell, the positive-parity orbitals should become more difficult to align and thus more similar to the negative parity orbitals. This is also what comes out from the quasiparticle levels of fig. 10. One would thus expect that for the heavier isotopes the odd-even energy difference would remain higher in spin for the positive-parity states in the odd isotopes. Furthermore, the general appearance of the \( N=10 \) states in fig. 7 appear to support this conclusion.

In the rotational case of fig. 10, the experimental energies must be interpolated from the observed states in the spin region \( \lambda = 10^{+}14 \) (see ref. \(^{13} \)). Before comparing theoretical and experimental data in fig. 10, it is also necessary to understand how the presence of an excited quasiparticle in one of the lowest 113/2-levels affects the interaction between the quasiparticle levels \( a \) and \(-b \) (or \( b \) and \(-a \)) of fig. 9, that is the so called blocking effect. Thus, in the favoured 113/2-band the levels \( a \) and \(-b \) are both filled (the levels \( b \) and \(-a \) are empty), which means that the interaction at \( \omega_0 = 0.035 \) only mixes the wavefunctions of two occupied levels, leaving the total many-particle wavefunction unchanged. The experimental quasiparticle energies, will therefore act as if there were no interaction, following the thin down-sloping solid line in fig. 9, which is a theoretical reconstruction of the non-interacting quasiparticle level. When making comparisons with experimental quasiparticle energies one must therefore use the non-interacting quasiparticle levels, which are also included in fig. 10 as the thin lines \([A], [B], [-A] \) and \([-B] \).

The frequency at which the non-interacting quasiparticle levels cross depend on \( \lambda \). At the frequency \( \omega/\omega_0 = 0.03 \) used in fig. 10 we are below the crossing frequency for \( \lambda > 6.46 \omega_0 \) and above the crossing frequency for \( \lambda < 6.46 \omega_0 \). This increase of the crossing frequency with increasing \( \lambda \) is a manifestation of the fact that the low-energy 113/2-orbitals are more easy to align than those higher up in the shell. The strong oscillations in the quasiparticle levels \([1^{+}, 1/2] \), \([1^{+}, -1/2] \) and their conjugate partners is a result of the oscillating interaction matrix element at the first crossing that involves these levels\(^{18,23} \). When comparing experimental and theoretical quasiparticle energies in fig. 10, we use the favoured 113/2 band as a reference for the odd isotopes. Also the energies which can be extracted from the side-bands of even isotopes are given relative to the favoured 113/2 level. This explains why one experimental point always coincide with the level \([A] \) in fig. 10.

It is very satisfying that relative to level \([A] \), the experimental quasiparticle energies show a good agreement with theoretical ones. The negative-parity states are systematically pushed up in energy compared to the positive-parity states. This would not be the case in absence of pair correlations, since then the positive- and negative-parity states would alternate as the lowest states, when the single-particle levels cross each other. Furthermore, the good quantitative agreement between experiment and theory in fig. 10 indicates that, for one- and two-quasiparticle configurations in the vicinity of the backbending frequency, the gap parameter must be close to the one used in the calculation.

6. Summary and conclusion

In the present paper we have studied systematics of nuclear properties as a function of particle number and spin. Special emphasis was put on the question of shape transitions. The analogy between such transitions and the transition to for example two-quasiparticle states at high spin (backbend in gauge space and in ordinary space, respectively) was pointed out. The variation with spin of the critical particle number, \( N_c \), where the shape transition occurs, was studied. Two methods were used to extract \( N_c \) (sect. 2 and sect. 3). In sect. 2 we thus studied irregularities in the experimental shell energies. In sect. 3 we use irregularities, manifesting the shape transition, were blown up in plots of the neutron number versus the Fermi energy. In sect. 4, all the information or \( N_c \) and \( I_c \) were put together in phase diagrams (fig. 6) to illustrate the interplay between rotation, deformation and pairing. We then studied the single-particle degree of freedom in some detail. The consequences of a pairing gap on the high-spin yrast spectrum was investigated.

The main conclusion of our study are:

i) The deformed regions appear to become larger with increasing spin. Transitional nuclei may thus be vibrational like at low spin and rotational at high spin (e.g. \( ^{125}\text{Gd} \), \( ^{129}\text{Dy} \) and \( ^{139}\text{Er} \)). The \( \gamma \) value of the odd isotopes get deformed at a lower \( N \)-value than the \( \pi \) isotopes. This is so in spite of the semimagic properties of \( ^{129}\text{Gd} \).

ii) In the sequence of isotopes \( ^{157}\text{Gd} \), \( ^{161}\text{Dy} \) and \( ^{165}\text{Er} \), the \( \gamma \) and Dy isotopes get deformed at a lower \( N \)-value than the Er isotopes. This is so in spite of the semimagic properties of \( ^{157}\text{Gd} \).

iii) A strong binding for the \( 0^+ \) state of a nucleus may have disappeared already for \( 2^+ \) state (fig. 3).

iv) In the rare-earth region, the odd-even energy difference has almost dis-
appeared for I \neq 14. However, if both positive- and negative-parity yrast states are considered, the existence of a substantial pairing gap also at high spin is revealed.

v) The systematics of low- and high-spin states as a function of particle number is well described by calculated quasi-particle energies.

Our studies could become more complete if the masses and yrast spectra were known over larger regions of neutron (or proton) number. For example, for the Yb-isotopes, the yrast spectra are quite well-known for the neutron-deficient isotopes with N=90-94 while the masses are not known. Similarly, if the masses were known for the neutron-deficient Hg-isotopes, we believe that some interesting results could be obtained with the present methods.

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References

4) R. Bengtsson, Jing-ye Zhang and S. Aberg, to be published
6) A. Bohr, J.M. Leinaas and F. Minnhagen, Nordita preprint 1979/13
8) A.H. Wapstra and K. Bos, Atom. Data and Nucl. Data Tables 19 (1977) 177
9) J. Blomqvist, private communications
10) C.M. Lederer and V.S. Shirley, "Table of Isotopes" 7th Edition (1978)
12) W.D. Myers and W.J. Swiatecki, Ark. Fys. 36 (1967) 343
17) P.O. Tjöm et al., private communications
18) R. Bengtsson and S. Frauendorf, Nucl. Phys. A327 (1979) 139
21) Lund-Risö ccll., private communication through W. Walus.
STUDY OF HEAVY Sn, Sb AND Te NUCLEI: A SHELL-MODEL DESCRIPTION OF THE INTERPLAY OF SINGLE-PARTICLE AND COLLECTIVE EXCITATIONS.

K. Heyde, Institute for Nuclear Physics, Proeftuinstraat, 36 B-9000 Gent (Belgium)

and

J. Sau and J. Van Maldeghem, Institut de Physique Nucléaire, 43 Bd. du 11 Novembre 1918, 69622 Villerbanne-Cedex (France)

Abstract.
A shell-model approach in order to study the interplay of collective and non-collective excitations, which is feasible for numerical calculations, is suggested. Study of some specific applications to odd-even and even-even nuclei near the doubly-closed shell nuclei $^{132}$Sn has been carried out. Finally, for the even-even nucleus $^{132}$Te, the fermion residual proton-neutron interaction is mapped onto a boson-boson interaction which enables us to describe the collective quadrupole excitations near $^{132}$Sn.

1. Introduction

In describing nuclei where the number of valence nucleons is not far from a closed shell configuration (e.g., $^{88}$Sr, $^{90}$Zr, $^{92}$Zr, $^{94}$Zr), specific nucleon configurations remain such as to make a description in terms of collective excitations only, difficult or impossible. This happens to be the case for nuclei near the doubly-closed $Z=50$, $N=82$ $^{132}$Sn nuclei [1-3]. In trying to couple the extra proton degree of freedom in describing heavy Sn, Te, I and Xe nuclei, with the underlying Sn core nuclear excitations, large deviations from the conventional macroscopic particle-core coupling mechanism are observed [4-8].

(see fig.1). In order to attempt a full description of either the core system as well as of the particle core coupled configurations, one has to start from a shell-model approach.

Therefore, we first derive (sect. 2) the basic equation for a shell-model approach to particle-core coupling, which is able to describe as well odd-even, odd-odd as even-even nuclei. In sect. 3, we discuss some specific applications to nuclei near $^{132}$Sn i.e., $^{128}$Sn and $^{132}$Te.

2. Shell-model approach

The aim is to derive a general expression for matrix elements of the two-body interaction $V_{i,j}$ between wave functions involving $n_i$ particles of type $i$ and $n_j$ particles of type $j$ (with type $i$ mean: protons and neutrons, particle and hole excitations, particle-hole and boson excitations).

We call furthermore $J_i$ ($J_j$) the resulting angular momentum of the $n_i$ ($n_j$) particles and $J$ the total angular momentum from coupling $J_i$ with $J_j$ in that order. Usually, the interaction $V_{i,j}$ is expanded as

$$V_{i,j} = \Sigma \left< p' n'; J_i M_i \right| V \left| p n; J_j M_j \right> a^{+}_{p' n'} a_{p n}$$

$$\times \left< j' m'; J_i M_i \right| J_j M_j \right> \left< j m; J_i M_i \right| J_j M_j \right>$$

(1)

In order to obtain more efficiently written expressions, we shall use the Wigner covariant notation of the 3j-symbols [9]. Moreover, we make the tacit assumption throughout this paper that in the two-body matrix elements $\left< p' n'; J_i M_i | V | p n; J_j M_j \right>$ we denote with $p', n', J, M$ not only the quantum numbers but also the exact nature of the type of excitations i.e., for fermion hole excitations $p', n'$ means $p', n'$.

We can now write an alternative expression for (1) as

$$V_{i,j} = \Sigma U(p') U(n') \left< p' n' | J' M' \right> a^{+}_{p' n'} a_{p n}$$

$$\times \left< J_i M_i | J_j M_j \right>$$

(2)

The quantities $U(p')$, appearing in eq(2) can be calculated once for all and be stored. Obviously, the $U$-matrix elements of (2) are related to the normal two-body matrix elements of (1), by equating (1) and (2), with as a result

$$U(p' n'; J') = \sum_{J} \sum_{M} \left< J J' M' M \right| p n; J M \right>$$

$$\times p' n'; J' M' \left| V \right| p n; J M \right>$$

If we now call $c_i J_i M_i \left| J \right>$ (for the resulting wave functions of the $n_i$ particles of type $i$) the $J_i M_i$ denoting all other quantum numbers necessary to label the wave functions uniquely, then the matrix elements for the resulting coupled wave function $c_i J_i k_J \left| J \right>$ become

$$+ \text{ In the summations of (1) and (2), all quantum numbers associated with the greek letters of the four operators are implied. A greek letter } \rho \text{ denotes } \rho \equiv (p, m) \text{ with } p \in \left[ n' \varepsilon p', J' \right].$$

Moreover, the coupled angular momenta $J_i M_i$ or $J' M'$ are summed.
In order to carry out calculations near the doubly-closed shell nucleus $^{133}\text{Sn}$, for which the first excited state occurs at $E_x = 4.041$ MeV, single-particle-(hole)-energies and effective two-body matrix elements are needed. In table 1, we give the

| Table 1 |
|---|---|
| PROTON | NEUTRON |
| $\epsilon_{19/2}^\pi$ | 0.0 | 0.0 |
| $\epsilon_{21/2}^\pi$ | 1.0 | $\epsilon_{3/2}^\chi$ |
| $\epsilon_{11/2}^\pi$ | 2.0 | $\epsilon_{11/2}^\chi$ |
| $\epsilon_{3/2}^\pi$ | 2.4 | 2.4 |
| $\epsilon_{3/2}^\chi$ | 2.8 | 2.8 |
| $V_o$ | -39.0 | -39.0 |
| $t$ | +0.2 | +0.2 |

The parameters for the proton-proton and neutron-neutron interactions as well as the proton single-particle and neutron single-hole energies.

proton single-particle and neutron single-hole energies as obtained from the experimental level schemes of $^{133}\text{Sb}$ (ref.10) and $^{133}\text{Sn}$ (ref.2), respectively. Neutron single-particle and proton single-hole energies could be obtained from the experimental level schemes of $^{133}\text{Sn}$ and $^{133}\text{Sb}$ respectively. However, lack of experimental data does not allow a good determination of these energies.

Two-body $p-p$ and $n-n$ interactions matrix elements have been obtained from a gaussian interaction $V_{nn} = e^{-R^2/2a^2}$, with parameters as given in table 1. This particular interaction has proven its ability to describe many even-even nuclei in this particular mass region (11-15). For the proton-neutron interaction, a sum of quadrupole and octupole forces have been used and parameters $\chi_p$ and $\chi_n$ (see eq.6), determined via a best fit to low-lying experimental levels in $^{129,130}\text{Sn}$ and $^{129,130} \text{Sb}$. Thus, for the particular $^{132}\text{Sn}$ mass region, the values $\chi_p = -0.15$ MeV and $\chi_n = -0.06$ MeV have been used (9,16). In some cases, calculations have also been carried out using a $\delta$-interaction, with spin exchange as proton-neutron interaction (9,16).

Starting from these basic nuclear parameters and using eq.4 after diagonalizing in the identical nucleon systems in order to obtain the wave functions $\langle c_{\lambda}^\downarrow M_{\lambda}^\downarrow | c_{\lambda}^\uparrow M_{\lambda}^\uparrow \rangle$, the actual energy matrices can be constructed and diagonalized.

### 3.2. Application to $^{129}\text{Sn}$

Results for the core nuclei $^{128,129,130} \text{Sn}$ have already been discussed at some length in refs.9 and 17. These nuclei can serve as a core in order to describe complex nuclei. The nucleus $^{131}\text{Sb}$ (1 particle-2 hole system) is discussed in much detail by F. Schussler et al. in the present proceedings (18). In this section, we point out that using eq.4 and having a good description of the 4 hole nuclei $^{126}\text{Sn}$ as well as the odd-proton moving in all the available proton single-particle orbits ($\epsilon_{13/2}^\chi$, $\epsilon_{11/2}^\pi$, $\epsilon_{11/2}^\sigma$, $\epsilon_{9/2}^\chi$), the $^{129}$Sb level scheme and $^{129}$Sb properties can be studied in a shell-model approach to the particle-core description. (see fig.2).
i) the $J^\pi = 7/2^+$ state has about equal single-particle amplitudes in both models. The strongest coupling occurs with the $|1g_{9/2}; 2^+_1\rangle$ configuration in both the shell-model and macroscopic calculations.

ii) the $J^\pi = 5/2^+$ level has again comparable single-particle amplitudes in both models. For the $|1h_{11/2}; 3^+_1; 5/2^+\rangle$ configuration, about equal admixtures occur although in the shell-model approach, the coupling occurs preferentially with two high-lying $J^\pi = 3^+$ levels ($|1h_{11/2}; 3^+_1; 5/2^+\rangle$ at $\approx 1.31$ MeV and $|1h_{11/2}; 3^+_1; 5/2^+\rangle$ at 3.97 MeV).These $3^+$ levels in $^{128}$Sn show very strong $B(E3)$ transition probabilities to the ground state and therefore serve as a description of the collective $3^+$ level.

iii) the $J^\pi = 11/2^+$ state also has comparable single-particle character in both calculations. For the $|2d_{5/2}; 3^+_1; 11/2^+\rangle$ configurations, the same comments as for the $J^\pi = 5/2^+$ level apply.

iv) for the $J^\pi = 3/2^+$ level, some differences occur when comparing both calculations. In the macroscopic calculation, the $J^\pi = 3/2^+$ state is mainly the $|1g_{7/2}; 2^+_1; 3/2^+\rangle$ configuration as is also the case in the shell-model approach. In the latter model, a $J^\pi = 3/2^+$ level occurs, containing as the most important configuration $|1g_{7/2}; 2^+_1; 3/2^+\rangle$, a configuration with no obvious counterpart in the macroscopic model.

v) for the $J^\pi = 1/2^+$ state, about equal fractions of the $3^+_1$ level and the $|2d_{5/2}; 2^+_1; 1/2^+\rangle$ configurations result in both descriptions. A second $1/2^+$ level ($J^\pi = 1/2^+$) is strongly mixed in the macroscopic model as well as in the $|1g_{7/2}; 2^+_1; 1/2^+\rangle$ configuration ($\Delta N_{sp}$ means the quadrupole two-phonon $4^+_1$ state) and in the shell-model calculation, the corresponding $|1g_{7/2}; 2^+_1; 1/2^+\rangle$ configuration dominates.

As a conclusion we find very strong similarities between both models. For the quadrupole degree of freedom, in both the macroscopic and the shell-model approach, coupling of the single-particle configuration goes preferentially via the $|n\ell_{2}; 2^+\rangle$ configurations. For the octupole degree of freedom, highly lying $|n\ell_{2}; 3^+\rangle$ configurations are strongly admixed via the $3^+_1$ and $5^+_1$ levels ($E \approx 4$ MeV). Also, the strong octupole force dependence of some particular levels is completely analogous in both models, due to the large non-spin flip reduced $V_3$ matrix elements resulting in both models.

Similar comparisons can be made for the levels which have the quadrupole one-phonon $|1g_{9/2}; 2^+_1; 3^+_n\rangle$ configuration as their main configuration. For the $|1g_{9/2}; 2^+_1; 3^+_n\rangle$ and $|1g_{9/2}; 2^+_1; 3^+_n\rangle$ configurations, negative parity multiplets result (see also fig.2) that are not readily obtained within the macroscopic particle-core coupling model.

In this subject, we have discussed the application of a shell-model approach to particle-core coupling (see eqs. 4. and 8) near closed shells. We have carried out an extensive comparison with the macroscopic particle-core coupling model calculations in $^{128}$Sn and obtain very similar results concerning energy spectra and nuclear wave functions. Nuclear levels, in which the neutron $2p_4p_4\ldots$ excitations show up explicitly can only be obtained in a consistent way from the shell-model approach to particle-core coupling.

3.3. Study of $^{132}$Te

Recently, we have reported on detailed shell-model studies along the lines discussed in eq.(4) for the even-even $^{132}$Te nucleus [9,16,23,24]. In this particular nucleus, the wave functions $\{c|J,M,\pi\rangle\rangle_{\Delta N_{sp}}$ describe the single-closed shell $^{130}$Te and $^{132}$Sn nuclei. Thus, the proton-neutron interaction will be decisive in describing the kind of coupling between both systems (weak or strong mixed final wave functions).

The basic experimental features are shown in fig. 3, where the idea of weak coupling particular proton excitations ($l^2; e^2$) to the neutron $0^+$ ground state or to specific neutron excitations ($l^2; e^2$) to the proton $0^+$ ground state, becomes clear. In the particular case of $^{132}$Te, the proton-neutron interaction used was the $\delta$-interaction with spin exchange.

\[ V = v_{eff} S(\tilde{T}_\mu) p_{\mu n}, \]

with $V_{eff} = 0.4$ MeV.m and $t=5$.

In this nucleus, a representation of the wave functions obtained by coupling the proton $2p$ and neutron $2h$ wave functions for $^{134}$Te and $^{130}$Sn respectively,
Figure 3: The most important experimental low-lying levels in $^{134}$Te, $^{130}$Sn and $^{132}$Te, indicating the weak -coupling pattern.

is particularly transparent and moreover gives a possibility of comparing with a boson model interpretation of the purely collective quadrupole excitations.

Diagonising within the separate proton and neutron spaces as well as by diagonalising within the full proton 2p-neutron 2h configuration space (dimensions of 1000x1000 occur), the wave functions

$$|k, J_n \rangle = \sum_{h_1, h_2} (h_1, h_2, J_n) |(h_1, h_2, J_n) \rangle, \tag{10}$$

$$|\ell, J_p \rangle = \sum_{p_1, p_2} \ell (p_1, p_2, J_p) |(p_1, p_2, J_p) \rangle, \tag{11}$$

and

$$|i, J \rangle = \sum_{h_1, h_2, J_n} \sum_{p_1, p_2, J_p} c_{h_1, h_2, J_n} (p_1, p_2, J_p) \langle h_1, h_2, J_n |(p_1, p_2, J_p) \rangle |\ell, J_p \rangle |k, J_n \rangle, \tag{12}$$

result for $^{130}$Sn, $^{134}$Te and $^{132}$Te, respectively. Inverting the relations (10) and (11), one can express the states (12) as

$$|i, J \rangle = \sum_{\ell, J_p} \sum_{k, J_n} \langle \ell, J_p |k, J_n \rangle |\ell, J_p \rangle |k, J_n \rangle, \tag{13}$$

Wave functions (13) for some particular important states are shown in Table 2.

The nucleus under study, $^{132}$Te, now presents an interesting case in order to study relations to the IBA model of Arima and Iachello. In this approach, particular collective states in nuclei with 2p active protons and 2n active neutrons (outside closed shells) are supposed to result from the interaction of proton and neutron bosons, with only spin 0 (s boson) and 2 (d boson) in the IBA approximation, a

Table 2

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>Wave function</th>
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<tr>
<td>0.000</td>
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<tr>
<td>1.467</td>
<td>$</td>
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<tr>
<td>1.566</td>
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<tr>
<td>2.384</td>
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<td>1.977</td>
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<td>2.408</td>
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<tr>
<td>1.582</td>
<td>$</td>
</tr>
<tr>
<td>2.310</td>
<td>$</td>
</tr>
<tr>
<td>2.480</td>
<td>$</td>
</tr>
<tr>
<td>1.705</td>
<td>$</td>
</tr>
<tr>
<td>2.697</td>
<td>$</td>
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<tr>
<td>2.764</td>
<td>$</td>
</tr>
<tr>
<td>2.704</td>
<td>$</td>
</tr>
<tr>
<td>2.035</td>
<td>$</td>
</tr>
<tr>
<td>1.823</td>
<td>$</td>
</tr>
</tbody>
</table>

In our case $s = 0$, $p = 0$ and $d = 0$, the boson is related to a pair of fermion particles (holes). In the ideal situation, the boson-boson interaction should be calculated from the residual fermion interaction. Now, in the particular nucleus $^{132}$Te, one is left with one boson of each kind and one can make the following correspondences: associate one g boson $s_n(i)$ with the $0^+$ ground state in $^{130}$Te ($^{130}$Sn) and associate one d boson $d_{\ell}(i)$ with the $2^+$ state in $^{134}$Te ($^{134}$Sn).

The necessary boson matrix elements for all possible angular momenta ($i^3 = k^3 = l^3 = m^3 = n^3 = o^3$) can easily be calculated. Indeed, we have at our disposal the shell-model matrix elements

$$\langle h_1 h_2 | \phi(p_1 J_1) \phi(p_2 J_2) | J_n J_p \rangle$$

resulting from the full shell-model calculations. Then a unitary transformation gives us the matrix elements of $V$ in the coupled basis of the states of $^{130}$Sn and $^{134}$Te. These matrix elements can then be interpreted as matrix elements of the boson-boson interaction. They are given in Table 3. In diagonalising the latter interaction within the restricted space (one $\pi$ one $\nu$ boson) and comparing with the full shell-model calculations, a very good agreement results as well in energy as for the nuclear wave functions (Table 4). By inspecting the wave functions corresponding with the $2^+$ states, one observes that the wave function antisymmetric for exchange of proton and neutron coordinates corresponds to the lowest $2^+$ state.

This feature can be easily pointed out to correspond to the lowest $2^+$ state for a proton $2p$-particle-neutron $2h$-hole system, when simplifying towards a single $1p$-shell, and a pair (for identical particles) quadrupole (for non identical particles) interaction within this scheme and taking into account the two unperturbed $J^p = 2^+$ states $|J_p = 2^+, J_n = 0; J = 2^+\rangle$ and $|J_p = 2^+, J_n = 0; J = 2^+\rangle$. 

- 522 -
\[|J_p = 0^+, J_n = 2^+; \ J = 2^+\rangle \] (neglecting other configurations).

Table 3

\[
\begin{align*}
\langle \phi_d \ | \ 0^+ \rangle & = 0.94 \\
\langle \phi_d \ | \ 1^+ \rangle & = 0.32 \\
\langle \phi_d \ | \ 2^+ \rangle & = 0.90 \\
\langle \phi_d \ | \ 3^+ \rangle & = 0.82 \\
\langle \phi_d \ | \ 4^+ \rangle & = 0.14 \\
\langle \phi_d \ | \ 5^+ \rangle & = -0.01 \\
\langle \phi_d \ | \ 6^+ \rangle & = 0.86 \\
\langle \phi_d \ | \ 7^+ \rangle & = 0.04 \\
\langle \phi_d \ | \ 8^+ \rangle & = 0.86 \\
\langle \phi_d \ | \ 9^+ \rangle & = 0.76
\end{align*}
\]

Proton-neutron boson residual interaction matrix elements for $^{132}$Te as obtained from the fermion two-body $\delta$ interaction.

The energy matrix for $J = 2^+$ then simplifies into the $2 \times 2$ matrix (calling $E_{\text{pair}} = -\frac{1}{2}(J + 1/2)$ and taking $\epsilon_J = 0$)

\[
\begin{bmatrix}
E_{\text{pair}} & b \\
\epsilon_J & E_{\text{pair}}
\end{bmatrix},
\]

with eigenvalues $E_{\text{pair}} - b$ and $E_{\text{pair}} + b$ corresponding respectively with the antisymmetric and symmetric wave functions:

\[
\begin{align*}
\frac{1}{\sqrt{2}} & \left| J_p = 2^+, J_n = 0^+, J = 2^+ > = \frac{1}{\sqrt{2}} \left| J_p = 0^+, J_n = 2^+, J = 2^+ >
\right.
\end{align*}
\]

For a proton 2-particle-neutron 2-particle system the off-diagonal matrix element changes sign, thus the same eigenvalues are obtained, but the wave functions change interchange.

Table 4

\[
\begin{align*}
| 0^+_1 > & = 0.99| 0^+_1 (v) \otimes 0^+_1 (n) > \\
| 0^+_4 > & = 0.99| 2^+_1 (v) \otimes 2^+_1 (n) > \\
| 2^+_1 > & = -0.60| 0^+_1 (v) \otimes 2^+_1 (n) > - 0.60| 2^+_1 (v) \otimes 0^+_1 (n) > \\
| 2^+_2 > & = -0.60| 2^+_1 (v) \otimes 0^+_1 (n) > - 0.60| 0^+_1 (v) \otimes 2^+_1 (n) > \\
| 2^+_4 > & = 1.00| 2^+_1 (v) \otimes 2^+_1 (n) >
\end{align*}
\]

Wave functions for $^{132}$Te, resulting from diagonalising the proton-neutron boson interaction in the restricted basis of collective excitations only.

Starting now from this $\pi\nu$ boson interaction, it should be possible to proceed towards more complex nuclei with $p$ bosons of the proton type and $n$ bosons of the neutron type. The $\pi\nu$ Hamiltonian is completely equivalent with the one discussed in ref. 26. Although another microscopic proton-neutron interaction is used by Otuka et al. i.e., a quadrupole-quadrupole interaction whereas the delta interaction with spin exchange is used here. One must have in mind however, that the interaction derived above is obtained near closed shells whereas, strictly speaking, the IBM is valid far from closed shells. Restricting to strongly collective states only, the approach discussed above may well give good results.

In conclusion, we can say that, by means of the shell-model calculations carried out for $^{134}$Sm and $^{136}$Te, it became possible to derive a macroscopic $\pi\nu$ boson interaction from a residual proton-neutron (delta) interaction, even identifying the respective $0^+_1$ and $2^+_1$ states in $^{136}$Sn and $^{136}$Te, as collective $s$ and $d$ boson excitations.

4. Conclusion

In this study, we have proposed a shell-model approach for studying, in a unified way, the interplay of collective and non-collective excitations. The formalism extends the simplified macroscopic particle-core coupling models in such a way as to allow for single-particle coupling to non-collective excitations. Applications for odd-mass and even-even nuclei near the doubly-closed shell nucleus $^{132}$Sn have been discussed in some detail. In the even-even nucleus $^{136}$Te, we have made an attempt to derive a collective proton-neutron interaction in...
terms of \( s(3^+=0^+) \) and \( d(3^-=2^+) \) boson-like excitations only.

The general method, as discussed in sect. 2, has also been applied to other mass region i.e. the 96–100Pt nuclei(27).

Going beyond \( 4p(4h) \) configurations away from closed shells will definitely need certain approximations such as taking only the lowest \( 3^+=0^+ \) and \( 2^+ \) two particle (-hole) states acting on the 4 particle (-hole) space, in order to produce 6 particle (-hole), 8 particle (-hole), ... configurations. In a certain sense, the approximations of the IBA have to be used.

The authors are most grateful to Prof. R. Chéry for his interest during the course of this work. Moreover, one of the authors (KH) is much indebted to Prof. R. Chéry for his hospitality during the many stays at the IPN, Lyon and to the IN2P3 for financial support. We also are much to discussions and communications with B. Fogelberg, F. Schössler, W.B. Walters, R.A. Meyer and P. van Isacker.

References

18. F. Schössler et al., these proceedings
ON THE NATURE OF THE LOWEST $K^\pi=0^-$ STATES IN THE Ra-Th REGION

A. Gyurkovich and A. Sobczewski
Institute for Nuclear Research, Roza 69, PL-00-681 Warszawa, Poland

B. Nerlo-Pomorska and K. Pomorski
Institute of Physics, The Maria Sklodowska-Curie University, Lublin, Poland

Abstract

Modified macroscopic-microscopic calculations of the potential energy of nuclei in the Ra-Th region are performed. A stable octupole deformation of the nuclei is obtained. The lowest $K^\pi=0^-$ states are interpreted as being associated with this deformation.

1. Introduction

There is a long discussion on the nature of the lowest-lying collective $K^\pi=0^-$ states of even-even nuclei in the Ra-Th region. The energies of the states come down to about 200 keV ($^{224}$Ra, $^{226}$Th). Three different interpretations have been proposed. In one of them, the states are treated as octupole vibrations. No stable octupole deformation is assumed. This treatment allows one to reproduce octupole energies of many nuclei in different regions rather well. It faces, however, difficulties in reproducing the lowest energies, discussed here, and their systematics (i.e. their dependence on the neutron number N). In the second interpretation, a stable octupole deformation is assumed. With such assumption, the potential energy $V$, treated as a function of the octupole deformation $E_3$, would look as in fig.1.

![Diagram](attachment:image.png)

Fig.1. Potential energy $V$ as a function of the octupole deformation $E_3$ in the case of a stable octupole deformation.

In such a case, the ground-state rotational band $K^\pi=0^+$, $I^\pi=0^+\bigoplus 2^+, 4^+\bigoplus \ldots$, and the excited band $K^\pi=0^-$, $I^\pi=1^-, 3^-, 5^-\ldots$ would be displaced with respect to each other by the energy $\Delta E$ which strongly depends on the octupole barrier height $E_B$ (fig.1). With increasing $E_B$, the displacement $\Delta E$ tends to zero. The situation is similar to that for the ammonium molecule. In the third interpretation, the states $K^\pi=0^-$ are associated with the second minimum in the potential energy, obtained at oblate shapes. The barrier $E_B$ is, however, very low (around 100 keV) in this case, what is not enough to explain the observed $\Delta E$. Also the barrier between oblate and prolate shapes, obtained in ref.2, is rather small (about 1 MeV) and expected to be still reduced by including the non-axial (y-deformed) shapes, as argued in that reference. In addition, the moments of inertia calculated for this second minimum are few times lower than those observed in experiment for the $K^\pi=0^-$ bands.

The main objection to the second interpretation, which assumes a stable octupole deformation of the ground state of a nucleus and which also seems to be favoured by experimental data3, is that such deformation has not been obtained in the theoretical calculations2,4). The calculations predict the reflection-symmetric shapes.

In the present paper, we notice that the stable octupole deformations for nuclei in the Ra-Th region can be obtained in a rather natural way. One needs only to improve the traditional macroscopic-microscopic method of the calculation of the potential energy. The improvement consists in an addition of a simple consistency condition between the macroscopic and microscopic parts of the energy. The improvement was proposed in ref.5 and applied to a study of the quadrupole and hexadecapole shapes. Here, we apply it to the study of the octupole shapes.

2. Description of the calculations

2.1. Potential energy

As mentioned in the Introduction, the potential energy is calculated in the present paper by a macroscopic-microscopic method improved by a consistency condition. The condition requires that the deformation of the liquid drop or droplet, describing the macroscopic part, is the same as the deformation of the density of matter generated by the potential, describing the microscopic part, and not as the deformation of the potential itself, as traditionally done (cf. e.g. ref.6). In the mathematical

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W) Supported in part by the Polish-US Maria Sklodowska-Curie Fund, Grant No. P-770037P
form, it reads
\[ Q_{\text{macro}} = Q_{\text{micro}}, \]  
(1)

where \( Q_{\lambda} \) is the moment of the density of multipolarity \( \lambda \). We include all multiplicities from \( \lambda = 0 \) up to \( \lambda = 8 \). Practically, for each deformation of the potential, the moments \( Q_{\lambda} \) are immediately calculated and then the deformation of the liquid drop or droplet is taken such as to get \( Q_{\text{macro}} \) equal to \( Q_{\text{micro}} \).

In the numerical calculations, the droplet model of ref.7) has been taken to describe the macroscopic part of the energy. The microscopic part is the Strutinski shell correction obtained with the Nilsson single-particle levels corresponding to the parameters "A=242" (cf. ref.8).

2.2. Mass parameters

The mass parameters are calculated by the cranking method (cf. e.g. ref.9).

2.3. Energy displacement \( \Delta E \)

The energy displacement \( \Delta E \) (between the heads of the ground-state and the lowest \( K\pi = 0 \)-rotational bands) is estimated in the quasiclassical approximation and under the assumption that the problem is one-dimensional.

We are only interested in \( V(\varepsilon_3) \) for \( \varepsilon_3 > 0 \), as the potential is symmetric with respect to the octupole deformation \( \varepsilon_3 \): \( V(-\varepsilon_3) = V(\varepsilon_3) \). Approximating \( V(\varepsilon_3) \) by two parabolas (one inverted with respect to the other) which are smoothly joined (continuous function and first derivative), we get the formula
\[ \Delta E = \frac{k_{\omega_0}}{\pi} \left( E_B - E_0 \right), \]  
(2)

where \( E_B \) is the height of the (octupole) barrier (fig.1), \( E_0 \) is the energy of the level which is split (due to the interaction through the barrier) into two, displaced by the energy \( \Delta E \). The quantities \( k_{\omega_0} \) are the curvature parameters of the parabolas: at the equilibrium point (\( \omega_B \)) and at the top of the barrier (\( \omega_B \)). These quantities are calculated as
\[ k_{\omega_0} = \frac{k_{\varepsilon_3} - C_{\varepsilon_3} \varepsilon_3}{B_{\varepsilon_3} \varepsilon_3}, \]  
(3)

where \( C_{\varepsilon_3} \) is the curvature of the potential and \( B_{\varepsilon_3} \) is the mass parameter with respect to the deformation \( \varepsilon_3 \), calculated at respective point \( \varepsilon_3 \). The curvature \( C \) is calculated directly from the microscopic energy \( V(\varepsilon_3) \) and the mass parameter \( B \) is calculated by the cranking method, as mentioned in subsect. 2.2. For \( E_0 \), we take the zero-point energy of the octupole vibration in the equilibrium point
\[ E_0 = \frac{1}{2} k_{\omega_0}. \]  
(4)

The approximation of the microscopic \( V(\varepsilon_3) \) by two parabolas is usually very good.

3. Results and discussion

In the modified (improved) calculations of the potential energy, the macroscopic part of the energy appears, as a rule, softer to deformation than in the traditional calculations. It is only a little softer to the quadrupole deformation, but much softer to deformations of a higher multipolarity. As a result, after an addition of the shell correction, a stable octupole deformation is obtained for nuclei in the Ra-Th region. This is directly illustrated in fig.2, where the potential energy of \( ^{226}\text{Th} \) is calculated traditionally (a) and in the modified way (b). We can see that in the traditional calcula-

![Fig.2. Contour map of the potential energy V calculated traditionally (a) and in the modified way (b), as a function of the quadrupole (plus hexadecapole), \( \varepsilon_{24} \), and octupole (plus multipolarity 5), \( \varepsilon_{35} \), deformations.](attachment:image.png)
tion no stable octupole deformation, $\varepsilon_3^O=0$, is obtained, exactly as in ref.\textsuperscript{2}. However, in the modified calculation, the minimum of the potential energy is obtained at $\varepsilon_3^O \approx 0.15$ and is quite deep. The deformation energy

$$E_{\text{def}} = V(0,0) - V(\varepsilon_2^O, \varepsilon_3^O)$$

is about 1.8 MeV and the height of the octupole barrier $E_B$ (cf. fig.1) is around 1.9 MeV. Similar results are obtained for other isotopes of Th. The quadrupole and octupole equilibrium deformations, $\varepsilon_2^O$ and $\varepsilon_3^O$, deformation energy $E_{\text{def}}$ and the octupole barrier $E_B$, calculated in the modified way for Th isotopes are given in table 1. One can

Table 1

<table>
<thead>
<tr>
<th>N</th>
<th>$\varepsilon_2^O$</th>
<th>$\varepsilon_3^O$</th>
<th>$E_{\text{def}}$</th>
<th>$E_B$</th>
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</thead>
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<td>132</td>
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<td>0.12</td>
<td>1.0</td>
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<td>0.04</td>
<td>0.14</td>
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<td>1.7</td>
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<td>136</td>
<td>0.02</td>
<td>0.15</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>138</td>
<td>0.00</td>
<td>0.15</td>
<td>1.8</td>
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<td>0.17</td>
<td>2.2</td>
<td>1.8</td>
</tr>
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<td>142</td>
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<td>0.16</td>
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</tr>
<tr>
<td>144</td>
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<td>0.14</td>
<td>3.8</td>
<td>1.2</td>
</tr>
<tr>
<td>146</td>
<td>0.23</td>
<td>0.14</td>
<td>4.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

see an interplay between the quadrupole and octupole deformations, expected\textsuperscript{9}) for nuclei just after $^{208}$Pb. The stable octupole deformation appears first and only after that, for heavier isotopes, the quadrupole deformation comes into sight. A stable octupole deformation is also obtained for isotopes of elements neighbouring Th, like Rn, Pa, U and Pu.

It is interesting to notice a clear correlation between the height of the octupole barrier $E_B$ and the experimental energy $E_{1-}$ of the lowest $K\pi=0^-, I\pi=1-$ state. The highest barrier, $E_B \approx 1.9$ MeV, is obtained for the isotope (N=136), just for which $E_{1-}$ is known. The correlation is illustrated in fig.3 for all isotopes, for which the experimental value of $E_{1-}$ is known. In fact, higher the barrier lower the energy $E_{1-}$. We think that this correlation is a significant support for the interpretation of the lowest $K\pi=0^-$ states in the Ra-Th region as associated with the stable octupole deformation.

We have calculated the energy displacement $\Delta E$ for Th isotopes, by the simple formula (2). The results appear by about one order smaller than the experimental values deduced from the $K\pi=0^-$ levels. One should stress, however, that a one order discrepancy in $\Delta E$ is not so much as one might think at the first moment. The calculations show that $\Delta E$ is an extremely subtle and sensitive quantity. For example, a 0.5 MeV change in the octupole barrier height $E_B$ changes $\Delta E$ by about 1.0-1.5 orders. Thus, $\varepsilon_3^O$, the dynamical treatment of the penetration of the octupole barrier may remove such discrepancy by itself. Having this in mind, we should not expect and intend to accurately reproduce the $K\pi=0^-$ energies, related to $\Delta E$, without subtle refinements and improvements of the calculations. Instead, we should rather treat these energies as supplying a chance for extremely subtle and sensitive tests for a number of theoretical quantities, in particular the potential energy, for nuclei in the Ra-Th region. The only similar tests are supplied by the third minimum Th data\textsuperscript{11}) and (for the quadrupole deformation and for slightly heavier nuclei) by the fission-isomer data\textsuperscript{12}).

![Fig.3. Correlation between the height of the octupole barrier $E_B$ and the experimental energy $E_{1-}$ of the lowest $K\pi=0^-, I\pi=1-$ state, for isotopes of Th.](image-url)
4. Conclusions

The following conclusions may be drawn from our study:

(i) A stable octupole deformation, $\varepsilon_3 \neq 0$, with a large octupole barrier $E_B$ (fig.1) is obtained in the calculations for nuclei in a rather wide region around Ra and Th. Besides Ra and Th isotopes, it appears also for the isotopes of Rn, U and Pu. The largest barrier is obtained for isotopes with the neutron number $N$ around 136.

(ii) A clear correlation between the experimental energy $E_3$ and the barrier height $E_B$ supplies a support for the interpretation of the lowest $K\pi=0^-$ states as being associated with the stable octupole deformation.

(iii) Assuming this interpretation, the energy of the lowest $K\pi=0^-$ states is a very sensitive function of the barrier height $E_B$, as well as of the inertia of a nucleus against the octupole deformation $\varepsilon_3$. Thus, this energy supplies a subtle test for both these quantities.

(iv) The obtained results show the importance of the consistency condition between the macroscopic and microscopic parts of the potential energy, which was disregarded in previous calculations. Account for this condition is particularly important for the deformations of multipolarity $\lambda$ higher than two.

We are grateful to Professor J. Zylicz for drawing the attention to the problem and to him and Dr. W. Kurcewicz for helpful discussions.

References


12) A. Lukasiak, A. Sobiczewski, A. Baran and K. Pomorski, these Proceedings.

DISCUSSION

J. Zielos: From the experimental data, Kurcewicz estimated the heights of barrier to be roughly half of your values. Can you comment on this difference?

A. Sobiczewski: In the estimate of Kurcewicz, it is assumed that the energy displacement $\Delta E$ may be exactly reproduced using a one-dimensional (only octupole) and very schematic barrier. I do not think one may consider such simple model as a very realistic one; it may only be useful to look at some general tendencies.
COLLECTIVE STATES AND NUCLEAR SYMMETRIES

V. Paar
Prirodoslovno-Matematički Fakultet, Zagreb, Yugoslavia

This paper had not been received when the volume went to press, but it will, if at all possible, be included as a post-deadline paper at the end of these Proceedings. The following discussion took place after the presentation of this paper.

DISCUSSION

A. Gelberg: 1) The IBM has reached a state at which we can investigate the validity limits of the model. They probably correspond to strong deformation and high spins (equivalently, introduction of g, i, etc. bosons). 2) What is the relation between your coherent state and that used by Ginochio and Kirson?

V. Paar: 1) As I have presented in my talk, the IBM is a particular type of quadrupole phonon model in which certain anharmonic terms (already of the third order) are neglected. The error made by this approximation approximately corresponds to the error made by truncation of the boson expansion. Therefore, one should look back at old papers on the limitations of quadrupole phonon approach (phenomenological, boson expansion, etc.). 2) It is exactly the same. Ginochio and Kirson have not been aware of the work done previously by Perelomov (Commun.Math.Phys., Springer Verlag, 1972) and Jolos, Janssen, Dörnan ( Yad.Fys. - Sov.J.Nucl.Phys., 1975).

N. Zeidler: I have two questions: 1) How close to doubly-closed nuclei can you use these models? 2) You mentioned a 'Low Seniority' approximation in the quadrupole phonon model. Is this Seniority related to the Seniority introduced by Racah in the shell model?

V. Paar: Up to about 6 nucleons or nucleon holes. - It is only similar, in the sense that the larger number of phonons corresponds to lower seniority.

K.K. Seth: What do you think is the prospect of applying the IBA type models to the light nuclei of the s-, d-shell (like Mg, Si, etc.) in which collective features are well developed? One could profit from the economy of description of these models and integrate the rotational + very vibrational levels which are abundant in these nuclei. It is in these nuclei that one can also test these models against microscopic theories.

V. Paar: Quadrupole phonon models, and so the SU(6) quadrupole phonon model as its special case, are applicable in the cases when the collective quadrupole mode is well developed, as is the case in most medium and heavy nuclei. This aspect is not as well pronounced in light nuclei, but for certain cases and properties (especially farther away from stability line) is present. For example, onset of deformation in the s,d shell due to lowering of f-orbitals may be described by collective quadrupole model. Generally, in light nuclei one would couple pronounced single particle degrees of freedom to these collective modes.
A NEW METHOD FOR A CONSISTENT DESCRIPTION OF THE STRUCTURE OF EVEN-EVEN AND EVEN-ODD NUCLEI

V. Klemt
Institut für Kernphysik, Kernforschungsanlage Jülich, Jülich, West Germany

Abstract

When adapted to finite systems, Landau's theory of Fermi liquids encounters the problem of how to deal consistently with even-even and even-odd systems. It is shown here that it is necessary as well as possible to generalize Landau's concept by setting up a closed set of equations that describes both kinds of systems, with the totally irreducible part of the many-body T-matrix playing the role of the fundamental interaction.

1. Introduction

As is well known, the energy spectrum of an even-odd system is described by the eigenvalues $E_S$ of Dyson's equation

$$E_S \delta_{\lambda\lambda'} - t_{\lambda\lambda'} - M_{\lambda\lambda'}(E_S) = 0$$

(1)

Here $\lambda$ denotes the set of quantum numbers of the single-particle basis that diagonalizes the equation, $t$ is the operator of the kinetic energy and $M$ is the mass operator, which contains all contributions resulting from the interaction of the particles. In first order perturbation theory it would be energy independent and eq. (1) would reduce to the Hartree-Fock equation.

The excitations of an even-even system, on the other hand, are governed by equations of the Bethe-Salpeter type, which are more complex in structure than eq. (1) and include, as their most widely used approximation, the RPA equations

$$(\omega - \varepsilon_{1\nu} - \varepsilon_{2\mu}) \delta_{\mu\nu} = (n_{\nu} - n_{\mu}) \sum_{34} F_{1234} \delta_{\mu\nu}$$

(2)

The interaction amplitude $F$ is the particle-hole (ph) irreducible part of the many-body T-matrix and is the finite-system equivalent to Landau's amplitude for infinite systems.

To handle eqs. (1) and (2) consistently one would like to have a relation between the mass-operator $M$ and Landau's amplitude $F$. In fact, $F$ is known to be the variational derivative of $M$ with respect to the particle density

$$F = \delta M / \delta \rho$$

(3)

which can be used to formulate consistency relations that have been exploited by several authors. But even disregarding the fact that eq. (3) is not so simple as it looks at first sight, it cannot be integrated straightforwardly, what would be needed to get an expression for $F$ in terms of $M$.

2. The basic set of equations

But there is another solution to the problem by using a well-known identity for the Hamiltonian, which makes it look somewhat single-particle-like:

$$H = \frac{1}{2} \sum_{12} (t_{12} a_{1\lambda} a_{2\lambda}^+ + H. a_{1\lambda} a_{2\lambda}^+)$$

$$= \frac{1}{2} \sum_{12} (t_{12} a_{1\lambda} a_{2\lambda}^+ + t_{12} a_{1\lambda} a_{2\lambda}^+)$$

(4)

In this form it can be used to form a response equation where it formally plays the part of an external single-particle field. This allows one to get an expression for the energy difference

$$E_S = \langle \psi_S(A+1)|H|\psi_S(A+1)\rangle - \langle \psi_S(A)|H|\psi_S(A)\rangle$$

that virtually is an alternative formulation of Dyson's equation (1) for magic $\nu$-nuclei:

$$E_S \langle 1|\lambda \rangle = \sum_{2,3} \langle \psi_S(A+1)|H|\psi_S(A+1)\rangle +$$

$$+ \sum_{34} \langle \psi_S(A+1)|H|\psi_S(A+1)\rangle$$

(5)

Here $G$ is the single-particle (sp) Green function, while

$$Z_S = \langle \psi_S(A+1) | \sum_{\alpha} a_{\alpha}^+ | \psi_S(A) \rangle$$

is the sp-strength of the state $|\psi_S(A+1)\rangle$, where $|\alpha\rangle$ is the eigenvector of eq. (5) corresponding to the eigenvalue $E_S$ and $T$ is the above-mentioned many body T-matrix.

The sp-strengths $Z_S$ can be obtained from a related equation,

$$1 - Z_S = \sum_{1234} \langle 1|2 \rangle \langle 2|1 \rangle$$

(6)

which is the counterpart of eq. (5) with the number operator as external field.

It is of course the T-matrix that contains all the necessary information of the many-body system and it depends on what we know about it how far we can proceed in numerical calculations. In any case there exists a system of equations that describes the structure of the T-matrix in terms of its totally irreducible part $K$. It shall be given here for short in matrix form:

$$T = K + FRF + \frac{\sigma}{4} IG_{11}$$

(7)

$F$, $F$ and $I$ are the irreducible parts of $T$ in the respective channels (the two ph-channels and the particle-particle [pp] channel). They are given in terms of $K$ by equations like (7), only one of which shall be shown here:

$$F = K + FRF + \frac{\sigma}{4} IG_{11}$$

(8)

Here $G_{11}$ is the two-particle Green function and $R$ its non-decomposing part,

$$R = G_{11} - GG$$

(9)

sometimes called the response function.

Eqs. (5) to (8) would be sufficient to describe the even-odd systems, if one would know $G_{11}$. To this end one needs a generalization of the RPA equation (2) that allows for the energy dependence of the
amplitudes $F$ and $I$. Such equations can be derived, as will be shown in a forthcoming paper$^3$), and they in fact complete the system of equations in the sense that the structure of nuclei (magic ones and their neighbours) can be described completely starting with the totally irreducible kernel $K$.

3. Discussion and conclusion

The above-mentioned considerations illustrate the well-known fact that the surface of finite nuclei has such an important influence on their structure that Landau's amplitude $F$ can no longer be considered inert. So one has to resort to the more fundamental totally irreducible amplitude $K$. Furthermore the formalism developed above is general enough to describe even-odd nuclei on the same footing as even-even ones. This is e.g. not the case for conventional perturbative approximations of the mass operator, where the simultaneous inclusion of ph- and pp-phonons leads to a double-counting problem that has to be mended by correcting second order graphs$^6$). This is probably due to the unavoidable omission of genuine three-particle clusters that cannot be traced back to simpler structures, a problem that is nonexistent in our formulation.

References
3) V. Klemt to be published.
1. Experimental study

The odd mass Sb nuclei, up to A = 127, have been the subject of many experimental \(^1\) as well as theoretical investigations \(^2\) since the interplay between the proton single-particle motion in the 50-Z+2 and the quadrupole and octupole vibrations of the underlying core nuclei is manifested in a clear-cut way in these nuclei.

In the case of \(^{123}\)Sb and \(^{131}\)Sb for which only scarce information exists\(^3\), \(^4\), \(^5\) limited validity of this approach is expected, due to the very strong deviations from the doubly even \(^{125}\)Sn nucleus and a harmonic quadrupole vibrator \(^6\).

An experimental effort was therefore made, in first time on \(^{131}\)Sb, in order to check more refined one-proton-one-hole two-neutron-hole shell model calculation with two different proton-neutron residual interactions.

We used the Lohengrin facility \(^7\) at the high flux reactor of the Institute Laue-Langevin in Grenoble, which separates the recoiling products of thermal neutron induced fissions within a few microseconds, to obtain pure \(^{131}\)Sb activity. The sharing of the different gamma-transitions between the two well known beta isomers of \(^{131}\)Sn, 11/2\(^-\) and 3/2\(^+\) whose half lives are 50 sec. and 30 sec. respectively, was performed by using the variation of the isomer formation ratio with kinetic energy in the fission, an effect which is easily exploited at Lohengrin \(^8\). In some earlier work, \(\text{ref. 4-5}\), an 50 \(\mu\)s excited isomeric state, was observed at 1676 keV in \(^{131}\)Sb by performing fragment-gamma delayed coincidences at Lohengrin. To find evidence for gamma transitions between levels above this isomeric level, and eventually fed by beta decay, delayed beta-gamma and gamma-gamma coincidences were also performed at Lohengrin with a time-window of several microseconds.

The on-line fission-fragment separator Josef \(^9\) at the K.F.A. Jülich was used for prompt gamma-gamma coincidence measurements needing more intense radioactive sources.

The proposed level scheme for \(^{131}\)Sb is shown in figure 1 where spin assignment are based on beta feeding considerations as well as gamma branching ratios. An additional line of 82.3 keV (8%) could not be definitely placed in the proposed level scheme; this line disappears in both prompt beta-gamma and delayed gamma-gamma coincidences and was not observed by fragment-gamma delayed coincidences performed on \(^{131}\)Sb

where 50 \(\mu\)s activities were identified. Nevertheless, as shown by the "Bp" identification method performed at Josef, this line belongs to \(^{131}\)Sb and his probable position is therefore above the isomeric level at 1675.9 keV.

In figure 2, we indicate the essential features concerning the odd-mass antimony isotopes from A = 121 up to A = 131. For \(^{125}\)Sb, an important lack of information on excited states shows up. Moreover, we further remark a smooth increase in excitation energy, with increasing neutron number, for the 5/2\(^-\), 3/2\(^+\) and 1/2\(^+\) levels with respect to the 7/2\(^+\) level. Finally, the existence of a multiplet containing the spin states 9/2\(^+\), 11/2\(^+\) near 1200 keV is evidenced, although only in \(^{131}\)Sb, a detailed knowledge of all members of the multiplet has been obtained.

The low lying 7/2\(^+\) and 5/2\(^+\) states probably contain most of the proton single particle states 1 \(g\) 7/2 and 2 \(d\) 5/2 respectively. The 3/2\(^+\) and 1/2\(^+\) higher lying states definitely contain important admixture of particle core compiles \(1 \text{g} 7/2, 2 \text{g} 5/2\) configuration besides the proton single particle 2 43/2 and 3 5/2 configuration.

2. Theoretical predictions

A more detailed description for the excited states in \(^{131}\)Sb can be obtained by treating all one-proton two-neutron-hole configuration with residual interaction, within a shell-model approach. Starting from the general formalism, developed in order to treat m-proton n-neutron nuclei \(^{141}\)Te, \(^{151}\)Sb, we have obtained in the specific case of a one-proton two-neutron hole nucleus (such as \(^{131}\)Sb), the expression

\[
\langle \beta'\lambda\rangle_{\text{pp}}\langle \gamma'\lambda\rangle_{\text{nn}}\langle \lambda\rangle_{\text{pp}}\langle \gamma\lambda\rangle_{\text{nn}} \chi_{\lambda}(-1)^{I_p+I'_p} \tilde{J}_p \tilde{J}'_p \tilde{J}_n \tilde{J}'_n \chi_{\lambda}
\]

\[
\chi_{\lambda} \equiv \left\langle \text{C}_n^{\lambda} \text{C}_n^{\lambda} \right\rangle \text{C}_n^{\lambda} \text{C}_n^{\lambda},
\]

whereas the residual proton-neutron interaction \(^12\). This expression is formally equivalent with the macroscopic particle-core coupling matrix element. The core matrix elements \(^11\) however, are defined in terms of their shell-model description. Therefore, first carrying out the two-hole shell-model calculation for \(^{125}\)Sn \(^8\) supple the wave-functions necessary to calculate the \(\langle \beta'\lambda\rangle_{\text{pp}}\langle \gamma'\lambda\rangle_{\text{nn}}\langle \lambda\rangle_{\text{pp}}\langle \gamma\lambda\rangle_{\text{nn}} \chi_{\lambda} \equiv \left\langle \text{C}_n^{\lambda} \text{C}_n^{\lambda} \right\rangle \text{C}_n^{\lambda} \text{C}_n^{\lambda}\) reduced matrix elements.

The proton-neutron residual interaction consists of a quadrupole + octupole expansion with strength
parameters (see also ref.2) $\chi = -0.08$ MeV, $\chi = -0.06$ MeV, giving a good agreement with the 131Sb experimental level scheme. Calculations with $\delta$ interaction have also been rather successful in describing nuclei near 132Sn (ref.13). Proton and neutron single-particle and single-hole energies respectively, were discussed in ref.3. The neutron residual interaction was a Gaussian interaction also fully described in ref.3.

Carrying out the calculations of energy spectra—shown figure 3—electromagnetic transition rates (M1,E2,M2,E3,...) the following interesting results occur (see also fig.3 and table 1):

- besides the low-lying single-particle states $1g_{9/2}$, $2d_{5/2}$, and $1h_{9/2}$ configurations, $3^{-}$, near $E_x \sim 1.6$ MeV, negative parity levels result from coupling the $1g_{9/2}$ proton single-particle orbit with the $1/2^+ \rightarrow 1/2^+$, $1/2^+ \rightarrow 3/2^+$, $1/2^+ \rightarrow 5/2^+$, $1/2^+ \rightarrow 7/2^+$, $1/2^+ \rightarrow 9/2^+$ states in $152Sn$. The latter levels cannot result from a purely macroscopic approach.

- some more positive parity levels are obtained by coupling the proton single-particle states to non-collective levels obtained from the two-hole shell model calculation describing levels in $132Sn$ i.e. $J^P = 2^+ \rightarrow 0^+$, $2^+$, $4^+$.

- Above $E_x \sim 2$ MeV, the level density, both experimentally and theoretically, becomes so large such as to make precise assignments impossible.

Electromagnetic M2 and E3 calculations point out that, in going from the $1g_{9/2}$, $7^-$ states towards the $1g_{9/2}, 2d_{5/2}$ configurations, the core wave function is undergoing an important change and thus nuclear isomerism can result. The theoretical calculation point out that the only candidates, compatible with the experimental data, are the $J^P = 13/2^+$ or $13/2^-$ levels. The theoretical excitation energy favours the $J^P = 13/2^+$ assignment for the isomeric level. The precise values for the half-lives, calculated using a $\delta$-interaction and a multipole interaction are given in Table 1. Finally, we can conclude that, up to $E_x \sim 2$ MeV, a good theoretical description of the experimental data in $131Sb$ is obtained by the one-proton two-neutrons hole shell-model calculation. Moreover, we point out that no important nuclear features are missing in a description of the nucleus $131Sb$.

### Table 1

<table>
<thead>
<tr>
<th>$J_1^P \rightarrow J_2^P$</th>
<th>$\delta$-interaction</th>
<th>Multipole interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$13/2^+ \rightarrow 7/2^+$</td>
<td>14</td>
<td>7.4</td>
</tr>
<tr>
<td>$\rightarrow 11/2^+$</td>
<td>573</td>
<td>260</td>
</tr>
<tr>
<td>$\rightarrow 9/2^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rightarrow 7/2^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$13/2^+ \rightarrow 7/2^+$</td>
<td>140</td>
<td>10</td>
</tr>
<tr>
<td>$\rightarrow 11/2^+$</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>$\rightarrow 9/2^+$</td>
<td>3.1</td>
<td>3300</td>
</tr>
<tr>
<td>$\rightarrow 7/2^+$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Theoretical partial $T_{1/2}(\gamma)$ values for the 13/2$^+$ and 13/2$^-$ levels. Half-life are given in usec.

### References

Fig. 1 - Proposed level scheme for $^{111}$Sb.
Spin assignments have to be considered as tentative.
Fig. 2 - Systematic of excited states in odd antimony isotopes.

Fig. 3 - Comparison of theoretical calculations, using a $\delta$-interaction or a quadrupole + octupole interaction as proton-neutron interaction, with experimental data. Angular momenta are denoted as $2\Omega$. The parentage (if very pronounced) on 2 hole levels of $^{112}\text{Sn}$ is also indicated. Dotted levels contain most of the corresponding proton single-particle configuration.
SINGLE-PARTICLE STATES AROUND DOUBLE-MAGIC $^{132}\text{Sn}$

J. Blomqvist,
Research Institute of Physics, S-104 05 Stockholm.

Abstract

Double-magic $^{132}\text{Sn}$ exhibits the strongest shell closure of any observed nucleus. The experimental data on single-particle states in the surrounding nuclei $^{131}\text{In}$, $^{131}\text{Sn}$, $^{132}\text{Sn}$ and $^{132}\text{Sb}$ are reviewed. Single-particle energies are calculated with a standard Woods-Saxon potential, and corrections resulting from a comparison with the $^{208}\text{Pb}$ region are applied.

1. The shell closure in $^{132}\text{Sn}$

The $^{208}\text{Pb}$ region has an established position of simple structure, where the properties of elementary modes of excitation can be studied under well defined conditions. There is a long history [1] of shell-model calculations for nuclei with a few valence nucleons outside of $^{208}\text{Pb}$, moving in a restricted number of shells above and below the Fermi surface. Collective particle-hole [2] and pair [3] excitations have been identified and described with the aid of tractable calculations. Polarization phenomena corresponding to the coupling of simple-particle and collective degrees of freedom can also be investigated under sufficiently simple conditions.

More recently it has been found [4] that $^{132}\text{Sn}$ shows a similar strong shell closure as $^{208}\text{Pb}$. This has opened the possibility to explore the properties of simple states in the $^{132}\text{Sn}$ region under conditions which are comparable to but not identical with those in the $^{208}\text{Pb}$ region. The experimental difficulties around $^{132}\text{Sn}$ relate to the circumstance that these nuclei are displaced - 10 nucleons away from the line of $\beta$-stability to the neutron-rich side (Fig. 1).

This implies that nuclear reaction studies are essentially excluded. The nearest approach [5] seems to be the $^{130}\text{Xe}(d,^3\text{He})$ reaction which leads to $^{131}\text{I}$, 3 protons away from $^{132}\text{Sn}$. The production method for $^{132}\text{Sn}$ and its closest neighbours is in practice limited to fission of actinides, in which case the heavy fragment has a reasonable chance to end up near $^{132}\text{Sn}$. Spectroscopic studies of specific fission fragments have so far required the use of mass separation to clear up the spectra.

The presently known levels in $^{132}\text{Sn}$ are shown in Fig. 2.

![Fig. 2 Levels in $^{132}\text{Sn}$](image)

The information comes partly from the $\beta$-decay [6] of $^{132}\text{In}$, partly from the direct production in fission [7] of the isomeric $\beta^+$ state. The $\beta$-decay proceeds mainly by a fast Gamow-Teller transition to a particle-hole state at 7.2 MeV. The very large $Q_\beta$ value and the predicted existence of other configurations which can be reached by strong $1^+$ forbidden transitions implies that it should be possible to observe more levels in $^{132}\text{Sn}$ with reasonable intensities.

The energies of the lowest levels in $^{132}\text{Sn}$ and $^{208}\text{Pb}$ are compared in Fig. 3.

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Fig. 3 All levels in $^{132}\text{Sn}$ below 5 MeV, and in $^{208}\text{Pb}$ below 4.5 MeV. The three dashed levels in $^{132}\text{Sn}$ are predicted by a shell-model calculation.

The 24 levels shown in $^{208}\text{Pb}$ have all been observed, and no further ones are expected to occur below 4.5 MeV. In $^{132}\text{Sn}$ three predicted levels have been included in order to complete the set of levels up to 5 MeV.

The most obvious feature in Fig. 3 is the larger gap between the ground state and the first excited state in $^{132}\text{Sn}$ compared to $^{208}\text{Pb}$. In fact, no other nucleus above $^{160}\text{O}$ has a gap as large as 4 MeV. Even allowing for an $A^{-1/3}$ dependence reflecting the variation with the size of the nucleus, the gap is considerably larger in $^{132}\text{Sn}$ than in $^{208}\text{Pb}$. From this point of view $^{132}\text{Sn}$ exhibits the strongest shell closure of any nucleus.

Looking in more detail at the excited levels one notices that the negative-parity states are very high in $^{132}\text{Sn}$, while the positive-parity states occur at about the same excitation energies as in $^{208}\text{Pb}$. The rapid lowering from $^{132}\text{Sn}$ to $^{208}\text{Pb}$ of the collective negative-parity states, in particular the $3^-$ state, is not expected in the liquid drop model. It is probably connected with the smaller octupole strength of the lowest stretched non-spinflip particle-hole excitations in $^{132}\text{Sn}$, compared with the analogous excitations in $^{208}\text{Pb}$.

The lowest positive-parity states are dominated by the $\Delta N = 0$ neutron excitation $\nu f_{7/2} h_{11/2}^{-1}$ in $^{132}\text{Sn}$ and $\nu g_{9/2} l_{13/2}^{-1}$ in $^{208}\text{Pb}$, with nearly equal single-particle energy differences.

2. Single-particle states in $^{131}\text{In}$, $^{132}\text{Sn}$, $^{133}\text{Sn}$ and $^{131}\text{Sb}$.

Of the four nuclei differing by one nucleon from $^{132}\text{Sn}$, the two farthest from stability ($^{131}\text{In}$ and $^{133}\text{Sn}$) have not yet been studied in any detail. Their ground state assignments are known, but a $1f_{5/2}$ isomer has been found in $^{131}\text{In}$ at an unknown excitation energy, but not other excited states have been observed. The experimental difficulty is due to the rapid decrease of the fission yield with increasing $N - Z$. The other two single-particle nuclei have been studied in some detail. The level schemes are shown in Fig. 4 ($^{131}\text{Sn}$) and Fig. 5 ($^{131}\text{Sb}$).
Levels in $^{133}$Sb have been observed both in the $\beta$-decay of $^{133}$In and in direct fission of $^{133}$Sn. The observed core-excited states between 4 MeV and 5 MeV are not understood in detail. Three of the five proton states in the major shell between 50 and 80 are firmly established in $^{133}$Sb, but $\pi s_{1/2}$ and $\pi d_{3/2}$ have not yet been identified.

In summary, 9 single-particle states have been observed out of a total of 20 in the four major shells above and below $Z = 50, N = 82$. In order to put these states on an absolute energy scale the nucleon separation energies $S_p(^{132}\text{Sn})$, $S_n(^{132}\text{Sn})$, $S_n(^{134}\text{Sn})$, and $S_p(^{133}\text{Sb})$ are needed.

3. Ground state masses of $^{131}\text{In}$, $^{133}\text{Sn}$, $^{132}\text{Sn}$, $^{133}\text{Sn}$ and $^{133}\text{Sb}$.

The masses of these nuclei are not all known. The experimental values that exist are based on measurements of total $\beta$-decay energies. The following mass excess values are adopted.

- $\text{ME}^{(131}\text{In}) = -68.50(25)$ MeV ref. 8
- $\text{ME}^{(133}\text{Sn}) = -76.59(8)$ MeV ref. 12
- $\text{ME}^{(133}\text{Sb}) = -78.98(21)$ MeV ref. 13

In order to estimate the masses of $^{131}\text{Sn}$ and $^{133}\text{Sb}$ we can apply mass relations derived from nuclearity model analysis of a simple $\nu\nu^-$ state in $^{132}\text{Sb}$ and another $\nu\nu^-$ state in $^{132}\text{Sn}$.

The ground state of $^{132}\text{Sb}$ has $I^\pi = 4^-$ and the dominant configuration $\pi g_{7/2} \nu d_{3/2}$. The particle-hole interaction energy is given by the difference between the proton separation energies

$$\text{INT} = S_p(^{133}\text{Sb}) - S_p(^{133}\text{Sn})$$

This interaction energy is expected to be small due to the large angle between the $g_{7/2}$ and $d_{3/2}$ angular momentum vectors in the $I = 4$ coupling. It may be taken equal to the interaction energy in the analogous

$$\pi h_{9/2} \nu f_{5/2}^{-}, \ I^\pi = 6^- \text{ state in } ^{208}\text{Bi}$$

$$\text{INT} = S_p(^{208}\text{Bi}) - S_p(^{208}\text{Bi}) + E(6^-, ^{208}\text{Bi})$$

$$-E(4^-, ^{207}\text{Pb})$$

$$= + 0.03 \text{ MeV}.$$
This value together with the measured mass excess \( ^{122}\text{Me}(^{132}\text{Sb}) = -79.67(7)\text{ MeV} \) gives

\[
\text{ME}(^{131}\text{Sn}) = \text{ME}(^{133}\text{Sn}) + \text{ME}(^{132}\text{Sb}) - \\
\text{ME}(^{133}\text{Sb}) - \text{INT} = -77.31(24)\text{ MeV}.
\]

It is assumed that the error in the estimated interaction energy is smaller than the error from the measured mass excesses.

A similar analysis can be made for the \( 4^- \) state in \(^{132}\text{Sn}\) at 4.03 MeV, which is described as

\[ v_f f_{7/2} d_{3/2}^{-1} \]

excitation. The particle-hole interaction energy is estimated by a comparison with the

\[ v_g g_{9/2} f_{5/2}^{-1}, I^\pi = 6^- \]

state in \(^{208}\text{Pb}\) at 3.92 MeV to be

\[ \text{INT} = -0.08\text{ MeV}. \]

From this follows the mass excess

\[ \text{ME}(^{131}\text{Sn}) = 2 \text{ ME}(^{133}\text{Sn}) - \text{ME}(^{131}\text{Sn}) + \\
E(4^-,^{132}\text{Sn}) - \text{INT} = -70.96(22)\text{ MeV}. \]

The single-nucleon separation energies derived from the mass excesses are

\[ S_p(^{133}\text{Sb}) = 9.68\text{ MeV} \quad S_n(^{133}\text{Sn}) = 2.44\text{ MeV} \]
\[ S_p(^{132}\text{Sn}) = 15.38\text{ MeV} \quad S_n(^{132}\text{Sn}) = 7.35\text{ MeV} \]
all with uncertainties of about 0.2 MeV.


For comparison with the empirical energies and in order to fill the holes in the systematics of single-particle states around \(^{132}\text{Sn}\) a calculation has been performed with a standard Woods-Saxon potential. This phenomenological approach is known to reproduce the experimental single-particle energies around \(^{208}\text{Pb}\) with similar or better accuracy than the more fundamental approach based on Hartree-Fock theory. The results of a Woods-Saxon calculation for the \(^{208}\text{Pb}\) region is shown in Fig.6.

![Fig. 6 Single-particle energies in the major shells around \(^{208}\text{Pb}\). The parameters of the Woods-Saxon potential are](image)

\[
V_{op} = 59.0\text{ MeV}, V_{on} = 44.5\text{ MeV}, \\
V_{ls} = 23\text{ MeV}, V_{ls} = 19\text{ MeV}, \\
r_o = 1.27\text{ fm}, r_{ls} = 1.15\text{ fm}, \\
a = 0.70\text{ fm}. 
\]

The Woods-Saxon potential summarizes different physical effects in a simplified manner. It is known from Hartree-Fock calculations that the bare single-particle energies around the Fermi surface are spread out, corresponding to an effective mass considerably smaller than the nucleon mass. This is compensated by a coupling of the single-particle states to collective vibrations, which compresses the spectrum so much that the resulting effective mass comes close to the nucleon mass. The extra large shifts of the neutron \(3^+\) and \(f_{7/2}\) states seen in Fig.6 are probably connected with strong near-resonance couplings to the low 2.6 MeV 3\(^-\) excitation.

The Woods-Saxon calculation for the \(^{132}\text{Sn}\) region is illustrated in Fig.7.
Fig. 7  Single-particle energies in the major shells around $^{132}$Sn. The parameters of the Woods-Saxon potential are

$$V_{op} = 60.6 \text{ MeV}, \quad V_{on} = 43.5 \text{ MeV},$$

$$V_{isp} = 20 \text{ MeV}, \quad V_{isn} = 19 \text{ MeV},$$

$$r_0 = 1.27 \text{ fm}, \quad r_{1s} = 1.15 \text{ fm},$$

$$a = 0.70 \text{ fm}.$$

The errors in the energies are expected to be of the same magnitudes in the $^{132}$Sn and $^{208}$Pb regions. Lacking a quantitative understanding of the finer details of the single-particle energies it may still be possible to correlate the differences between the Woods-Saxon and the experimental energies in the two regions. By comparing Figs. 6 and 7 one will notice a close similarity between the shell structures in the two regions. Every state in the $^{132}$Sn region corresponds to one particular state in the $^{208}$Pb region with the same radial quantum number n but one unit larger angular momenta l and j. With a few exceptions the correspondence also applies to the ordering and energy spacings of the single-particle states. This makes it natural to assume that the discrepancies between calculated and experimental energies have similar origin and should be roughly equal for the related levels in the two regions. For definiteness we may assume

$$\Delta_{n1j}(^{132}\text{Sn}) = \left(\frac{^{208}\text{Pb}}{^{132}\text{Sn}}\right)^{1/3} \Delta_{n1j+1}(^{208}\text{Pb})$$

where $\Delta$ is the difference

$$\Delta = \varepsilon_{WS} - \varepsilon_{Exp}.$$

These shifts are added to the Woods-Saxon energies in the $^{132}$Sn region. The resulting energies and a comparison with the known experimental energies are shown in Fig. 7 and Table 1.

Table 1. Calculated and experimental single-particle energies in the $^{132}$Sn region (MeV).

<table>
<thead>
<tr>
<th>Protons</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>l j</td>
<td>1 j</td>
</tr>
<tr>
<td>WS + $\Delta$</td>
<td>Exp</td>
</tr>
<tr>
<td>h $^{1/2}$</td>
<td>-6.70</td>
</tr>
<tr>
<td>d $^{3/2}$</td>
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</tr>
<tr>
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<td>d $^{5/2}$</td>
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</tr>
<tr>
<td>g $^{7/2}$</td>
<td>-9.57</td>
</tr>
<tr>
<td>g $^{9/2}$</td>
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</tr>
<tr>
<td>p $^{1/2}$</td>
<td>-16.30</td>
</tr>
<tr>
<td>p $^{3/2}$</td>
<td>-17.23</td>
</tr>
<tr>
<td>f $^{5/2}$</td>
<td>-18.65</td>
</tr>
<tr>
<td>d $^{5/2}$</td>
<td>-8.83</td>
</tr>
</tbody>
</table>

The rms deviation of the calculated and measured values is 0.3 MeV. A similar accuracy is expected for those states which have not yet been observed.
References


9) Fogelberg, B. private communication


13) Wapstra, A.H. and Bos, K. Atomic Data and Nuclear Data Tables 19 (1977) 177

DISCUSSION

K. Aleklett: Which error bars on the masses in the $^{132}$Sn region will improve your calculations?

J. Blomqvist: An improvement of the accuracy of some of the $Q_{zz}$ values to 50-100 keV would be very welcome.

K. Bloemer: Had you to change the parameters of the Wood-Saxon potential when going so far off from the stability line?

J. Blomqvist: Yes, the Woods-Saxon potential was allowed to vary from Pb to Sn. However, the changes were small, of the order of 1 MeV for the depth of the potentials.

F. Tondeur: When fitting your Woods-Saxon potential, did you allow a full free variation of all parameters, e.g. different radii for protons and neutrons, or different diffuseness?

J. Blomqvist: No. Of the 7 parameters only the two central potential depths were allowed to vary. The radii and diffuseness parameters were kept constant.
THE $2.57$ MeV $19/2^-$ TWO-PHONON OCTUPOLE STATE IN $^{147}$Gd

P. Kleinheinz, J. Styczen, M. Piparinen, M. Kortelainen
Institut für Kernphysik, KFA Jülich, Jülich, F.R. Germany

J. Blomqvist
Research Institute of Physics, Stockholm, Sweden

Abstract

The half life of the $(v_{1/2} \times 3^+ \times 3^-)$ $19/2^-$ two-phonon octupole state at $2.572$ MeV in $^{147}$Gd was measured as $T_{1/2} = 0.37(8)$ ns, which gives a transition strength of $52(15)$ W.U. for the $1525$ keV E3 transition to the $0.997$ MeV $(v_{1/2} \times 3^+)_{13/2^+}$ one phonon excitation. The $v_{13/2}$ admixture in the $13/2^+$ one-phonon state, as well as the dominant $n_{11/2}g_{5/2}$ component of the $146$Gd $3^-$ state give rise to large anharmonicities for the two-phonon excitation. An estimate of the energy shifts based on empirical coupling matrix elements gives $2.66$ MeV excitation for the $19/2^-$ two-phonon state, in good agreement with the observed energy of that state.

Since many years attempts have been made to identify two-phonon octupole states in nuclei. Such excitations could in principle be most clearly observed in Coulomb excitation with heavy ions. But even in the simple case of $^{208}$Pb, which was studied through Coulomb excitation with $^{208}$Pb beam as well as through other experiments, it was so far not possible to identify the two-phonon octupole states expected in the $5.2$ MeV region.

In $^{146}$Gd the octupole phonon lies 1 MeV lower than in $^{208}$Pb, at $1.6$ MeV, and in the neighbouring $^{147}$Gd nucleus it occurs as low as $1$ MeV. This low excitation, and the detailed knowledge of the $^{147}$Gd level structure below $3$ MeV, makes this nucleus particularly favourable for a study of two-phonon octupole excitations.

Some time ago we have observed$^1$ in $^{147}$Gd a $19/2^-$ level at $2.572$ MeV which decays by two stretched E3 transitions to the $v_{1/2}$ ground state (Fig. 1). In ref. 1 we have discussed that this level must have a significant $v_{1/2} \times 3^+ \times 3^-$ two-phonon contribution, but at that time the experimental data were insufficient to determine the properties of this state in detail. Since then more quantitative knowledge on octupole-particle coupling phenomena in this region$^{2,3}$ which will also strongly affect the two-phonon excitations. Furthermore, we have now measured the strength of the $19/2^-\rightarrow 13/2^+$ E3 transition.

A measurement of the $19/2^-$ level half life is difficult since other high-spin isomers, with $T_{1/2} = 4$ ns and $27$ ns, occur closely above in the level scheme (Fig. 1) and since only $13$ % of the yrast decay proceeds through the $19/2^-$ state. Moreover, an $84$ keV E1 $\gamma$-ray competes with the $1575$ keV E3 deexcitation, and therefore the level half life is expected to be well below $1$ ns. For these reasons, various coincidence measurements involving detection of $\gamma$-rays and conversion electrons only gave an upper limit of $<1$ ns for the half life of $1/2$. A much better population yield for the $19/2^-$ level is achieved in the $(^{4}He,3n)$ reaction where the direct side feeding to the state is quite large and where the higher-lying isomers are only weakly populated. This makes it possible to determine the half life in a singles timing experiment. In a measurement of the time delay relative to the beam burst of $1575$ K electrons carried out with a $22$ MeV $^3$He beam from the cyclotron at Jyväskylä we obtained the result

$$T_{1/2} (19/2^-, 2.57 \text{ MeV}) = 370(80) \text{ ps}.$$ 

The conversion electrons were focussed in a magnetic lens spectrometer operated in swept-current mode and energy analyzed in a S(1L) spectrometer$^4$. This measurement simultaneously provided several prompt standards at neighbouring energies which were essential for evaluation of the final result. (In an independent measurement at slightly higher bombarding energy the $146$Gd $3^-$ state at $1.58$ MeV is also populated, and from the delay of the $1579$ K electrons we obtained $T_{1/2} (3^-, 1.58 \text{ MeV}) = 1.06(6) \text{ ns in perfect agreement with the earlier result}$. Taking into account the error in the $1575$ to $84$ keV intensity ratio the measured half life gives

$$B(E3, 1575 \text{ keV}) = 52(15) \text{ W.U.}.$$ 

This very high transition strength supports the two-phonon character of the $19/2^-$ level.

The simplest expectation is that the two-phonon state should occur at twice the energy of the one-phonon state, and should decay with a rate twice as large as the one-phonon transition. It is apparent that the experimental findings deviate from this simple predictions for both, energy and transition rate.

Two different phenomena are expected to affect the energy of the two-phonon state in $^{147}$Gd. The first is associated with the coupling of the neutron $f_{7/2} \rightarrow 1_{13/2}$ excitation to the octupole vibration, while the second reflects the action of the Pauli principle between the particle-hole components of the two phonons.

The $13/2^+$ level at $1.00$ MeV has a considerable admixture of the $1_{3/2}$ single neutron state due to the large coupling matrix element

$$m = |c_{13/2}^i |^2 H_{\text{coup}} |f_{7/2} \times 3^+; 13/2^+\rangle.$$ 

The situation is basically similar to that observed in the $N=127$ nucleus $^{209}$Pb, where the corresponding single particle orbits are $g_{9/2}$ and $f_{15/2}$ (Fig. 2). Whereas however in $^{208}$Pb the $1.42$ MeV $15/2^+$ state is is $= 70%$ single particle character$^5$ with about $30%$ admixture of $g_{9/2} \times 3^-$, the situation is reversed in $^{147}$Gd, where the octupole lies lower in energy than the $11/2^+$ single particle state.

When the difference $\delta$ between the single particle excitation energy $\varepsilon_{13/2} - \varepsilon_{7/2}$ and the phonon energy $\omega_3$

$$\delta = \varepsilon_{13/2} - \varepsilon_{7/2} - \omega_3$$
is comparable to the coupling matrix element \( m \), the energy \( E \) of the low-lying mixed state is obtained by diagonalizing the \( 2 \times 2 \) Hamiltonian

\[
E_{13/2} = \frac{J}{2} - \frac{1}{2} \sqrt{6^2 + 4m^2} - \frac{J}{2} \sqrt{6^2 + 8m^2} - \frac{J}{2} \sqrt{6^2 + 8m^2} + 6
\]

Similarly, the energy of the lowest 19/2\(^{-}\) state is obtained by diagonalizing the Hamiltonian in the basis of the two states \( \gamma_{1/2} \times 3^{-} \times 3^{-} \) and \( \gamma_{13/2} \times 3^{-} \)

\[
E_{19/2} = 2\hbar
\]

In second order perturbation theory the harmonic spectrum is preserved,

\[
E_{13/2} = \hbar - \frac{m^2}{8}
\]

\[
E_{19/2} = 2\hbar - 2\hbar = 2E_{13/2}
\]

However, for strong coupling, as in the present situation, this result is modified. \( E_{19/2} \) is higher than \( 2E_{13/2} \) by the amount

\[
\delta E_{19/2} = \sqrt{6^2 + 4m^2} - \frac{1}{2} \sqrt{6^2 + 8m^2} + 6
\]

The unperturbed \( \gamma_{13/2} \) energy in \( ^{147}\text{Gd} \) (and hence \( \delta \)) is experimentally not well known, but systematics of the N=83 isotones and other indirect spectroscopic evidence suggest \( a = 2.1 \text{ MeV} \) for the single particle energy separation, which is indicated in fig. 2. Using this \( \delta = 0.52 \text{ MeV} \), the observed \( E_{13/2} = 1.00 \text{ MeV} \) excitation is reproduced with \( m = 0.8 \text{ MeV} \). These values give

\[
\delta E_{19/2} = 0.26 \text{ MeV}
\]

The second effect is associated with the microscopic composition of the octupole phonon. There is evidence that the proton \( h_{11/2}d_{5/2} \) particle hole component occurs with large probability in the \( 3^{-} \) state. This is in particular seen clearly in the \( h_{11/2} \times 3^{-} \) particle-phonon multiplet in \( ^{147}\text{Tb} \). The experiment identified the \( 17/2^{+} \) and \( 15/2^{+} \) members of this group, which are separated by the large energy of 772 keV. This can be understood as an effect of the Pauli principle where the \( h_{11/2} \) proton particle in the phonon interferes with the \( h_{11/2} \) valence proton. The associated particle-phonon interaction matrix element \( M \) in the exchange process (fig. 3) is obtained from the \( 772 \text{ keV} 17/2^{+} \) to \( 15/2^{+} \) splitting to be

\[
M = 1.1 \text{ MeV}
\]

Fig. 1: High-spin levels in the one-neutron nucleus \( ^{147}\text{Gd} \) observed in the \( (\alpha,5n) \) reaction\(^{1}\). The 19/2\(^{-}\) half life is from the present work.

Fig. 2: Coupling of the valence neutron to the core octupole in \( ^{209}\text{Pb} \) and \( ^{147}\text{Gd} \).
taking for the energy denominator $\Delta$ the value

$$\Delta = \varepsilon_{11/2} - \varepsilon_{5/2} - h_{03} = 1.5 \text{ MeV}. $$

![Diagram](image)

Fig. 3: Coupling of the $h_{11/2}$ valence proton of $^{147}$Tb to the core octupole.

The two-phonon exchange process, which is analogous to the exchange coupling in fig. 3, is illustrated in the fourth order diagram of fig. 4. The large $|h_{11/2}d_{5/2}\rangle$ components in the two octupole phonons interact by exchanging the particle (or the hole). The interaction vertices in figs. 3 and 4 are the same, and we can therefore use the empirical values of $M$ and $\Delta$ which describe the Pauli effect in the $^{147}$Tb case to evaluate the energy shift $\delta E_{\text{I}}$ corresponding to the diagram in fig. 4. The shift is given by the expression

$$\delta E_{\text{I}} = 98 X (11/2, 2, 3; 5, 11/2, 2, 3, 3, 3, 1) \times \delta E_{\text{II}}$$

where $X$ is the coupled angular momentum of the two phonons. For the case $I=6$ the geometric coefficient is

$$X = 44239 / 52272 = 0.846$$

![Diagram](image)

Fig. 4: Phonon-phonon coupling in $^{146}$Gd.

and the energy shift

$$\delta E = 0.846 \times 1.1 = 0.93 \text{ MeV} = +0.41 \text{ MeV}.$$ This shift can also be adopted for the $19/2^+$ state of $^{147}$Gd, neglecting the $13/2^+ \times 3^-$ content in that state. This approximation may be of similar quality as the use of fourth order perturbation theory in describing the $3^- \times 3^-$ coupling.

Adding up the two contributions (fig. 5) the total energy shift $\delta E$ for the $19/2^+$ state is

$$\delta E = \delta E_{19/2} + \delta E_6 = (0.26 + 0.41) \text{ MeV} = 0.67 \text{ MeV},$$

which compares well with the experimental shift

$$\delta E_{\exp} = (E_{19/2} - E_{13/2}) - (E_{13/2} - E_{7/2}) = (1575 - 979) \text{ keV} = 0.58 \text{ MeV}.$$

Similar processes as those discussed above causing the energy shifts will also give rise to a reduction relative to the harmonic expectation of the $19/2$ to $13/2$ $E3$ strength.

The present data provide the first clear indication of a two-phonon octupole state. It has been shown that the large departure from equal energy spacing corresponding to harmonic vibration can be quantitatively understood in terms of the microscopic composition of the states and can be connected with other observed features of the octupole vibrations in this region.

References:
1) P. Kleinheinz, R. Broda, P.J. Daly, S. Lunardi, M. Ogawa, J. Blomqvist, Z. Physik A290 (1979) 279
2) R. Broda, M. Behar, P. Kleinheinz, P.J. Daly, J. Blomqvist, Z. Physik A293 (1979) 135
6) A. Bohr and B. Pottelso, Nuclear Structure Vol.II, P. 564 ff (Benjamin 1975)
8) S. Lunardi, M. Ogawa, M.R. Maier, P. Kleinheinz, ASHPIN, ANL/PHY-79-4, p. 393
ATOMIC MASSES ABOVE $^{146}$Gd DERIVED FROM A SHELL MODEL ANALYSIS OF HIGH SPIN STATES

J. Blomqvist
Research Institute of Physics, Stockholm, Sweden

P. Kleinheinz, R. Broda
Institut für Kernphysik, KFA Jülich, Jülich, Germany

P. J. Daly
Chemistry Department, Purdue University, Lafayette, Indiana, USA

Abstract

Using the extensive spectroscopic data on high spin states involving aligned valence nucleons in the very neutron deficient nuclei above $^{146}$Gd we have derived excitation energies of $^{146,148,150,152}$Gd, $^{148,153,155}$Ho, $^{149,150,151}$Er, and $^{150,151,152}$Er from a shell model analysis. The obtained mass values show a pronounced irregularity in the two-proton separation energies at $^{146}$Gd. The results also link nine $\alpha$-decay chains to the known masses.

Yrast states of moderately high spin in a region of nuclei around $^{145}$Gd can be well described in terms of spherical shell model configurations with a few valence nucleons. The stability of the spherical shape is mainly due to the N=82 shell closure, but the single particle energy gap$^{-1}$) at Z=64 must also be a significant contributing factor. The most direct evidence for the proton shell closure would be provided by observing a break in the masses of even nuclei across Z=64, but so far the measurements have not been extended to sufficiently proton-rich nuclei around N=82. In the present work we make detailed predictions of ground state masses for a number of nuclei in this region by exploiting relations between excitation energies for high-spin states of simple shell-model configurations. This method of relating spectra of excited states in neighbouring nuclei, and thereby also their ground state masses, was implemented many years ago in light nuclei by Talmi and collaborators. In heavy nuclei such complete shell model calculations are rarely feasible, however the same principles can still be applied by restricting the analysis to states dominated by a single shell model configuration. For example, it has been possible to calculate, with a precision of a few keV, the excitation energies of many aligned yrast states in the lead region$^{2}$ using the known ground state masses.

In the $^{146}$Gd region where crucial ground state masses are not known, one can apply the same techniques in a reverse manner to calculate the ground state masses from the known excitation energies of selected yrast states. The well known Garvey-Kelson method, connecting nuclear ground state masses through transverse and longitudinal mass relations, is also based on the assumptions of the shell model with interacting nucleons. Our scheme is founded on the same general ideas, but it takes account of excited states also, and considers more general types of mass relations.

Many aligned yrast states involving the $\pi_{1/2}^2$, $\nu_{5/2}^2$ and $\nu_{3/2}^2$ shell model orbitals are known in nuclei above $^{146}$Gd from recent in-beam $\gamma$-ray investigations. By combining the excitation energies of 65 such high-spin levels, three known Q$_{α}$ values and 7 known ground state masses, we have derived the ground state masses for the twelve nuclei shown in Fig. 1. This was done in several independent ways so that the consistency of the results could be checked. The mass uncertainties given in Fig. 1 are obtained from

\[
\begin{array}{ccc}
\text{MASS EXCESSES (keV)} \\
\text{Er} & -56909(420) & -57723(280) & -60105(164) \\
\text{Ho} & -61040(280) & -61579(164) & -63378(83) \\
\text{Dy} & -67459(164) & -67547(84) & -69178(30) \\
\text{Tb} & -70443(83) & -70402(40) \\
\text{Gd} & -75951(30) \\
\end{array}
\]

Fig. 1: Masses of ground states (high spin $\beta$-decay isomers) from the present analysis.

diagonal elements of the error matrix; in most cases the relative masses of neighbouring nuclei can be given with much better accuracy.

An examination of two-proton separation energies provides the most satisfactory test for a break in the nuclear mass surface, since complications of the odd-even staggering due to pairing can thus be avoided. Accordingly, the two proton separation energies obtained from our results are plotted in Fig. 2. A sharp discontinuity at Z=64 is obvious for the N=82 nuclei, but it is also apparent that this irregularity decreases rapidly when neutrons are added.

\[
\begin{array}{c}
\text{MeV} \\
9.5 \\
9 \\
8.5 \\
8 \\
\end{array}
\]

\[
\text{S_{2p} + 1.01(Z-64) - 0.4(N-82)}
\]

Fig. 2: Two-proton separation energies in the $^{146}$Gd region from the 1977 Wapstra-Bos mass table (dots) and from the present work (diamonds).
The results also link the nine $\alpha$-decay chains with $14 < N-Z < 18$ to the known masses, which now provides altogether 40 new mass values. The Fig. 3 shows a comparison with various mass predictions.

References

1) P. Kleinheinz, R. Broda, P.J. Daly, S. Lunardi, M. Ogawa, J. Blomqvist, Z. Physik A290 (1979) 279

Fig. 3: Comparison with various mass formulae. The present results minus the predicted mass values are shown.
DISCUSSION

P. Tondre: Your pairing calculations also give you results which can be of interest for masses: even-odd mass differences and the BCS chemical potentials \( \lambda \) which can be compared with the \( S_{2p} \) or \( S_{2n} \). Do you reproduce the experimental even-odd mass differences, and how does your \( \lambda \) compare with \( S_{2n} \) and \( S_{2p} \)? It seems to me that your proposal of two medium-sized gaps at \( N = 82 \) and \( Z = 64 \), not very different each from the other, contrasts with the small shift in \( S_{2p} \) and large shift in \( S_{2n} \) when crossing the magic numbers \( Z = 64 \) and \( N = 82 \), respectively.

P. Kleinheinz: The principal interest in our BCS analysis was only to see whether one could reproduce the \( N = 82 \) odd proton gap energies with a set of reasonably constant single particle energies (our results are given in Styczen et al., IRP Ann. Rep. 1980, p. 51, and preprint, submitted for publication, May 1981). It certainly would be quite attractive to carry out a more exhaustive theoretical analysis which reproduces these gap energies, the proton particle-hole (and \( 2p2\pi \)) excitations in \(^{146}\text{Gd}\) as well as the now available single proton and two-proton separation energies (Schmidt-Ott et al., and Blomqvist et al., these proceedings). If the resulting potential parameters are believed to also be valid for \( A = 132 \), it should also reproduce the known single particle energies in \(^{135}\text{Sb}\) [Sistemic et al., Z. Phys. A285 (1978) 305]. Equally attractive would be a similar analysis of the same four sets of experimental data on the \( N = 82 \) neutron gap in \(^{146}\text{Gd}\) which have now become available (Pardo et al., Pipestone et al., Schmidt-Ott et al., on the masses; Styczen et al., separate contribution to these proceedings on the quasi-particle energies and neutron particle-hole excitations). We mainly do experiments to obtain such data, which keeps us rather busy. But it would be nice if you could consider to carry out such analyses.

V. Zeidner: I would like to clarify the situation in relation to the seemingly contradictory evidence concerning the proton gap above \( Z = 64 \): from the separation energies, as shown by Prof. Schmidt-Ott on Monday, and also from the excitation energies of the \( \hbar \omega \) levels in Eu isotopes, the gap appears to be smaller than 1 MeV. On the other hand, Kleinheinz et al. (Z. Phys. A290 (1979) 279) claim that it is like the neutron gap above \( N = 82 \), of about 3.5 MeV. However, in their paper it is stated explicitly that their gap is the gap of a proton-hole in \( \text{Gd} \), which includes additionally to the above small proton-particle gap also the much larger proton pairing energy. Thus there is real contradiction.

R.K. Sheline: Just a short comment. This beautiful work presents the first case (at least the first proven case) of a two-phonon octupole vibration.

V. Paar: 1. We did a systematic calculation of systematics of odd \( \text{Pm} (Z = 61) \) nuclei in the cluster-vibration model. The results are in very good agreement with experiment if one takes \( Z = 64 \) as a cloud shell. This is strong evidence that the \( Z = 64 \) closure effect persists even \( Z = 61 \) nuclei.

2. The octupole multiplet \( h_{1/2} \times 3 \) is split much more than the octupole multiplet in \(^{259}\text{Bi}\), because it involves non-spin-flip matrix element \( \langle h_{1/2} | Y_{3} | \alpha_{3/2} \rangle \) while in \(^{259}\text{Bi}\) the splitting is reduced due to spin-flip matrix element \( \langle h_{1/2} | Y_{3} | \alpha_{3/2} \rangle \). Thus, the large difference in splitting is a geometrical effect and not the effect of goodness of \( Z = 62 \) and \( Z = 64 \) shell closure.

P. Kleinheinz: From our comparison of the septuplet splittings we did not draw any conclusions on the relative qualities of the \( Z = 64 \) and \( 82 \) closures. We only implied (to appear in Z. Phys.) that a 0.8 MeV splitting is maybe more attractive for analysis compared to the 1.0 MeV \(^{259}\text{Bi}\) splitting where other small admixtures more likely could complicate the situation. I have certainly no comment on the explanation for the different magnitudes of the splittings in Bi and \( ^{70} \).

C. Baktash: How much would your conclusions regarding the double-octupole phonon in \(^{146}\text{Gd}\) change if you vary the energy of the \( 1h_{1/2} \) neutron orbital, assumed to lie at 2.1 MeV in your calculations.

P. Kleinheinz: We would not expect a great influence of the \( 1h_{1/2} \) single particle energy on the energies of the two-phonon quartet in \(^{146}\text{Gd}\).
THE N=82 GAP IN $^{156}$Gd FROM $\beta$-DECAY STUDIES OF Tb ISOTOPES

J. Styczek\textsuperscript{a}, P. Kleinheinz, M. Piiparin\textsuperscript{a}++
Institut für Kernphysik, KFA Jülich, Jülich, Germany
J. Blomqvist
Research Institute of Physics, Stockholm, Sweden

Abstract

A $\beta$-decay study of 23 s $^{156}$Tb suggests a $(v\pi_{1/2} d_{3/2})^5$ configuration for this activity. In its decay we have identified a $v\pi_{3/2} + v\pi_{3/2}$ GT branch which populates neutron particle-hole states in $^{156}$Gd. From the results we conclude that the N=82 single particle energy gap is less than 4 MeV. Neutron one-particle two-hole and two-particle one-hole states in $^{155}$Gd and $^{157}$Gd were identified in the $\beta$-decays of 29 s $^{155}$Tb and 1.6 h $^{157}$Tb.

There exists quite detailed knowledge on the proton ph states in $^{146}$Gd. These states are strongly populated in the yrast decay\textsuperscript{1}, and their excitation energies are in accord with the $\approx 3.5$ MeV $2^+_1$ energy gap as derived from the difference of the $^{147}$Tb and $^{146}$Gd single proton separation energies. On the other hand it is well known that pairing is important at Z=64, and from an analysis of single proton particle energies\textsuperscript{2,3} in the neighbouring $^{151}$Eu and $^{147}$Tb isotones a value of $\sim 2.5$ MeV was derived for the energy gap in the single particle spectrum.

From the single neutron separation energies one obtains for $^{146}$Gd an N=82 gap of $\approx 3.7$ MeV, but nothing so far is known on the $^{146}$Gd neutron particle hole excitations which should occur at about that excitation. Furthermore, the excitation energies in the neighbouring isotopes with one neutron lifted across N=82 (1p2h states in $^{146}$Gd and 2ph states in $^{147}$Gd), which are crucial to determine the gap in the neutron single particle energies, are also not known. These states have in general low spin and are therefore not populated in in-beam experiments. However, it was possible to locate such neutron ph excitations in the three Gd isotopes through $\beta$-decay studies of $^{145}$Tb, $^{146}$Tb, and $^{147}$Tb, which we will report here.

The parent activities were produced through $(a,2n)$ reactions ($x = 8, 9, 10$) in bombardments of $^{152}$Gd and $^{151}$Eu targets with $\alpha$-particle beams between 90 and 130 MeV from our cyclotron. Gamma-ray singles and two-detector coincidence measurements with various coaxial and planar Ge detectors were carried out during 20 to 40 sec beam pauses following similar irradiation periods during which the detectors were blocked.

Our results for $^{146}$Tb decay are shown in Fig. 1. In contrast to earlier studies\textsuperscript{4,5} we find negligible feed to the 3$^+$ 1st excited state and the coincidence results locate three new levels in $^{146}$Gd above 3.4 MeV.

From the shell model one expects for the $^{146}$Tb parent nucleus a $v\pi_{1/2} d_{3/2}$ configuration which can couple to $I^+ = 4^+, 5^+, 6^+$ or $7^+$, where the $\pi$ residual interaction will be repulsive for the two extreme spins. The strong feeding of the $v\pi_{1/2} d_{3/2}$ states at about 3 MeV excitation proceeds through the allowed $d_{3/2} \rightarrow d_{3/2}$ GT transition. Excellent agreement of the $\beta$-branchings to the $(v\pi_{1/2} d_{3/2}^2)^4, 5^+$, and $6^+$ states with theoretical ratios unambiguously classifies the $^{146}$Tb parent state as $I^+ = 5^+$.

The clearly observed 1579 - 3140 keV coincidences establish a new level at 4719 keV. We attribute the feeding $\beta$-branch to the other expected GT transition, $v\pi_{1/2} \rightarrow v\pi_{3/2}$, which systematically occurs with essentially equal log ft value in other Tb isotopes in this region. This classifies the 4719 keV state as $(v\pi_{3/2} d_{3/2})^{4+}$ neutron particle hole excitation. Only the $5^+$ multiplet member is predicted to be also fed in $\beta$ decay, but 14 times weaker than the $4^+$ state.

A weak 1297 - 1844 keV parallel decay branch proceeds from the 4$^+$ state, where the transition ordering is determined from $^{145}$Sm$(a,2n)$ excitation function measurements\textsuperscript{6} close to threshold. We interpret the intermediate 3423 keV level as $v\pi_{1/2} d_{5/2}$ state, which is the lowest neutron particle hole excitation in $^{146}$Gd. Its energy should be equal to the N=82 gap at Z=64, except for small contributions of collective or nuclear-nucleon interactions. The nearagreement with the $\approx 3.7$ MeV N=82 gap as derived from the neutron separation energy difference is in accord with this view.

In our spectra we also observe weakly the known\textsuperscript{6} 1972 keV $2^+ \rightarrow 0^+$ transition, and a 1059 keV line in coincidence with it. As no connecting transitions to any of the strongly $\beta$-fed levels could be found it remains unclear how the $2^+$ state is fed. Most likely it is directly populated in $\beta$ decay of a low spin $^{146}$Tb isomer involving the $d_{3/2}$ (or $s_{1/2}$) proton particle, which is possibly produced at the present bombarding energies via precompound particle emission. Such a low spin $^{146}$Tb activity has been identified\textsuperscript{7} following $\beta$ decay of $^{146}$Gd.

The $^{145}$Tb activity was previously not known. The mass identification was derived from excitation function and from X-ray coincidence measurements, and the $^{151}$Tb half life was found as $T_1/2 = 29 \pm 4$ sec. This value is in agreement with an Independent determination\textsuperscript{8} reported in a recent abstract.

The $^{145}$Tb decay scheme is shown in Fig. 2. From systematics we attribute $I^+ = 11/2^+$ to its ground state. Levels in $^{151}$Gd have previously been investigated\textsuperscript{3} through the $^{144}$Sm$(a,3n)$ reaction, but the energy levels observed in this study above 750 keV are not populated in $^{145}$Tb decay. However, most of the levels seen in $\beta$ decay have been observed in concurrent $^{145}$Sm$(a,2n)_y$ and $e^+$ measurements\textsuperscript{10} which gave the spin-parity assignments shown in Fig. 2 for the levels between 1 and 2 MeV. The transition multipolarities quoted in the figure are also from the in-beam work. Our $\beta$-decay branchings are in accord with the $11/2^+$ $^{151}$Tb parent spin. Strongly fed in $\beta$-decay is the 2382 keV $^{146}$Gd level, and the log ft = 4.2 suggests a $v\pi_{3/2} d_{3/2}^2$ configuration. The other 1p2h state, the $o\pi_{3/2} d_{5/2}^2$ level at 1273 keV is known from the in-beam work\textsuperscript{10}.

\textsuperscript{+} On leave from Institute of Nuclear Physics, Cracow, Poland

\textsuperscript{++} A. v. Humboldt fellow 1978-80, on leave from Univ. of Jyväskylä, Finland
Fig. 1: Decay scheme of 23 s $\text{Pu}^{239}$. For feeding of 1972 keV 2$^+$ state see text.

Fig. 2: Decay scheme of 29 s $\text{Pu}^{239}$. The QEC value is derived from comparison with $\text{Pu}^{237}$, It is assumed that the 0$^+$ neutron hole pair of $\text{Pu}^{237}$ will not affect the QEC ($\text{Pu}^{237}$ value). The transition multiplicities are from the ($\text{He}^3$,3n) reaction study$^{16}$.

Fig. 3: Decay scheme of 1.6 h $\text{Pu}^{237}$. The QEC value is from Ref. 11, assuming that the 1/2$^+$ and 11/2$^-$ $\text{Pu}^{237}$ $\beta$-activities lie close$^3$ in energy.
Our data on 1.6 h $^{147}$Tb $\beta$ decay are given in Fig. 3. The energy levels are in agreement with those reported$^1$ earlier, but the new 1/2$^+$ assignment$^2$ for 1.6 h $^{147}$Tb, together with new data on transition multipolarities lead to a revision of $^{147}$Gd spin parity assignments. In addition to the $v\pi_{3/2}$ state at 1152 keV now also the $v\pi_{1/2}$ level is identified at 1847 keV. We interpret the 1292 and 1412 keV levels respectively as $v\delta_{3}\pi_{2}J_0$ and $v\delta_{5}\pi_{2}J_0$ 2p1h excitations.

In conclusion, the present $\beta$ decay studies have located neutron particle hole states in $^{146}$Gd which suggest a gap of less than 4 MeV in the neutron single particle energies. Although one would not expect that pairing at N=82 is equally significant as at Z=64,$^1$ it will be interesting to analyse the present results for the three Gd isotopes within the pairing theory.

References
1) P. Kleinheinz, R. Broda, P.J. Daly, S. Lunardi, M. Ogawa, J. Blomqvist, Z. Physik A290 (1979) 279
10) A. Pakkanen, J. Muhonen, M. Piiparinen, J. Blomqvist, Dept. of Physics, Univ. of Jyväskylä, Res. Report No. 5/1981, and to be published.
11) J. Blomqvist, P. Kleinheinz, R. Broda, P.J. Daly, separate contribution to this volume, and to be published.
STUDIES NEAR \( N=82 \); EVIDENCE FOR A SHELL CLOSURE AT \( Z=64 \)

K. S. Toth

Oak Ridge National Laboratory\(^*\), Oak Ridge, Tennessee 37830, USA

Abstract

In the study of nuclei far from stability radioactive decay becomes a major mechanism with which to obtain nuclear structure information. The program described here has to do with the investigation of short-lived nuclei near the \( N=82 \) closed shell.

1. Introductory Remarks

Highly neutron-deficient isotopes were produced in compound-nuclear reactions by bombarding enriched rare earth targets with energetic heavy ions ranging from \(^{14}\)B to \(^{20}\)Ne. Product nuclei knocked out of the thin targets by the incoming projectiles were thermalized in helium gas. The products were then pumped out of the reaction chamber together with the helium and transported through a Teflon capillary to a shielded area suitable for \( \gamma \)-ray, x-ray and \( \alpha \)-particle counting. The program has been two-fold in purpose: 1) the study of \( \alpha \)-decay energies and partial \( \alpha \) half-lives for elements with \( 64\leq Z \leq 76 \), and 2) the investigation of low-lying levels in nuclei around the \( N=82 \) closed shell. Figure 1 shows the region of the periodic table being studied. Solid squares indicate \( \beta \)-stable nuclei, squares enclosed in heavy borders represent \( \alpha \)-active nuclides and cross-hatched squares show the nuclei whose level structures we have investigated. The intent has always been to obtain particular pieces of information concerning specific nuclei. However, due to the wide range of nuclides involved, one result has been the accumulation of half-life and decay-energy systematics for neutron-deficient nuclei with \( 144\leq A \leq 172 \). A total of 27 new isotopes have been identified; these are marked by dots in Fig. 1. Much of the work has been summarized recently in three review articles\(^{1-3}\). Herein we present new results on \(^{145}\)Tb and \(^{145}\)Tb decay and discuss those portions of our data which indicate a shell closure at \( Z=64 \).

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Fig. 1 Portion of the periodic chart under investigation. Dots mark isotopes we have identified, while cross-hatched squares represent nuclei whose level structures we have investigated. Missing squares for lutetium, hafnium, tantalum, tungsten and rhenium indicate isotopes which have not been identified as yet.
Identification of $^{144}$Tb and $^{145}$Tb

For the past several years we have been making a systematic study of the decay properties of nuclides around the W=82 shell to learn more about their low-lying levels, states whose structure should be describable in terms of a single-particle formalism. In particular, we have investigated isomerism in $^{145}$Gd and $^{147}$Tb and have examined their levels and those of other W=81 nuclei as a function of Z. The nucleus $^{145}$Gd is especially interesting since there is evidence that $^{146}$Gd exhibits properties characteristic of a doubly magic nucleus. States in $^{145}$Gd have been studied via $^{145}$Gd$^{m+}$ decay and in-beam $\gamma$-ray experiments. These studies, however, have identified only two excited states at energies below 2.3 MeV, while one would expect, on the basis of shell model predictions, a greater density of levels. To obtain more information concerning $^{145}$Gd, we undertook a search for $^{145}$Tb in concert with our decay studies of neutron-deficient holmium isotopes made in $^{18}$O bombardments of $^{149}$Sm. [Terbium nuclides are produced copiously in $^{149}$Sm($^{18}$O,$\alpha\alpha\alpha$) reactions.] Ions of $^{18}$O$^+$ were accelerated in the Texas A&M University isochronous cyclotron and used to bombard targets of samarium oxide enriched in $^{149}$Sm. These targets consisted of oxide layers deposited onto thin aluminum backing foils. In two separate experiments, the energies of the $^{18}$O ions extracted from the cyclotron were ~101 and 129 MeV. However, because the particles first were intercepted by the aluminum foils, the maximum energies incident on target were ~96 and 125 MeV, respectively. Incident energies were further varied by using additional aluminum absorbers. The overall energy range covered in the two experiments was from 75 to 125 MeV.

Figures 2 and 3 show portions of $\gamma$-ray spectra (~200 - 1200 keV) measured at 96 and 125 MeV, respectively. The 96-MeV spectrum represents the first 30 seconds of counting following 1-min irradiation and collection cycles. This $^{18}$O energy was the lowest one investigated where the $\gamma$ rays eventually assigned to $^{145}$Tb were clearly observed. In Fig. 2 $^{145}$Tb transitions are labeled by energy only; other peaks that could be identified are labeled by isotope as well. The $^{145}$Tb transition data are summarized in Table 1. The evidence that these $\gamma$ rays do in fact represent $^{145}$Tb decay is as follows: (1) The strongest transitions at 257.6, 537.1, 572.4, 987.7 and 1109.7 keV were all found to be in coincidence with gadolinium K x-rays; (2) each of these transitions was also observed to be in coincidence with three or more of the others; (3) the relative intensities of these transitions remained approximately constant as the bombarding energy was varied between 96 and 125 MeV; and (4) each transition was found to decay with essentially the same half-life, i.e., 30 $\pm$ 3 sec.

The observed $^{145}$Tb $\gamma$ rays were placed in a decay scheme as shown in Fig. 4. The 27.3- and 748.7-keV states were known from $^{145}$Gd$^{m+}$ decay; the other four excited levels are proposed on the basis of our singles and coincidence $\gamma$-ray measurements. The first three levels in $^{145}$Gd represent (see e.g. Ref. 4) the $s_{1/2}$, $d_{5/2}$ and $h_{15/2}$ neutron hole states, while the next highest state, 1014.9 keV, is probably due to the $d_{5/2}$ neutron orbital.

![Fig. 2 Portion of a $\gamma$-ray spectrum obtained in 96-MeV $^{18}$O bombardments of $^{149}$Sm. Transitions assigned to $^{145}$Tb are labeled by energy only.](image)

<table>
<thead>
<tr>
<th>Table 1. Transitions following the decay of $^{145}$Tb.</th>
</tr>
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<tbody>
<tr>
<td>$E_\gamma$ (keV)</td>
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<tr>
<td>------------------</td>
</tr>
<tr>
<td>27.3 (1)</td>
</tr>
<tr>
<td>257.6 (2)</td>
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<tr>
<td>523.9 (2)</td>
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<tr>
<td>537.1 (2)</td>
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<tr>
<td>572.4 (2)</td>
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<tr>
<td>721.4 (2)</td>
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<tr>
<td>987.7 (2)</td>
</tr>
<tr>
<td>1014.9 (4)</td>
</tr>
<tr>
<td>1109.7 (3)</td>
</tr>
<tr>
<td>1553.5c)</td>
</tr>
<tr>
<td>1684.1c)</td>
</tr>
</tbody>
</table>

a) Normalized to 100 for the 987.7-keV transition.
b) Intensity not determined because $\gamma$ ray also follows the decay of $^{145}$Gd$^{m+}$ a nuclide produced independently in the $^{149}$Sm($^{18}$O,$\alpha\alpha\alpha$) reaction.
c) Transition observed in the $^{149}$Sm($\alpha$,3n$\gamma$) study.
Fig. 3 Portion of a γ-ray spectrum obtained in 125-MeV bombardments of $^{144}$Sm. Transitions assigned to $^{145}$Tb are labeled by energy only. Note the 742.9-keV γ-ray which is assigned to $^{144}$Tb.

The remaining levels shown in Fig. 4 (together with other states so far unobserved) can be accounted for by the coupling of these neutron hole orbitals to the 1579-keV, $3^+$, and 1971-keV, $2^+$, levels in the $^{146}$Gd core.

From the systematics of neighboring N=80 nuclides, the ground state spin of $^{145}$Tb is most likely $5/2^+$ since the isotopes $^{143}$Eu through $^{139}$Pr all have $5/2^+$ ground states. In addition, $^{147}$Tb and $^{149}$Tb have $5/2^+$ assignments. An $11/2^+$ spin is also a possibility; the $n_{11/2}$ proton orbital is known to exist as a low-energy isomeric state in $^{147}$Tb and $^{149}$Tb. It is unlikely, however, that the $^{145}$Tb species we observe is $11/2^+$ for the following reason. In Ref. 6, two intense transitions, 1553.5 and 1684.1 keV, were observed to depopulate a 13/2 state at 2302.0 keV and a 15/2 level at 2432.8 keV, respectively. In our decay work these transitions were not seen. An upper limit on their relative γ-ray intensities is 5 units in both cases (see Table 1). Thus, the spin of the $^{145}$Tb parent is likely to be $5/2^+$, rather than $11/2^+$.

The 125-MeV spectrum shown in Fig. 3 represents 20 seconds of counting following 20-sec bombardments. Once again the $^{145}$Tb γ rays are labeled by energy, while other identifiable peaks are labeled both with energy and isotope. One of the latter peaks, 742.9 keV, is assigned to the new isotope $^{144}$Tb. The assignment is based mainly on two facts: 1) the γ ray is in coincidence with gadolinium K x-rays and 2) its energy corresponds to the known $^1D^0$ first-excited state of $^{144}$Gd. In addition, the γ ray was first observed at a log energy of 114 MeV, that is, 20 - 25 MeV above the threshold for the production of $^{145}$Tb. The difference is close to the expected increase in energy needed to evaporate another neutron in this proton-rich region of the periodic chart. A decay analysis of the 742.9-keV γ ray yielded a half-life of 5 ± 1 sec for $^{145}$Tb. We were unable to observe the 959.3-keV, $3^+ + 2^+$, and 1001.4-keV, $4^+ + 2^+$, $^{144}$Gd transitions (see Ref. 10). The indication is that the spin of $^{145}$Tb is $1^+$, as is the case for the other N=79 doubly-odd isotopes.

Fig. 4. Proposed $^{145}$Tb decay scheme.
3. Shell Closure at Z=64

The first evidence for a closure at gadolinium (Z=64) came from an examination of α-decay energies in the rare earth region. For a given element, α-decay energies increase with decreasing neutron number. Discontinuities in this monotonic trend appear at 154, 128, and 84 neutrons as a consequence of the shell closures at 152, 126, and 82 neutrons, respectively. In an analogous way the energies for a given N increase smoothly with increasing atomic number. In the rare earths, however, a plot of $E_\alpha$ vs. N (see Fig. 5) reveals a discontinuity at Z=64, while the normal spacing between adjacent even-Z nuclides is ~0.5 MeV the difference between dysprosium (Z=66) and gadolinium is ~1.1 MeV. The increased gap shows the additional stability of the Z=64 configuration.

Another set of results which relates to the Z=64 closure has to do with α-decay rates. In α-decay, half-lives for transitions between ground states of doubly-even nuclei are taken to represent unhindered decays. The reduced widths (or transition probabilities) of these so-called s-wave α-decays are considered to be standard. They exhibit regular trends as a function of N and Z. They are largest for nuclei with 2 or 4 particles beyond a closed shell. After a sharp minimum at the shell the widths increase once again in value as the next closure is approached. The trends can be understood in terms of the shell model, namely, the probability amplitude for the formation of an α-particle is related to the magnitude of the single-particle wave functions at the surface. For closed shells these states are more tightly bound and the result is a sharp decrease in the α-decay rate.

The discontinuity in α-decay energies at Z=64 mentioned above was reproduced by calculations which used the BCS method to take into account correlations between protons outside the Z=50 shell. The authors also utilized their wave functions to calculate α reduced widths for N=84 even-even nuclei. The calculations showed a significant dip at Z=64 between the (4f7/2 + 5s1/2) and 5p1/2 proton orbitals. However, the data available at that time indicated a general constancy in widths with a dramatic reduction at 154 Dy (Z=66).

Fig. 5 Alpha-decay energies plotted as a function of neutron number for isotopes in the rare-earth region. Only even-Z elements have been labeled and their points connected.
Fig. 6 Reduced widths for N=84 even-A α-emitters compared with BCS calculations.\textsuperscript{11)}

Our investigations of α-decay rates showed that the 150\(^g\)Pb α-decay branching ratio was in error; it is 36\% rather than 18\% as earlier data has indicated. Based on new experimental data, the α-decay rates for N=84 nuclei show (see Fig. 6) that the experimental α widths agree with the calculations\textsuperscript{11)} and that a shell closure exists at Z=64.

The first 2\(^+\) states in a group of singly closed even-even nuclei lie at approximately equal excitations. If, however, one nucleus of these is doubly magic, then this excitation energy becomes substantially higher. Energy systematics for the lowest 2\(^+\), 4\(^+\), 6\(^+\), and 3\(^-\) states in N=82 isotones (\(^{134}\)Te to \(^{148}\)Ba) is summarized in Fig. 7.

Information concerning \(^{146}\)Gd and \(^{148}\)Sm levels is taken from our data on the decay of \(^{146}\)Tb and \(^{148}\)Ho (Refs. 12 and 7) and from recent in-beam γ-ray work (Refs. 5, 9, and 13). General trends in Fig. 7 are that the 2\(^+\), 4\(^+\), and 6\(^+\) states, up to \(^{144}\)Sm, increase gradually in energy as Z increases, while the 3\(^-\) level drops precipitously. At \(^{146}\)Gd, the 3\(^-\) is the first-excited state, while the 2\(^+\) excitation increases sharply from its energy in \(^{144}\)Sm. In \(^{148}\)Sm, the 2\(^+\) level drops in energy and, once again, is the first-excited state. Its excitation of 1677 keV is close to the 2\(^+\) energy in \(^{144}\)Sm, 1.6\times, 1660 keV. The unusually high energy of the 2\(^+\) level in \(^{146}\)Gd and the fact that its first-excited state is 3\(^-\) provide additional evidence for a closure at Z=64.

Fig. 7 Systematics of low-lying 2\(^+\), 4\(^+\), 6\(^+\), and 3\(^-\) levels in doubly even N=82 nuclei.
Based on three different types of experiments there is now a compelling indication that 64 pro-
tons represent a closed configuration. This progress should stimulate new shell-model calcula-
tions in this mass region wherein an \((N=82 + Z=64)\) core is assumed rather than the usual \((N=82 + Z=50)\)
closure.

Acknowledgments

The author would like to thank C.R. Bingham, H.K. Carter, E. Newman, A.E. Rainis, W-D. Schmidt-
Ott, D.C. Sousa, and D.R. Zolnowski, who participated in various phases of the work described in
this paper.

References

1) "Investigation of Nuclei near \(N=82\) and \(Z=64\) via Radioactive Decay of High-Spin Isomers", K.S. Toth, Symp. on High-Spin Phenomena in Nuclei, Argonne National Laboratory, March 1979, ANL Report No. ANL-PHY-79-4, October 1979, p. 413.


ANGULAR CORRELATION AND COINCIDENCE STUDIES OF EXCITED 0+ AND OTHER LEVELS IN THE
TRANSITIONAL Ce NUCLEIDES 142Ce, 144Ce, 146Ce and 148Ce

W. B. Walters and C. Chung
University of Maryland
College Park, MD 20742 USA

D. S. Brenner
Clark University
Worcester, MA 01610 USA

Brookhaven National Laboratory
Upton, NY 11973 USA

F. K. Wohn, K. Sistemich** and H. Yamamoto
Iowa State University
Ames, IA 50011 USA

R. Petry
University of Oklahoma
Norman, OK 73019 USA

Abstract

The decays of the neutron-rich nuclides 142La, 144La, 146La and 148La to the levels of the transitional nuclides 142Ce, 144Ce, 146Ce and 148Ce, respectively, have been studied using mass-separated sources. Angular correlation studies have been employed to identify new excited 0+ levels in 146Ce and support spin and parity assignments for 1-, 3+, 2+, 3, 4+ and 6+ levels in 144Ce and 146Ce. An excited 4+ level in 148Ce is indicated by coincidence ratios and electron studies, while no clear evidence can be found for the location of an excited 0+ level below 2 MeV in 144Ce. The resulting isotonic and isotopic systematics are discussed in terms of the transition from the closed shell at N=92 and Z=50 to the region of deformed nuclides.

1. Introduction

As no single, unified description of nuclear structure exists that offers reliable results for all nuclides, much interest is focused on nuclides at the edges of regions where good theoretical fits are found. The great success of the rotational description of nuclides1,2) with N>90 has stimulated extensive experimental and theoretical study of the nuclides with 92≤N≤90 in various attempts to both observe rotational features below N=90 and to gain an understanding of the nature of the transition from the closed shell at N=82 to the deformed region at N=90. Until recently, the lightest nuclides studied in detail in this region were the 3=60 Nd nuclides and 2=61 Pm nuclides whose structures were consistent with a transition to deformed structures for N=90. These nuclides have 10 or more protons beyond the closed shell at Z=50 and show few, if any, effects related to that shell closure. The measurement3 of a 3/2+ ground state for the N=88 nucleus 143Cs has stimulated considerable study of the nuclides with 54≤N≤60 and 82≤N≤90 to further investigate this transition. In particular Scott et al.4,5) have reported studies of the decay of odd-odd Cs nuclides to even-even Ba nuclides and found evidence to support the extension of the deformed region to N=88.

2. Experimental Procedures

We have studied the decays of the neutron-rich La nuclides, 92.5-min 142La, 40-sec 144La, 6-sec 146La and 1.2-sec 148La, to levels of 142Ce, 144Ce, 146Ce and 148Ce, respectively, using sources produced at the on-line mass separator TRISTAN located at the High Flux Beam Reactor at Brookhaven National Laboratory. Both the general layout of the facility6) and the data collection systems7) are described in detail elsewhere. For these experiments several specific experimental arrangements were used. The most complete angular correlation studies were performed on 142Ce and 146Ce where data were collected in separate experiments at 90°, 130° and 180° using a 15% n-type Ge detector and a 20% Ge(Li) detector, each at 5 cm from the source. Approximately 2x10^6 three parameter γγγ events were collected at each angle. The characteristic 0+–2+–0+ function (considerably attenuated by the small source-to-detector distance, especially at 130°) was observed for the decay of the 2030-keV level in 142Ce and for the 1656- and 1043-keV levels in 146Ce. The 2030-keV assignment8) in 142Ce had been

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*Now at Los Alamos National Laboratory, Los Alamos, NM 87545 USA
**On leave of absence from KFA Julich, West Germany
suggested earlier using a NaI(Tl)-Ge(Li) setup. In a similar experiment on $^{144}$Ce $\gamma$ rays no cascade with the 0$^+$-2$^+$-0$^+$ shape was observed.

In a second experiment on $^{144}$La decay to $^{144}$Ce levels, 2x10$^7$ events were collected on tape at 90$^\circ$ and 3x10$^7$ events were collected on tape at 180$^\circ$. During the 90$^\circ$ experiment at third 18$^\circ$ Ge detector was positioned at 130$^\circ$ relative to the 15$^\circ$ detector and used with a single channel analyzer to accumulate a spectrum in coincidence with the 397-keV 2$^+$ to 0$^+$ $\gamma$ ray.

The data at 90$^\circ$ and 180$^\circ$ have been used separately to determine 180$^\circ$/90$^\circ$ anisotropies for the stronger cascades and have been summed to search for weak $\gamma$-ray coincidences. The levels established in $^{144}$Ce below 2 MeV are shown in Fig. 1. The largest 180$^\circ$/90$^\circ$ anisotropy of ~1.6 was observed for the 1422-keV $\gamma$ ray. The data at 130$^\circ$ were of limited usefulness for many of the weaker $\gamma$ rays as there was no provision for Compton background subtraction. The characteristic dip at 130$^\circ$ was not observed for the 1422-keV $\gamma$ ray and a 2$^+$(1,2)2$^+$(2)0$^+$ cascade indicated with δ1<5<1.7 for the 2$^+$ to 2$^+$ transition. The difficulty encountered in observing excited 0$^+$ states in $^{144}$Ce arises directly from the 3$^-$ spin and parity of $^{144}$La as contrasted with 2$^+$ for the other odd-odd La nuclides. As allowed $\beta$ decay will populate only 2$^-$, 3$^-$ and 4$^-$ levels, direct cascades from 2$^-$ to 0$^+$ states by M2 transitions are quite unlikely. Thus, excited 0$^+$ states in $^{144}$Ce can be fed directly only from 2$^+$ states following forbidden beta decay or by two-$\gamma$ cascades following allowed $\beta$ decay.

The measured anisotropy values did, however, give strong support for the other spins and parities shown for the levels below 2 MeV in Fig. 1. In particular, the peak ratios for the $\gamma$ rays de-exiting the three 4$^+$ levels were identical at both angles, whereas the 1294-keV $\gamma$ ray showed a large negative 180$^\circ$/90$^\circ$ anisotropy of 0.5 that is characteristic of a 4$^+$(1,2)2$^+$(2)0$^+$ cascade. Such a large negative value is not possible for a 2$^+$(1,2)2$^+$(2)0$^+$ cascade and indicates a δ value of ~0.5~δ~4.0 for the 3$^+$ to 2$^+$ transition. The $\gamma$ rays from the 1$^-$ and 3$^-$ levels at 1346.1 and 1242.3 keV, respectively, showed 180$^\circ$/90$^\circ$ anisotropies fully consistent with 1$^-$(1,2)2$^+$(2)$^0+$ and 3$^-$(1,2)2$^+$(2)$^0+$ cascades. Similar cascades in $^{146}$Ce from the 524- and 960-keV levels were observed. The identification of the 0$^+$ level in $^{144}$La is described in detail by Gill et al. elsewhere in these proceedings.

![Fig. 1 The low-lying levels of $^{144}$Ce populated in the $\beta$ decay of $^{144}$La.](image-url)
3. Discussion

The systematic movement of the low-lying levels in the Ce nuclides as N increases beyond 82 is shown in Fig. 2. The levels of 150Ce from the fission product studies of Chefitz9) are also shown. The first 2⁺ state is seen to drop by a factor of ~0.625 with the addition of each successive pair of neutrons. The 4₁⁺ and 6₁⁺ states drop more slowly by factors of ~0.75 shifting the E₄⁺/E₂⁺ ratio from near the vibrational limit of 2 to near the rotational limit of 3.33. The higher-lying states compress somewhat less smoothly but many also drop by ratios of between 0.75 and 0.85 with the addition of each neutron pair. These trends serve to suggest the presence of an underlying behavior dependent strongly on neutron number.

A very different picture of these nuclides is shown in Fig. 3 where the partial level structures of the N=84, 86, 88 and 90 isotones are shown that include only the ground band (0⁺, 2⁺, 4⁺) octupole band (1⁻ and 3⁻), β-band head (0⁺) and γ-band head (2⁺). The most obvious difference lies in the upward trend in the level structures of the ground band as proton pairs are added to the nucleus for N=84, 86 and 88 versus the downward trend for N>90 (and for neutron pair addition). A similar shift is observed for the γ-band head which trends upward in N=84 and downward on N=88 and lies nearly flat in N=86. The octupole band undergoes the opposite shift, trending down in N=84 (and also in N=82 as noted by Kleinheinz et al.11)) and N=86 and upward in N=88 and N=90. The β band exhibits yet a third type of behavior, peaking in Ce or Nd for N=84, 86 and 88, and then bottoming in Nd for N=90.

The erratic behavior shown in Fig. 3 by these isotones as protons are added beyond the closed shell at Z=50 stands in sharp contrast to the very smooth behavior shown for the Ce nuclides in Fig. 2. The

```
0⁺ 2030
2⁺ 2004

4⁺ 1830
2⁺ 1819

1742
3⁺ 1692
4⁺ 1674
2⁺ 1536
6⁺ 1524
2⁺ 1489
1⁻ 1346
4⁺ 1242
3⁺ 1242
2⁺ 1274
5⁺ 1184
6⁺ 1171
0⁺ 1043
4⁺ 938
3⁻ 960
1⁻ 924
4⁺ 668
1⁻ 760

2⁺ 641

2⁺ 397
2⁺ 258
2⁺ 158
2⁺ 98

0⁺ 0
0⁺ 0
0⁺ 0
0⁺ 0
0⁺ 0

142Ce 84
144Ce 86
146Ce 88
148Ce 90
150Ce 92

Even-even Ce nuclides
N=84 to N=92

Fig. 2 The low-lying levels of the even-even Ce nuclides with 84<N<92.
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- 559 -
Fig. 3 Selected members of the ground band (0<sup>+</sup>, 2<sup>+</sup>) octupole band (1<sup>-</sup>, 3<sup>-</sup>), β band (0<sup>+</sup>) and γ band (2<sup>+</sup>) for the N=84, 86, 88 and 90 isotones with 56×4×64.
upward trend for the ground band also stands in sharp contrast to the isotonic behavior observed for the N=80 two-hole nuclides, the N=78 four-hole nuclides and the N=76 six-hole nuclides, etc.

Because of the apparent strong, smooth dependence of the Ce level structures on neutron number, the Interacting Boson Approximation (IBA) should provide a particularly appropriate as a unified basis for describing these nuclides. In view of the very different trends observed for the isotopes and isotones, we have made calculations for these structures using the IBA-2 code, NRPOs, that treats neutron and proton bosons separately. The parameters have been taken from the thesis of Scholten who made a strong effort to fit the levels of Nd, Sm and Gd in the region 84<\text{N}<94. Using a proton coupling constant for \( \varepsilon=58 \) taken from below the N=82 closed shell and neutron coupling constants from the Nd, Sm and Gd isotones, and deriving other parameters by smooth extrapolation from the respective Nd, Sm and Gd isotones, qualitative fits for the trends observed in the Ce nuclides can be obtained. For \(^{146}\text{Ce}\) where the ground band is rather closely fit, we observe two 0\(^+\) states and two 2\(^+\) states. The calculated 0\(^+\) and 2\(^+\) states are further apart than the observed states, both the centroid is relatively close. Because the proton coupling constant was derived for the shell and in view of the very different isotonic trends above and below the shell, we found a better fit for the two 0\(^+\) states could be obtained by lowering the proton coupling constant to a value consistent with the trend found by Scholten for the neutron coupling constants. That remains a number of experimental features to be fully resolved and much calculational work to determine if a unified fit can be found for these nuclides with \( Z>50 \) and \( N>82 \).

4. Acknowledgements

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References


9. R. Gill et al., paper in this volume.


DISCUSSION

W.D. Hamilton: I wish to point out some differences between your spin assignments and those obtained at OSTIS. In \(^{144}\text{Ce}\) we find that the 1219 keV state is 2\(^+\) rather than 4\(^+\) with a possible 4\(^+\) state lying a little (~10 keV) above. We find that the 0\(^+\) state in \(^{144}\text{Ce}\) occurs at 1810 keV. These points are mentioned in our contribution to this meeting. We also show the behaviour of the negative parity state and this closely follows the behaviour of the 1\(^-\) and 3\(^-\) levels found in the barium isotopes.

A. Gelberg: Successful calculations for Ba and Ce have been carried out on the neutron deficient side. It is probably the first time that IBA has been applied to an isotopic chain on both sides of the magic number.

D.S. Brennan: Yes. As far as we know this is the first time that IBA-2 calculations have been done in this region and it was very gratifying to find that the systematic trends predicted by the calculations were found experimentally.
LEVELS IN $^{146}$Ce AND THE $^{N=88}$ ISOTONES*

G. M. Gowdy, R. E. Chrien, Y. Y. Chu, R. L. Gill, H. I. Liou, M. Shmid and M. L. Stelts*
Brookhaven National Laboratory, Upton, New York, 11973, USA

K. Sistemich,† F. K. Wohn and H. Yamamoto
Ames Laboratory-USDOE and Iowa State University, Ames, Iowa, 50011, USA

D. S. Brenner
Clark University, Worcester, Massachusetts, 01610, USA

T. R. Yeh
Cornell University, Ithaca, New York, 14853, USA

R. A. Meyer
Lawrence Livermore National Laboratory, Livermore, California, 94550, USA

C. Chung and W. B. Walters
University of Maryland, College Park, Maryland, 20742, USA

R. F. Petry
University of Oklahoma, Norman, Oklahoma, 73019, USA

Abstract

An investigation of the level structure of $^{146}$Ce following the beta decay of the low-spin isomer of $^{146}$La has been carried out at the ISOL facility TRISTAN at Brookhaven National Laboratory. The half-life for the low spin isomer was found to be $6.0 \pm 0.4$ h. A partial level scheme for $^{146}$Ce below 2 MeV is given. The level energies and some B(E2) values extracted from our data have been compared with IBA-2 calculations done entirely with extrapolated parameters from neighboring Z nuclei in order to check the predictive power of the model. Systematics of the Z=58 isotopes and N=88 isotones indicate that although $^{146}$Ce is more deformed than its isotones with Z=60, the transition to the well-deformed region can probably more correctly be thought to occur after $^{146}$Ce, between N=88 and N=90, as it does for Z=60. The abrupt onset of deformation present in the higher Z isotopes is not seen in the Ce isotopes where the trend is found to be rather smooth throughout.

1. Introduction

The onset of deformation in the rare earth region for Z=60 has been well known for many years to occur between N=88 and N=90 where the transition from the near spherical to the aligned coupling scheme appears to occur rather abruptly. The lower nuclear charge (Z=58) members of this transitional region of rare earth nuclei have not been studied previously in any great detail. Little was known of the effect of the lower nuclear charge on the deformation until recently when studies of the heavy Ba (Z=56) isotopes were undertaken. This investigation yielded evidence that the transition to the well-deformed region already occurred for the N=88 nucleus $^{144}$Ba, unlike the case for the known higher-Z nuclei. Recently a study of the heavy Ce (Z=58) isotopes in this region has been undertaken at the TRISTAN mass-separator facility which operates on line with the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL). This study is primarily concerned with the investigation of the low-lying level structure of the pivotal N=88 nucleus, $^{146}$Ce, produced in the $\beta$ decay of $^{146}$La. Comparisons of experimental level energies and B(E2) transition probabilities with IBA-2 calculations are presented. Systematic comparisons among the N=88 isotones and Z=58 isotopes are also made. Of particular interest is the determination of the onset of deformation for the Ce isotopes, specifically whether it occurs between N=88 and N=90 as for Z=60 or earlier as it does in Ba.

Previous studies have given a variety of inconclusive information on the isomer and half life situation in $^{146}$La. Skarnemark et al. have reported two isomers for this isotope with half lives of 8.5s and 4.5m. Recent studies with on-line mass separators indicate 6.2s and 10.0s isomers instead of the 8.5s isomer of Skarnemark. Earlier only one state with an 11s half life was reported for $^{146}$La. Very little previous information exists on the level properties of $^{146}$Ce. Levels at 1172, 668 and 258 keV have been assigned to be the 6+, 4+ and 2+ members of the ground state band. In addition, levels at 925, 961, 1043 and 1183 have tentatively been assigned to be 2+, 3+, 1+ or 2+, and 3+, respectively. Another study assigns the 1183 keV level a spin-parity of 5- and a level at 1551 keV to be 7-. Seven additional levels have been proposed and 24 gamma rays placed in the most complete level scheme previously known.

* Research at all institutions supported by the U. S. Department of Energy.
† Present address: Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA.
++ On leave of absence from KFA, Jülich, FRG.
The 146Ce activities of interest for this work were obtained as mass-separated fission fragments from the ISOL facility TRISTAN on-line to the HFBR at BNL. Ion beams of Cs and Ba isotopes were directly produced by a surface ionization integrated target-ion source system. These beams were then separated by mass and deposited on a moving tape collector system where the desired activities were counted and recorded by various detector analyzer systems. The implanted ions were time-sequenced by the moving tape to optimize the desired activity.

No direct production of the desired 146La parent was observed in our experiments. In this case 146La is produced only following the β decay of even-even 146Ba. Singles spectra (both low <2 MeV and high up to 7 MeV) and γγ coincidence data (low-low and low-high energy ranges) were taken at the point of deposition on the tape collector with hyperpure gamma-X and 20% Ge(Li) detectors in order to study 146Ba and 146La decays simultaneously. The activities were gathered and transported every 16s in order to avoid buildup of contaminating longer-lived A=146 isotobars. The high-low coincidence data were taken with 1/4" Pb on the high energy side to remove many of the contaminating low-energy 146Ba events. In addition, gamma spectrum multiscaling and three angle (90°, 130° and 180°) γγ angular correlations were taken with the same two detectors at a detection station 60 cm from the point of deposition. Mass 146 ions were collected for 8 (or 16) s, moved 30 cm to an intermediate point for 8 (or 16) s to allow the 146Cs and 146Ba to decay into the La, and then transported another 30 cm to the detection station for 8 (or 16) s of counting.

3. Experimental Results and Discussion

Gamma spectrum multiscaling measurements on a number of strong lines attributed to the decay of 146La yield only a single half life of 6.0 ± 0.4s. In our experiments, 146La is only produced following the β decay of even-even 146Ba. Thus only the low-spin isomer of 146La is populated from the 0+ ground state of its Ba parent. The 6.0s half life found in our work agrees well with the 6.2s half life previously reported for the low-spin isomer in 146La, but disagrees with a half life of 8.5s proposed by Skarnemark et al. as the only short-lived state of 146La.

Forty-five levels (and over 150 γ rays) up to 5 MeV and 150 levels (and 90 γ rays) below 2.5 MeV have been established for 146Ce from extensive sets of coincidence relationships studied (>4x107 events recorded in the 146La-enhanced high-low γγ experiment alone). Table 1 lists the γ rays observed connecting levels below 2 MeV. Information on the nature of the low-lying levels in 146Ce was deduced from the γ ray deexcitation patterns, systematic trends of the levels of the lighter even Ce isotopes and surrounding N=88 isotones, and angular correlation measurements. The possible spin parity assignments for these levels are given in Table 2. Figure 1 shows a partial level scheme for 146Ce which includes all positive parity levels below 2 MeV. All levels in the figure are assigned a single most probable spin and parity.

The previously reported 2+ , 4+ , 6+ ground state band members have been confirmed in our measurements. Anisotropies

<table>
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<tr>
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<td>1374+ 274</td>
<td></td>
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</tr>
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<td>194.8(5)</td>
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<td>1577+ 1382</td>
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<td>258.47(6)</td>
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<td>275.5(3)</td>
<td>4.04(30)</td>
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<td>338.6(3)</td>
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<td>1.8(3)</td>
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<td>100(5)</td>
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<td>7.6(20)</td>
<td>1382+ 668</td>
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<td>1.9(10)</td>
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<td>784.66(6)</td>
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<td>15(1)</td>
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<td>6.8(8)</td>
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<td>908.2(2)</td>
<td>4.7(4)</td>
<td>1577+ 668</td>
<td></td>
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<td>924.56(8)</td>
<td>123(6)</td>
<td>928+ 0</td>
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<tr>
<td>1015.9(1)</td>
<td>52(3)</td>
<td>1274+ 258</td>
<td></td>
</tr>
<tr>
<td>1028.5(2)</td>
<td>3.7(4)</td>
<td>1989+ 961</td>
<td></td>
</tr>
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<td>1123.4(2)</td>
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<td>1134.2(3)</td>
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<td>1274.4(2)</td>
<td>20(2)</td>
<td>1274+ 0</td>
<td></td>
</tr>
<tr>
<td>1318.3(2)</td>
<td>19(2)</td>
<td>1577+ 258</td>
<td></td>
</tr>
<tr>
<td>1368.8(3)</td>
<td>7.0(5)</td>
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<td></td>
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<td>1382.1(2)</td>
<td>27(2)</td>
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<td>1398.9(3)</td>
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<td>1498.2(2)</td>
<td>22(2)</td>
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<td>1544.0(3)</td>
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<td></td>
</tr>
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<td>1550.3(3)</td>
<td>6.1(6)</td>
<td>1808+ 258</td>
<td></td>
</tr>
<tr>
<td>1756.7(3)</td>
<td>12(1)</td>
<td>1757+ 0</td>
<td></td>
</tr>
</tbody>
</table>

*Errors given in parentheses are the uncertainties in the last number(s) reported, e.g. 12.1±12.1.

**Intensity and energy determined from coincidence spectrum.

Intensities are relative to the 258 keV γ ray = 1000.

Doublet, actual energies of the two γ rays are estimated from coincidence measurements.
Table 2
Possible spin-parity assignments for levels of $^{146}$Ce below 2 MeV.*

<table>
<thead>
<tr>
<th>$E_{level}$</th>
<th>$I^+$</th>
<th>$E_{level}$</th>
<th>$I^+$</th>
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<tr>
<td>0</td>
<td>0$^+$</td>
<td>1381.9</td>
<td>2$^+$</td>
</tr>
<tr>
<td>258.5</td>
<td>2$^+$</td>
<td>1576.7</td>
<td>3$^+$($2^+$,3$^-$,4$^+$)</td>
</tr>
<tr>
<td>668.3</td>
<td>4$^+$</td>
<td>1627.5</td>
<td>2$^+$,3$^-$,4$^+$</td>
</tr>
<tr>
<td>924.6</td>
<td>1$^-$($1^+$,2$^+$)</td>
<td>1657.4</td>
<td>0$^+$</td>
</tr>
<tr>
<td>960.8</td>
<td>3$^-$($2^+$,3$^+$,4$^+$)</td>
<td>1753.8</td>
<td>1$^-$,2$^+$,3$^-$</td>
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<td>1043.1</td>
<td>0$^+$</td>
<td>1756.7</td>
<td>1$^+$,2$^+$</td>
</tr>
<tr>
<td>1171.3</td>
<td>6$^+$($2^+$,3$^+$,4$^+$,5$^+$)</td>
<td>1802.5</td>
<td>2$^+$,3$^+$,4$^+$</td>
</tr>
<tr>
<td>1183.1</td>
<td>5$^-$($2^+$,3$^+$,4$^+$,5$^+$,6$^+$)</td>
<td>1808.4</td>
<td>4$^+$($2^+$,3$^+$)</td>
</tr>
<tr>
<td>1274.3</td>
<td>2$^+$</td>
<td>1989.2</td>
<td>1$^-$,2$^+$,3$^-$</td>
</tr>
</tbody>
</table>

*Preferred assignments are listed first.

observed in the 785-258 and 1399-258 keV cascades from our $\gamma\gamma(0)$ angular correlation experiments2,11) indicate that levels at 1043 and 1657 keV are good candidates for low-lying $0^+$ levels in $^{146}$Ce.

Assuming the level at 1043 keV is the $0^+$ level and band head of the $\beta$ band, then the state at 1274 keV is the most likely candidate for the $2^+$ member of the band. The deexcitation of this level to both the $0^+_1$ ground state and $4^+_1$ level indicate a $2^+$ spin-parity assignment for this level. In the systematics of the low lying (<2 MeV) levels for the $N=88$ isotones (Fig. 2), the $E_{2^+} - E_{0^+}$ energy difference is approximately equal to or slightly less than the excitation energy of the $2^+_1$ state. The 231 keV difference in energy between the 1274 and 1043 keV levels compared with the 258 keV energy of the first excited $2^+$ state is consistent with this pattern. A good candidate for the $4^+$ member of the $\beta$ band is the level at 1808 keV. This level follows the trends of the heavier $N=88$ isotones smoothly. In addition, there is a

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>IBA-2</th>
</tr>
</thead>
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<tr>
<td>(4$^+$) 1808</td>
<td>4$^+$ 1866</td>
</tr>
<tr>
<td>0$^+ 1657$</td>
<td>0$^+ 1878$</td>
</tr>
<tr>
<td>(3$^+$) 1577</td>
<td>3$^+$ 1641</td>
</tr>
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<td>2$^+$ 1382</td>
<td>4$^+$ 1683</td>
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<tr>
<td>6$^+$ 1171</td>
<td>2$^+$ 1456</td>
</tr>
<tr>
<td>0$^+ 1043$</td>
<td>6$^+$ 1230</td>
</tr>
<tr>
<td>4$^+$ 668</td>
<td>2$^+$ 1125</td>
</tr>
<tr>
<td>2$^+$ 258</td>
<td>0$^+ 892$</td>
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<td>0$^+ 0$</td>
<td>4$^+$ 654</td>
</tr>
<tr>
<td>$^{146}$Ce 58 88</td>
<td>2$^+$ 238</td>
</tr>
<tr>
<td>$^{146}$Ce 58 88</td>
<td>0$^+ 0$</td>
</tr>
</tbody>
</table>

Fig. 1 Experimental positive parity levels below 2 MeV in $^{146}$Ce and their comparison with values predicted by the IBA-2 model. Parameters used in this calculation: $\chi_q=1.2$, $x_0=-0.8$, $\kappa=-0.120$, $\tau=0.65$. 

- 564 -
Fig. 2 Low-lying level systematics of the \( N=88 \) isotones. Dotted lines are drawn to guide the eye and are used to suggest related structures in successive isotones. The data used are taken from: \( ^{144}\text{Ba},1^+ \) \( ^{146}\text{Ce} \) (present study), \( ^{148}\text{Nd},8,15^+ \) \( ^{150}\text{Sm},8 \) \( ^{152}\text{Gd},8 \) \( ^{154}\text{Dy},8 \) and \( ^{156}\text{Er},16^+ \).

relatively large depopulation of this level to the \( 2^+ \) member of the \( \beta \) band. This strong intraband transition is another indication of the connection of this state with the \( \beta \) band.

The level at 1382 keV is assigned a spin-parity of \( 2^+ \) due to its deexcitation pattern of feeding both the \( 0^+ \) ground state and the \( 4^+ \) level. This level is assumed to be the band head of the \( \gamma \) band in \( ^{146}\text{Ce} \).

The level at 1577 is the best candidate for the \( 3^+ \) member of this band. The 1577-1382 keV level difference closely follows the trend observed for this difference from the heavier \( N=88 \) isotones. Higher spin members of the \( \gamma \) band are not obvious among the remaining low lying levels in \( ^{146}\text{Ce} \).

The systematics of the \( N=88 \) isotones and Ce (\( Z=58 \)) isotopes both predict the lowest lying negative parity states, \( 1^- \) and \( 3^- \), to be between 800 and 1000 keV excitation energy. The most probable candidates for these states are the levels at 925 and 961 keV, respectively. This is supported by the coincidence/singles intensity ratios for the 925-258 keV and 961-258 keV transitions. These ratios are consistent with \( E1 \) multipolarities for the \( \gamma \) rays connecting these levels. Also the branching ratios for \( \gamma \) rays depopulating these negative parity levels agree reasonably well with the values from the other \( N=88 \) isotones.

In addition, the angular correlation study yields results for these levels consistent with \( 1-2-0 \) and \( 3-2-0 \) spin sequences. The level at 1183 keV is possibly the \( 5^- \) member of the octupole band built on the \( 1^- \) and \( 3^- \) states. The \( 5^-\rightarrow 3^- \) energy differences in the \( N=88 \) isotones \( ^{150}\text{Sm} \) and \( ^{152}\text{Gd} \) are found to be comparable to the corresponding \( 2^+ \) level energies. The difference of 223 keV between the proposed \( 5^- \) level and the \( 3^- \) level in \( ^{146}\text{Ce} \) is close to the \( 2^+ \) level energy of 258 keV, in agreement with the expected trend.

Despite the fact that the spin-parity assignments made for several of the levels in \( ^{146}\text{Ce} \) are tentative, they are the best choice based on the known data. Changing
Fig. 3 Low-lying level systematics of the even Ce isotopes with N>82. Data were taken from the following references: 142Ce,8 144Ce,8,14 146Ce (present study), 148Ce,13 and 150Ce.8

these level assignments would lead to inconsistencies in the deexcitation patterns or to irregularities in the systematics. Smooth systematic trends are expected throughout this region, especially for the ground state and octupole bands, and to a lesser degree for the $\delta$ and $\gamma$ bands.

Based on the above arguments, the $2^+$, $4^+$, $6^+$ ground state band(8) and $3^-$ state at 961 keV(6) reported in previous experiments are confirmed. The $5^-$ assignment for the 1183 keV level(9) is chosen over the $3^-$ assignment from another previous work. The $2^+$ and $1^-$ or $2^+$ levels reported(8) for 925 and 1043 keV levels are not confirmed. Our experimental results lead us to choose $1^-$ and $0^+$ respectively, as the spins and parities for these levels.

The interpretation of the partial level scheme in terms of the (quasi-) band structure is shown in Fig. 1. The $0^+$, $2^+$, $4^+$ and $6^+$ members of the $\delta$ band; $2^+$ and $3^+$ states in the $\gamma$ band; and the $0^+$ band head of the $\delta\delta$ band are shown.

Comparison of our proposed level structure with calculations using the Interacting Boson Approximation with neutrons and protons treated separately (IBA-2)12,13 is also shown in Fig. 1. In this case the boson Hamiltonian for positive parity states is represented by four parameters, the boson energy $\epsilon$, the quadrupole-quadrupole neutron-proton interaction strength $\kappa$, and two parameters from the proton and neutron quadrupole operator terms $\chi_y$ and $\chi_x$. $\chi_x(\chi_y)$ is assumed to be independent of the number of neutrons (protons), as suggested by the microscopic theory.14 The IBA-2 calculations involved no parameter fitting. Parameters were generally extrapolated from the values determined for the heavier rare earth nuclides, Nd, Sm and Gd. 13) $\chi_y$ for 146Ce was extrapolated from the heavier N=88 isotones. $\chi_y$, on the other hand, was chosen using an interpolated value taken from Ba in addition to the $2>60$ isotopes. Thus the IBA is being tested here essentially as to its ability to predict the expected low lying level structure in 146Ce. (A more detailed study of IBA-2 predictions for Ce isotopes with 142$<A<150$ is given in another contribution to this meeting.15) Despite the lack of parameter
Reduced transition probabilities between levels in $^{146}$Ce compared with IBA-2 calculations. One transition from each level is normalized to 100. IBA-2 parameters used in this calculation: $\chi_T = 1.2$, $\chi_\nu = -0.80$, $\kappa = 0.12$, $\epsilon = 0.65$, effective charges for $p$ and $n = 1$.

<table>
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<th>Energy</th>
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<td>100</td>
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<td>91</td>
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<td>$^3s \rightarrow ^0z_2$</td>
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<td>$^0z_3 \rightarrow ^2z_1$</td>
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<tr>
<td>$^4z_2 \rightarrow ^2z_3$</td>
<td>(426.5)</td>
<td>&lt;5201</td>
<td>1451</td>
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</table>

Table 3

Systematic trends of $E_{41z_1}^4$ levels and the $E_{41z_2}^4/\gamma_{41z_1}^4$ ratios for even-even nuclei with $N \leq 64$ and $84 \leq N \leq 92$. Data were taken from reference 8.

<table>
<thead>
<tr>
<th>$E_{41z_1}^4$/</th>
<th>$E_{41z_2}^4/\gamma_{41z_1}^4$</th>
<th>$E_{41z_2}^4/\gamma_{41z_1}^4$</th>
</tr>
</thead>
</table>
| $Z = 56$ | $Z = 58$ | $Z = 60$ | $Z = 62$ | $Z = 64$
| $N = 86$ | 602 | 641 | 696 | 747 | 784 |
| $N = 86$ | 360 | 397 | 453 | 550 | 638 |
| $N = 88$ | 199 | 258 | 301 | 334 | 344 |
| $N = 90$ | 181 | 158 | 130 | 122 | 123 |
| $N = 92$ | 142 | 98 | 76 | 82 | 89 |

| $N = 84$ | 1.98 | 1.90 | 1.89 | 1.85 | 1.81 |
| $N = 86$ | 2.12 | 2.36 | 2.30 | 2.15 | 2.02 |
| $N = 88$ | 2.66 | 2.59 | 2.49 | 2.31 | 2.19 |
| $N = 90$ | 2.83 | 2.87 | 2.93 | 3.00 | 3.02 |
| $N = 92$ | 3.13 | 3.17 | 3.25 | 3.23 |

Table 4

The half life of $^{146}$La was determined to be $6.0^{+0.4}_{-0.2}$ s, in agreement with the reported value of 6.2 s for the low spin $^{146}$La isomer. The $^{146}$Ce level scheme resulting from the decay of the low spin $^{146}$La isomer has been considerably extended and refined. Four members of the ground state band, three members each of the $8$ and octupole bands, two states in the $\gamma$ band, and the $0^+_3$ band head of the $88$ band have been identified. Comparisons of the experimental level energies and B(E2) values with IBA-2 calculations demonstrate the predic-

4. Conclusions

of the $Z=58$, (Ce) isotopes. Several interesting structural features centering around $^{146}$Ce can be seen from these systems. The $1^+$ and $2^-$ members of the octupole band cross (with the peaks below the $3^+$) at $^{146}$Ce for both the $Z=58$ isotopes and $N=88$ isotones. There is a noticeable drop of the $2^+_1$ level energy and a corresponding increase in the $E_{41z_1}^4/\gamma_{41z_1}^4$ ratio (see Table 4) in going from Nd to Ce in the $N=88$ isotones. Note that this trend also exists in the $Z=58$ isotopes (Table 4) between $N=86$ and 88 (and to a lesser extent between $N=88$ and 90) but is much less severe than the trends observed between $N=86$ and 88 in $Z=56$ and $N=88$ and 90 in $Z=60$. These features seem to indicate some tendencies towards retaining the prolate deformation present in the heavier rare earth nuclides at $N=88$ for the Ce isotopes. However, $^{146}$Ce retains essentially a transitional character and this deformation does not clearly set in for Ce until $N=90$). The Ce isotopes do not, however, show the abrupt onset of deformation characteristic of the Nd, Sm, Gd...($Z=60$) isotopes between $N=88$ and 90 and to a lesser extent of Ba ($Z=56$) between $N=86$ and 88. The effect of fewer protons above the closed shell and the shift of deformation onset from $N=90$ to $N=88$ has "washed out" the sudden appearance of prolate deformation for the $Z=58$ isotopes.

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tive power of this model. It is important, however, to extend our knowledge of unique spin-parity assignments and transition probabilities significantly in order to provide a more stringent test of IBA-2.

Systematic evidence indicates that although some signs of the onset of deformation are present in Ce, this deformation should not be considered to have occurred in Ce until N = 90 (148Ce). The onset of deformation is not sudden in Z = 58 as it is for neighboring isotopic groups. Instead the transition to the well-deformed region follows the smooth pattern present throughout the Ce isotopes (N > 82).

5. Acknowledgements

The authors would like to thank D. D. Warner and R. F. Casten for their many enlightening discussions and helpful suggestions concerning the IBA calculations.

References

9) E. Monnand, private communication (1980).
BAND STRUCTURE IN $^{148}\text{Ce}$ FROM THE DECAY OF MASS SEPARATED $^{148}\text{La}$

R. L. Gill, R. E. Chrien, M. Shnid, G. M. Gowdy and H. I. Liou
Brookhaven National Laboratory, Upton, New York, 11973, USA

D. S. Brenner
Clark University, Worcester, Massachusetts, 01610, USA

F. K. Wohh, K. Sistemich* and H. Yamamoto
Iowa State University, Ames, Iowa, 50010, USA

C. Chung and W. B. Walters
University of Maryland, College Park, Maryland, 20742, USA

Abstract

$^{148}\text{La}$ The $\beta$ decay of $^{148}\text{La}$ to levels in Ce has been studied at the TRISTAN ISOL facility at Brookhaven National Laboratory's High Flux Beam Reactor. A level scheme for $^{148}\text{Ce}$ is presented which identifies a first excited $0^+$ state at 770.16 keV. $0^+$, $2^+$ and $4^+$ members of the ground state band, as well as $0^+$, $2^+$, $4^+$, $2^+_1$, $3^+$ and the $1^-$ and $3^-$ members of an octupole band are identified. IBA-2 calculations for the N=90 isotones and Z=58 isotopes are presented.

1. Introduction

The rare earth region of deformed nuclei has been studied very extensively in the past three decades. The investigations provided unusually complete knowledge of these isotopes and revealed impressive examples of smooth systematics of nuclear properties over a wide range of masses. Yet, there are parts of this region where information is still scarce. Thus the nuclei with nuclear charge Z=56-58 have been studied only partially. This is because these isotopes are not easy to access experimentally. They are neutron rich, and many have very short half-lives and can at present only be produced in nuclear fission. Efficient separation techniques are needed for these investigations. Recently the level schemes of even Ba isotopes (Z=56) were studied. Evidence was found that the onset of deformation occurs at lower neutron numbers in Ba than for isotopes with higher Z (Nd, Sm, Gd..) where it is known to be situated at N=90. Now, the separator TRISTAN$^{2,3,4}$ at the High Flux Beam Reactor (HFBR) of the Brookhaven National Laboratory offers the possibility of studying the very neutron rich Ce isotopes through the $\beta$ decay of their La parents. The investigation of $^{148}\text{Ce}$, which is discussed here, was undertaken in order to establish the low-lying levels of this isotope and thus to complete the systematics of the N=90 isotones. In particular, it was of interest to ascertain whether deformation begins at N=90 as in the heavier isotones or at N=88 as in Ba.

Prior to the present investigation information has been published on the half-life of $^{148}\text{La}$ and on a few gamma transitions in $^{148}\text{Ce}$. For the half-life of the $\beta$ decay of $^{148}\text{La}$ values of $t_{1/2} = 1.29 \pm 0.08$ sec, $t_{1/2} = 1.7 \pm 0.5$ sec and $t_{1/2} = 2.61 \pm 0.61$ sec have been reported.\footnote{Gamma-ray singles spectra were taken at the place where the fission products are deposited onto the tape (the parent port). The tape was moved every 4 sec in order to suppress the radiation from long-lived A=148 isobars. In a separate experiment, gamma-ray spectra were registered in the multiscaling mode. The ion beam was deflected for 3 sec and then the beam was shut off for 4 sec while 32 spectra were taken during time intervals of 0.125 sec. Afterwards the tape was moved 15 cm and then the cycle was repeated. The multiscaling measurements enabled determination of the half-life for the $\beta$ decay of $^{148}\text{La}$, the assignment of gamma transitions to this decay and the reduction of the activity of the shorter lived precursors of $^{148}\text{La}$. The detectors were positioned 180° apart at the parent port during the $\gamma-\gamma$ coincidence measurements. Both detectors were positioned 1 cm from the source which formed a line of 1 mm width and 5 mm height. The addresses derived from the energy signals and the time relationship between responses from both detectors were stored in event-by-event mode on magnetic tape.}

Gamma transitions of 386, 295 and 159 keV have been attributed to $^{148}\text{Ce}$ as transitions between the $6^+$, $4^+$, $2^+$ and $0^+$ members of the ground state band.\footnote{Gamma-ray singles spectra were taken at the place where the fission products are deposited onto the tape (the parent port). The tape was moved every 4 sec in order to suppress the radiation from long-lived A=148 isobars. In a separate experiment, gamma-ray spectra were registered in the multiscaling mode. The ion beam was deflected for 3 sec and then the beam was shut off for 4 sec while 32 spectra were taken during time intervals of 0.125 sec. Afterwards the tape was moved 15 cm and then the cycle was repeated. The multiscaling measurements enabled determination of the half-life for the $\beta$ decay of $^{148}\text{La}$, the assignment of gamma transitions to this decay and the reduction of the activity of the shorter lived precursors of $^{148}\text{La}$. The detectors were positioned 180° apart at the parent port during the $\gamma-\gamma$ coincidence measurements. Both detectors were positioned 1 cm from the source which formed a line of 1 mm width and 5 mm height. The addresses derived from the energy signals and the time relationship between responses from both detectors were stored in event-by-event mode on magnetic tape.}

2. Experimental Techniques

2.1 TRISTAN

The TRISTAN isotope separator facility 2,3,4,7 is installed at an external beam tube of the HFBR. For the studies of the La decays a Surface Ionization Source\footnote{Gamma-ray singles spectra were taken at the place where the fission products are deposited onto the tape (the parent port). The tape was moved every 4 sec in order to suppress the radiation from long-lived A=148 isobars. In a separate experiment, gamma-ray spectra were registered in the multiscaling mode. The ion beam was deflected for 3 sec and then the beam was shut off for 4 sec while 32 spectra were taken during time intervals of 0.125 sec. Afterwards the tape was moved 15 cm and then the cycle was repeated. The multiscaling measurements enabled determination of the half-life for the $\beta$ decay of $^{148}\text{La}$, the assignment of gamma transitions to this decay and the reduction of the activity of the shorter lived precursors of $^{148}\text{La}$. The detectors were positioned 180° apart at the parent port during the $\gamma-\gamma$ coincidence measurements. Both detectors were positioned 1 cm from the source which formed a line of 1 mm width and 5 mm height. The addresses derived from the energy signals and the time relationship between responses from both detectors were stored in event-by-event mode on magnetic tape.} was implemented into the system. About 59 of highly enriched $^{235}\text{U}$ are impregnated into a graphite cloth cylinder. The cylinder of 3 cm length and 2 cm diameter is exposed to a flux of about $1.5 \times 10^{10}$ neutrons per cm$^2$ per sec. The target is located inside the ion source and is heated by electron bombardment to approximately 2200°C. The fission products are evaporated from the cylinder and ionized on a Re surface. They are separated according to their mass through a 90° magnet and focussed onto a moving tape collector.

2.2 Gamma-ray Measurements

Gamma-ray singles spectra were taken at the place where the fission products are deposited onto the tape (the parent port). The tape was moved every 4 sec in order to suppress the radiation from long-lived A=148 isobars. In a separate experiment, gamma-ray spectra were registered in the multiscaling mode. The ion beam was deflected for 3 sec and then the beam was shut off for 4 sec while 32 spectra were taken during time intervals of 0.125 sec. Afterwards the tape was moved 15 cm and then the cycle was repeated. The multiscaling measurements enabled determination of the half-life for the $\beta$ decay of $^{148}\text{La}$, the assignment of gamma transitions to this decay and the reduction of the activity of the shorter lived precursors of $^{148}\text{La}$. The detectors were positioned 180° apart at the parent port during the $\gamma-\gamma$ coincidence measurements. Both detectors were positioned 1 cm from the source which formed a line of 1 mm width and 5 mm height. The addresses derived from the energy signals and the time relationship between responses from both detectors were stored in event-by-event mode on magnetic tape.
2.3 Beta Measurements

A short, 12 hr, $\beta$ spectrum was accumulated using a thin hyperpure Ge detector with an 12 $\mu$m Ti window. This detector has high efficiency for electrons up to 10 MeV and views the source with an overall solid angle of about 4% of 4$\pi$. The energy shift due to window losses (8.25 keV) was determined by counting an uncovered 207$\text{Bi}$ source. A singles spectrum of $^{148}\text{La}$ was taken at the parent port with the tape moving at 5 sec intervals, while the detector was performing for the explicit purpose of identifying E0 electron transitions.

3. Results

3.1 Gamma Intensities and Half-life

The information on the energies and the relative intensities of the gamma transitions in $^{148}\text{Ce}$ is compiled in Table 1. The intensities take into account the energy dependence of the efficiency of the detectors, but these were not corrected for internal conversion. They are normalized to 1000 units for the 158.40 keV transition from the excited state of $^{148}\text{La}$ up to now. Gamma transitions with intensities as low as 6 relative units were observed in the present study. Analysis of the multispectra data yielded a value of $1.19 \pm 0.05$ sec for the half-life of $^{148}\text{La}$.

Table 1. List of energies (in keV) and intensities of the $\gamma$ transitions in $^{148}\text{Ce}$.

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<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$</th>
<th>$E_\gamma$ (keV)</th>
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<td>1985.43</td>
<td>44.1</td>
</tr>
</tbody>
</table>

3.2 Level Scheme

The level scheme of $^{148}\text{Ce}$ is shown in fig. 1. It has been constructed from the coincidence information and the intensities and coincidence information have been corrected for internal conversion where possible. Since most of the levels are depopulated through more than one gamma transition their energies are well established. Only 3 of the gamma lines of Table 1 are not incorporated into the scheme. The $\beta$ feedings and the log ft values have been calculated from the relative gamma intensities including internal conversion. They do not take into consideration a possible $\beta$ transition into the ground state of $^{148}\text{Ce}$ or unobserved gamma feedings of the levels through high energy transitions from high lying levels. The fact that the probable $0^+_1$ level is only weakly fed in the $\beta$ decay suggests that the ground state feeding should not be strong.

3.3 Ground State Band

The $2^+_1$ and $4^+_1$ levels which were identified previously are confirmed. No population of the $6^+_1$ level has been observed in the present investigations. The level at 841.23 keV is not identical with the $6^+_1$ level, the energy of which has been reported to be 840.9 keV. The energy difference is beyond the experimental uncertainties and the deexcitation excludes spin 6 for the level observed. A level at 537 keV in $^{148}\text{Ce}$ could not be confirmed. The coincidence data require a different position of the gamma rays which were supposed to deexcite this state.

4. Discussion

Information on the nature of the low lying levels in $^{148}\text{Ce}$ is deduced from the gamma ray deexcitation pattern and from the systematics of the levels both of the lighter even Ce isotopes and of the N=90 isotones. The position of the first excited $0^+_1$ level (032) is of special interest for the understanding of nuclear structure. It is well known that inside a series of isotopes the $0^+_2$ level lies lowest at the onset of deformation. If the vibrational light isotopes the $0^+_2$ state belongs to the two phonon triplet and lies high. In the deformed region it forms the head of the $\beta$ band and again has a higher energy.

4.1 $0^+_2$ State

The lowest candidate for the $0^+_2$ state in $^{148}\text{Ce}$ is the level at 770.16 keV. All other new levels below 1300 keV are depopulated either into the ground state or into the $4^+_1$ level. Those gamma transitions would be strictly forbidden or highly improbable from a $0^+_1$ level. There is a gamma ray (770.52 keV) which could suggest a crossover transition from the 770.16 keV level to the ground state. However, this gamma ray is observed in coincidence with the 294.93 keV (4^+_1 to 2^+_1) and the 158.40 (2^+_1 to 0^+_1) transitions. Therefore, it cannot depopulate the level at 770.16 keV. The $\beta$ spectrum from the experiment described in sect. 2 showed evidence for an E0 transition between the 770.16 keV level and the ground state. But due to background contamination
Fig. 1 The proposed level scheme of $^{148}$Ce. The placement of all transitions is established through coincidence results.

from a previous experiment, the electron line was not completely resolved. An upper limit for the E0 transition from the 770.16 keV level was placed at 3 percent of the total depopulation of that level.

Hence, based on its depopulation, the tentative observation of the E0 line and N=90 isotope systematics, fig. 2, it is supposed that the level at 770.16 keV is a 0+ state. Its interpretation as the first excited 0+ level in $^{148}$Ce is suggested by the systematics of the N=90 isotones and the failure to observe other E0 lines in the 8 spectrum.

4.2 Octupole Band

Both the systematics of the Ce isotopes, fig. 3, and of the N=90 isotones predict the 1+ and 3+ levels around 500 to 1000 keV excitation energy. Good candidates for these levels are the states at 760.26 and 841.23 keV respectively. This assignment is also supported by the deexcitation pattern of these levels.

4.3 Beta Band

If the 0+ 0.2% level is supposed to lie at 770.16 keV then it is very likely that the state at 935.55 keV is the 2+ member of the 8 band. The systematics, figs. 2 and 3, support this choice. In the other N=90 isotones the difference in energy between the 2+ and 0+ level is approximately equal to the excitation energy of the 2+ state.

The 2+ assignment of the 935.55 keV level would give 165.39 keV for the 2+ - 0+ difference in $^{148}$Ce compared to 158.40 keV for the energy of the 2+ level. The fact that no transition from the 935.55 keV level
into the ground state or the $0^+$ state has been observed in line with the generally weak $2^+_2$ to $0^+_1$ and $2^+_3$ to $0^+_3$ transitions in the isotones.

A good candidate for the $4^+$ state of the $\beta$ band is the level at 1223.85 keV. With this assignment, the ratio of the $4^+_8$ level over that of the $4^+_4$ level is 2.7, which compares favorably with the corresponding ratios of 2.5 to 2.7 for the heavier N=90 isotones. The deexcitation pattern is also in reasonable agreement with the situation in the heavier isotones.

4.4 Gamma Band

The level at 989.87 keV is considered as the $2^+_2$ head of the $\gamma$ band because of its deexcitation which connects it with the ground state, the $2^+_4$ state and the $4^+_4$ state. The $3^+_6$ level of this band might be the state at 1116.65 keV. The difference between 1116.65 and 989.87 keV is very similar to the difference of the $3^+_7$ and $2^+_5$ levels in $^{152}$Sm and $^{154}$Gd. Higher spin members of the $\gamma$ band are not obvious among the observed levels in $^{148}$Ce.

4.5 Systematic Trends

Although the above-mentioned spin and parity assignments are by all means tentative, they form a best choice at the present state of knowledge about the level scheme of $^{148}$Ce. A different grouping of the levels would lead to irregularities in the systematics. With the proposed assignments the systematics are very smooth. This is especially true for the ground state and $\beta$ band as well as for the $1^+$ and $3^-$ levels. The $\beta$ band follows the tendency of the ground state band which have the lowest lying members at $^{152}$Sm and $^{154}$Gd. The $\gamma$ band reveals less regularity since there is a rise of the $2^+_3$ level between $^{146}$Ce and $^{146}$Ba.

The trends of the levels in the Ce isotopes make it clear that the onset of deformation cannot be considered to take place earlier than N=90. All relevant levels decrease strongly between $^{146}$Ce and $^{148}$Ce in contrast to the situation for $^{144}$Ba and $^{146}$Ba. This was known for the ground state band; it has been shown in the present work for the other low lying states. Especially the energies of the lowest observed $0^+$ levels decrease strongly between $^{146}$Ce and $^{148}$Ce. If these levels are indeed the $0^+$ states then they can have their minimum at $^{148}$Ce at the earliest.

It is of interest to inspect the ratios of the energies of the $0^+$ levels over the energies of the $2^+$ states. These ratios are plotted in fig. 4. They are considered as a clear indication of the onset of deformation. A different grouping of the levels would lead to irregularities in the systematics. With the proposed assignments the systematics are very smooth. This is especially true for the ground state and $\beta$ band as well as for the $1^+$ and $3^-$ levels. The $\beta$ band follows the tendency of the ground state band which have the lowest lying members at $^{152}$Sm and $^{154}$Gd. The $\gamma$ band reveals less regularity since there is a rise of the $2^+_3$ level between $^{146}$Ce and $^{146}$Ba.

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for Ba as to the present knowledge.\textsuperscript{1)} Here the ratio rises continuously which can be an indication of a more gradual change of nuclear shapes. The investigations at TRISTAN show an intermediate situation for the Ce isotopes.

4.6 IBA Calculations

Prior to the experimental studies on the level scheme of \textsuperscript{148}Ce calculations using the Interacting Boson Approximation Model were performed for this nucleus. The parameters for the Hamiltonian of IBA-2 have been determined by detailed fits to isotopes and isotones of \textsuperscript{148}Ce to produce values for $\chi_n$ and $\chi_y$ respectively. Values for the boson energy, $\varepsilon$, and the quadrupole interaction strength, $\kappa$, have been determined by requiring the $2^+_1$ and $4^+_1$ energies (which were previously known) to be calculated exactly. No other parameters were allowed to vary. When the results of this calculation are compared to the experimental data, the agreement is good which supports the proposed identification of the observed low lying levels in \textsuperscript{148}Ce.

Figure 5 shows a comparison of IBA-2 calculations with experiment for the low lying levels of the $N=90$ isotones. The IBA-2 results for Nd, Sm and Gd were obtained using parameters given in id). The experimental points are from ref. 5). Figure 6 shows a similar comparison for the Ce ($Z=58$) isotopes. The IBA-2 model is not expected to work well too near a closed shell and the calculations do show considerable discrepancy for the Ce isotopes near $N=82$. However, as N gets larger, the agreement improves. In any case, the model does predict the correct trends in the systematics, except for the $2^+_2$ state in \textsuperscript{142}Ce.
Fig. 4 The $E_{2}^{0}$/$E_{2}^{+}$ ratios for the rare earth region.

Fig. 5 Comparison of IBA-2 calculations (solid line) with experimental data for low lying levels in the $N=90$ isotones.

deexcitation pattern suggest spin and parity assignments. All evidence shows that the onset of deformation in the Ce isotopes does not take place prior to $N=90$ in contrast to the situation in Ba. The reported value of the deformation parameter $\beta_{2}=0.25$, the $E_{2}^{0}$/ $E_{2}^{+}$ ratio of 2.86 and the $E_{2}^{0}$/ $E_{2}^{+}$ ratio of 4.9 indicate that $^{148}\text{Ce}$ is deformed but still in the transition to a classical rotor. The comparison with the IBA-2 calculations demonstrates the predictive power of this model.

$^{148}\text{La}$ confirms the published value of 1.2 sec. There is no unambiguous evidence for the existence of a $\beta$-decaying isomeric state in $^{148}\text{La}$ while in $^{146}\text{La}$ isomerism has been observed. Most of the $\beta$ feedings of fig. 1 can be accounted for if $^{148}\text{La}$ has a spin of $2^+$. The feedings of the proposed $0^+$ and $4^+$ levels in $^{148}\text{Ce}$ may indicate the presence of another isomer, but the magnitude of the feedings must be considered cautiously since they are based on gamma-ray intensity balances.

5. Conclusions

The level scheme of $^{148}\text{Ce}$ has been extended considerably. Although the low intensities of the transitions prohibited the unambiguous experimental identification of the levels, the systematics and the

References


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*On leave of absence from KFA Julich, Germany.
NUCLEAR SPECTROSCOPY OF NEUTRON RICH A=147 NUCLIDES: DECAY OF 147Cs, 147Ba AND 147La

M. Shmid, Y. Y. Chu, G. M. Gowdy, R. L. Gill, H. I. Liou, M. L. Stelts and R. E. Chrien
Brookhaven National Laboratory, Upton, New York, 11973, USA
R. F. Petry and H. Dejbakhsh
University of Oklahoma, Norman, Oklahoma, 73019, USA
C. Chung
University of Maryland, University Park, Maryland, 20742, USA
D. S. Brenner
Clark University, Worcester, Massachusetts, 01610, USA

Abstract

A study of the beta decay of neutron rich nuclides of the A=147 chain was carried out at the TRISTAN isotope separator. Half lives of 147Cs, 147Ba and 147La were measured. Six gamma lines are assigned to 147Cs decay. A decay scheme for 147Ba with levels up to 2 MeV is proposed for the first time. A partial decay scheme for 147La is proposed, which confirms the previously existing one, with five new levels added from the present work.

1. Introduction

Recent developments in the field of on-line isotope separation made the transition region 141<A<148 more and more accessible for detailed nuclear structure studies. A systematic study of the short-lived, neutron-rich nuclides in this region has been undertaken now at the TRISTAN ISOL facility at Brookhaven National Laboratory. As a part of this effort a preliminary study of the decay of 147Cs, 147Ba and 147La is here reported. Previously reported data on these members of the A=147 chain is very limited. The half life of 147Cs was first measured at the OSTIS facility; the values reported were 0.235 + 0.010 sec\(^2\) and 0.218 + 0.009 sec\(^2\) for 147Cs decay 85, 181 and 246 keV.\(^2\) The half lives of 147Ba and 147La were first measured at the SOLIS facility and they are reported to be 0.72 + 0.07 sec for 147Ba and 4.4 + 0.5 sec for 147La.\(^3\) No gamma lines were reported for the 147Ba decay. For 147La a partial decay scheme was proposed with 11 levels and 20 transitions.\(^4\) In this work the decay of 147Ba was studied in detail and a decay scheme is proposed for the first time. For 147La the existing decay scheme is confirmed and further improved.

2. Experimental Methods

The TRISTAN isotope separator facility, which was recently installed at the High Flux Beam Reactor at Brookhaven Natl. Lab. is described in ref. 5. Ion beams of Cs and Ba isotopes were produced by an integrated target-ion source system\(^6\) which is similar to a previously reported version; 7,8) The target consisted of 5 gr of 239Pu coated on graphite cloth and heated to \(\sim\)2000°C. The target was exposed to a neutron flux of \(\sim\)5 x 10\(^{10}\) n/cm\(^2\)/sec. Cs and Ba fission products which evaporated from the target were ionized with high efficiency by the surface ionization process on a Re surface. At the point of deposition, A=147 beam produced a source intensity of \(\sim\)1 \(\mu\)Ci.

Half lives were determined by multi-scaling gamma activity, using a gamma-x HPGe detector and also by multi-sampling beta activity with a 2\(\mu\) plastic scintillator. Gamma-gamma coincidence events were recorded with two Ge(Li) detectors. The data acquisition and analysis system which supported these experiments is described in ref. 5.

The ion beams were implanted on a moving tape collector, cycled to optimize the experiment for the desired activity. 147Cs and 147Ba activities were detected at the point of deposition. To reduce 147La activity the tape collector was moved every two seconds. 147La was detected at a measuring station 60 cm from the point of deposition. The tape collector was cycled so that the beam was deposited for 8 sec, and then the tape was moved to an intermediate point to allow 147Cs and 147Ba activities to decay for 8 sec. The source was then moved to the detection station for an 8 sec counting interval.

3. Results

3.1 147Cs Decay

For the half life of 147Cs a value of 0.212 + 0.010 sec was obtained from beta decay curves and a value of 0.3 + 0.1 sec was obtained from gamma multiscaling of the 84.7 and 110.0 keV lines. These values are in good agreement with the previous measurements\(^1,2\) and the prediction derived from semiempirical systematics.\(^3\) Six gamma lines were associated with the 147Cs decay: 84.7, 110.0, 280.1, 312.6 and 366.7 keV.

The 181.0 keV line, which decays with the 147Cs half life, is the first \(2^+\) to \(0^+\) transition of 116Ba and is a result of delayed neutron branching. This is based on the coincidence relations of this line. Analysis of the beta decay curve shows that the ratio of direct production of 147Cs to 147Ba is \(\sim\)1:10 but the very low gamma intensity (less than 2% of 147Ba) indicates that high percentage of the beta decay goes to 147Ba ground state.

3.2 147Ba Decay

The half life of 147Ba was determined by beta and gamma multiscaling; the average value was 0.93 + 0.05 sec which is somewhat higher than the previously reported values.\(^2,3\)
More than 200 gamma lines were assigned to 147Ba decay by their decay and their coincidence relations were established using ten million coincidence events. A partial coincidence matrix is given in Table I and the decay scheme, proposed for the first time, is shown in Figs. 1 and 2.

The starting point for building the decay scheme was the level at 167.4 keV which is based mainly on the intensity of the transition. The coincidence lists and the coincidence intensities suggest that the 97.4, 144.0, 190.5, 249.3 and 264.8 keV all depopulate the same level. The fact that the 97.4 line is in coincidence with 167.4 keV and, the high intensity of the 249.3 line, fix a level at 264.8 keV. The coincidence relations of the 157.7 and 144.0 lines indicate that the 105.2 and 120.8 keV lines depopulate the same level.

The high intensity of the 105.2 keV line and the place of the 144.0 transition place this level at 120.8 keV. This structure necessitates the assumption of a level at 15.6 keV. A 15.6 keV transition could not be observed because the detector used could not see lines below ~30 keV. The rest of the decay scheme was constructed around this basic skeleton to fit the coincidence relations.

3.3 147La Decay

The half life of 147La was determined by multiscaling the seven highest intensity gamma lines associated with its decay. The weighted average obtained is 4.48 ± 0.08 sec. This is in good agreement with the previously reported value, but the precision is improved.
Fig. 2 A proposed decay scheme for $^{147}$Ba: decay pattern of levels above 600 keV.

The partial decay scheme proposed is shown in fig. 3. The previously existing decay scheme is substantially confirmed. Two levels at 401.0 and 402.3 keV could be resolved. Five more levels were added at 273.8, 505.0, 558.2, 785.8 and 831.1 keV.
Fig. 3 A partial decay scheme for $^{147}$La. *Multiple placement.
The level at 495.1 keV was confirmed but the 161.5 transition, associated with it, was not seen and the 495.3 keV is not the ground state transition of this level since it is in coincidence with the 215 keV doublet.

4. Discussion

No attempt has as yet been made to arrive at any spin or parity assignments for the 147Ba levels. For the ground state, 7/2+ and 5/2+ seem to be possible assignments. The absence of beta feeding and conversion coefficient data make the relative intensity of the transitions of low-lying levels too uncertain for identifying the multipolarities of the transitions involved. Therefore the work on 147Ba decay should be continued. The level at 15.6 keV should be confirmed by future low-energy gamma spectroscopy, and beta-gamma coincidence experiments will be needed to confirm the decay scheme proposed and to supply information about beta feeding and conversion coefficients.

For the ground state of 147Ce the assignment of J = 5/2− seems to be reasonable from the trend found in the Ce isotopes (3/2− for 143Ce, 5/2− for 145Ce, 5/2− for 147Ce) and also from the trend in the Nd isotopes (5/2− for both 149Nd and 151Sm). Intensity balances suggest that the 177.6 and 186.8 keV transitions are M1 or E2 transitions which is expected from the trend found in the neighboring N=89 isotopes. The intensity balances indicate significant beta feeding to the 117.6 keV level and very little of the feeding to the 186.8 keV level, in agreement with the previously reported beta-gamma coincidence work.

Table I
A partial coincidence matrix for 147Ba decay

<table>
<thead>
<tr>
<th>Gate (keV)</th>
<th>Gamma lines in coincidence (keV)</th>
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<tr>
<td>46.6</td>
<td>74.3  97.4  105.2  120.8  149.9  175.0  211.7  309.5  1055.8  356.1</td>
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<tr>
<td>74.3</td>
<td>93.0  97.4  144.0  158.7  175.0  190.5</td>
</tr>
<tr>
<td>90.9</td>
<td>105.2 120.8</td>
</tr>
<tr>
<td>93.0</td>
<td>74.3  97.4  149.9  175.0  211.7  309.5</td>
</tr>
<tr>
<td>97.4</td>
<td>74.3  93.0  105.2  149.9  167.4  211.7  925.1  1055.8</td>
</tr>
<tr>
<td>105.2</td>
<td>90.9  97.4  144.0  149.9  157.7  175.0  211.7  309.5  1055.8  1268.1</td>
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<tr>
<td>144.0</td>
<td>74.3  105.2  120.8  211.7  925.1  1268.1</td>
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<td>149.9</td>
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<td>167.4</td>
<td>97.4  149.9  175.0  309.5  925.1  1055.8  1268.1</td>
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<td>211.7</td>
<td>74.3  93.0  105.2  144.0  167.4  190.5  249.3  598.6  1055.8</td>
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<td>309.5</td>
<td>93.0  105.2  158.7  232.9  1055.8</td>
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<td>356.1</td>
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<td>1268.1</td>
<td>105.2  167.4  190.5  249.3  264.8</td>
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References


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THE TRANSITIONAL CERIUM ISOTOPES $^{142,144}$Ce

E Michelakakis*, W D Hamilton*, P Hungerford**, S Scott**, G Jung* and B Pfeiffer**

* Physics Division, University of Sussex, Brighton BN1 9QH, England
† Institute v Laue-Langevin, 38042 Grenoble, France
O Physikalisches Institut der J Liebig Universität, 63 Giessen, West Germany

Abstract

The levels populated in $^{142,144}$Ce and the $\gamma$-ray transitions between these levels have been studied by the $\gamma$-directional correlation method following the $\beta$-decay of $^{142,144}$Ta. Coincidences were measured at six angles by Ge(Li) detectors operating in the event-by-event mode.

Coincidence data were analysed for selected gates and formed the basis for constructing extensive decay schemes. The directional correlation results enabled spin assignments to be made to most levels and the multipole mixing ratios of many transitions were determined.

1 Introduction

Lying between the semi-magic $^{148}$Ce (N = 82) nucleus and $^{146}$Ce which begins to show the characteristic level structure of a rotational nucleus, we have a group of nuclei in a transitional region. Their low-lying levels and the transitions linking these may be studied through the $\gamma$-ray transitions which occur following the $\beta$-decay of the parent lanthanum isotopes. These are conveniently produced in the mass-chains of the caesium fission products which are produced following thermal neutron capture by $^{233}$U. The 142, 144 and 146 mass caesium isotopes were selected by the OSTRIS on-line separator at the ILL Grenoble and in this paper we report briefly on off-line measurements on levels and $\gamma$-ray transitions in $^{142,144}$Ce.

The principle features of the experiment were similar to those used by Scott et al.\(^1\) in measurements on the neutron-rich even-mass barium isotopes in which the caesium decays were studied in the on-line mode. In the present experiments the measurements were made in an off-line position approximately 20 cm from the isotope collection point. This separation allowed adequate shielding to be placed between the isotope collection and measuring positions. The period between tape transports was chosen to optimise the ratio of lanthanum activity to those of preceeding shorter-lived decays.

Gamma rays were detected by two 20% efficient Ge(Li) detectors and the source-detector separations were each 6 cm which ensured a relatively good coincidence efficiency without greatly decreasing the directional sensitivity of the system. The correlation table was automatically controlled and measurements were made at 6 angles approximately evenly spaced between 90° and 180°. The activity was monitored by the stationary detector and corrections were applied for changes in source strength and source decay and for the small miscentering of the source with respect to the moving detector.

Data were recorded in the event-by-event mode and the output of the TAC was also digitised. In the subsequent analysis it was possible to set gates corresponding to true-plus-accidental and accidental events and the spectrum of true events was obtained from the difference in these two spectra.

2. Data evaluation

2.1 Coincidence data

The coincidence data recorded at all angles were summed to give the total or 'global' spectrum for each decay. These spectra differ from the singles spectra as all non-coincident $\gamma$-ray transitions to the ground state are absent.

A selection of gating transitions was made and the coincidence spectra corrected for accidents and background were obtained. These spectra formed the basis for constructing the decay schemes.

Level energies were determined from the $\gamma$-ray energies and when a level had several alternative and established decay modes it was required that the total decay energies were consistent within the quoted errors. Errors arose partly from the energy calibration, which was made using $^{152}$Ba, but mostly from the analysis of the spectrum. We further required that the population and decay of a level was consistent with transition intensities. As a result of these conditions multiple placements of transitions are possible in only a few cases and these are indicated in the decay schemes.

2.2 Directional correlation data

Peak intensities were evaluated for the most intense transitions in coincidence with $\gamma$-rays which have a usefully large correlation coefficient. Corrections were made for the background contributions and for source miscentering and we obtained $a_\lambda$-correlation coefficients in the equation

$$W(\theta) = 1 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta)$$

where $\theta$ is the angle and the $B_\lambda$ and $A_\lambda$ describe the first and second members of the cascade.

In total $2 x 10^7$ coincidence events were recorded for $^{144}$Ce and $4 x 10^7$ coincidences for $^{142}$Ce and in many of the evaluate correlations the statistical precision of the results was high as may be judged from Fig 6. Several assumptions were made in the data evaluation:

Levels decaying to the $0^+$ ground state have possible spin-parity assignments of $2^+$ or $2^-$. A transition with an $L = 2$ intensity greater than 10\% is E2 and links states of the same parity. The converse statement is not always true but tentatively, and if not prevented by strong reasons a predominantly $L = 1$ transition is considered to be E1.

Spin assignments and mixing ratios were made at the level of one standard deviation on the $a_\lambda$-coefficient.

The sign convention of Steffen and Alder\(^2\) was used in the evaluation of multipole mixing ratios.
3 Experimental results

3.1 Levels and transition in $^{142}$Ce

Our previous knowledge of the decay of $^{142}$La is summarised in Tables of Isotopes\(^1\) and Nuclear Data Sheets\(^1\) and the several earlier experiments indicate that the decay is complex with spin assignments made to only the first few levels and most $\gamma$-rays were unplaced in the scheme.

![Image 1](image1.png)  
**Fig 1** The single $\gamma$-ray spectrum of transition in $^{142}$Ce following the $\beta$-decay of $^{142}$La.

Figs 1 - 4 show the $\gamma$-ray singles spectrum, the total coincidence spectrum, and examples of gated spectra. Altogether seven gates were used and on the basis of these data the level scheme shown in Figs 5a,b was constructed.

Only the 2043.4 keV level is in some doubt for although a 1402.2 – 641.2 keV coincidence was noted no other transition from the level was seen.

The 641.2 keV $2^+ - 0^+$ ground-state transition has a usefully large $A_2$ coefficient and all correlations were recorded in coincidence with this gate. Figure 6 show some of these results on plots of the coefficients $B_2$ vs $B_4$ as a function of the $I=1: L$ mixing ratio. An extensive discussion of all levels is given by Michelakakis\(^1\).

It should be noted that the 1219.3 keV level previously considered to be $4^+$ is $2^+$. The $A_2$-correlation result lies at approximately six standard deviations from the value for a $4^+-2^-0$ cascade. This spin $2^+$ assignment now allows the 1323.7 keV transition to populate the level from the 2542.7 keV $1^-$ state as shown by the coincidence data and the $I=1$ character of the latter is given by the correlation data.

A possible $4^+$ level occurs at 1280.7 keV and is indicated by the presence of a weak 639.5 keV peak in the spectrum coincident with the 641.2 keV $2^+ - 0^+$ transition and with no other one. Its weakness arises because direct feeding from $^{142}$La is unlikely as it would be via a $\Delta J=2$ first forbidden transition and similarly $\gamma$-ray feeding from higher lying low spin states is also improbable.

The results of the correlation measurements are summarised on the decay scheme and the extensive multipole mixing ratio data is contained in Michelakakis\(^1\).

![Image 2](image2.png)  
**Fig 2** The spectrum of coincident $\gamma$-rays obtained by summing the correlation data measured at six angles. It contains all $\gamma$-rays which are in coincidence with another transition.

![Image 3](image3.png)  
**Fig 3** The spectrum of $\gamma$-rays in coincidence with the 641.2 keV gate. The background and accidental contributions have been subtracted.

![Image 4](image4.png)  
**Fig 4** The spectrum of $\gamma$-rays in coincidence with the 578.1 keV gate. The background and accidental contributions have been subtracted.
Fig 5b The higher energy section of the level scheme in $^{142}\text{Ce}$
This new decay scheme of $^{142}$Ce contains 20 additional levels and allows the 40 previously identified but unplaced transitions to be located and in addition some 40 transitions have been identified for the first time. Spins have been assigned to 20 levels and the multipolarity of 30 transitions determined.

3.2 Levels and transitions in $^{142}$Ce

A summary of data from previous experiments shows that the decay scheme is complex and extensive and thus considerable care must be taken in the analysis of spectra.

The presence of preceding decays in the mass 144 chain was identified in the singles spectrum by the presence of the 103.9 keV γ-ray in $^{144}$La and the 199.4 keV γ transition in $^{144}$Ba. These had intensities of 4.6% and 0.12% respectively relative to the 397.9 keV 2 - 0 ground-state γ-ray in $^{142}$Ce.
Fig 7 The decay scheme of $^{146}$Ce. Transition intensities are indicated.
Thirteen gates were used in the analysis and subsequently several of these were shown to contain unresolved components. Thus in this experiment it was particularly important to measure γ-ray relative intensities in the various gated spectra. The decay scheme based on this work is shown in Fig 7 and the relative intensities of γ-rays are included.

In Figs 8 - 11 we show examples of singles and coincident γ-ray spectra.

Before the present work only the first two excited states had firm spin-parity assignments and these were based on IC data. The coincidence data allowed many correlations to be measured and the 397.3 and 541.1 keV gates could be usefully used. Again a full summary of the data is contained in Michielanakis2).

This study of $^{145}$Ce has revealed about eighty additional γ-rays and thirty-seven new levels. It has also lead to a considerable revision of previous data. Spins have been assigned to more than forty levels and the multipole character of a similar number of γ-rays has been made.

3.2.1 The Qγ value of $^{145}$La

Previous measurements of the Qγ value by Stippler et al.13 were based on a decay scheme which differs in many respects from the present one. In particular the low lying levels have many alternative γ-ray feeding modes and thus contain a large number of γ-ray components and are perhaps not so suitable. If the 1523.5 keV γ-ray is used as the gating transition we may expect this to provide the greatest purity Qγ-spectrum as it comes from the decay of the 3197.2 keV level (see Fig 12). Previously it had been assumed to come from the decay of the 2767 keV level. We obtain, using the data of Stippler et al the result $Q_γ = 5882 \pm 180$ keV and this is in good agreement with the value $Q_γ = 5820$ keV based on the mass formulae of Liran and Zeldes8 and is contrary to the previous conclusion about the most appropriate mass formulae for this region.

4 Discussion

The two decay schemes show differences in their general features. In $^{144}$Ce there is a preponderance of low spin states while in $^{145}$Ce there are few, and only one 0+ state has been identified. These differences are thought to arise from the selectivity of the 5-decay process and are due to the different spins of the parent lanthanum nuclei;

$$I^+(^{145}\text{La}) = 2^-$$ and $$I^+(^{144}\text{La}) = 4^-$$ or 5-.

rather than from a fundamental change in level structure.

The level structures differ in one important aspect as may be seen in Fig 13. The second excited state in $^{144}$Ce has a spin-parity of 2+ rather than 4+ which is common to the other cerium isotopes and also to the neighbouring N = 84 isotopes, $^{142}$Ba and $^{140}$Nd. We have weak evidence that a 4+ level occurs at 1280.7 keV.

The general trend in the relative energies of the 1- and 3- levels with increasing neutron number and the tendency to a rotational-like level structure is similar to that observed in barium isotopes by Scott et al. The interchange of the 1- and 3- levels again occurs between N = 86 and N = 88 and the 2g4 level continues to fall in energy in cerium as the neutron number increases but unfortunately the position of the Qγ level in the N = 88 and N = 90 isotopes is still unknown. These features suggest that we might interpret the cerium data in a similar way to that adopted for the group of barium isotopes and conclude that in cerium the onset of nuclear deformations occurs between N = 86 and N = 88 although it is apparent that $^{146}$Ce, like $^{148}$Ba, is not a good rotational nucleus.

Acknowledgements

We are grateful to the Directors of the Institute of Laue-Langevin for the facilities which they placed at our disposal. We wish to express our thanks to Mr. McCrone of the computing group at Daresbury Laboratory where much of the data analysis was done. BR acknowledges the receipt of an award from the Greek Scholarship Foundation (IKY).
References
4 Tuli J K 1978 Nuclear Data Sheets 25 53
5 Michelakakis E 1981 DPhil Thesis, University of Sussex
6 Tuli J K 1979 Nuclear Data Sheets 27 97
8 Liran S and Zeldes N 1976 Atomic Data and Nuclear Data Tables
9 Monnand E et al 1978 Bull CNRS Grenoble 13 27
10 Pfeiffer B 1981 Private Communication
NUCLEAR SPECTROSCOPY OF NEUTRON RICH A = 147 NUCLEI

F. Schussler++, B. Pfeiffer++, H. Lawin+++, E. Monnand++, J. Münzel++++, J.A. Pinston++, K. Sistemisch++++

1. Experimental Techniques

Several ISOL systems, using different separation techniques, were used to perform a systematic study of odd-mass neutron rich nuclei in the transitional region around A = 89.

The mass chain A = 147 is, up to now, the most exotic one we could extensively study with the existing equipments.

At the recoil separator for unslowed fission products Lohengrin (ILL/Grenoble), extremely pure gamma single spectra of \(^{115}\)La, \(^{115}\)Ce and \(^{119}\)Pr, were obtained.

The gamma-gamma coincidences for these nuclei were performed at the recoil separator Josef (K.F.A.-Jülich).

The mass separator Ostis (ILL/Grenoble), equipped with a conventional thermonisation source, was used to observe the decay of \(^{137}\)Cs and its daughter products \(^{138}\)Ba, \(^{137}\)La and \(^{137}\)Ce. Owing to the extreme complexity of the gamma spectra a high-temperature ion source was also installed at this separator in order to enhance drastically the relative intensities of \(^{138}\)Ba, \(^{138}\)La and their daughter products.

Standard techniques were used to perform \(\gamma\)-single, \(\gamma\)-\(\gamma\)-time and \(\gamma\)-\(\gamma\)-time coincidence measurements. A Si(Li) detector was used for conversion electron measurements, which were necessary for the identification of some mixed gamma transitions. For the most important transitions, K/L ratios could be measured leading to the mixing ratios M1/E2.

All these measurements were performed on line with a more or less rapid evacuation of the collected activity.

2. Discussion

The decay schemes proposed for the different nuclei are shown figure 1 to 4. The ground state beta branchings were determined by the "fillation method" using the thermonisation source of OSTIS and the absolute intensities of some gamma transitions in the decay of \(^{117}\)Pr[1]. The rather low logt values of these beta branches may possibly result from an underestimation of the Qβ value (Cs and Ba decays) and from possible systematic error in the "fillation method" due to eventual direct extraction of a small amount of Ba and La, even with the thermonisation source: these two effects would not affect in an appreciable manner the relative beta feedings of the excited states. Another perturbing effect could be a lot of weak unobserved gamma transitions from the region of high density levels, specially in Ba and La were we could not observe levels higher than 1 MeV in spite of the high Qβ values.

It is difficult to identify the huge amount of levels observed below 1 MeV in the nuclei of A = 147 with the rather poor arguments we have for definite spin assignments, as up to now no \(\gamma\)-\(\gamma\) angular correlations were performed.

The total amount of levels with spins lower than 9/2 below 1 MeV in the even-odd or odd-even nuclei around N = 89 neutrons shows a maximum value for the nuclei with A = 147: this maximum is near-by twice the value observed for the neighbouring spherical or well deformed nuclei. This may be considered as an additional indication for the transitional character of the nuclei studied here.

In spite of these considerations, a tentative identification of some low lying levels may be performed, partly owing to the extended systematics which are now available in this region.

The slow, regular decrease of the first excited 2+ levels in the even-even nuclei of that transition region around N = 89 suggests that the deformation appears very progressively: a smooth behaviour of some levels in the neighbouring odd nuclei may therefore also be observed.

Spin of \(^{137}\)Cs ground state:

Spin and parity of \(^{137}\)Cs ground state are unknown; nevertheless, 3/2[422] would be in agreement with the values directly measured by Ekström et al[12] for \(^{137}\)Cs and \(^{135}\)Cs, although a spin 1/2[420] cannot be totally excluded.

Levels of \(^{138}\)Ba:

Considerations concerning the neutron orbits available in that region, suggest that the retardation of the two M1 transitions at 85 and 110 keV can be explained by assuming h/2 character for the two excited states at 85.2 and 109.7 keV and f/2 character for the ground state. The regular decrease observed for the 3/2[532] level in \(^{135}\)Gd, \(^{135}\)Sm and \(^{135}\)Nd - extensively studied nuclei which all have 91 neutrons - with decreasing proton number[3], gives a reasonable support for assuming that the ground state of \(^{138}\)Ba is 3/2[532] from the orbit f/2 (figure 5).

The positive parity states at 46.2, 75.1, 198.9 and 292.0 keV belong to the 113/2 neutron system. A doublet with about 22 keV energy difference, and identified as the beginning of a strongly perturbed 3/2[651] rotational band, is observed at low energy in the heavier N = 91 isotones mentioned above.

The doublet we observe here at 46.2 and 75.1 keV is possible this one. Another possibility, if the existence of the level at 75.1 keV could not be proved, is to consider that the three well established positive parity states at 46.2, 198.9 and 292.0 keV are the low spin states of a strongly mixed band 1/2[660] + 3/2[651] observed in less deformed nuclei in that region, for example \(^{135}\)Nd[3]. One of these positive parity states could also have a non negligible 5/2[532] state which was only observed in \(^{135}\)Gd and \(^{135}\)Sm.

+++ Institut Laue-Langevin, 156 X - 38042 Grenoble Cédex, France.
++ Centre d'Etudes Nucléaires de Grenoble, Département de Recherche Fondamentale, Laboratoire de Chimie Physique Nucléaire, 85 X, 38041 Grenoble Cédex, France.
+++ Kernforschungsanlage Jülich, Institut für Kernphysik, Postfach 1913 - 5170 Jülich, Germany.
++++II. Physikalisches Institut, Justus-Liebig Universität, 6300 - Giessen, Germany.

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Positive parity states were also observed in $^{141}$Ba and $^{143}$Ba. The systematic of some odd Baryum isotopes shown figure 5, where some results of our recent conversion electron and life-time measurements are included, shows the regular lowering of these levels with increasing neutron number. Such an effect, which is also observed in odd Neodymium isotopes, is attributed to the crossing of the 1f3/2 and 2f7/2 neutron orbits when the deformation increases.

As shown in ref. 6 and 9, the doublet1/2$^{-}$-5/2$^{-}$ near the ground state in $^{141}$Ba, is identified in all N = 87 isotones by a strong E2 transition and probably comes from the orbit h9/2 which crosses the orbit f7/2 - responsible for most of the other observed negative parity states - when the deformation increases; it is possible that we observe the same E2 transition in $^{143}$Ba and that the level at 85 keV is the favoured 5/2$^{-}$ level of a strongly perturbed band built on the orbit 1/2$^{-}$ [530] coming from h9/2.

Levels of $^{147}$Ce

The most striking feature in this nucleus is the existence of two-clearly evidenced by their K/L ratios - E2 transitions of 186 and 215 keV feeding the ground state, the second one being faster than the first one. A spin 5/2 for the ground state of $^{147}$Ce, in agreement with the systematic of N = 89 neutrons shown figure 6, would lead to 1/2$^{-}$ for the spins of the levels at 186 and 215 keV; but then we would have no observed candidate for the 7/2$^{-}$ level which is expected at low energy in $^{147}$Ce (as it is in $^{149}$Nd) and which has to be fed by beta decay from $^{147}$La(5/2$^{-}$).

Therefore, we cannot exclude that the ground state of $^{147}$Ce has a spin 7/2$^{-}$, the spins of the two levels at 186 and 215 keV being then 3/2$^{-}$; $^{147}$Ce would then be only a weakly deformed nucleus, as it is also suggested by the absence of positive parity states at low energy.

Concerning the ground state and the first excited state at 64 keV observed in $^{147}$Ce(9) spin sequences 7/2$^{-}$-3/2$^{-}$ or 5/2$^{-}$-1/2$^{-}$ are equally possible on ground of experimental arguments.

Levels of $^{147}$La:

The spin assignment of 5/2$^{-}$ for the ground state of $^{147}$La and 1/2$^{-}$ for the first excited state at 74.9 keV is in agreement with the E2 transition observed between them and with the beta feeding of both levels from the 3/2$^{-}$ ground state of $^{147}$Ba; spin 1/2 is excluded for the ground state of $^{147}$La since levels up to 5/2 are fed in $^{147}$Ce.

The delayed E1 transition of 105 keV probably connects levels belonging to the two different proton orbits g7/2 and d5/2.

In $^{145}$La, the existence of two E1 and one E2 transitions, as shown figure 7b leads to a spin 5/2$^{-}$ for the ground state of this nucleus. A systematic of some odd Lanthanum isotopes is shown figure 7b, which includes also our recent results concerning conversion electron measurements on $^{145}$La. Also included is the level structure of $^{151}$Pm(11) which has the same neutron number as $^{145}$La.

The lowering of negative parity states with increasing neutron number was already observed in odd Pm and Eu nuclei and is regarded as a characteristic feature of the levels originating from the h11/2 proton state. By assuming the structures 5/2$^{-}$ [5/2], 1/2$^{-}$ [4/2] and 3/2$^{-}$ [4/2] for the ground state and the levels at 75 and 105 keV, respectively, the observed retardations of the ground state transitions could be explained by the d5/2 and g7/2 character of these levels.

Levels of $^{147}$Pr:

According to reference 1), where the beta decay of $^{147}$Pr was studied, the most probable spin for the ground state of this nucleus is 5/2$^{-}$.

A spin 3/2$^{-}$ can therefore be deduced for the level at 93 keV, due to the weakness of the beta feeding to this level from the 7/2$^{-}$ ground state of $^{147}$Ce and in agreement with the observed M1 transition of 93 keV. Owing to the gamma branching ratios the level at 2.6 keV could be 5/2$^{-}$.

A spin 7/2 is also probable for the level at 218 keV since no gamma transition to the low spin state at 93 keV is observed.

The systematic shown figure 7a suggests that the levels at 0, 93 and 218 keV may belong to a strongly perturbed rotational band built on the proton orbit d5/2, whereas the level at 2.6 keV could be the lowest level of an equally perturbed band built on the orbit g7/2, as observed in $^{149}$Pm(12).

3. Conclusion

The need of more refined measurements, such as angular correlations, in order to have a chance to understand these nuclei, is obvious.

Nevertheless, our work seems to show that in the mass chain A = 147, Baryum is the most deformed nucleus, and that the most probable spin sequence for the ground state is 5/2$^{-}$ for $^{147}$Cs, 3/2$^{-}$ for $^{147}$Ba, 5/2$^{-}$ for $^{147}$La, 7/2$^{-}$ for $^{147}$Ce and 5/2$^{-}$ for $^{147}$Pr.

List of References


7) F. SCHUSSLER, E. MONNAND, J.A. PINSTON,  
Note CEA-N-2074.

8) G. LOVHOIDEN et al.  

9) R. ROUSSILLE, J.A. PINSTON, F. BRAUMANDL,  
P. JEUCH, J. LARYSZ, W. MAMPE and  
K. SCHRECKENBACH,  
Nuclear Physics A258 (1976) 257-263.

10) B. PFEIFFER, F. SCHUSSLER, J. BLACHOT,  
S.J. FEENSTRA, J. van KLINKEN, H. LAWIN,  
E. MONNAND, G. SADLER, H. WOLLNIK, K.D. WUNSCH  
and the JOSEF, LOHENGREN and OSTIS collabora- 
tion,  

11) T. SEO,  

12) M. KORTELAHTI, A. PAKKANEN, M. PIPARINEN,  
E. HAMMAREN, T. KOMPPA and R. KOMU.  
Nuclear Physics A332 (1979) 422-432.
Figure 2 - Proposed level scheme for $^{147}$La.
Figure 4 - Proposed level scheme for $^{147}\text{Pr}$. 
Figure 5 - Level systematic for N = 91 nuclei and for some odd Baryum isotopes. Position of the 2⁺ states of neighbouring even-even nuclei are shown by black dots.

Figure 6 - Level systematic for N = 89 nuclei and for some odd Cerium isotopes.
Figure 7a and 7b - Level systematic for some odd-proton nuclei around A = 147 and N = 89.
THE DECAY OF $^{153}$Ho TO THE TRANSITIONAL N = 87 NUCLEUS $^{153}$Dy

P. Paris, C.F. Liang, A. Péghaire and the ISOCELE Collaboration
C.S.N.S.M. - B.P. 1 - 91406 ORSAY - FRANCE.

ABSTRACT:

A preliminary $^{153}$Dy level scheme, fed from the decays of $^{153}$Ho and $^{153m}$Ho, is presented. At both Ho isotopes correspond two distinct level schemes, with respectively low and high spins. The low spin part seems very similar to the low spin scheme of the $^{151}$Gd isotone, the interpretation of which suppose a small deformation. The high spin part, dominated by the strong $^6S$ transition ($h\!l/2 = h\!l/2)n$, can be correlated to the scheme obtained by in-beam excitations.

1. INTRODUCTION

Level schemes of neutron deficient odd Dysprosium isotopes obtained from Holmium decays, are well known for $N > 89$. They correspond to deformed nuclei, based on the groundstate $J/2^-$ configuration and the $^{153}$Dy ($N = 89$) scheme can be interpreted in term of other Nilsson configurations, strongly mixed by Coriolis interactions (1). The transition between deformed and spherical shape is expected near $N = 88$ and, indeed, the $7/2$ spin value measured by Rosen et al (2) for the $^{153}$Dy groundstate scheme $7/2^+$ prediction.

Schmidt-Ott et al (3) produced Ho isotopes by bombarding $^{144,147}$Sm with $^{11,10}$B. By using a gas jet capillary transport technique, they observed various $\gamma$ transitions corresponding to two $^{153}$Ho isomers : a low spin one, with a $9.3$ mm half-life, and a high spin one with $T_{1/2} = 2.0$ mm. No level scheme was presented. A study of the first levels fed by the $9.3$ mm isomer, obtained from spallation reactions on a tantalum target and mass separation, was made by Zuber et al (4). Their work was developed by Andrieu et al (5). They measured $\gamma$ and conversion electron spectra, single or in coincidence, level half-lives, and presented a scheme with 4 excited levels at 108.8, 270.6, 500.9 and 565.8 keV. Their 108.8 keV half-life measurement give $1.35 \pm 0.10$ ns.

$^{153}$Dy levels, excited by (a,xn) reactions on Gd targets, are more precisely known after the concordant studies of Kleinheinz et al (6) and Jansen et al (7). From these works, a $h\!l/2$ band, presenting the characters of a large deformation ($J/2^-$) configuration) coexists with two less developed more spherical, $f\!l/2$ and $h\!l/2$ bands. The $i\!l/2$ intrinsic state corresponds to a more complex coexistence of two $\Delta I = \pm 2$ bands.

The new possibility of separating Holmium isotopes at ISOCELE (8) allowed us to extend our previous systematics on odd Dysprosium level schemes. We present here some preliminary results on the $^{153}$Ho decay.

2. HOLMIUM-DYSPROSIUM ON-LINE SEPARATION

Holmium isotopes have been produced by Tb(He, xn) reactions with the I.P.N.-ORSAY synchrocyclotron ($^3$He beam energy = 280 MeV). On-line separations were performed with the ISOCELE 2 facility (9). In this region, the difference between metal volatilities, correlated to the corresponding boiling points (Ho = 2695°C, Dy = 2562°C, Tb = 3123°C) is small, but the Tb-Ho difference is sufficient for using the Terbium as a target for Ho-Dy production, although supporting a small consumption.

By this method, a strong mixing Ho-Dy is unavoidable, but we observed that the Holmium/Dysprosium proportion was improved by a factor up to 4 by using the Terbium target as an anode.

3. EXPERIMENTAL METHODS

The mass-separated Ho-Dy ions were implanted in the nylar tape of a tape transport system associated with various semi-conductor detectors.

Coaxial and planar Ge, Ge(Li) and Si(Li) detectors were used for $\gamma$ and X rays measurements. Conversion electrons were registered with a Si(Li) detector in a magnetic "selector" (10). $\gamma$-e and e-e coincidence experiments (2048 x 2048 channels) were performed with these detectors and analyzed with the Orsay ARIEL IBM Computer. Discrimination between transitions issued from each Holmium isomer was obtained by systematically registering two successive 2 nm spectra after the source transport.

Pure daughter spectra ($^{153}$Dy = $T_{1/2} = 6.5$ h) were obtained by a final delayed counting. Single spectra were analyzed by a special program associated with an ONTEC Ultima analyzer.

4. RESULTS

Two typical : single $\gamma$ and conversion spectra are presented in fig. 1 and 2. A $\gamma$ spectrum obtained with the Terbium target as anode and corresponding to the energies under 700 keV is shown in fig. 2. As a 153 daughter spectrum, practically free of Holmium, was registered in the same conditions, a fraction of it is subtracted from the first spectrum and the result is plotted above in fig. 2, for facilitating the Holmium decay identification. Figure 1 shows some conversion lines at low energies. The use of a magnetic selector eliminates X rays and $^5S$ and most of the daughter spectrum can also be subtracted, but results are not so complete than for $\gamma$ spectra, due to the weak intensity of most of the transitions. In electron as in $\gamma$ spectra, the presence of an intense 295.8 keV M1 transition is predominant.

**Fig. 1:** Conversion spectrum registered with a magnetic "selector".
The decay scheme built from the experimental results is presented in Figure 3. Indeed, the $^{153}$Ho level scheme is the juxtaposition of two very different schemes, issued from each of the 9.3 mm-low spin (left) and the 2 mm-high spin (right) Holmium isomers. The 2 mm levels with spins probably 9/2 and higher, decay by some transitions (inclined on the drawing) on the 9.3 mm levels, the spins of which seem less than 7/2. The high spins part can be correlated with levels obtained by in-beam excitation (6,7) where the 295.8, 636.9, 712.6 and 837.1 keV levels are also identified. The 9.3 mm scheme essentially confirms the Andreiev's work (5) and extends it. Multipolarity determinations are in agreement with his previous measurements but they are not sufficient to univocally determine the spins of the first excited levels. Nevertheless, the fact that the 2 mm high spins scheme decays essentially on the 366.1 and 108.8 levels, very probably 5/2, is in favor of lower values for the other spins and the retained sequence : 7/2, 5/2, 3/2, 5/2, 1/2 of negative parity levels is strikingly similar to the one determined in the $^{151}$Gd (11).

In Figure 3, the transitions for which location is confirmed by γ-γ coincidence measurements are quoted with small circles. Intensities and conversion results of the scheme transitions are presented in Table 1. These intensities are relative to the 295.8 one, fed by the 2.0 mm Ho isomer. As the proportion of the two Ho isomers depends of the excitation mode and owing to the decays of the 2 mm scheme on the 9.3 mm levels, the relative intensities of the 9.3 mm transitions are not completely fixed and change during the first mm of the decay time. The Table 1 corresponds to the spectra registered for the two first minutes following a 4 mm collection time.

Future work is foreseen for measuring $Q_{\beta}$ values and to precise the isomeric level position in $^{153}$Ho (as no Ho x rays were seen with our Si(Li) detector), a direct transition in Holmium seems almost nonexistent). But assuming the theoretical value (12) : $Q_{\beta} = 4300$ keV, we find a low log ft = 4.5 for the 295.8 level, strongly in coincidence with the 511 keV annihilation peak. The 1381.3 and 1276.1 keV levels correspond to other low log ft values near 5.0 and the 9.3 mm levels to log ft values above 5.8.

5. DISCUSSION

As previously mentioned, the 7/2 spin measurement (2) for the Dy groundstate can be identified to the $^{7/2}$ negative parity shell model configuration and, from the conversion results, the four first "9.3 mm" excited levels have the same negative parity. Apart the $^{7/2}$, we expect the presence of the $^{9/2}$ and $^{11/2}$ configurations and, indeed, the in-beam experiments (6) identify the 295.8, 636.9 et 712.6 levels with respectively the $^{9/2}$ (h9/2), $^{11/2}$ (h7/2) and $^{13/2}$ configurations. The 295.8 keV level h9/2 assignment is supported by the strong $^{7+}$ allowed transition from the high spin Holmium isomer. The isomeric level existing in numerous Ho isotopes discloses the existence of the h1/2 shell, separating the d5/2 and d3/2 ones, and the 295.8 keV feeding corresponds probably to the (h1/2)p -> (h9/2) transition. The 2mm half-life Ho isomer should be 11/2 or 9/2, more probably 11/2-, owing to the direct feeding of the 712.6, 13/2 level (log ft ~ 6.1). Such a configuration prohibits any transition to the 11/2-[505] deformed band, found by Kleinheinz et al. and based on a 1068 keV level. The other 9.3mm half-life Ho isomer should be in one of the d3/2, d5/2 configurations, decaying by forbidden $^{7+}$ transitions to the low spin levels.
Concerning these ones, we already noticed the analogy with the corresponding levels in the isotope $^{151}\text{Gd}$ (11). Hämmeren et al. conclude for $^{151}\text{Gd}$ to the probable permanence of a deformation ($\beta > 0.12$), a pure spherical model being unable to explain the number of low spin levels and, especially, the existence of a $1/2^-$, 575.7 keV level which seems similar to the 501.1 keV level in $^{153}\text{Dy}$. Further examinations are planned for interpreting this last isotope.

The 1276.1 and 1381.3 levels, decaying to number of low energy levels in both schemes, seem to be collective levels based on the $f7/2 - h9/2$ configurations, mixed by Coriolis interaction.

![Diagram](image)

**Figure 3**

**Table 1:** Principal transitions, relative intensities and conversion results.

<table>
<thead>
<tr>
<th>$E_Y$</th>
<th>Ir</th>
<th>$Q_X$</th>
<th>K/L</th>
<th>Multip.</th>
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<tr>
<td>75.7±1</td>
<td>10</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>108.8±1</td>
<td>51</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
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<tr>
<td>117.5±1</td>
<td>2.1</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>141.6±2</td>
<td>6.7</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>161.8±1</td>
<td>27</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>186.9±1</td>
<td>4.3</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
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<td>193.4±2</td>
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<td>2.71±.56</td>
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<tr>
<td>230.3±2</td>
<td>15</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>257.0±2</td>
<td>2.9</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
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<td>270.7±1</td>
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<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
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<tr>
<td>295.8±1</td>
<td>1000</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
<tr>
<td>341.0±3</td>
<td>3.7</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
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<tr>
<td>366.1±1</td>
<td>61</td>
<td>1.07±1</td>
<td>2.71±.56</td>
<td>M1+M2</td>
</tr>
</tbody>
</table>

* Theoretical value [I.A. Sliv and I.M. Band [13]].

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- 600 -
REFERENCES:


(2) A. Rosén et al. Ph. Scripta, 6, 24, 1972.


(9) P. Paris et al. 10th EMIS Conference, Zinal, to be published in N.I.M.


(11) E. Hammarén et al. Z. Physik, A272, 341, 1975


IDENTIFICATION OF NEW NEUTRON-RICH RARE-EARTH NUCLEI PRODUCED IN $^{252}$Cf SPONTANEOUS FISSION

R. C. Greenwood, R. J. Gehrke, J. D. Baker and D. H. Meikrantz
Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho 83415, USA

Abstract

A program of systematic study of the decay properties of neutron-rich rare-earth nuclei with $30 \text{ s} < t_{\beta} < 10 \text{ min}$, produced in $^{252}$Cf spontaneous fission, is currently underway using the Idaho ESOL (Elemental Separation On Line) Facility. The chemistry system used for the rare earth elemental separations consists of two high-performance chromatography columns connected in series and coupled to the $^{252}$Cf fission source via a helium gas-jet transport arrangement. The delay for separation and initiation of $\gamma$-ray counting with this system is typically 2-3 min. Significant results which have been obtained to date with this system include the identification of a number of new neutron-rich rare-earth isotopes including $^{155}$Sm ($t_{\beta} = 48 \pm 4 \text{ s}$) and $^{163}$Gd ($t_{\beta} = 68 \pm 3 \text{ s}$), in addition to $5.51 \text{ min}$ $^{158}$Sm which was identified in an earlier series of experiments.

1. Introduction

A comprehensive program of nuclear structure studies of fission products using both on-line chemical and mass-separation techniques has recently been initiated at the INEL. A unique feature of this program, apart from the use of ESOL (Elemental Separation On Line) and ISOL facilities in combination, is the use of $^{252}$Cf as the source of the fission products. As illustrated in Fig. 1, the fission-product yield curve for spontaneous fission of $^{252}$Cf has significant differences from those of the more conventional thermal-neutron fission in either $^{235}$U or $^{239}$Pu. Specifically, one notes in $^{252}$Cf the narrower valley region and the significantly higher yields for isotopes with $A \geq 150$. Because of the long-standing interest at this laboratory in the deformed rare-earth region our initial experimental thrust has been to exploit the higher yields of the rare-earth fission-product isotopes available in $^{252}$Cf. To accomplish this, we have developed a microprocessor controlled high-performance liquid chromatography (HPLC) system which, at the present stage of development, is capable of providing separated fission-product rare-earth elemental fractions within 2-3 min of the end of sample collection. This HPLC system is coupled on-line to the $^{252}$Cf fission sources via a helium gas-jet transport arrangement.

Because of the relative inaccessibility of this region of more neutron-rich rare-earth isotopes, either from other more conventional fission reactions or from particle-induced reactions, there are many such isotopes with expected half-lives $>30 \text{ s}$ which have not previously been observed. As a preliminary step to detailed studies of the structure of nuclides in this region we are presently undertaking a systematic experimental study to observe these unknown isotopes. In this paper we discuss some of the initial results of this effort.

2. The ESOL Facility

2.1 The fission product source

The fission products for this experiment are obtained from two $\sim 300 \mu$g electrodeposits of the spontaneously fissioning isotope, $^{252}$Cf. These sources, which are electrodeposited at Oak Ridge National Laboratory, are located in a specially-designed hot cell and are mounted inside a pressurized chamber which forms an integral part of the gas-jet transport arrangement. A photograph of the source chamber, together with one of the $^{252}$Cf sources is shown in Fig. 2. The He gas pressure in the chamber is sufficient to thermalize the fission products which then rapidly attach themselves to the NaCl aerosols which have previously been seeded into the He gas stream. From the source chamber the fission products, now attached to the NaCl aerosols, are transported via a $\sim 25$-m capillary (1.3-mm i.d.) to the radiochemistry laboratory. There, they exit into an evacuated chamber, located in the radiochemistry hood, and are collected on mylar tape. After a preset collection time, the mylar tape is moved through a vacuum seal to a wash chamber where the deposited NaCl and

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Fig. 1 Comparison of the cumulative yields for spontaneous fission of $^{252}$Cf and thermal neutron fission of $^{235}$U and $^{239}$Pu.

Fig. 2 The $^{252}$Cf source chamber and a $^{252}$Cf source holder with attached N1 window.

*Work supported by the U. S. Department of Energy under DOE Contract No. DE-AC07-76ID01570.
fission products are washed from the tape with 3M HNO₃. Both the tape movement and wash operations are controlled via a microprocessor. Schematic diagrams of the gas jet transport arrangement and the fission product collection and dissolution system are shown in Figs. 3 and 4, respectively.

Fig. 3 Schematic floor plan of the laboratories containing the 25°C hot cell, the mass separator and the chemistry hood.

Fig. 4 Automated fission product collection and dissolution apparatus.

2.2 Rare-earth chemistry

The chemical separation of individual rare-earth elemental fractions involves two steps. First, the rare-earth elements are isolated as a group by extraction chromatography. Second, specific separation of the individual rare earths is accomplished by cation exchange. Each of these chemical steps is under the control of a microprocessor. The details of this radiochemical separation technique are given in Refs. 2 and 3. The following is a brief description of the automated radiochemical separation.

After the fission products are washed from the collection tape, they are pumped onto the extraction chromatography column where the rare earths adhere to the extractant, dihydroxideethylcarbamylmethylene phosphonate (DHDECMP), which is adsorbed on Vydac C₈ resin. After the non-rare-earth fission products have passed through the column to waste, the rare earths are eluted with α-hydroxyisobutyric acid (α-HIBA). The eluted rare earths pass to the loop of the injection valve of the second column where they are trapped and subsequently injected onto the cation exchange column which is made up of Aminex A-9 resin. The rare-earth fission products are eluted in inverse order of Z (i.e., heaviest first) by gradient elution using α-HIBA as the eluent. The individual radio-elements are monitored as they come off the second column with a shielded NaI(Tl) detector. This detector is coupled to a strip chart recorder to provide a chromatogram of the separation. A schematic diagram, together with a photograph, of the high performance liquid chromatography columns coupled in series are shown in Figs. 5 and 6, respectively. Figure 7 shows a chromatogram of a typical separation designed for the separation of the heavier rare-earth fission product fractions, i.e., for Tb and Dy. By changing the program controlling the eluant concentration and pH as a function

Fig. 5 Schematic diagram of the series coupled HPLC system.

Fig. 6 Photograph showing the two HPLC columns coupled in series.
of time, the higher rare-earth fractions can be separated in shorter times than those shown in Fig. 7.

![Fig. 7 Typical chromatogram obtained for fission product separations. The time scale is started from the end of the fission product collection period.](image)

2.3 \( \gamma \)-ray measurements

The selected rare-earth elemental fraction, contained in a few drops of solution, is counted at 42 cm source-disk distance using a 102-cm\(^3\) coaxial Ge(Li) detector. A 1.235-g/cm\(^2\) Be absorber is used to reduce the background in the detector associated with the \( \beta \) continuum. The resulting 4096 channel pulse height spectra are stored in an Ampex DM 980 80 MByte disc via a PDP 8/E processor. In each experiment a preset sequence of multiscaled 4096 channel \( \gamma \)-ray spectra are obtained following each separation, in order to obtain half-life information for each of the \( \gamma \)-ray lines in the spectra. The availability of the large 80 MByte storage disc allows us to store separately the set of multiscaled spectra obtained following each separation. Following the experiment, the quality of each separation can be assessed and the multiscaled data combined as desired (i.e., data resulting from "bad" separations can be excluded from the final multiscaled spectral sums). For example, in the case of the Pm separation, which is typical of the rare-earth elemental fractions studied, a 2-min He-Jet collection was employed and the first \( \gamma \)-ray spectral count was started \( \geq 2 \) min after the end of the fission-product collection. For each of the 13 radiochemical separations performed, forty 18-s counts were made with a 2-s delay time between each count. Thus, in the completed experiment a total of 520 4096-channel spectra were accumulated.

3. Experimental Measurements and Results

3.1 Measurements

In an earlier series of experiments performed with the series coupled HPLC system, the new isotope, \( 5.51\)-min \( ^{155}\text{Sm} \), was identified.\(^1\) Since that time the speed of the radiochemical separation has been improved (by greater than a factor of 2) and larger \( ^{252}\text{Cf} \) sources have been acquired. With these improvements in the ESOL facility, it therefore seemed profitable to renew our search for new neutron-rich rare-earth isotopes. In this most recent series of experiments, elemental fission-product fractions of Nd, Pm, Sm, Eu, Gd, Tb and Dy were separated and individually \( \gamma \)-ray counted in the multiscaled mode. Analysis of these data is presently being carried out. The results reported in this present paper are from analysis of the data from the Pm and Gd fractions.

3.2 The \( ^{155}\text{Pm} \) isotope

In Fig. 8 we show the lower energy portions of the first and fifth (i.e., 80-s time separation between them) multiscaled spectra summed over the 13 Pm separations performed. The activities observed in this spectrum are 4.1-min \( ^{152}\text{Pm} \), 7.5-min \( ^{152}\text{Pm} \), 5.4-min \( ^{153}\text{Pm} \), 1.7-min \( ^{154}\text{Pm} \), 2.7-min \( ^{155}\text{Pm} \), 46.8-h \( ^{153}\text{Sm} \) (Later spectra only), 22.4-min \( ^{155}\text{Sm} \), 12.4-min \( ^{151}\text{Nd} \), 11.6-min \( ^{152}\text{Nd} \) and \( ^{152}\text{Sm} \) activity in this study as \( ^{155}\text{Pm} \). The 725- and 778-keV \( \gamma \) rays in Fig. 8 are the most prominent which can be associated with this latter activity. As seen from the figure, they are clearly decaying at a much faster rate than those \( \gamma \) rays which can uniquely be associated with the decay of the 1.7-min \( ^{154}\text{Pm} \) (e.g., the 839-keV peak).

The assignment of the 48-s activity to \( ^{155}\text{Pm} \) is based on the following three observations:

1. the activity is present only in the Pm fraction, it is not observed in either of the adjacent Nd or Sm fractions;
2. the intensity of the 104-keV \( \gamma \) ray emitted in the decay of 22.4-min \( ^{155}\text{Pm} \) increased throughout the first 7 multiscaled spectra, indicating that it is being fed by a 50-s parent activity (as illustrated in Fig. 9); and
3. the prominent 725- and 778-keV \( \gamma \) rays can be placed in \( ^{155}\text{Pm} \) on a consistent basis with the level scheme of \( ^{155}\text{Sm} \) proposed by Smither et al.\(^9\) from studies of the \( ^{156}\text{Sm}(n,\gamma) \) reaction.

A summary of the \( \gamma \)-ray energies and relative intensities which can be associated with the \( ^{155}\text{Pm} \) decay is given in Table 1. A value of 48 \( \pm 4 \) s was obtained for the half-life of this isotope, based on the decay rates of the 409-, 725- and 778-keV \( \gamma \) rays. From a comparison of the relative intensities of the 104-keV \( \gamma \) ray in the \( ^{155}\text{Sm} \) daughter (using a value of 70 \( \pm 6 \) \( \gamma \) rays per 100 decays for its intensity\(^10\)) to that of the 778-keV \( \gamma \) ray in the \( ^{155}\text{Pm} \) parent we obtain a value of 7.9 \( \pm 0.8 \) \( \gamma \) rays per 100 decays for the absolute intensity of the 778-keV \( \gamma \) ray. (In obtaining this value, a correction was made to the 104-keV \( \gamma \)-ray intensity for the \( ^{155}\text{Sm} \) initially present as a contaminant in the Pm fraction following the separation.)

From the level assignments for \( ^{155}\text{Sm} \) of Smither et al.\(^9\) the \( \gamma \) rays shown in Table 1 are quite straightforwardly fit into a decay scheme for \( ^{155}\text{Pm} \) as illustrated in Fig. 10. The prominent decay into the spin-3/2 member of the 3/2\( ^{2}\)[\( ^{52}\text{Zr} \)] band in \( ^{155}\text{Sm} \) is analogous to that in the decay of \( ^{153}\text{Pm} \). In fact, if we assume a Q value of 3.1 MeV for the decay of \( ^{155}\text{Pm} \),\(^11\) this branching rate yields a log ft value of 5.6, which is essentially identical to the value of 5.5 reported\(^10\) for the same transition in \( ^{153}\text{Pm} \) decay. Such a fast transition is, as has been proposed for \( ^{155}\text{Pm} \), consistent with 5/2\( ^{2}\)[\( ^{52}\text{Zr} \)] assignment to the \( ^{155}\text{Pm} \) ground state.
Fig. 8 Lower energy portion of the first (upper) and fifth (lower) multiscaled γ-ray spectra, with a time separation of 80 s, measured with the Prm fraction. The γ-ray peaks are identified by the following key: (a) 1.4-min 152Prm; (b) 7.5-min 152Prm; (c) 5.4-min 153Prm; (d) 1.7-min 154Prm; and, (e) 2.7-min 114Prm.

Table 1. Energies and relative intensities of the γ rays associated with the decay of 155Prm

<table>
<thead>
<tr>
<th>γ-ray energy (keV)</th>
<th>Relative intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.1(5)</td>
<td>12(2)</td>
</tr>
<tr>
<td>409.8(2)</td>
<td>28(2)</td>
</tr>
<tr>
<td>725.4(2)</td>
<td>68(3)</td>
</tr>
<tr>
<td>762.0(3)</td>
<td>19(4)</td>
</tr>
<tr>
<td>778.6(2)</td>
<td>100</td>
</tr>
</tbody>
</table>

Q_{sys} = 3100

Fig. 9 Grow-in of the 104-keV γ ray from the 22.4-min 155Sm decay as a function of time after separation.

3.3 The 169Gd isotope

In Figs. 11 and 12 we show the first and fourth (i.e., 3-min separation time between them) multiscaled spectra of the Gd fraction, summed over all

Fig. 10 Proposed decay scheme for the 48-s 155Prm isotope.

of the individual Gd separations. The activities observed in this spectrum are 3.6-min 161Gd, 9-min 162Gd, 7.7-min 162Gd, 19-min 162Gd, 53Gd, and Eu contaminants and a 68-s activity identified in this study to be 163Gd.
Fig. 11 The first (upper) and fourth (lower) multiscaled γ-ray spectra, with a time separation of 3.0 min, measured with the Gd fraction. The γ-ray peaks are identified by the following key: (a) $^{161}$Gd, (b) $^{162}$Gd; and, (B) $^{162}$Tb.

Fig. 12 The first (upper) and fourth (lower) multiscaled γ-ray spectra, with a time separation of 3.0 min, measured with the Gd fraction. The γ-ray peaks are identified by the following key: (a) $^{161}$Gd, (b) $^{162}$Gd; and, (B) $^{162}$Tb.
The assignment of the 68-s activity to $^{163}$Gd
is based on the following: (1) the $\gamma$-ray lines
associated with this activity are present only in
the Gd fraction; and (2) the grow-in of the 351-keV
$\gamma$ ray emitted by 19-min $^{163}$Tb is consistent with its
being fed by a 68-s parent activity (as illustrated in
Fig. 13).

A summary of the energies and relative intensi-
ties of the $\gamma$ rays which can be associated with the
$^{163}$Gd decay is given in Table 2. A value of $68 \pm 3$ s
was obtained for the half-life of $^{163}$Gd based on an
average of each of the decay rates of the $\gamma$-rays
shown in Table 2. A value of $16 \pm 3$ $\gamma$ rays per 100
decays was obtained for the absolute intensity of
the 287-keV $\gamma$ ray based upon comparison of its
intensity with that of the 351-keV $\gamma$-ray emitted in the
decay of 19-min $^{163}$Tb (with an absolute
intensity of $26.3 \pm 0.4$ $\gamma$ rays per 100 decays$^{19}$)).

Table 2. Energies and relative intensities of the
$\gamma$ rays associated with the decay of $^{163}$Gd

<table>
<thead>
<tr>
<th>$\gamma$-ray energy (keV)</th>
<th>Relative $\gamma$-ray intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>214.0(3)</td>
<td>46(3)</td>
</tr>
<tr>
<td>287.8(3)</td>
<td>100</td>
</tr>
<tr>
<td>373.4(3)</td>
<td>25(2)</td>
</tr>
<tr>
<td>575.1(3)</td>
<td>11(2)</td>
</tr>
<tr>
<td>1167.8(3)</td>
<td>20(2)</td>
</tr>
<tr>
<td>1311.6(3)</td>
<td>13(5)</td>
</tr>
<tr>
<td>1562.0(3)</td>
<td>36(3)</td>
</tr>
<tr>
<td>1684.5(3)</td>
<td>32(3)</td>
</tr>
</tbody>
</table>

Fig. 13 Grow-in of the $\gamma$ rays from the 19.5-min
$^{163}$Tb decay as a function of time after
separation.

4. References

1. J. D. Baker, R. J. Gehrke, R. C. Greenwood,

2. J. D. Baker, R. J. Gehrke, R. C. Greenwood
51.

3. J. D. Baker, R. J. Gehrke, R. C. Greenwood
and D. H. Meikrantz, to be published.

4. R. C. Greenwood, R. A. Anderl, R. J. Gehrke
and S. T. Croney, J. S. ERDA Report TREE-1116
(1977) p. 76.

5. $^{252}$Cf sources made available through J. E.
Bigelow, Coordinator for the National Trans-
plutonium Element Production Program, Oak Ridge
National Laboratory, Oak Ridge, TN 37830, USA.


7. L. D. McIsaac, J. D. Baker and J. W. Tkachyk,

8. L. D. McIsaac, J. D. Baker, J. F. Krupa, R. E.
LaPointe, D. H. Meikrantz and N. C. Schroeder,

9. R. K. Smither, K. Schreckenbach, H. G. Börner,
W. F. Davidson, T. von Egidy, D. D. Warner,
R. F. Casten, M. L. Stelts and A. I. Namenson,
Argonne National Laboratory Report ANL-80-94
(1980) p. 90; and, R. K. Smither, private
communication.

10. C. M. Lederer and V. S. Shirley (Editors),
Table of Isotopes, 7th ed. (Wiley, New York,
1978).

11. A. H. Wapstra and K. Bos, At. Data Nucl. Data
THE DECAY OF NEUTRON-DEFICIENT Lu ISOTOPES

S. Rastikerer, C. Garrett* and W. Gelletly
Schuster Laboratory, University of Manchester, Manchester M13 9PL, U.K.

Abstract
Neutron-deficient isotopes of Lu with masses 158, and 160-165 have been produced in $^{155}$Gd(14N,xn) and $^{153}$Yb(14O,xn) reactions with beams of $^{14}$N and $^{16}$O from the Manchester HRILAC. Gamma ray energies and relative intensities have been measured as well as X-γ, γ-γ and $\gamma^*$-γ coincidences. The half-lives and decay energies for $\gamma^*$/EC decay have been measured. Gamma-gamma correlations and conversion electron singles spectra were studied in the case of the even isotopes. Preliminary results are reported here.

1. Introduction
The transition from a spherical to a deformed equilibrium was studied in the Sm, Nd and Gd isotopes has been studied in some detail and it is usually agreed that deformation occurs suddenly between N = 88 and 90. The basic aim of the present work was to examine the effect on this transition of the presence of extra protons by studying the low-lying level structures of the Yb (Z = 70) isotopes. The vehicle chosen for this particular investigation was the study of the $\gamma^*$/EC decays of neutron-deficient Lu isotopes to levels in the Yb isotopes. The information obtained should complement the results of (H,E,xn) studies.

Prior to this investigation little was known about the decay of the Lu isotopes lighter than $^{166}$Lu. Meijer et al.1) had assigned a list of γ rays to $^{165}$Lu decay. Hunter and al.2) had studied $^{164}$Lu decay and produced a decay scheme for this isotope. Burman et al.3) had studied the decays of $^{162}$Lu, $^{164}$Lu and $^{166}$Lu and produced fragmenary decay schemes. Adam and al.4) reported e-γ delayed coincidence studies for a number of cascades in $^{165}$Yb following $^{165}$Lu decay, and recently Alkhazov and al.5) reported the energies and relative intensities of γ-rays emitted from some of these Lu decays as well as the half-lives for $\gamma^*$/EC decay. The level structures of $^{163}$Yb, $^{163}$Yb and $^{165}$Yb as observed in (H,E,xn) reactions have been reported by Richter.6)

2. The Experiments
The activities were produced by bombarding self-supporting metallic foils enriched in $^{153}$Gd and $^{153}$Lu to 91.6% and 96.8% respectively with beams of $^{14}$N and $^{16}$O ions from the Manchester heavy ion linear accelerator. The full beam energy of 9.6 MeV/A could be degraded by a series of Al absorbers in front of the target. The activity was transported to a magnetic tape transport system7) in a shielded counting position with a He-jet recoil transport system (HeJRTS) described previously.8)

Measurements of excitation functions allowed us to tag the observed γ rays by mass, and γ-ray coincidences with K X-rays detected in a low energy photon spectrometer (LEPS) pinned down the element involved. Weak γ-rays were associated with the decay by their observation in prompt coincidence with the intense γ-rays already assigned. A variety of coincidence experiments with large Ge(Li) detectors and LEPS was carried out for each decay studied with sources produced at the peak of its excitation function. Coincidence studies with two LEPSs were invaluable in sorting out the decays of the odd-A isotopes where low energy transitions play a key role.

The half-lives for $\gamma^*$/EC decay were determined by routing the singles spectrum into sixteen, equal, consecutive divisions of the counting period, which was chosen to correspond to several half-lives of the isotope under study. Decay energies were measured by studying $\gamma^*$-γ coincidences. Off-line analysis allowed reconstruction of the $\gamma^*$-spectrum in coincidence with individual γ-ray photopeaks. A linear least squares fit of $\gamma$ vs. $E$ near the end point allowed a measure of the decay energy. Table I lists the half-lives and decay energies for the cases where we have a final result.

<table>
<thead>
<tr>
<th>Isootope</th>
<th>Half-lives</th>
<th>Decay Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{158}$Lu</td>
<td>10.6±0.3 s</td>
<td>-</td>
</tr>
<tr>
<td>$^{160}$Lu</td>
<td>36±1 s</td>
<td>7.21±0.24 MeV</td>
</tr>
<tr>
<td>$^{162}$Lu</td>
<td>78±2 s</td>
<td>6.74±0.27 MeV</td>
</tr>
<tr>
<td>$^{164}$Lu</td>
<td>1.37±0.02 min</td>
<td>4.86±0.17 MeV</td>
</tr>
<tr>
<td>$^{166}$Lu</td>
<td>258±8 s</td>
<td>4.35±0.14 MeV</td>
</tr>
<tr>
<td>$^{168}$Lu</td>
<td>5.15±0.08 min</td>
<td>4.25±0.14 MeV</td>
</tr>
<tr>
<td>$^{170}$Lu</td>
<td>10.7±0.04 min</td>
<td>-</td>
</tr>
</tbody>
</table>

In the case of the even isotopes γ-γ directional correlations were studied with two Ge(Li) detectors. The detectors were placed a distance of 8 cm from the source and coincidences were recorded event-by-event at six angles. Fig. 1 shows examples of the gated spectra at these angles and the correlation function for the 839-167 keV and 631-167 keV cascades in $^{162}$Lu decay which are fitted by the spin sequences 0-2-0 and 2-2-0 respectively.

The conversion electron spectra were studied in singles with a Si(Li) detector and mini-orange filter for the decay of $^{162}$Lu and $^{164}$Lu with the aim of obtaining information about the decay of the excited 0+ states in $^{162}$Yb and $^{164}$Yb.

3. Results
3.1 The odd-A Yb Isotopes
On the basis of the measured energies, relative intensities and coincidence relationships decay schemes were constructed for the isotopes studied. Figs. 2 and 3 show the resulting decay schemes for $^{163}$Lu and $^{165}$Lu. The ground state of $^{165}$Yb is assigned to the $\frac{1}{2}^+$ (523) orbital because it is observed9) to decay by $\gamma^*$/EC to a level of spin $\frac{1}{2}^+$ in $^{165}$Sm by an allowed, uninhanced $\gamma^*$/EC transition with log ft = 4.8 and the only such transition expected in this region is due to the $\frac{1}{2}^+$ (523)$_p$ + $\frac{1}{2}^+$ (523)$_p$, transition10). The other spins and parities which have been assigned are then fixed by the multipolarities reported by Adam et al.10) and the observed branching. The log ft values of the $\gamma^*$/EC transitions to the 87.6 and 126.5 keV states are allowed with $\Delta I = 0$, $\Delta \gamma = \pm$ which indicates spin $\frac{1}{2}$ for the $^{163}$Lu ground state in disagreement with a value of $J = \frac{1}{2}$ from atomic beam magnetic resonance.11)

Examination of the level systematics12) reveals
that the $\frac{7}{2}^{-}[404]_p$ quasi-particle orbital is the ground state in the heavier odd-A Lu isotopes but the $\frac{5}{2}^{-}[411]_p$ orbital is rapidly approaching the ground state as A decreases. In $^{163}$Lu the two orbitals may be expected to be very close together in energy. It may well be that both levels decay with the $\frac{7}{2}^{+}$ state being made predominantly in the ($^{16}$N,xn) reaction used here and the $\frac{5}{2}^{+}$ state being made strongly in the proton- induced reaction used by Ekström\textsuperscript{11}.

In the case of $^{161}$Lu one would anticipate that the $\frac{5}{2}^{-}[411]_p$ state will have become the ground state. The ground state of $^{163}$Yb has also changed to the $\frac{5}{2}^{-}[521]$ orbital\textsuperscript{13} with the 54 keV level being the $\frac{5}{2}^{-}$ member of the ground state rotational band.

3.2 The even-A Yb Isotopes

Fig. 4 summarises our results for the systematics of the low-lying levels in the even-even Yb isotopes. It incorporates our results for $^{160}$Yb, $^{162}$Yb and $^{164}$Yb. The dashed lines connect levels of similar character. The solid lines show the rotational and vibrational values for the energy of the $2^{+}$ state predicted from the observed $2^{+}$ energy. One can see clearly a fairly smooth change from the rotational level structures known in the heavy Yb isotopes towards a more vibrational pattern as we approach the $N = 82$ closed shell.

Fig. 5 shows $E_{2}^{+}$, $E_{4}^{+}/E_{2}$, $E_{6}^{+}$ etc as a function of N for Yb, Sm ($Z = 62$) and Ba ($Z = 56$) isotopes. There is a clear difference in the behaviour of the Sm and Yb isotopes. The apparent abruptness of the transition is clear for the various parameters shown in the case of Sm, and it is equally clear that the transition has been smoothed out by the presence of the extra protons in Yb. The transition also appears

\textsuperscript{Fig. 1}

Upper part shows $^{162}$Lu $\gamma$-ray spectrum in coincidence with 167 keV, $2^{+} \rightarrow 0^{+}$ transition at 3 angles. Lower part shows correlation functions for 839-167 and 631-167 cascades. Solid lines show best fits.

\textsuperscript{Fig. 2}

The decay scheme of $^{163}$Lu
The decay scheme of $^{165}$Lu

Systematics in the low spin band structure observed in the neutron-deficient Yb isotopes.

This figure shows $E_2^+$ (keV), $E_s/E_i$, $E_2^+$ (MeV), $E_3^+$ (MeV) and $E_2^{*2}$ (MeV) as a function of $N$ for the even isotopes of Yb ($Z = 70$), Sm ($Z = 62$) and Ba ($Z = 56$).
Fig. 6
Measured X-values for the O$_2^+$ states in even Yb isotopes

to occur at a higher neutron number. In Ba the information is more fragmented but Scott et al$^{12}$ concluded that the main effect of having fewer protons present is to modify the nature and extent of the nuclear deformation adopted immediately after the transition.

From the conversion electron measurements it was possible to obtain a value of

$$X = \frac{B(\text{E2}; O_2 - 2\text{l})}{B(\text{E0}; O_2 - 2\text{l})}$$

for the O$_2^+$ states in $^{162}$Yb and $^{164}$Yb. The values of X for the known O$_2^+$ states in even Yb isotopes are shown in fig. 6, with the values of X = 0.016±0.007 and 0.038±0.009 for $^{162}$Yb and $^{164}$Yb included. If these states were due to $\alpha$-vibrations then one would expect$^{13}$ a value of X = 48$^2$, which would range from X = 0.23-0.31 as we go from $^{162}$Yb to $^{170}$Yb. On this basis one would conclude that these O$_2^+$ states are not due to simple $\alpha$-vibrations.

References

1) B.J. Meijer, F.W.N. de Boer, and P.F.A. Goudsmit, Radiochimica Acta 19 (1973) 150
6) L. Richter, Z. Physik A 290 (1979) 213
10) M.E. Bunker and C.W. Reich, Rev. Mod. Phys. 43 (1971) 348
THE GROUND STATES OF $^{176-186}$Pt: AN EXAMPLE OF A SHELL MODEL INTRUDER STATE CONFIGURATION* 

John L. Wood

School of Physics, Georgia Institute of Technology, Atlanta, GA. 30332, USA

Abstract

The systematics of excited states in the neutron-deficient even-mass Pt isotopes are shown to provide evidence that a strongly deformed configuration is present in the ground states of these isotopes. This configuration is proposed to be due to $(\hbar/2)_j^2$, based on proton intruder state systematics and the importance of valence neutrons and protons in producing deformation. It is suggested that this phenomenon is unprecedented and, for the present, unique to the neutron-deficient even-mass Pt isotopes. A simple test of this picture using the blocking effect of an $h_\gamma/2$ proton coupled to the $^{184}$Pt core, as observed in $^{187}$Au, is discussed. The consequences of this intruder state structure in the neutron-deficient Pt isotopes on other observable quantities in this region are considered.

1. Introduction

Historically, the properties of nuclear ground states have provided the first view of the frontiers of the nuclear mass surface. This continues, as is evident from the new results presented at this conference. The reason for this is simple. It is the ground state (or sometimes also a low-energy isomeric state) of a nucleus that lives long enough for the species to be isolated for study, and to be subjected to external fields as a means of study. These fields can be due either to the natural atomic electron environment giving rise to atomic hyperfine studies (e.g. laser spectroscopy) or, to a man-made environment, giving rise to e.g. direct mass measurements.

The most pronounced feature among nuclear ground states, beyond nuclear shell structure, is unquestionably the universal occurrence of $^+$ spin-parity for the ground states of doubly-even nuclei. This is due to the dominance of a residual pairing force between like nucleons throughout the mass surface. This, together with a weaker residual quadrupole force, appears to control the structure of most nuclei to a very fine level of detail. The residual pairing and quadrupole forces give rise to very smoothly varying collective properties in a given shell region, as can be illustrated by e.g. two-nucleon separation energies and first excited $^2$ state energies, respectively. It is the departure from these smooth properties that has produced some of the greatest excitement and stimulation to further work in studies far from stability. Historically, none of these "exotic" regions of nuclear structure (e.g. the neutron-rich Na and Zr isotopes, the neutron-deficient Hg isotopes) have been predicted by existing theories. Specific predictions of exotic behaviour for yet-to-be-studied nuclei should be of great interest to experimentalists; the prediction of nuclear properties far from stability was widely discussed recently at the Nashville Symposium. A critical aspect of $^+$ states in nuclei, and therefore of the ground states of all doubly-even nuclei, is that excited $^0^+$ states in nuclei are often very poorly understood (see ref.7 and the discussion below). This suggests that even the calculation of ground-state properties of doubly-even nuclei is not always reliable: a point often obscured by the familiarity of these states!

The neutron-deficient Hg isotopes form a classic illustration of a totally unexpected phenomenon: the sudden appearance of strong deformation in the ground states of $^{184,185}$Hg, as first seen in optical pumping studies of the atomic hyperfine structure of these nuclides at ISOLDE by Otten and coworkers. Following this discovery, a large amount of experimental and theoretical work ensued (see below). Recent studies include the demonstration of shape isomerism in $^{185}$Hg by laser hyperfine spectroscopy, and the extension of the phenomenon to the neutron-deficient Pt isotopes by $\alpha$-decay measurements on the Hg isotopes. Despite numerous theoretical investigations of this shape isomerism in the neutron-deficient Hg isotopes, there were no predictions of the similar behaviour in the neutron-deficient Pt isotopes!

The present investigation provides a new way of looking at the shape isomerism in the neutron-deficient Hg and Pt isotopes. The approach taken emphasizes the importance of shell and subshell gaps in nuclei, together with the role played by orbitals that intrude across these gaps, in producing shape coexistence and exotic structures. This approach has its conceptual origin in the proton-neutron interacting boson approximation (IBA 2), and preliminary details have been reported already by the author. Independently, the concept has been introduced by Duval and Barrett in an explicit IBA 2 formalism for the neutron-deficient Hg isotopes. Although the IBA 2 is ideally suited to formulating the concept theoretically, the picture is not dependent on the IBA, and independently of the boson picture, it leads to the prediction of simple phenomena.

2. $^+$ States in Nuclei

Excited $^+$ states are probably the most poorly understood modes of excitation below the pairing gap in doubly-even nuclei. This was illustrated drastically by the recent

*This work was supported in part by the U.S. Dept. of Energy, Contract No. DE-AS05-80ER10599.
discovery that the lowest excited $O^+$ state in $^{116}$Sn is strongly deformed with a well-defined rotational band built on it. Consequently, it is now believed that the excitation of nuclear pairs across closed shells can give rise to fairly low-lying excited $O^+$ states which are much more deformed than the ground state. Although less dramatic, the lowest excited $O^+$ state in a number of Ra, Th, U and Pu isotopes is still the subject of considerable debate (see Refs. 9, 10, 11) and references therein. The lack of understanding of actinide states was emphasized even further by the very recent observation that they are strongly populated in alpha-transfer reactions (They have been shown previously to possess anomalous alpha-decay feeding hindrance factors).

Despite the generally widespread lack of understanding of excited $O^+$ states, there are some cases which appear to be at least partially understood. These cases can be characterized roughly into (a) excitations of pairs of nucleons across subshell gaps, (b) excitations of pairs of nucleons across major shell gaps and (c) coupling of bosons to $J^\pi = O^+$ in the IBA. The best example of (a) is probably the first excited $O^+$ state in $^{158}$Er and of (b) are the first excited $O^+$ states in the Sn isotopes: these are discussed in some detail in Ref. 12. Case (c) has been widely illustrated: e.g. the lowest excited $O^+$ states in the Sn isotopes [4] and the the spectrum of excited $O^+$ states below the pairing gap in $^{196}$Pt (Ref. 13) and $^{148}$Er (Ref. 14).

The pairing structure of $O^+$ states is naturally probed by two-neutron, two-proton and alpha transfer reactions. Two-neutron transfer reactions have been used widely to explore neutron pairing correlations throughout the mass surface [15]. A twoproton transfer reactions have been used far less due to experimental difficulties (see e.g. Ref. 16). Alpha transfer reactions can probe proton pair-neutron pair correlations; but it is only recently that this kind of spectroscopy has come into use (see e.g. Ref. 17 and references therein). Information on pairing structure can also be obtained from the blocking effect, i.e. the Pauli exclusion principle, and results in a loss of pairing correlation energy. The effect is universally manifested in the odd-even mass difference of nuclear ground states. The rates of alpha decay also offer some information analogous to alpha-transfer reaction data (see the comment on the actinide $O^+$ states above). At present, the systematic behaviour of E0 transition probabilities is not understood well enough to be of use. However, all probes of $O^+$ state structure using transfer reactions require stable or long-lived targets and thus are confined to studies of nuclear ground states far from the line of stability. Only odd-particle blocking and alpha-decay rates can provide information on the pairing structure of $O^+$ states far from stability. Odd-particle blocking as a probe of pairing correlations in excited $O^+$ states has not been used widely as a tool. The best examples (which have been investigated by blocking and transfer reaction studies) are probably the studies of the first excited $O^+$ states in $^{133}$Ge and $^{117}$Pd, $^{130}$U and $^{132}$Sn (see e.g. Refs. 18, 19). The odd proton evidently blocks the excited $O^+$ configuration strongly and it has not been observed as a core configuration in $^{117}$As. In $^{133}$Pd, $^{131}$U, $^{133}$Sn, the odd neutron particle strongly blocks the even-$O^+$ state $O^+$ configuration and does not significantly block the excited $O^+$ configuration. These cases illustrate strong and weak blocking of the excited state and ground state configurations, respectively.

3. The $O^+$ States in the Neutron-Deficient Pt and Hg Isotopes and Intruder Configurations

The essential features of the neutron-deficient Pt and Hg isotopes for this discussion are shown in Figs. 1 and 2. These figures are taken from Ref. 19 and the reader is referred thereto for further details. The most puzzling feature of Figs. 1 and 2 is: where are the strongly excited states in the odd-Pr and even- and odd-Hg isotopes? The decay scheme of Hager et al. [4] shows that the moment of inertia parameter is e.g. 14.7 keV for $^{188}$Pt and 25.8 keV for $^{188}$Pt. The answer to this puzzle is illustrated by Fig. 3, which shows the systematics of the yrast bands in the N=106 isotones and the deformed band in $^{188}$Hg. Evidently the yrast band in $^{188}$Pt increases in deformation with increasing spin, as seen from the rotational parameter extracted from the transition energies. A consideration of the low-spin excited states in $^{188}$Pt (see Fig. 1) suggests that the $O^+$ ground state and $O^+$ excited state mix strongly and the ground state energy is lowered. To a lesser extent, the $2^+$ and $3^+$ states similarly mix and repel. The E0 transition between these two states supports this. A similar systematic behaviour is found for the even-Pr nuclei with A=176-186 (see Refs. 19, 20). Thus, the $188$Pt ground state contains the major component of a strongly deformed $O^+$ configuration. Fig. 3 shows that this configuration does not contribute to the ground state in $^{188}$Os.

In the proton-neutron interacting boson approximation (IBA 2) nuclear deformation comes about through a proton-neutron quadrupole interaction (between bosons). This requires the valence configuration for a nucleus to contain a number of each kind of nucleons before deformation results, and nuclei with a closed or near-closed shell (e.g. Pb, Hg isotopes) will be spherical or weakly deformed. This suggests that the valence space for proton configurations in the neutron-deficient Hg isotopes (and for the neutron-deficient Pt isotopes) is increased for the deformed excited $O^+$ states: this can be achieved most simply by promoting a pair of protons across the Z=82 closed shell. It is in just this region that proton intruder orbitals come very low in energy, the most notable structure being the $\ell = 2$ states in the odd-Tl and $\ell = 3$ states in the odd-Au isotopes. Thus, it is proposed that the configuration $(2s_2)/2$ plays a major role in the first excited $O^+$ state of the neutron-deficient Hg isotopes and in the ground state of the neutron-deficient Pt isotopes.
Fig. 1 A schematic summary of the structure of $^{181-188}$Pt. The deformed states in $^{181,183,185}$Pt are labelled by the Nilsson quantum numbers $N_n \Lambda_\Sigma$. EO transitions in the even-Pt isotopes are shown by arrows.

$\beta_2$ from $T_{1/2}$ (E2)

$Nn_2 \Lambda \Sigma = 52 \Sigma$ from optical hf spectroscopy

Fig. 2 A schematic summary of the structure of $^{181,183,185}$Hg. The $\beta_2$ values are deduced from $T_{1/2}$ (E2) measurements.
THE SYSTEMATICS OF THE YRST STATES IN THE N = 106 ISOTONES

![Diagram showing yrast states in N=106 isotones]

The yrast states in the N=106 isotones and the O₁⁺, O₂⁺, 2₁⁺, 4₁⁺, 6₁⁺ and 8₁⁺ states in ¹⁸⁶Hg (see also Fig. 2). The rotational parameter \( \hbar^2/2I = (E_J - E_{J-2})/(4J-2) \) is shown in parentheses between the levels. Energies are shown relative to the 8₁⁺ states.

Further, this configuration does not lie at low energy in the neutron-deficient Os isotopes. This bears some resemblance to the Sn and Cd isotopes, where a proton pair excitation across the Z=50 closed shell gives rise to deformed excited O⁺ states below the pairing gap. However, the assertion that this configuration plays a major role in the ground states of the neutron-deficient Pt isotopes and not in the ground states of neighboring doubly-even isotopes is believed to be unprecedented.

This picture leads to a number of simple tests: Such a pairing excitation will be strongly populated in two-proton transfer reactions, and will be blocked by an odd proton occupying the \( \hbar s_{9/2} \) orbital. Unfortunately, the first test is not widely applicable because there are few targets suitable for studying this region by two-proton transfer (see below). However, the second test is readily applicable and it has been carried out\(^{23}\) for \( ^{187}\text{Au}(^{184}\text{Pt} \otimes \hbar s_{9/2}) \) and \( ^{184}\text{Pt}(^{184}\text{Hg} \otimes \hbar s_{9/2}) \):

From the above discussion we can predict that an \( \hbar s_{9/2} \) proton coupling to a Pt core in the neutron-deficient Au isotopes will block the O⁺ ground state \( (O_1^+) \) more than the first O⁺ excited state \( (O_2^+) \), and the converse will be true for Hg \( \otimes \hbar s_{9/2} \) coupling in the neutron-deficient Tl isotopes. In \( ^{187}\text{Au} \), the separation of the 9/2⁻ states due to the couplings \( ^{184}\text{Pt}(O_1^+) \otimes \hbar s_{9/2} \) and \( ^{184}\text{Pt}(O_2^+) \) is observed to be 323 keV, which is to be compared with the \( O_1^+ - O_2^+ \) core separation energy of 471 keV. This alone is insufficient to demonstrate that an unpaired proton in the \( \hbar s_{9/2} \) orbital blocks the O⁺ core configuration more than the O⁺ core configuration. The O⁺ and O⁺ configurations are unlikely to have equal quadrupole moments and thus, since the coupling of a particle to the core is strongly affected by Qcore-qparticle (see e.g. ref.\(^{24}\)), the 9/2⁻ - 9/2⁻ separation energy is not a direct reflection of the blocking effect. It is asserted that this problem can be circumvented by considering the bands of states with 9/2⁻, 7/2⁻, 5/2⁻, 3/2⁻, 1/2⁻ formed by the couplings to the O⁺ and O⁺ configurations and their respective 2nd excitations. The difference in energy of the centroids of the two groups is then considered to reflect a particle-core coupling energy that is relatively independent of Qcore-qparticle, i.e. that reflects particle-core blocking effects. All of these states (except 9/2⁻, 7/2⁻) have been found\(^{23}\) in \( ^{187}\text{Au} \) and the difference in energy of the centroids of the two groups...
of five states is 320 keV. It is thus concluded that indeed the $^{188}\text{Pt}(0^+)$ configuration is blocked more than the $^{188}\text{Pt}(0^+_2)$ configuration by an $h_9/2$ proton and hence $(h_9/2)^2$ plays an important role in the $^{188}\text{Pt}(0^+_2)$ configuration. The non-observation$^{22}$ of an EO transition in $^{188}\text{Tl}$ below 1 MeV is also consistent with this picture, since the $(h_9/2)^2$ blocking will affect the excited $0^+$ state in $^{188}\text{Hg}$ and result in a raising of the EO transition energy.

4. Implications and Future Work

The unique structure proposed here for the ground states of the even-Pt isotopes with $A=176-186$ leads to a number of unusual predictions. The involvement of the $(h_9/2)^2$ configuration in the ground states of just the even-Pt isotopes with $A \leq 186$, and not in the neighbouring even-mass Os and Hg isotopes and the even-Pt isotopes with $A \geq 186$, implies that an island of discontinuous behaviour in ground state properties exists for these isotopes. For example, ground state masses should show a discontinuity: a preliminary report of decay energies in the $A=182$ decay chain$^{23}$ is consistent with this. The reduced widths for ground state-to-ground state $\alpha$ decay between even-mass Hg and Pt isotopes and Pt and Os isotopes also should be anomalous: although some discrepancies still exist between experimental reduced $\alpha$ widths in this region$^{24,27}$, it can safely be stated that anomalous behaviour is seen$^{7,22,27}$. Evidently, both decay energies and reduced widths for $\alpha$ decay in this region need detailed study in order to test the structures proposed here.

The most direct test available is the $^{144,146}\text{Os}(^4\text{He},n)$ reactions. This should show strong population of the $0^+_1$ and $2^+_1$ states in $^{184,188}\text{Pt}$. Unfortunately, the natural abundance of $^{144,146}\text{Os}$ is 0.02% and 1.6%, respectively. In addition, the $(^4\text{He},n)$ reaction would be difficult to study with the high resolution required for the high final state density involved in the Pt isotopes. Possibly, a $(^4\text{He},^1\text{C})$ reaction study would overcome this.

Recently, a successful prescription for the shape isomerism in the even Hg isotopes, involving a mixing of boson states with proton boson numbers $N_1=1$ and $N_3=3$, was reported$^{6}$. The structure proposed here for the even-Pt isotopes would involve $N_1=2$ and $N_3=4$ proton boson states and would form an exciting test of this prescription. (The IBM$^{12}$ calculations of Bjerke et al.$^{18}$ are recognized to have some shortcomings$^{29}$; primarily, the calculations used too large a quadrupole interaction between neutron bosons.)

Similar odd-proton blocking experiments to the ones described here need to be done for neighbouring odd-mass Tl and Au isotopes. These are either in progress or will soon begin at UNISOR.

Perhaps the most interesting questions to be answered are: how widespread is the occurrence of such low-lying structures? And, do multi-particle-multi-hole structures appear at low-energy? Some progress in answering these questions can be found in a forthcoming review article$^4$. It would be particularly interesting to locate the $(h_9/2)^2$ configuration in the even-Os isotopes.

References


22) E.F. Zganjar, in ref.1, p. 49.

23) E.F. Zganjar, J.D. Cole, J.L. Wood and M.A. Grimm, Contribution to this Conference.


27) K. Toth and UNISOR coworkers, Contribution to this Conference.


29) R. Bijker and F. Iachello, private communication.

DISCUSSION

R.A. Sheline: You did not talk about beta vibrations and pairing vibrations.

J.L. Wood: The beta vibrations are manifested in the Sm example where the vibrational - rotational transition gives rise to softness and low beta vibrational energies. Pairing vibrations are another name for the example of excitation of pairs across shell or subshell gaps. I avoided the use of the term vibration since the dynamical degree of freedom is not in a physical space and is thus difficult to visualize.

A. Gelberg: Could this Duval-Barrett mechanism in which two configurations with different N's are mixed play a role in the case of states with I \neq 0?

J.L. Wood: Possibly. But such a state would almost certainly lie above an I = 0 state with a similar structure; this might play an important role in yrast structures.

J.H. Hamilton: I had not seen your abstract prior to this conference. It is very interesting to see the similarity of these light Pt isotopes to ^{74,78}_{72,76}Kr which I presented this morning where the depression of the 0^+ ground state energies make these nuclei look less deformed than they really are, when only the 2-0 energies are considered. Also I note in a little-known review program 0^+ states at the Delhi Conference in 1974, we presented lifetime states and suggested shape-coexistence where the 0^+ expected level in ^{116}_{74}Sn was deformed. Of course, the beautiful Amsterdam work more clearly establishes the deformation of these 0^+ states and shape coexistence in the Sn isotopes.
THE DECAY OF $^{185}\text{Hg}$: LOW-SPIN STATES IN $^{185}\text{Au}$ AS A PROBE OF THE NUCLEAR MODELS

C. Bourgeois\textsuperscript{\textasteriskcentered}, M. G. Desthuilliers-Porquet\textsuperscript{\textdagger}, P. Kilcher, B. Roussière, J. Sauvage-Letessier and the ISOCELE Collaboration

Institut de Physique Nucléaire, IN2P3, 91406 Orsay, France.

\textsuperscript{\textdagger} and Université Paris VII

\textsuperscript{\textdaggerdbl}Centre de Spectrométrie Nucléaire et de Spectrométrie de masse, IN2P3, 91406 Orsay, France.

Abstract:

The $^{185}\text{Au}$ has been studied from the $b^+$/EC decay of $^{185}\text{Hg}$ using the ISOCELE facility. Conversion electron measurements have been performed by means of a semi-circular magnetic spectrograph: new low-energy transitions have been observed. A 330 keV Very Converted Transition has also been found. Its existence is discussed. In addition to the usual states observed in heavier gold isotopes, numerous negative-parity low-spin states have been located. The experimental states corresponding to a prolate shaped nucleus are compared with those extracted from an "axial rotor + quasi-particle" coupling model. They could be identified with two state families, the first one arising from the $h_9/2 + f_5/2$ sub-shells, the second from the $p_3/2 + f_7/2$ sub-shells.

1. Introduction

The Au nuclei lie in a very complex transitional region where several states corresponding to different nuclear shapes occur within the same energy value. Numerous experimental and theoretical studies have been already carried out in this region. In order to improve our comprehension of the observed phenomena it was useful to extend the systematic study of the gold nuclei down to $^{185}\text{Au}$. Indeed in this nucleus, the deformation is expected to be larger than those of the heavier odd gold isotopes and thus new levels should appear.

The high-spin states of $^{185}\text{Au}$ (from $7/2^+$ up to $45/2^+$) have already been investigated\textsuperscript{1}) by means of (HI, xny) reactions. Four decoupled level sequences, $I, I+2, I+4...$ have been observed. They arise from the alignment of the single-particle angular momentum with the core-rotation angular momentum under the effect of Coriolis force. The shape coexistence in the $^{185}\text{Au}$ nucleus has been established from these results but the $11/2^+$, $9/2^+$ and $13/2^+$ quasi-rotational bandhead states could not be located with

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Fig. 1: Low-energy electron microdensitogram from a film obtained with the b-spectrograph. The 28.1 keV transitions belongs to $^{185}\text{Hg}$.
respect to the ground state. The ground state spin had been measured \((I = 5/2)\) by C. EKSTROM et al.\(^2\).

We present here our most recent results concerning the low-spin states of \(^{185}\text{Au}\) (from \(1/2^-\) up to \(17/2^-\)) populated by the \(\beta^+\)/EC decay of \(^{185}\text{Hg}\). In order to produce mercury, a molten gold target was irradiated by the proton beam \((E_p = 200\text{ MeV}, I_{\max} = 2.5\text{ \mu A})\) of the synchrocyclotron of the Institut de Physique Nucléaire (ORSAY) and then the mercury isotopes were mass-separated using the ISOCELE facility\(^3\).

2. Experimental procedure

Usual \(\gamma_1 - \gamma_2 - \gamma_{12}\) coincidence measurements have been performed. In order to improve the conversion electron measurements we have used the semicircular magnetic spectrograph working on-line with the mass-separator ISOCELE II. Radioactive ions are collected on a mylar/aluminium tape, the sources are then transported into the spectrograph by means of a fast mechanical tape-transport system. The electrons are deflected by a magnetic field and then detected by a photographic plate. For sources as thin as \(0.7\text{ mm}\), the energy resolution of this system is \(0.2\text{ \%}\).

It is very useful to have such an equipment for spectroscopic measurements: it allows us to see low energy transitions, to measure the transition energy with good accuracy, to verify that a transition belongs to the element of interest, to determine the transition multipolarities and consequently to assign spin values to the excited states.

3. Results

The electron conversion spectra obtained by means of the magnetic spectrograph have shown the existence of a \(17.2\text{ keV}\) transition (M1 + E2), a \(23.6\text{ keV}\) transition (M2) and a \(107\text{ keV}\) doublet in \(^{185}\text{Au}\) (Fig. 1). Moreover, the \(330.2\text{ keV}\), transition has been found to be abnormally converted \((\alpha_k = 1.1)\) (Fig. 2).

Gamma-Gamma coincidence results adduced to the existence of the \(107\text{ keV}\) doublet have allowed us to locate the \(9/2^-\) state at \(8.9\text{ keV}\) with respect to the \(5/2\) ground state. We have also been able to locate the \(1/2^+\) state at \(23.6\text{ keV}\) and numerous negative-parity states connected to the \(17.2\text{ keV}\) state. Furthermore the lowest energy states belonging to the high spin bands arising from the \(h\ 9/2\), \(h\ 11/2\) and \(i13/2\) sub-shells have also been observed during the course of this work.

The low-energy level scheme of \(^{185}\text{Au}\) which has been built from all these results is shown in figure 3.

<table>
<thead>
<tr>
<th>I</th>
<th>(E_h) keV</th>
<th>h 9/2</th>
<th>f 5/2</th>
<th>p 3/2</th>
<th>f 7/2</th>
<th>h 11/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2^-</td>
<td>0</td>
<td>68 %</td>
<td>21 %</td>
<td>39 %</td>
<td>32 %</td>
<td>13 %</td>
</tr>
<tr>
<td>3/2^-</td>
<td>23</td>
<td>65</td>
<td>20</td>
<td>40</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>9/2^-</td>
<td>63</td>
<td>59</td>
<td>22</td>
<td>38</td>
<td>31</td>
<td>8</td>
</tr>
<tr>
<td>1/2^-</td>
<td>518</td>
<td>64</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/2^-</td>
<td>142</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2^-</td>
<td>233</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/2^-</td>
<td>235</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Discussion

4.1 Negative-parity low-spin levels

Most of the models which can be used in this transitional region are able to explain high spin sequences. This is however not always the case for low spin states. Thus their representation provide a good test of nuclear models. Here we shall compare our experimental results concerning the \(9/2\) system with the theoretical results extracted from a rotor + quasi-particle coupling model\(^4\). A brief survey of the method is given in another contribution to this conference\(^5\). This model has already given a good description of soft\(^4,5\) and largely\(^6\) deformed nuclei. The theoretical calculations have been performed from the \(^{184}\text{Pt}\) and \(^{186}\text{Hg}\) prolate-shaped cores. A family of states which comes from the coupling of the \(h9/2 + f5/2\) single-particle to the core is calculated to appear at low-energy from both \(^{184}\text{Pt}\) and \(^{186}\text{Hg}\) cores. A second state family corresponding to the \(p3/2 + f7/2\) sub-shells is calculated to appear at lower energy from \(^{186}\text{Hg}\) core than from \(^{184}\text{Pt}\) core. We can observe in figure 4 a good agreement between theory and experiment for the high-spin states. The model that we use is also able to reproduce nicely the low-spin states (cf. fig. 4b). The main wave function percentages of the lowest energy states are given in table 1 for both state families.

- 619 -
Fig. 2: Partial microdensitogram obtained with \( B = 10^{-2} \) T.

Fig. 3: \(^{185}\text{Au}\) partial level scheme established from mass-separated \(^{185}\text{Hg}\) decay.
Table 2

Very Converted Transition in $^{185}$Au and $^{187}$Pt.
The theoretical $\alpha_\text{sp}$ are calculated with the assumption of (I) a point nucleus and (II) a finite size nucleus.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Energy keV</th>
<th>$\alpha_\text{sp}$ exp.</th>
<th>$\alpha_\text{sp}$ (M1)</th>
<th>$\alpha_\text{sp}$ (E2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{185}$Au</td>
<td>330</td>
<td>1.1</td>
<td>0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{187}$Pt</td>
<td>260.3</td>
<td>3.4</td>
<td>0.47</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>262.5</td>
<td>5.4</td>
<td>0.37</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>498.2</td>
<td>0.58</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>498.8</td>
<td>0.95</td>
<td>0.07</td>
<td>0.019</td>
</tr>
</tbody>
</table>

In order to get a more complete identification of the experimental levels it is quite clear that we still have to take into account their de-excitation modes. The B(M1) and B(E2) transition probably calculations are in progress in this region.

4.2 Very Converted Transitions

The 330 keV transition is abnormally converted: its conversion coefficient $\alpha_\text{sp}$ is five times greater than the one expected for an M1 transition. This result looks like those we obtained in 1977, concerning four transitions in $^{187}$Pt. The experi-
mental $\alpha_k$ values were found to be about ten times greater than theoretical $\beta_1$ $\alpha_k$ values (table 2). So we are in the presence of a new kind of transitions which we have called Very Converted Transitions (V.C.T.). The VCT are either anomalously converted $\beta_1$ transitions or more likely caused by the existence of a large percentage of E0. In both cases, dynamic penetration effects of the electronic wave function inside the nucleus are responsible for the VCT phenomenon. The $g(E0)$ strength being related to the variation of the mean square charge radius between the initial and final states, it seems very likely that VCT phenomenon is related to shape coexistence. VCT are very interesting because they may be a new probe to improve our knowledge of the nuclear structure, in particular to study shape, rigidity or softness of the transitional nuclei. It may be noted that such transitions have also been found in $^{233}$Th$^{11}$ and $^{197,195,193}$Hg$^{12}$.

5. Conclusion

The study of the low-energy low-spin states in the $^{185}$Au transitional nucleus provides a good test of theoretical approaches. The experimental difficulties to establish such levels have been overcome by precise conversion electron measurements using a magnetic spectrograph. An open question is the occurrence of VCT in this region which is probably related to shape coexistence phenomenon.

References

3) P. Paris et al., J.C. Putaux et al., Contributions to the 10th EMIS conference Zinal (Switzerland), September 1980, to be published in Nucl. Instr. Meth.
9) E. Church, J. Wüeser, Phys. Rev. 104 (1956) 1382.
    A. Ben Braham et al., XXVIII Nat. Conf. on spectroscopy and structures of the Atomic Nucleus, Alma Ata (Mars 1978).
12) G.M. Gowdy, Thesis (1976), Georgia Institute of technology;

DISCUSSION

D. Hamilton: In order to use transitions containing an E0 contribution it is necessary to know the $\beta_1$ and E2 contributions. Do you have the possibility to determine E2:MI ratios with sufficient accuracy to all E0 matrix elements to be extracted?

J. Sauvage-Letessier: In the case of the VCT of which I talked here, the experimental conversion lines in the $\text{L}_{II}$ and $\text{L}_{III}$ shells are extremely weak, thus we cannot determine the E2:MI ratios from conversion measurements. In order to determine these ratios, we have to perform other kinds of experiment like $\gamma\gamma$ and $\gamma\chi$ angular correlations, for example.
DEFORMATION PROPERTIES OF EVEN-EVEN Os, Pt, Hg NUCLEI AND SPECTROSCOPIC PROPERTIES OF ODD Re, Os, Ir, Pt, Au, Hg NUCLEI FROM SELF-CONSISTENT CALCULATIONS

M.G. Desthuilliers-Porquet (CSNSM, 91406 Orsay France)  
M. Meyer (IPN-Lyon I, 69621 Villeurbanne France)  
P. Quentin (ILL, 38042 Grenoble France)  
J. Sauvage-Letessier (IPN, 91406 Orsay France).

Abstract

Static properties of even-even Os, Pt, Hg nuclei have been obtained from HF + BCS calculations. Single-particle wave functions which come from these self-consistent calculations have been used to calculate some spectroscopic properties of odd Re, Os, Ir, Pt, Au and Hg nuclei, within the rotor + quasiparticle coupling model. Our calculations are able to give a good description of most of available experimental data.

1. Introduction

The Re, Os, Ir, Pt, Au and Hg nuclei belong to a transitional region of the nuclide chart. Numerous experimental and theoretical studies have been already devoted to these nuclei. The coexistence of oblate and prolate nuclear shapes which is found in all calculations, may explain most of experimental trends concerning these transitional nuclei. In the present work we have performed an extensive self-consistent study of this nuclear region. The static properties of 17 even-even Os, Pt, Hg nuclei have been determined. From these calculations we have extracted quasi-particle states to estimate spectroscopic properties of many odd nuclei within a rotor + quasiparticle coupling approximation. So far we have restricted our study to axially symmetrical solutions.

2. Deformation properties of even-even Os, Pt and Hg nuclei

Assuming axial symmetry and using the Skyrme phenomenological effective force SIII, HF + BCS calculations have been performed for the 180,184,186,190,192,200pg, 182,184,186,188,190,192,196pt and 184,188,192,196 Os nuclei. Potential energy curves exhibit two minima for most of these nuclei. Static properties (masses, charge radii r\(_c\), deformation parameters \(\beta_2\)...) of the equilibrium solutions so obtained, are in good agreement with available experimental data. It is interesting to note that the coexistence phenomena which explains most of experimental data is well reproduced by our calculations. As an example fig.1 shows the variation of the calculated charge radii of Hg isotopes against the neutron number for the oblate (\(\beta_2 < 0\)) and prolate (\(\beta_2 > 0\)) equilibrium solutions as well as for the constrained spherical solution (\(\beta_2 = 0\)).

The differences between prolate and oblate \(r_c\) values in 184,186 Hg are in excellent agreement with experimental results obtained by isotopic shift measurements. If shape coexistence is assumed.

3. Spectroscopic properties of odd Re, Os, Ir, Pt, Hg nuclei

3.1 A brief survey of the method

We have evaluated the spectroscopic properties of odd-A nuclei within a rotating core + quasi-particle coupling model. The quasi-particle energies and wave functions in use come from axially symmetrical equilibrium HF + BCS calculations and are thus determined in a self-consistent way. The standard unified model wave functions for odd nuclei have been expanded onto good core angular momentum \(R\) states. This has allowed us to introduce the core variable moment of inertia extracted from core experimental energies. Furthermore we have included all quasiparticle states whose HF energies belong to a ±5 MeV energy interval around the Fermi level. Finally we stress that there is no adjustable parameter in our calculations (e.g. attenuation factor). This model has already been applied with success to transitional nuclei (Cd, Er with \(\beta_2 \approx 0.15\), to deformed nuclei (actinide region with \(\beta_2 \approx 0.3\)) and even to fission isomers (with \(\beta_2 \approx 0.6\)).

3.2 Results: Spectroscopic calculations have been performed for odd Re, Os, Ir, Pt, Au, Hg nuclei. In what follows we shall only give some examples of our results.
Odd neutron nuclei results

\[ E \text{ (MeV)} \]

\[ 9/2^- \quad 11/2^- \]
\[ 5/2^- \quad 7/2^- \]
\[ 3/2^- \quad 1/2^- \]

\[ ^{184}\text{Os} \quad ^{188}\text{Os} \quad ^{192}\text{Os} \]

\[ \beta_2 \]
\[ .25 \quad .21 \quad .16 \]

Fig. 2: Theoretical and experimental evolution of 1/2^- and 3/2^- band states along the Os isotopic series (--- 1/2^- band, \ldots 3/2^- band).

The nuclei have been extensively studied by \((p,t; q,2n; n,y; \ldots)\) reactions. Quasi-rotational bands built on 1/2^- and 3/2^- states have been found over the whole isotopic series. As shown on fig. 2 our calculations are able to very well reproduce these experimental data for Os prolate shaped nuclei. The wave functions of 1/2^- and 3/2^- band states are very much mixed (cf table 1) and therefore we have more or less arbitrarily performed the band assignment in terms of the major quasiparticle component.

A decoupled band built on the 111/2 level has been observed in \(^{187}\text{Pt}\) and a \(\Delta I = 1\) band has been found in \(^{185}\text{Pt}\). In order to represent the \(^{185}\text{Pt}\) nucleus, calculations have been performed from both \(^{184}\text{Pt}\) and \(^{186}\text{Pt}\) cores for both oblate and prolate solutions. If we compare the experimental \(\Delta I = 1\) band in \(^{185}\text{Pt}\) with prolate \(^{184}\text{Pt}\) or \(^{186}\text{Pt}\) core calculations we find that they nicely agree as shown on fig. 3. We also confirm the ground state spin which was assumed to be 9/2 from disintegration properties. On the contrary the data seem incompatible with the results of oblate \(^{184}\text{Pt}\) or \(^{186}\text{Pt}\) core calculations exhibiting a strongly Coriolis mixed or even (for the \(^{186}\text{Pt}\) core) decoupled character. The calculations performed with oblate \(^{185}\text{Pt}\) or \(^{188}\text{Pt}\) core are in qualitative agreement with the observed decoupled band in \(^{185}\text{Pt}\) (see fig. 3).

Such decoupled bands built on 13/2^+ states corresponding to oblate shaped nuclei are also observed in the mercury nuclei \(^{190,191}\text{Hg}\). When the nucleon number decreases,
15/2^+ and 13/2^+ state energies decrease whereas 17/2^+ and 21/2^+ state energies increase. This calculated trend comes from the penetration of the Fermi level inside the 111/2 shell as shown on fig. 4 and is consistent with the experimental evolution of the high spin bands of the mercury isotopes.

### 3.5.3 Odd-proton nuclei results

In addition to a decoupled 9/2^- band and a normal 11/2^- band corresponding to a prolate shaped nucleus, two low spin bands (1/2^+ and 3/2^+) have been observed in Ir isotopes ^8). A comparison between theoretical results and experimental data shows that the 1/2^+ band corresponds to an oblate intrinsic shape for the ^185Ir nucleus and seems to correspond to a prolate intrinsic shape for ^183Ir ^3) (fig. 5). For the decoupled 9/2^- band which comes from the 1h9/2 shell, our calculations are able to reproduce rather nicely all states up to 1 MeV for ^185Ir when calculated with a prolate shaped core (fig. 6).

The comparison of recent experimental results concerning the lowest energy states of ^185Au with our calculated results shows that some states due to 3p3/2 + 2f7/2 shells exists at an excitation energy of about 200 keV (fig. 7). These last results are discussed more completely in another contribution to this conference ^12).

### 4. Conclusions

Available static properties of even-even nuclei have been well reproduced by means of HF + BCS calculations performed with the Skyrme SIII effective force. Furthermore, in spite of the restrictive axial symmetry hypothesis and the absence of any adjustable ad hoc parameter, the rotating core + quasi particle coupling model using single-particle wave functions determined in a self-consistent way, is able to represent the set of available experimental data better than expected for the slightly deformed nuclei under consideration here.

### REFERENCES

Fig. 4:
Theoretical and experimental evolution of high spin states \((J > 13/2)\) for some neutron deficient Mercury isotopes.

Fig. 5: Comparison of \(1/2^+\) band states in \(^{185}\)Ir and \(^{183}\)Re with those calculated from \(^{184}\)Os and \(^{186}\)Pt core for prolate and oblate HF solutions.


12) C. BOURGEOIS, M.G. DESTHUILLIERS-PORQUET, F. KILCHER, B. ROUSSIERS, J. SAUVAGE-LETESSIER, paper presented to this Conference.

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**Fig. 5:** The $9/2^-$ band arising from the $h9/2$ shell in $^{185}$Re and $^{185}$Ir, compared to the calculated bands from $^{184}$Os and $^{186}$Pt core for a prolate HF solution.

**Fig. 7:** Comparison of experimental results concerning lowest energy states of $^{185}$Au and $^{186}$Hg prolate core (--- states which come from $h9/2$ ($\sim 65\%$) $+ 5/2^+ \ (\sim 25\%)$, --- states from $p3/2$ ($\sim 40\%$) $+ 7/2^+ \ (\sim 30\%)$ + $h11/2$ ($\sim 10\%$)).
y - TRANSITION RATES IN TRANSITIONAL ODD GOLD NUCLEI

V. Berg, Z. Hu, J. Oms and the ISOCLE collaboration
Institut de Physique Nucléaire, B. P. n°1
91406 Orsay Cedex, France

Abstract
The results of two half-life measurements of excited states in $^{185}$Au are presented. One supports the proposed interpretation of the ground state configuration, the other one calls attention to the h $9/2$ to h $11/2$ M1 transitions in odd mass gold nuclei, which, in spite of considerable deformation changes of the h $9/2$ state, all show the same retardation.

A. Introduction
The impressive number of experimental data on odd Au nuclei has focused attention on these nuclei as an attractive field for test and development of old and new nuclear models. The sequence and spacings of the excited states of these nuclei are now rather well reproduced theoretically; to go further it is important to make comparisons with experimentally determined absolute y-transition probabilities. To produce such data, half-life measurements of excited levels in the $\beta$ decay of 60 s $^{185}$Hg and 30 s $^{185}$Hg have been made at the ISOCLE separator, using an on-line Gerholm-Lindskog $\beta^-$-spectrometer. As examples two results are presented.

B. Experiments and results

1. The ground state of $^{185}$Au

In $^{185}$Au the ground state with spin $5/2^+$ has been suggested to be, as in $^{185}$Ir, the anti-aligned $5/2^-$ member of a decoupled h $9/2$ band. The ample information on the structure of this band $^{2,3}$ has invited to several theoretical studies $^{1,2}$ and, in order to obtain a low lying $5/2^-$ state, all of them have predicted a pronounced prolate deformation ($\beta \approx 0.25$). The $9/2^-$ band head was proposed $^3$ at 8.9 keV on account of the systematic trend of the $9/2^-$ level in odd mass Au nuclei (see Fig. ) and of $\gamma-\gamma$ coincidence relations. It seemed important to verify the existence of the 8.9 keV ground state transition and if possible get an estimate of the nuclear deformation.

Thanks to the application of an electron accelerating potential in front of the magnetic lens spectrometer it is possible to detect very low energy electrons. In the spectrum of $^{185}$Au an electron line corresponding in energy to 8.9 M was observed.

\[\begin{array}{c}
\begin{array}{c}
185\text{Au} \\
187\text{Au} \\
189\text{Au} \\
191\text{Au} \\
193\text{Au} \\
195\text{Au}
\end{array}
\end{array}\]

\[\begin{array}{c}
\begin{array}{c}
17000 \\
17000 \\
15000 \\
16000 \\
17000
\end{array}
\end{array}\]

$F_w(M1,9/2^-11/2^-) = 17000$ $17000$ $15000$ $16000$ $17000$

+ Institute of Atomic Energy, Academy of Science, P. O. B. 275, Peking, China.
Delayed electron-electron coincidences between this line and the K electrons of the h 11/2 to h 9/2 transition gave the half-life of the 8.9 keV level equal to (4.8 ± 0.4) ns. The result corresponds to a B(E2) = 1.2 e²b² = 185 B(E2)s. p. compatible with an intraband E2 transition. Assuming a K = 1/2, 9/2 → 5/2 transition the collective model relations:

\[ B(E2; I^+ → I^-) = \frac{5}{16\pi} Q_0^2 \langle I^+ K 20 | I^- K \rangle \]

\[ Q_0 = 0.8 Z R_0^2 \delta \left(1 + 0.5 \delta \right) \]

give the deformation \( \delta = 0.20 \).

Consequently the result strongly supports the interpretation of the ground state as the 5/2 member of the h 9/2 band. It also agrees with the prediction of a well developed prolate shape.

In 185 Au where the 9/2 state lies at 5.8 keV the corresponding results are: B(E2) = 1.4 e²b² = 200 B(E2)s. p. and \( \delta = 0.21 \).

2. The h 9/2 to h 11/2 M1 transition in 185 Au and in odd-mass gold nuclei.

The measurement of the half-life, (26 ± 2) ns, of the 11/2 state in 185 Au has permitted the calculation of the M1 transition probability between the heads of the h 11/2 and the h 9/2 systems of states. As seen in the figure these two uncoupled systems develop in very different ways in the odd mass Au nuclei. The 11/2 state stays nearly unchanged from 195 Au to 185 Au with the bandhead at about 250 keV and is well described in all nuclei using the deformation parameters \( \beta = 0.15, \gamma = 35° \).

The 9/2 state on the contrary lowers rapidly in energy with decreasing massnumber (bandhead at 1064 keV in 195 Au, at 8.9 keV in 185 Au, ).

The deformation changes drastically from \( \beta = 0.15, \gamma = 33° \) in 195 Au to \( \beta = 0.25, \gamma = 0° \) in 185 Au. Taking into account these observations one could expect notable variations in the transition probabilities of the 9/2 to 11/2 transition probabilities connecting the two systems. Our experiments have shown the contrary; in spite of the change of the 9/2 system, the transition rates stay constant as witnessed by a very high but stable hindrance factor (\( F_\psi \sim 1 \times 10^6 \)) (see Fig. 1). The E2 parts of the transitions are retarded by a factor \( \sim 10 \).

One would conclude that the hindrance of the 9/2 to 11/2 transitions only weakly depends on the changes of shape and deformation but very strongly on the level configurations. According to the simple rotation aligned model, the 9/2 and the 11/2 states are represented as respectively an h 9/2 particle coupled to a Pt core and an h 11/2 hole coupled to a Hg core. Could this difference in structure explain the important

hindrance of the interband transitions? Evidently not completely. In order to reproduce the 9/2 band structure in 185 Au ref. 1 and 3 are led to admit the admixture of other states, for instance f 7/2 and p 3/2. The oretical values of the 9/2 to 11/2 transition rates have never been calculated even for the nuclei where the two systems have the same shape (A \( \gg \) 191).

References


THE INVESTIGATION OF COMPLEX RADIOACTIVE DECAY SCHEMES FAR FROM BETA STABILITY: THE STRUCTURE OF 187-Au

E.F. Zganjar and J.D. Cole

Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA, 70803 USA

J.L. Wood and M.A. Grimm

School of Physics, Georgia Institute of Technology, Atlanta, GA, 30332, USA

Abstract

Procedures used to perform detailed nuclear spectroscopy following radioactive decay in regions far from beta stability are described. Examples from a search in \(^{187}\)Tl and \(^{187}\)Au for bands formed by \(\hbar_3/2\) coupling to \(O^+\) states in \(^{188}\)Hg and \(^{188}\)Pt, respectively, are presented. The head of this band has been located in \(^{187}\)Au at 443.5 keV, but this band has not been found in \(^{187}\)Tl. Its energy of excitation in \(^{187}\)Au and its non-observation in \(^{188}\)Tl support a picture of proton pairs occupying the \(h_{3/2}\) intruder orbital to give rise to the \(O^+\) state in the even neutron deficient Hg isotopes and the ground state in the even neutron-deficient Pt isotopes.

1. Introduction

The quest for nuclear species ever further from beta stability has precipitated a rapid development of on-line systems which enable one to overcome the primary experimental difficulties associated with short half-lives and small formation cross-sections. Initially, of course, the first step in the investigation of a new region is isotope identification and the determination of primary characteristics. This can be accomplished with relatively modest use of on-line beam-time. Ultimately, however, detailed spectroscopy must be performed in order to extract the information required for the development of nuclear theories which describe the low-energy structure of nuclei. The achievement of this latter goal requires a sizeable dedication of on-line beam time to a relatively small region of the nuclear chart. Concomitantly, it also requires a sizeable devotion of scientific time to data analysis. These ideas are developed here within the context of a detailed study at UNISOR of the odd-A nuclei \(^{187}\)Au and \(^{189}\)Tl which are part of a systematic study of the Z=82 region. The investigation involves an attempt to locate and classify the structures in \(^{187}\)Tl and \(^{189}\)Au which arise from the proton core couplings \(\hbar_3/2 \times O^+\) (\(^{188}\)Hg) and \(\hbar_3/2 \times O^+\) (\(^{188}\)Pt), respectively. This is shown schematically in fig. 1. A clear signature for the existence of bands built on these states is a large E0 strength in the I-I interband transitions.

2. Discussion

The only means one has available to study the low-energy, low-spin structure of nuclei far from beta stability is radioactive decay. In regions far from stability, however, the study of radioactive decay schemes gives rise to a number of unique problems which must be overcome. In addition to the short half-lives and small formation cross sections mentioned above, the most critical sources of difficulty include the high Q-values, which lead to the population of many levels in the daughter nucleus, and hence result in very complex \(\gamma\)-ray and conversion electron spectra; and, the production methods available, which all give a spread in \(Z\) for a given mass, and hence result in contaminating daughter and grand-daughter activities. Even with mass separation using chemically selective ion sources, the typically short half-lives usually result in interference from the decay of

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Fig. 1 A systematic sketch of the \(h_3/2\) band head in odd-A Tl and Au isotopes, the \(O^+\) band in even Hg and Pt isotopes and a schematic representation of the coupling of the \(h_3/2\) intruder orbital to the even \(^{188}\)Hg and \(^{188}\)Pt cores. For the N=108 isotones the bands represented by levels shown as solid lines are well established. The bands represented by dashed lines indicate the \(h_3/2 \times O^+\) coupling which is explored in this work as a probe of the \(O^+\) and \(O^+\) structures in \(^{188}\)Hg and \(^{188}\)Pt.
daughter activities, thus making the already complex spectra even more complicated. The situation is not too serious in even-even nuclei because of the relatively low level density below the pairing gap; but for odd-A nuclei, previous studies on far from stability species have generally been rather incomplete. Completion of a band of states has, of course, a formative task and not a virtue in itself; but, our earlier studies\textsuperscript{1,2} combined with more recent results\textsuperscript{3,4} have clearly demonstrated that much of the important physics lies in those transitions which comprise less than ten per cent of the total decay intensity.

A well-known example of this is the location of the non-yrast states in odd-A nuclei. They are in some cases only weakly populated, yet it is precisely these states, rather than the yrast levels, which are most sensitive to the parameters of various models.\textsuperscript{5,6} Equally important is the establishment of isotopic and isotonic trends of such states over a wide mass range. The development of broad systematics of this type have lead to the elucidation of new and unexpected nuclear phenomena\textsuperscript{1,2}.

Previous work on the odd-A nuclei of Au and Tl has clearly established the existence of odd levels in Au and Tl.\textsuperscript{7,8} Equally important is the establishment of the shell model intruder orbital (see ref. 1, for example, and references contained therein), and has demonstrated that one can use the $h_{9/2}$ proton as a particle-core coupling probe.\textsuperscript{9,10} In the absence of these con- siderations, one is left with the inherent limitations of static model calculations. The $h_{9/2}$ proton in the odd-A nuclei of Au and Tl has been used to study the odd-A nuclei of Au and Tl.

In the study of $\gamma$-ray and conversion-electron spectra with an ever increasing line density, one inevitably reaches the point where the resolution of the detection system cannot separate the lines. The situation for electron spectroscopy is even worse because significant internal conversion occurs in several electron shells for each transition. Generally, the strong lines can be correctly located and adequately measured in the singles spectrum. The weak lines can be also be correctly located through conversion spectroscopy with gates set on the stronger lines. The major difficulty arises when the $\gamma$-rays of interest are weak and are only in coincidence with each other. This situation is further exacerbated by daughter and granddaughter activities. To demonstrate this latter effect consider fig. 2 where a small portion of the electron and $\gamma$-ray spectra from the decay of $^{184}$Pb are shown normalized to the same scale (keV/channel) and with the electron spectrum shifted up in energy by 85.5 keV (The Tl K-shell electron binding energy). Although one can easily resolve the 388.0 keV component in the gamma-ray spectrum, it is clearly not possible to resolve the two 386.6 keV components. For the case shown in fig. 2 the conversionelectron spectrum enables one to easily resolve the components arising from daughter and granddaughter activities because of the different electron binding energies. However, it is impossible to resolve the components from the conversion spectra between 386.6 keV from those "singles" spectra since the relative $\gamma$-ray intensity cannot be determined. Such spectra are very useful for $\gamma$-ray identification and, like X-ray gated spectra, are widely used for that purpose in our studies. If transitions of the same energy occur within the same isotope, then the situation is even more difficult. In any case, alternative procedures must be employed to extract quantitative information from the massively complex spectra encountered in these studies.

We have made considerable progress in overcoming these problems by taking $\gamma$-$\gamma$, $\gamma$-e, e-$e$, and e-$\gamma$ coincidence data of very high statistical quality with state-of-the-art electronics and with high energy gains (low values of keV/channel) in coincidence with other detectors. As an example, in our study\textsuperscript{4} of the decay of $^{187}$Hg we collected $\approx 2 \times 10^5 \gamma$-$\gamma$ and $\gamma$-e coincidence data with a TAC time resolution of $\tau = 9$ ns (FWHM). A portion of gated and ungated $\gamma$-ray and conversionelectron spectra are shown in fig. 3 which is used later to illustrate the technique of using coincidence (gated) spectra to extract internal conversion coefficients. Clearly, the 335 keV electron line and the 388 keV gamma line are badly obscured in the ungated spectra. We return to this figure later.

In fig. 4 is shown an example of how the high quality coincidence data is used to separate the components of multipoles. The two transitions involved are both multipoles to the ground state of $^{187}$Au. Although both transitions are critical for the study since one of the 272 keV and one of the 299 keV transitions are critically involved with the $\gamma = 0^+ \times 0^+$ (1440) ground state of $^{187}$Au. Although all coincidence data are scanned with a very large number of energy gates, when the line density is high or where multipoles are suspected, as for the cases shown in fig. 4, these gates are advanced one or two channels at a time (typically 0.3 keV) and the resultant coincident events when plotted as a function of gate position enable one to separate channels as close as 0.3 keV. Each point on the left side in fig. 4 represents an advance of 0.3 keV on the energy set on $\gamma_2$ at the energy denoted on the horizontal axis; and the number of coincident events observed for $\gamma_2$ in the region scanned by $\gamma_1$ is denoted by the vertical axis. The right hand side of fig. 4 represents a more coarse (0.64 keV/step) example of the reverse of the same procedure. Careful analysis of the data of figure 4 reveals that there is a 298.8$\pm 0.3$ keV and a 299.6$\pm 0.2$ keV coincident pair of $\gamma$-rays. Obviously data of high statistical quality are necessary for these procedures. In addition to locating the $\gamma = 0^+ \times 0^+$ (1440) ground state of $^{187}$Au, the data have led to a level scheme\textsuperscript{11,12} for $^{187}$Au with 19 new levels below 1 MeV when compared to the most recent study\textsuperscript{13}. Not
Fig. 2 A portion of the electron and γ-ray spectra from the decay of $^{187}\text{Pb}$ normalized to the same scale (keV/channel), with the electron spectrum shifted by +85.5 keV (the Tl K-shell electron binding energy). The data were obtained at the UNISOR facility using the $^{186}\text{W} (^{16}\text{O},7n) ^{187}\text{Pb}$ reaction, an 13% Ge(Li) γ-ray spectrometer and a 3 mm x 200 mm$^2$ Si(Li) electron detector.

Fig. 3 A portion of gated and ungated conversion electron and γ-ray spectra from the decay of $^{187}\text{Hg}$ normalized to the same scale (keV/channel) and with the electron spectra shifted by +80.7 keV (the Au K-shell electron binding energy). The 233 keV γ line provides the gating signal for the gated spectra. Since the 233 keV transition is in direct coincidence with both the 335 and 388 keV transitions (see fig. 5 below), knowledge of the ICC of one transition uniquely determines the ICC of the other. The data indicate that $\alpha_g(388) = (13\pm2) \times \alpha_g(335)$. The data were obtained at the UNISOR facility using the $^{186}\text{W} (^{14}\text{N},p6n) ^{187}\text{Hg}$ reaction, a 19% Ge(Li) γ-ray spectrometer and a 3 mm x 200 mm$^2$ Si(Li) electron detector.
Fig. 4 Coincidence scans at $\gamma = 272$ and 299 keV for the $\gamma-\gamma-t$ data from the $^{187}\text{Hg}$ decay. Each point on the left hand side represents an advance of 0.31 keV of the gate set on $\gamma_2$ at the energy denoted on the horizontal axis; and the number of coincident events recorded for $\gamma_3$ in the regions of 386 and 299 keV denoted on the vertical axis. The right hand side represents a more coarse (0.64 keV/step) example of the reverse of the same procedure. The data reveal coincident pairs of $\gamma$ rays at 298.8 - 271.7 and 299.6 - 271.2 keV.

only is there a substantial increase in the available information, but 6 of these new levels comprise the searched for band. This is shown in fig. 5 where both the $\pi h_{9/2} \otimes O_1^+$ ($^{186}\text{Pt}$) and $\pi h_{9/2} \otimes O_2^+ (^{184}\text{Pt})$ bands are sketched along with several of the transitions which are pertinent to the discussion.

Data such as that shown in fig. 4 were used to unravel the apparent contributions in the conventional type of gated (fixed window) spectra. The 271.7 - 298.8 keV correlation appears as shown in fig. 5; and the 271.2 - 299.6 keV correlation appears elsewhere in the $^{187}\text{Au}$ level scheme$^9)$. Data such as that shown in fig. 3 were used to demonstrate that the band at 443.5 keV in figure 5 is indeed sought for $\pi h_{9/2} \otimes O_2^+ (^{184}\text{Pt})$ band. As stated earlier, the necessary signature identifying the band, apart from its energy, spin sequence and intra/interband transition branching ratios, is the presence of a large EO strength in the I=I interband transitions. Note in fig. 5 that by gating both the $\gamma$-ray and the conversion electron spectrum with the 233 keV transition, one can extract relative internal conversion coefficients for the 335 and 388 keV transitions. These spectra, shown in fig. 3, yield $\alpha_K (388) = (13 \pm 2) \times \alpha_K (335)$. Since the 335 keV transition is seen in-beam as the $17/2^+ \rightarrow 13/2^+$ yrast transition in the lowest $h_{9/2}$ band$^8)$, and since a singles measurement$^7)$ of its ICC is consistent with E2 multipolarity, we adopt E2 multipolarity for the 335 keV transition. This then leads to $\alpha_K (388) = 0.64 \pm 0.09$. The corresponding theoretical values$^{15}$ are 0.12 (M1) and 0.035 (E2). Since the prompt coincidence relationships are inconsistent with higher multipolarity, a sizable EO component must be present in the 388 keV transition. The analysis for the other case shown in fig. 5 (gate on the 299 keV transition) requires a more detailed analysis because of the 271.7 - 298.8 / 271.2 - 299.6 multiplet problem (see fig. 4). The corresponding results are: $\alpha_K (233) = 0.66 \pm 0.17$ to be compared with theoretical values$^{16}$ of 0.23 (M1) and 0.054 (E2). A sizable EO component is therefore also present in the 323 keV transition.

A schematic overview of the bands located in $^{187}\text{Au}$ is presented in fig. 6. The picture that emerges is that the deformed structure in the neutron deficient Pt and Hg isotopes can be understood as arising from the excitation of a pair of protons across the $Z=82$ shell closure. Since the $h_{9/2}$ proton orbital is known$^1)$ to intrude to very low energies in this region (see fig. 1), the energy required to excite a proton pair across $Z=82$ is anomalously low. One can use odd-proton blocking to sample these proton pairing correlations in the $O_1^+$ and $O_2^+$ states of the even neutron
deficient Pt and Hg isotopes\(^5\)). Note from fig. 1 that the \(O_{1}^+\) level in \(^{186}\text{Pt}\) lies 472 keV above the \(O_{1}^+\). This should be compared with the centroid shift between the bands of 320 keV when taking the 9/2\(^-\), 5/2\(^-\), 7/2\(^-\), 11/2\(^-\) and 13/2\(^-\) members of each band. The difference between these numbers (151 keV) represents the amount by which the coupling of an \(h_{9/2}\) proton to the \(^{186}\text{Pt}\) core blocks the \(O_{1}^+\) core state more than it blocks the \(C_{0}^+\) core state. For the case of \(^{186}\text{Hg}\), we note from fig. 1 that the \(O^+\) \(-\) \(O_{1}^+\) separation is 825 keV\(^6\). Since it is expected\(^7\) that the proton blocking in this case will affect the \(O_{1}^+\) state more than the \(O^+\) state, the interband transitions in \(^{187}\text{Tl}\) will be greater than the \(O^+\) \(-\) \(O_{1}^+\) energy separation. Our level scheme for \(^{187}\text{Tl}\) suggests that the band head resulting from the \(h_{9/2}\) \(C_{0}^+\) \((^{186}\text{Hg})\) coupling probably lies at least 1 MeV above the \(h_{9/2}\) \(O_{1}^+\) \((^{186}\text{Hg})\) state. These ideas are discussed further by J.L. Wood in the following paper.

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\(^7\)Present address: Department of Physics, University of Louisville, KY, USA.

![Diagram of energy levels and transitions in \(^{187}\text{Au}\).](image)

Fig. 5 The \(\pi h_{9/2} \times O_{1}^+(^{186}\text{Pt})\) and \(\mu h_{9/2} \times O_{2}^+(^{186}\text{Pt})\) bands in \(^{187}\text{Au}\) together with several transitions which are pertinent to the discussion. Those which are boxed were used as gates to generate spectra such as that shown in fig. 3.

![Diagram of energy levels and transitions in \(^{187}\text{Au}\).](image)

Fig. 6 A schematic over-view of the bands located in \(^{187}\text{Au}\).

2) J.L. Wood, ibid., p. 37.

3) E.F. Zganjar et al., work in progress.

4) M.A. Grimm et al., work in progress.


DEcay of $^{198m}$Po: Isomeric Transitions in $^{199}$Po and $^{199}$Bi

C.R. Bingham, R.E. Stone*, L.L. Riedinger, and R.W. Lide

University of Tennessee†, Knoxville, Tennessee 37916, U.S.A. and Oak Ridge National Laboratory**, Oak Ridge, Tennessee 37830, U.S.A.


ABSTRACT

The M4 isomeric transition (Eγ=238 keV) of the 13/2+ state in $^{199}$Po to the 5/2+ level, with a half life of 4.17 min, has been observed in mass separated sources. An 72 keV transition in coincidence with the isomeric transition suggests the placement of the 5/2+ level above the 3/2+, and when combined with α-decay Q values, this results in a placement of the 13/2+ isomeric state in $^{199}$Pb at ~200 keV. The transition rate for the M4 transition in $^{199}$Po is similar to that for other M4 transitions in this region. Contrastingly, a M4 transition in $^{199}$Bi, which is highly likely to occur on the basis of systematics of 5+ and 9/2- states and a sequence of gamma rays among low spin states observed in our data, is highly retarded. Although, this M4 transition is not observable in our data, an upper limit for its strength is established at ~1/1000 the intensity of typical M4 transitions in this region. Possible interpretations of this retardation will be discussed.

1. Introduction

The intrusion of shell model states (h9/2 and f5/2) from above the Z=82 shell closure into the low excitation region of light Tl nuclei has been a subject of considerable interest in recent years.1 Two of these states are believed to be 3/2+ states while the 3/2+ state is low in excitation and thus a deep intrusion of the h9/2 level results in its isomerism. It decays by an E3 transition as long as it is above the 3/2+ state (e.g. in $^{197}$Tl); for $^{197}$Tl and $^{199}$Tl the h9/2 level is believed to be above the 3/2+ state as well as a detailed study of the bands built on the single particle levels, is of interest in investigating the role of the closed shell and the possible onset of deformation as one moves away from stability. A portion of the results of this study, relating the placement and decay strength of the 13/2+ isomer in $^{199}$Bi, was previously reported and are cited here also for comparison with other results.6

The relevant levels in $^{199}$Po are odd neutron states 5/2+, f7/2 and i13/2. The 13/2+ state was known to be isomeric from α-decay studies;9,10 in the present study the location of the 13/2+ isomer and its decay characteristics are investigated. The M4 decay strength for this isomeric state is compared with those for other M4 transitions in the Pb-Po region and with a Weisskopf estimate.

2. Experimental Details and Results

The $^{199}$Po was produced by bombarding natural iridium foils in the ion source of the University Isotope Separator (UNISOR) with 115-MeV $^{14}$N+ ions from the Oak Ridge isochronous cyclotron. The $^{199}$Po atoms, ionized in the high temperature source, were mass separated and collected on an automated tape system which periodically moved the freshly collected source into a detector system. Part of the time the detector system was comprised of two large volume Ge(Li) detectors from which γ-ray multiscaled singles spectra and γ-γ-time coincidence data were obtained. For the remainder of the time an electron Si(Li) detector replaced one of the Ge(Li) detectors and e-+e- coincidence data were obtained.

The low energy portion of the electron spectrum is shown in Fig. 1. The dominance of the 99 keV E3 transition in $^{199}$Pb and the 424-keV M4 transition in $^{199}$Po is apparent. These two transitions and the 394 keV transition in $^{199}$Pb were used for final calibration of the e- detector. A group of conversion electrons corresponding to a transition energy of 238 keV in $^{199}$Po are also apparent in Fig. 1. The measured half life for these lines is 4.3±0.2 min, which agrees with the half life of the 13/2+ isomer (4.17 min) obtained from a summary of the α-decay results.1 A coincidence gate set on the K line for the 238 keV transition showed Po...
x-rays in coincidence confirming it to be a transition in Po. In addition, a gamma ray peak at about 72 keV was observed in the coincidence spectrum. The K/L and K/M ratios for the electron peaks from this transition establish that it is a M4 transition.

3. Isomeric Energy Levels in Po, Bi, and Pb

The coincidence of Po x-rays and a 72 keV gamma ray with the 238-keV isomeric transition establishes that there are two states below the 13/2+ isomer in $^{199}$Po. A spin of 5/2+ can be assigned to the upper one of these two states due to the M4 multipolarity of the isomeric transition. An assignment of 3/2+ for the ground state of $^{199}$Po can then be deduced from the systematics of the odd-A Po isotopes, shown in Fig. 2.

![Fig. 1](image1)

![Fig. 2](image2)

![Fig. 3](image3)

Fig. 1 The low energy portion of the electron spectrum from $^{199}$Po decay. Some peaks of decay products or contaminants are identified as $A = ^{197}$Bi, $B = ^{195}$Pb, $C = ^{199}$Pb, and $G = \text{unidentified Pb}$.

weighted average Q-value of 6183 keV, while the study of the ground state decay gives a Q-value of 6074 keV. Since the excitation energy of the 13/2+ state in Po is ~310 keV, the excitation energy of the 13/2+ state in $^{199}$Pb is ~200 keV.

3. Isomeric Energy Levels in Po, Bi, and Pb

The coincidence of Po x-rays and a 72 keV gamma ray with the 238-keV isomeric transition establishes that there are two states below the 13/2+ isomer in $^{199}$Po. A spin of 5/2+ can be assigned to the upper one of these two states due to the M4 multipolarity of the isomeric transition. An assignment of 3/2+ for the ground state of $^{199}$Po can then be deduced from the systematics of the odd-A Po isotopes, shown in Fig. 2.

![Fig. 2](image2)

Fig. 2 Systematics in odd-A Po isotopes. Data for $^{201-215}$Po are from Ref. 18.

The establishment of the energy of the 13/2+ isomer in $^{199}$Po permits the placement of the 13/2+ isomer in $^{195}$Pb as shown in Fig. 3. Alpha decay studies of the 13/2+ isomer in $^{199}$Po yield a

![Fig. 3](image3)

Fig. 3 Placement of the 13/2+ state in $^{195}$Pb by combining present results with α-decay Q-values.

The ground state of $^{197}$Bi is the h $^9/2$ proton level. A low spin isomer of $^{197}$Bi has been observed by α-decay to the ground state of $^{197}$Tl in several previous experiments with an adopted half life and energy of 24.7 min and 5484 keV. Combining the α-decay Q-value (5596 keV) with the Q-value estimated from mass systematics for the h $^9/2$ ground state (~4820 keV), we obtain an estimate of ~776 keV for the excitation energy of the low spin isomer in $^{199}$Bi. A low spin isomer was also observed in $^{195}$Bi and based on the systematics of $^1^+_g$ states in odd-A Bi isotopes (see Fig. 4) it is apparently also a $^1^+_g$ state. The measured multi-
Fig. 4 Relative positions of the 5/2+ and 3/2+ states with respect to the $\frac{1}{2}$+ state in odd-A Bi isotopes. The energies of the $\frac{1}{2}$+ state relative to the ground states are given under the bottom line of each isotope. Data for $^{201-207}$Bi are from Ref. 8, 19, 20, 21, 22, 23.

polarity (M4) of the decay of this state to the $\frac{3}{2}$+ ground state confirms that assignment. Also shown in Fig. 4 are level structures known to decay to the $\frac{1}{2}$+ state in the different isotopes. A similar level structure was observed in $^{199}$Bi in the present work and probably assignments of spins can be made based on these systematics as indicated in Fig. 4. The decay of the $\frac{1}{2}$+ isomer to the ground state was not observed in the present data, but from the systematic trend of the $\frac{1}{2}$+ state excitation energy (shown under the bottom line for each isotope in Fig. 4) an estimate for the excitation energy for the $\frac{1}{2}$+ state in $^{199}$Bi of 600 keV is made. This is close to the estimate deduced from α-decay and mass systematics above.

4. Isomeric Transition Rates

Relative intensities were determined for each transition mentioned above as well as for the other transitions in $^{199}$Bi leading to the $\frac{3}{2}$+ ground state. The electron intensities for the 238 keV transition were combined with the known conversion coefficients for a M4 transition in order to obtain the total intensity of that isomeric transition. The γ-ray intensities observed in $^{199}$Bi were also corrected for internal conversion. The intensity of the e.c.-B+ decay of the 13/2+ isomer in $^{199}$Po is somewhat more uncertain since the 3/2+ ground state also decays to $^{199}$Bi. It was assumed that the population of the $\frac{1}{2}$+ isomer and the 5/2- level in $^{199}$Bi was from the decay of the 3/2+ ground state and that the remaining levels in $^{199}$Bi were populated by decay of the 13/2+ isomer in $^{199}$Po. Since ~70% of the intensity assigned to the 13/2+ decay originated with population of states with assigned high spins, it is clear that the assumed intensity cannot be grossly in error. The relative strength of the isomeric transition to the e.c.-B+ decay was thus found to be 0.034. Since the α-decay branching ratio for the 13/2+ isomer is 39%, the branching ratio for the isomeric transition is 2.1% while that for the e.c.-B+ decay is 59%. Using these branching ratios and the known half life (4.17 min) the probability for isomeric γ-ray decay is found to be 8.5x10^-7 s^-1 which can be compared with a Weisskopf single particle estimate of 3.2x10^-7 s^-1. The experimental transition rate is thus equal to 2.6 Weisskopf units or the transition has a retardation factor of 0.38. This value is similar to the retardation factors for several other M4 transitions in odd-A nuclei as illustrated by several examples in Table I.

Table I

<table>
<thead>
<tr>
<th>Isomer</th>
<th>Transition Energy (keV)</th>
<th>Retardation Factor</th>
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</thead>
<tbody>
<tr>
<td>$^{197}$Hg</td>
<td>165</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{197}$Pb</td>
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<td>0.33</td>
</tr>
<tr>
<td>$^{198}$Hg</td>
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<td>0.33</td>
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<tr>
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<td>0.76</td>
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<tr>
<td>$^{199}$Po</td>
<td>238</td>
<td>0.37</td>
</tr>
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</table>

*See Ref. 11 and 12.

Although a group of transitions feeding the $\frac{1}{2}$+ state in $^{199}$Bi was observed, the expected isomeric transition of this state to the 9/2+ ground state was not observed. A search for a M4 transition in the 500-1000 keV energy range yielded no likely
candidate. Nevertheless, the largest unexplained electron line was interpreted as the K line for such a transition and corresponds to a Bi transition energy of 667 keV, which is between the two estimates made in Sect. 3. This upper limit on the K electron intensity and internal conversion coefficients for the transition were used to project a γ-ray intensity which was well below our threshold for observation. The feeding of the 4+ level was assumed to be entirely due to the 246 and 453 keV transitions (see Fig. 4); this estimate is clearly a lower limit of the feeding since the 3/2+ ground state of 199Po may decay directly to the 1+ isomer. A correction factor to account for the finite counting time and half lives of the 199Po and 199Bi was made. Thus, an upper limit on the isomeric transition branch in the decay of the 4+ state of 3.2% was deduced. Correcting for conversion and using the measured 24.7 min half life, one obtains an upper limit to the γ-ray transition rate of 61/390 Weisskopf estimate for a M4 transition. As seen in Table I, this lower limit on the retardation factor (390) is about 1000 times larger than typical retardation factors for M4 transitions in odd-A nuclei.

In summary we note that the isomeric decay rate for the 13/2+ + 5/2− transition in 199Po is closely comparable to those of other M4 transitions (see Table I and a more extensive survey of M4 transition rates in Ref. 8). However, the retardation of the 13/2+ − 9/2+ isomeric transition in 201Bi is ~1000 times as retarded as typical M4 transitions. The only other case of such a large reported retardation factor is for the same transition (13/2+ − 9/2+) in 201Bi. This is no doubt related to the fact that the 4+ state is predominantly a s1/2 hole state in a Pb core whereas the 9/2− is predominantly a h 3/2 proton coupled to a Pb core. In a similar situation the intrusion of the h 3/2 level to become the first excited state in 109Tl and 111Tl, the M4 isomeric decay to the s1/2 ground state of these nuclei has not been reported, perhaps also because of large retardation. The transitions could be retarded due to the 1 selection rule for transitions between pure single particle shell model states, thus indicating extreme purity of these states. Considered as an E5 transition, the retardation would be less extreme. Nevertheless, for the one case where the isomeric transition was observed, a 201Bi, it was shown to be an almost pure M4 transition with a retardation factor of ~2000. This would indicate that the retardation is not merely due to 1 forbiddenness, but that other factors related to the different cores for the particle and hole states are involved.

References


THE DECAY $^{207}\text{Hg} \rightarrow ^{207}\text{Tl}$

B. Jonson  
CERN-ISOLDE, CERN, Geneva, Switzerland  
O.B. Nielsen  
Niels Bohr Institute, Copenhagen, Denmark  
L. Westgaard  
Chemical Institute, University of Oslo, Norway  
J. Żylicz  
Institute of Experimental Physics, University of Warsaw, Poland  
The ISOLDE Collaboration

Abstract

$^{207}\text{Hg}$ was produced in a secondary (n,2p) reaction on $^{208}\text{Pb}$. The decay scheme was studied by means of a plastic scintillator and Ge(Li) detectors. Fourteen excited levels in $^{207}\text{Tl}$ are discussed in terms of proton hole states coupled to the core excitations of $^{208}\text{Pb}$.

1. Introduction

An investigation of the decay scheme of $^{207}\text{Hg}$ is of considerable interest since it might add to our knowledge of the levels in $^{207}\text{Tl}$, which can be considered as a hole in a $^{208}\text{Pb}$ core. Until now, $^{207}\text{Hg}$ has, however, not been reported in the literature, probably because it has one neutron more than any convenient target material, which makes it difficult to produce in charged-particle reactions. It turned out, however, that it was produced in the ISOLDE facility by a secondary (n,2p) reaction on $^{208}\text{Pb}$ together with the lighter mercury isotopes, which were formed in the primary reactions $\text{Pb}(p,3\text{pn})\text{Hg}$.

2. Production of $^{207}\text{Hg}$

As the production of a radioisotope in a secondary reaction is somewhat untraditional, the experimental conditions shall be briefly outlined. The ISOLDE targets used for the production of mercury isotopes consist of molten natural lead of an effective thickness $\sim 15$ cm or 170 g/cm$^2$. This is not much less than a radiation length, and a large fraction of the 600 MeV protons give rise to spallation reactions in which protons and neutrons are emitted with energies that are sufficient for secondary reactions. Protons of 600 MeV cause, on the average, the ejection of 2-3 neutrons with an energy above 50 MeV, which is enough for the (n,2p) reaction. The target size also allows a considerable part of these neutrons to react with the $^{208}\text{Pb}$ part of the lead, resulting in a yield of $^{207}\text{Hg}$ that is 2-3 orders of magnitude lower than that of the $^{208}\text{Hg}$ formed in the primary $^{208}\text{Pb}(p,3\text{p})$ reaction.

As could be expected, the (n,2p) reaction was enhanced in targets having dimensions larger than those of the standard ISOLDE type, and the final version contained more than 500 g of lead. With a proton beam of $\sim 2 \times 10^{12}$ particles/s, the yield of $^{207}\text{Hg}$ was about $10^5$ atoms/s or a few $\mu$Ci (Fig. 1).

3. The detector system

The $^{207}\text{Hg}$ was collected inside the separator vacuum on a metalized mylar tape, and was moved via an automated transport system$^{10}$ to a position inside a plastic scintillator, which had a narrow slit cut through the middle. The $\beta$-particles were accordingly detected with almost 100% efficiency. A Ge(Li) detector, of either 63 or 40 cm$^3$, was placed outside the vacuum, close to the scintillator, and the $\gamma$-rays could be recorded in coincidence with the $\beta$-particles as well as in the singles mode.

With the much higher production rate for the lighter mercury isotopes, the problems arising from cross-contamination in the isotope separator, and general room background had to be considered. However, unlike $^{207}\text{Hg}$, none of the likely impurities emit high-energy $\beta$-particles in coincidence with high-energy $\gamma$-rays. The transitions originating in $^{207}\text{Tl}$ could therefore be easily identified in the $\gamma$-ray spectra measured in coincidence with $\beta$-particles above a certain energy.
The γ-γ coincidence measurements were performed with two Ge(Li) detectors placed in a 90° geometry. The experimental conditions allowed the establishment of only a limited number of coincidence relations.

4. Half-life and decay energy of 208Hg

The half-life was determined by two different selective methods of counting, performed by means of the above detector system. Firstly, gross coincidences between high-energy β's and high-energy γ's were recorded as a function of time. Secondly, the decay of one of the strong lines in the γ-spectrum was followed. The result in both cases was a half-life of 2.9 ± 0.2 min.

The continuous β-ray spectrum was investigated in the plastic scintillator, using a technique described elsewhere. In the present case, only β-particles in coincidence with high-energy γ-rays were recorded. The subsequent analysis of the decay scheme shows that the β-groups of highest energy populate four levels with energies between 2912 and 3143 keV. The measured maximum energy of 1800 keV was a weighted average for these groups, and the total decay energy is estimated, with a modest accuracy, as 4775 ± 150 keV.

The half-life and the Q-value of 207Hg are almost identical to those of 208Pb: 3.05 min and 4992 keV.

5. Preliminary considerations on the levels of 207Tl

Before the experimental facts are discussed, we shall briefly outline some main features of the level structure of 207Tl as suggested from our knowledge of the neighbouring nuclei around 208Pb. Figure 2 shows the proton hole states as found in charged-particle reactions, the assignments being relatively unambiguous. To the right are indicated the lowest states of 208Pb, which are core excitations, i.e. a rather collective two-particle excitation. The level scheme of 207Tl is expected to arise from the coupling of the proton hole states to these core excitations. Below 2600 keV, the level scheme should accordingly be simple, but above that energy a considerable number of negative-parity states can occur. Above ~3500 keV, the level density is likely to be so high that an interpretation of individual levels will be difficult.

In addition to the states of the above configurations, a level corresponding to the ground state of 208Hg coupled to a h_1/2 proton is expected. Blomqvist has estimated its position as being at 2963 keV.

6. The decay scheme

The following discussion of the levels in 207Tl is based upon the γ-ray and γ-γ coincidence measurements performed with the Ge(Li) detectors. We have no information about conversion lines, angular correlations, etc., and all assignments of spins and multipole orders are based on systematics. Most of the experimentally determined levels of Fig. 3 are proposed on the basis of energy fits better than 0.3 keV. The γ-γ coincidence relations are decisive in some cases, and the whole scheme is supported by a satisfactory intensity balance.

6.1 The h_1/2 and d_3/2 states

The isotope 207Hg has 127 neutrons, and the odd particle is thus the first outside the closed shell and is assigned as g_9/2. This neutron can decay to the h_1/2 state of Fig. 2, but the transition is expected to be weak. Owing to the 1.3 s half-life of the h_1/2 state, such a β-group could not be singled out by coincidence measurements, but we are able to conclude that only a small fraction of the population of the level might be the result of direct β-feeding. Beta-decay to the other single-particle states of Fig. 2 are highly forbidden and were not observed.

The 1/2^- state was strongly populated by γ-transitions from higher levels (Fig. 3). The de-excitation was mainly by an intense 997.1 keV line to the 351.0 keV 5/2^- level, but the cross-over transition of 1348.1 keV was seen in the γ-spectrum with

<table>
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<td></td>
</tr>
<tr>
<td>207 Tl</td>
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</table>

Fig. 3 Part of the decay scheme 207Hg → 207Tl. The γ-transitions are indicated by their energy and intensity in units of one per mille of all decays. Corrections for internal conversion are made where possible.

- 641 -
an intensity which could not be explained by summing in the Ge(Li) detector. The summing contribution was estimated by the measurement of spectra with different distances from source to counter. After correction, the intensity of the 1348.1 keV γ-ray was found to be $(4 \pm 1)$% of the 997 keV line. It must be interpreted as an E5 transition, which is able to compete with a predominantly M4 transition of 997 keV. An E5 transition between corresponding levels in $^{207}$Tl has been observed earlier.

6.2 The strongly excited levels

More than 80% of all β-decays proceed to seven levels in $^{207}$Tl between 2912 and 3558 keV. They decay predominantly to the $\frac{11}{2}^+$ state; in four cases, weak cross-overs to the $\frac{7}{2}^-$ state at 351 keV were also observed. The cross-overs were all seen in coincidence with the 351 keV γ-ray, whereas for natural reasons the transitions to the long-lived $\frac{11}{2}^+$ state were missing in the coincident spectrum.

The $^{207}$Hg with spin $\frac{11}{2}^+$ can decay to levels of spin $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^+$ with allowed or first-forbidden transitions. Most of the β-decays of $^{208}$Pb to $^{208}$Tl excite the 5° and 4° levels by transitions with log ft values 5.6 and 5.7. Similar transition rates are expected in the decay of $^{207}$Hg to states corresponding to the same core excitations in $^{207}$Tl.

Blomqvist$^3$ has estimated that the coupling of $s_{\frac{7}{2}}$ to the 5° and 4° states and of $d_{\frac{7}{2}}$ to $\frac{3}{2}^-$, $\frac{5}{2}^-$, and 4° gives rise to nine states of spin $\frac{11}{2}^+$, $\frac{13}{2}^+$, and $\frac{15}{2}^+$ between 2500 and 3500 keV. In addition, the $^{209}$Hg $h_{\frac{1}{2}^-}$ state is predicted in the same energy region. Most of these states will be strongly admixed, but even if it is not possible to give unambiguous assignments to the experimental levels of Fig. 3, the main features of the β-decay of $^{208}$Hg are well explained by the model outlined above. For example, the "β-strength functions" are almost identical for the $^{208}$Tl → $^{208}$Pb and $^{207}$Hg → $^{207}$Tl decays.

Negative-parity assignments for the strongly excited levels imply that the γ-transitions to the $\frac{11}{2}^+$ state are M1 or E2. The cross-overs to the $\frac{7}{2}^-$ state are then E3. The 3° state of $^{208}$Pb is connected to an enhanced E3 transition strength, which apparently also in $^{207}$Tl can compete with M1 and E2 transitions of lower energy.

6.3 Some weakly populated levels

The γ-ray measurements further revealed the four levels in Fig. 4. They are only weakly excited and must partly be fed by unidentified β-groups and γ-rays from higher-lying levels.

The excitation of the $d_{\frac{7}{2}}$ state at 1682.7 keV is indicated by the ground-state transition and the 1331.2 keV γ-ray, which is seen in coincidence with 351 keV. Since the feeding of this state is of considerable interest, time was invested in the measurement of the coincident γ-ray spectrum gated by the 1331 keV line. With the low intensity the experiment was marginal, but the line of 1590.3 was clearly shown to be coincident, establishing a level at 3273 keV.

Hamamoto$^7$ has pointed out that a γ-ray from the 2675.2 keV level (see below) might have a high transition strength to the $d_{\frac{7}{2}}$ state. Its energy, ~ 992.5 keV, made it impossible to observe it in the single γ-ray spectrum, as it is situated in the tail of the 997 keV line (about 100 times stronger) from the $\frac{11}{2}^+$ state, but this line was strongly suppressed in the coincident spectrum, and there was a clear indication of an ~ 993 keV line of the intensity given in Fig. 4.

Two levels at 2675.2 and 2709.1 keV are interpreted as the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ states of the $s_{\frac{7}{2}}$ 5° configuration. The experimental evidence for the lowest level is a 2675.2 keV γ-line, which is probably not coincident with 351 keV, although its weakness made this conclusion marginal. As mentioned, there is also a strong indication of a transition to the 1682.7 keV state, and a weak line of 596.4 keV fits in energetically as a transition from the 3273 keV level. The 2709.7 keV level decays with the 2358 keV γ-ray, which is coincident with 351 keV. Like the 2675 keV state, it seems to be partly excited from the 3273 keV level.

This de-excitation can be understood by assuming that the state assigned as $\frac{7}{2}^-$ decays by an E3 transition to the $s_{\frac{7}{2}}$ ground state, whereas the $\frac{9}{2}^-$ state can reach the 351 keV state by an E1 transition.

The decay mode of the 3273 keV state is so different from that of the negative-parity states in the same energy region that another structure is indicated and may be of positive parity. It is most likely populated by a weak β-group, but some feeding from higher-lying levels is not excluded.

Finally, a level at 3592.7 keV is suggested. A weak, unassigned γ-line of 1909.2 keV showed up in coincidence with the 1531 keV transition. The level is shown dotted, however, as the evidence consisted of only three coincidences observed on a negligible background.
6.4 Unassigned transitions

In addition to the $\gamma$-transitions placed in the decay scheme, a considerable number of low-energy lines could be fitted in energetically between the high-energy levels, several of them in more than one position (Fig. 3). Two $\gamma$-lines, which probably go to the $^{11/2}_2$ level, might indicate states at 3633 and 3644 keV; and as usual in this type of decay scheme work, a number of weak, unassigned lines are left over.

We are indebted to Drs. I. Hamamoto and J. Blomqvist for invaluable help and guidance.

REFERENCES

4) C.M. Lederer and V.S. Shirley, Table of isotopes, Seventh ed. (1978).
5) J. Blomqvist, private communication.
STUDY OF LEVELS IN $^{208}$At HAVING SIX VALENCE NUCLEONS

B. Fant and T. Weckström

Department of Physics, University of Helsinki, Helsinki, Finland

and

K. Fransson, C.J. Herrlander, K. Honkanen, A. Källberg, C.G. Lindén and T. Lännroth

Research Institute of Physics, Stockholm, Sweden

Abstract

Levels in $^{208}$At have been populated in the $^{208}$Bi($a$,5n) reaction. It is observed that the yrast cascade from high-spin states in $^{208}$At is divided into two parallel cascades. It is proposed that one of them originates mainly from proton excitations, while the other derives mainly from neutron hole excitations.

Two isomeric states are observed. There is a 46(3) ns isomeric state, which can be identified as arising mainly from the $(\hbar\pi_2^+ \otimes \hbar\pi_2^-)$, interaction, and a 1.5(2) μs isomeric state, which can be identified as the $(\hbar\nu_1^+ \otimes \hbar\pi_2^- \otimes \nu_1^+ \otimes \nu_3^-)$, state.

1. Introduction

In our studies of the applicability of the shell model in the lead region, we have found that nuclei with up to four valence particles are well described in terms of the model 1). Also, for the case of $^{208}$Bi with six valence particles, it is found that the energy levels can be calculated using only a "moderate" configuration mixing 2).

High-spin states in the lead region have been observed up to $J^\pi = 22^+$ using an $\alpha$-beam and up to $J^\pi = 30^+$ using a $^{133}$C-beam. It is observed that the yrast line in the lead region is built up from valence nucleon states, but when the spin is close to or above the spin $J$(max) generated by the valence particles, excitation of the $^{208}$Pb-core is also observed. In the present investigation we continue our study of astatine isotopes 2) with the $^{208}$At nucleus which so far has an almost unknown nuclear structure 4). $^{208}$At has three protons and three neutron holes ([$\pi^v^-$]) as compared to the core of $^{208}$Pb. One can thus regard $^{208}$At as a nucleus where the three protons corresponding to $^{211}$At interact with the three neutron holes in $^{208}$Pb. The level scheme of $^{208}$At can, on the other hand, be compared with that of $^{210}$At, where we have the ($\pi^v^-$) interaction, and $^{208}$Bi, where the ($\nu^v^-$) interaction occurs.

2. Experimental procedure and results

The high-spin states in $^{208}$At were studied through the $^{208}$Bi($a$,5n)$^{203}$At reaction using $\alpha$-particles from the Stockholm 225 cm cyclotron. The energy of the $\alpha$-beam was varied from 51 to 59 MeV. 59 MeV $\alpha$-energy represents an optimal beam energy and intensity combination for producing $^{208}$At with this cyclotron. The experimental information from singles $\gamma$-ray spectra, $\gamma$-ray angular distribution measurements and conversion electron spectra is presented in Table 1.

The singles spectra were recorded both with a high-resolution 4 cm$^2$ planar detector and with high-efficiency 60 cm$^2$ coaxial Ge(Li) detectors.

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<th>$A_{44}$</th>
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<th>$\alpha$ th</th>
<th>Sugg. Mult.</th>
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<td>16</td>
<td>0.22(1)</td>
<td>-0.21(2)</td>
<td>0.036</td>
<td>0.038</td>
<td>E2</td>
</tr>
<tr>
<td>454.2</td>
<td>8.1</td>
<td>-0.10(3)</td>
<td>-0.13(5)</td>
<td>0.081</td>
<td>0.15</td>
<td>M1</td>
</tr>
<tr>
<td>467.1</td>
<td>7.0</td>
<td>0.36(4)</td>
<td>-0.10(6)</td>
<td>0.044</td>
<td>0.027</td>
<td>E2</td>
</tr>
<tr>
<td>469.1</td>
<td>17</td>
<td>-0.26(2)</td>
<td>-0.03(3)</td>
<td>0.14</td>
<td>0.14</td>
<td>M1</td>
</tr>
<tr>
<td>472.2</td>
<td>25</td>
<td>0.12(4)</td>
<td>-0.16(6)</td>
<td>0.096</td>
<td>0.066</td>
<td>E3</td>
</tr>
<tr>
<td>481.9</td>
<td>4.9</td>
<td>0.57(3)</td>
<td>-0.28(3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>490.5</td>
<td>7.5</td>
<td>-0.29(2)</td>
<td>-0.10(3)</td>
<td>0.19</td>
<td>0.13</td>
<td>M1</td>
</tr>
<tr>
<td>499.9</td>
<td>3.9</td>
<td>-0.19(16)</td>
<td>-0.26(22)</td>
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<tr>
<td>502.6</td>
<td>11</td>
<td>-0.31(4)</td>
<td>-0.22(6)</td>
<td>0.23</td>
<td>0.12</td>
<td>M1</td>
</tr>
<tr>
<td>533.8</td>
<td>14</td>
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<td>-0.15(5)</td>
<td>0.07</td>
<td>0.12</td>
<td>M1</td>
</tr>
<tr>
<td>542.1</td>
<td>10</td>
<td>-0.16(5)</td>
<td>0.05(7)</td>
<td>0.14</td>
<td>0.10</td>
<td>M1</td>
</tr>
<tr>
<td>543.6</td>
<td>33</td>
<td>-0.50(4)</td>
<td>-0.14(5)</td>
<td>0.087</td>
<td>0.093</td>
<td>M1</td>
</tr>
<tr>
<td>553.1</td>
<td>22</td>
<td>-0.44(2)</td>
<td>-0.07(3)</td>
<td>0.087</td>
<td>0.093</td>
<td>M1</td>
</tr>
<tr>
<td>558.2</td>
<td>73</td>
<td>-0.31(3)</td>
<td>-0.14(4)</td>
<td>0.027</td>
<td>0.019</td>
<td>E2</td>
</tr>
<tr>
<td>567.5</td>
<td>6.8</td>
<td>0.11(5)</td>
<td>-0.07(6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>577.7</td>
<td>62</td>
<td>-0.57(6)</td>
<td>-0.10(12)</td>
<td>(0.077)</td>
<td></td>
<td></td>
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<tr>
<td>621.0</td>
<td>9.8</td>
<td>-0.15(6)</td>
<td>-0.10(11)</td>
<td>0.030</td>
<td>0.048</td>
<td>M1</td>
</tr>
<tr>
<td>630.7</td>
<td>8.4</td>
<td>-0.04(6)</td>
<td>-0.10(12)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>701.3</td>
<td>10</td>
<td>0.07(5)</td>
<td>-0.10(12)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>716.7</td>
<td>14</td>
<td>-0.35(4)</td>
<td>-0.13(7)</td>
<td>0.030</td>
<td>0.048</td>
<td>M1</td>
</tr>
<tr>
<td>750.9</td>
<td>29</td>
<td>0.19(4)</td>
<td>-0.03(6)</td>
<td>0.039</td>
<td>0.024</td>
<td>E3</td>
</tr>
<tr>
<td>788.2</td>
<td>69</td>
<td>0.32(17)</td>
<td>0.14(35)</td>
<td>0.0096</td>
<td>0.0096</td>
<td>E2</td>
</tr>
<tr>
<td>832.2</td>
<td>168</td>
<td>0.30(1)</td>
<td>-0.08(5)</td>
<td>0.0075</td>
<td>0.0087</td>
<td>E2</td>
</tr>
</tbody>
</table>

$^d$ Double.

The $\gamma$-rays belonging to $^{208}$At were assigned using the information from excitation functions, and $\gamma$-spectra recorded in coincidence with the $\alpha$ X-ray peaks in addition to the summed coincidence information. The strongest transitions were also assigned to astatine through the conversion electron measurements.

The time measurements were performed using both the natural bursts of the cyclotron, 104 ns apart, as well as bursts selected by an electrostatic system which was tuned to pick out every eleventh pulse. The time measurements revealed two isomeric states in $^{208}$At. One of these appeared to have a half-life 46(3) ns being depopulated mainly by the
71.7, 186.5 and 832.2 keV transitions, (cf. Fig. 1), and the other a 1.5(2) µs half-life appearing in many transitions, for instance, in the 149.4, 278.7, 396.0, 467.1, 472.2, 750.9, 788.2 and 832.2 keV transitions (Fig. 1). The transitions 186.5 (46(3) ns) and 472.2 and 750.9 keV (1.5(2) µs) were found to be isomeric.

Three-parameter γγ-coincidence measurements were carried out at Eγ = 59 MeV. These were performed in two steps using two 60 cm² coaxial Ge(Li) detectors and a 60 cm³ coaxial detector together with a 4 cm³ planar detector. Some gated spectra are shown in Fig. 2.

The coincidence measurements reveal that the yrast cascade from the high-spin states is divided into two parallel branches. One branch contains the decay of the 1.5 µs isomeric state and the other branch feeds into the 46 ns isomeric state.

The decay order of the transitions feeding into the 46 ns isomeric state is difficult to determine because several of the observed gamma transitions are doublets or triplets. Thus the composite line at 542-545 keV turned out to be a quartet where the 545 keV peak contains strong 209Bi activity and a double peak from 208At. Furthermore, the 534 keV peak is double and the 577 keV peak is found to be very complex. This latter peak gains intensity from the (α,3n), (α,4n) and (α,5n) channels, e.g. 576.4 keV in 206At and 577.0 and 577.4 keV in 208At. A double peak is also found in the 208At spectrum, where the strongest part (~45%) of the relative intensity, Table 1) feeds the 558.2 keV transition and has the energy 577.7 keV determined from the gated spectra.

Angular distribution measurements were performed at five angles between 90° and 150°. The data were normalized to include dead time and geometric effects and fitted to the function

\[ W(\Theta) = A_0 + A_2 \cos^2 \Theta + A_4 \cos^4 \Theta \]

The coefficients \( A_m = A_m / A_0 \) are presented in Table 1.

Conversion electron measurements were performed using the TARM® electron spectrometer which utilizes a solenoid magnetic field to transport the electrons from the target to a cooled Si(Li) detector. Targets consisting of 0.6 mg/cm² 208Bi evaporated on carbon foils were used. The spectrometer was calibrated using both a 153Eu source and the 206Po target activity. The conversion electron data were stored on magnetic tapes as two parameter lists and thus prompt, singles and delayed conversion electron spectra were obtained. The conversion electron intensities were normalized to the 788.2 keV transition for which a pure E2 multipolarity was assumed. The conversion coefficients obtained for 208At, i.e. for the 424.2, 596.5 and 725.1 keV transitions, are in agreement with those previously reported \( 5b \). The information from the conversion electron measurement is given in Table 1.

3. Spin and parity assignments

The level scheme of 208At

Spin-parity \( 6^+ \) is proposed for the ground-state of 208At through shell model considerations and α-decay properties \( 5c \). The strongest γ-ray observed in the 209Bi(α,5n) reaction is the 832.2 keV transition (cf. Table 1). In coincidence with this transition is the 71.7 keV transition, which is prompt; this suggests M1-multipolarity for the transition. The conversion coefficient for an M1-transition of 71.7 keV is 6.1 giving a total intensity which is almost the same as that of the 832.2 keV transition. We propose that the 71.7 keV transition is a ground-state transition and that the first excited state, as observed in these experiments, is a 7^+ state. The 903.9 keV state depopu-
Table 2. Delayed intensities and conversion coefficients for the transitions depopulating the 1.5-µs isomeric state in $^{208}$At.

<table>
<thead>
<tr>
<th>$E_y$</th>
<th>$I_y$</th>
<th>Meas. $I_y$</th>
<th>Conv. coeff.</th>
<th>$I_{tot}$</th>
<th>$I_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.5</td>
<td>M1</td>
<td>26.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.2</td>
<td>105</td>
<td>M1</td>
<td>5.48</td>
<td>679</td>
<td>99</td>
</tr>
<tr>
<td>149.4</td>
<td>134</td>
<td>M1</td>
<td>4.13</td>
<td>686</td>
<td>100</td>
</tr>
<tr>
<td>278.7</td>
<td>175</td>
<td>M1</td>
<td>0.721</td>
<td>302</td>
<td>44</td>
</tr>
<tr>
<td>396.0</td>
<td>259</td>
<td>E2</td>
<td>0.061</td>
<td>275</td>
<td>40</td>
</tr>
<tr>
<td>467.1</td>
<td>252</td>
<td>E2</td>
<td>0.049</td>
<td>264</td>
<td>38</td>
</tr>
<tr>
<td>472.2</td>
<td>227</td>
<td>E3</td>
<td>0.143</td>
<td>259</td>
<td>38</td>
</tr>
<tr>
<td>750.9</td>
<td>291</td>
<td>E3</td>
<td>0.037</td>
<td>302</td>
<td>44</td>
</tr>
</tbody>
</table>

Fig. 3. The decay scheme of $^{208}$At as obtained in the $^{206}$Bi(a,Sn) reaction.

lated by the 832.2 keV E2-transition is then a 9+ state, see Figure 3.

The 903.9 keV state is populated by the 186.5 and 396.0 keV transitions. The latter transition is an E2-transition (cf. Table 1) giving an 11+ state at 1299.9 keV. The 1299.9 keV state is also depopulated by the 44.5 keV transition (Fig. 3). The most probable multipolarity for this transition is M1, because no half-life is observed for the transitions depopulating the 1299.9 keV state. The requirement that the delayed intensity from the above-lying 1.5-µs isomeric state should be conserved is also in agreement with the multipolarity M1 for the 44.5 keV transition. The multipolarity E2 for the 467.1 and 782.2 keV transitions, which appear in the yrast cascade together with the 44.5 keV transition (cf. Fig. 3) and the M1 transition of 716.7 keV (Table 1 and Fig. 3) determines the spin-parity of the 782.3, 1255.4 and 1299.9 keV states as 8+, 10+ and 11+, respectively.

The suggested M1 multipolarity (Table 2) for the 76.2 and 149.4 keV transitions gives spin-parity 12+ and 13+ for the states at 1376.1 and 1525.5 keV, respectively. The small intensity discrepancies appearing in Table 2 indicate that a branching which is not yet observed may occur from the 10+ or 11+ state.

The conversion coefficient of the 278.7 keV transition supports an M1 transition and the positive $A_2$-coefficient indicates a non-stretched transition. $J^\pi = 13^+$ is suggested for the state at 1804.2 keV. The 750.9 and 472.2 keV transitions may be either M1 or E3 as a result of the conversion electron measurement, but a positive $A_2$-coefficient for both (Table 1) suggests that the E3-alternative is to be preferred. Multipolarity M1 for the two transitions would give $J^\pi = 13^+$, $14^+$ for the state at 2276.4 keV, with preference for $J^\pi = 13^+$ due to the positive $A_2$-coefficients of the two transitions. If, on the other hand, unlikely that a non-yrast 13+ state would be so strongly populated. Therefore the E3-multipolarity assignment is to be preferred also from that point of view; this gives $J^\pi = 16^+$ for the 2276.4 keV state. This state is then isomeric, which is supported by the fact that almost no prompt component is observed in the 750.9 and 472.2 keV transitions. The small prompt component in the two transitions (cf. Fig. 1) can be explained by a small contamination, which could not be separated. The strong attenuation ($A_{46} = 0.2$) of the E3-transitions is to be expected, in view of the long half-life.

The $J^\pi$-value 10+ is proposed for the 46 ns isomeric state at 1090.4 keV. Since the isomeric (Fig. 1) 186.5 keV transition depopulating this state could not be resolved in the conversion electron measurement, the multipolarity of this transition has not been determined. The half-life 46(3) ns observed for the isomeric transition is too short for a typical E3- or M2-transition in the lead region and too long for an E2-transition; thus the most probable multipolarity for this transition is E1. The measured angular distribution coefficients $A_2 = 0.081(1)$, $A_4 = -0.172(2)$ may also be fitted with the theoretical distribution of an E1-transition with suitable mixing.

The intensity of the transitions depopulating the 16+ and 10+ isomeric states indicates a strong feeding into these states from higher states. The number of transitions feeding the 10+ isomeric state, according to the coincidence measurements, indicates that we observe the decay of states having $J \geq 20$.

4. Discussion

The structure of the $^{204}$At nucleus is determined by six valence nucleons and a core of $^{204}$Pb. In the description of the nuclear excitations one can use a configuration space where all six valence nucleons interact with each other, but the calculations, which have not yet been performed, may be simplified by using known multiparticle configurations, viz., the known three-proton levels of $^{211}$At and the known three-neutron-hole levels of $^{203}$Pb. The observed decay-pattern shows two independent yrast cascades, which may be interpreted as depending primarily on proton excitations in one case and on neutron excitations in the other case. Although the feeding into the 10+ state is not shown in Figure 3, this feeding is independent of the yrast cascade depopulating the 1.5-µs isomeric state.
As indicated in Figure 4, the 1.5 μs isomeric state and its decay may be compared with excited states of $^{210}\text{At}$. Accordingly, the excited states of $^{208}\text{At}$ may be described as $\pi_{01/2}^{(1)}(J^+)^+$ excitations, i.e. the excitations of $^{211}\text{At}$ coupled to a neutron-hole in the $^{208}\text{Pb}$-core. On the other hand, excitations of the main configuration $\pi(J^r_2)^+$ may also occur in the yrast cascade feeding the 10$^+$ state, and the excited states of $^{208}\text{At}$ may in this case be compared to the excited states of $^{208}\text{Bi}$ (cf. Fig. 4).

The observed reduced transition rate for the 472.2 keV E3-transition is 61400 e²fm⁶, which is of the same order as for a typical $\pi_{13/2}^+ \to \pi_{7/2}^+$ transition in the lead region. Thus for the $\pi(\hbar/2,1/2)_3^+\rightarrow \pi(\hbar/2,1/2)_3^+$ transition in $^{211}\text{At}$, the B(E3) value 51000 e²fm⁶ is found. The B(E3) value of the 750.9 keV transition is 3000 e²fm⁶, which is of the same order as for the spin-flip $\pi(\hbar/2,1/2)_3^+ \rightarrow \pi(\hbar/2,9/2)_4^+$ transition observed in $^{210}\text{Po}$. The measured $^{12}$ B(E3) value of the corresponding $\pi_{13/2} \rightarrow \pi_{9/2}$ transition in $^{208}\text{Bi}$ is 22000 e²fm⁶. According to these B(E3) values the most probable configuration of the 1.5 μs isomeric state is $\pi(\hbar/2,3/2)^+ \rightarrow \pi(\hbar/2,3/2)^+$, while the configuration of the second 13$^+$ state is $\pi(\hbar/2,1/2)^+ \rightarrow \pi(\hbar/2,1/2)^+$ and for the first 13$^+$ state it is $\pi(\hbar/2,1/2)^+ \rightarrow \pi(\hbar/2,1/2)^+$. The 16$^+ \rightarrow 13^+$ transition may also occur through a mixing of the 13$^+$ configuration into the 13$^+$ state and then the faster E3-transition will determine the transition rate of the slower E3-transition.

From the nuclear level systematics shown in Figure 5 the most probable configuration for the 46 ns 10$^+$ isomeric state is $\pi(J^r_2)^+ \rightarrow \pi_J(1/2)^+ \rightarrow \pi_J(1/2)^+$, which also is in agreement with the calculated energy for this state in $^{208}\text{At}$. This 10$^+$ state, arising from the $\pi_{01/2}(J^r_2,7/2)$ interaction, is isomeric in the ms-region in the even Bi-isotopes, indicating that the transition strength is determined mainly by the $\pi_J(1/2)^+ \rightarrow \pi_J(3/2)^+$ transition, while the half-life in the At-isotopes is in the ns-region due to the possibility of an E1-transition.

The 6$^+$ and 7$^+$ excited states show a systematic behaviour. These states are due to the $\pi_{01/2}(J^r_2,7/2)$ interaction, which seems to be rather pure in the considered nuclei.

A more extensive report, which includes the transitions feeding the isomeric states, is in preparation.
Fig. 5. Level systematics showing the \((\frac{3}{2}^+\frac{3}{2}^+\frac{3}{2}^-)_{10^-}\) state and states below this in even Bi isotopes compared to \(^{210}\text{At}\) and \(^{208}\text{At}\).

References


13) J. Blomqvist, private communication.
COLLECTIVE EXCITATIONS IN THE TRANSITIONAL NUCLEI $^{224,226,228,230}$Ra

W. Kurcewicz
Gesellschaft für Schwerionenforschung mbH, D-61 Darmstadt, Fed. Republic of Germany and
Institute of Experimental Physics, University of Warsaw, Poland

E. Ruchowska
Institute of Experimental Physics, University of Warsaw, Warsaw, Poland

N. Kaffrell
Institute of Nuclear Chemistry, University of Mainz, Mainz, Fed. Rep. of Germany

T. Björnstad and G. Nyman
CERN, Geneva, Switzerland

Abstract

The $\gamma$-rays following the $\beta$-decay of $^{224,226,228,230}$Fr have been investigated by
means of $\gamma$-ray singles (including multi-
spectrum analysis) and $\gamma\gamma$ coincidence
measurements using Ge(Li) spectrometers.
The study of the excited levels in
$^{224,226,228,230}$Ra was focused on the properties
of collective states. The analysis of the results leads one to the conclusion
that a ground-state octupole deformation is
the most likely explanation for the special
features of the collective excitations in Ra and some neighbouring nuclei in the
N=136 region.

1. Introduction

In the even isotopes of radium and thorium with neutron numbers from 134 to 138
the K,$\frac{3}{2}$=0,1$^-$ states occur at an unusually
low excitation energy. These states can be interpreted as rotational states of a per-
manently octupole deformed nucleus. This
has been discussed in previous studies$^1$ of the $\gamma$-rays following the $\beta$-decay of the
corresponding precursors. The moment-of-
inertia parameter $\Lambda$ ($h^2/2J$) should then be the same for the $K=0^+$ ground-state and
$K=0^-$ bands, but experimentally they are
found to be different. However, this
difference can be explained by assuming a
strong Coriolis interaction of the $K=0^+$
band with the experimentally unobserved
$K=1^-$ band. In the present study we have
undertaken a search for these $K=1^-$ bands in
$^{224,226}$Ra by investigating the $\beta^-$ decay
schemes of $^{224,226}$Pr. In order to extend
the evidence for the $K=0^+$ excitations, we have also undertaken a study of $^{222}$Pr$\rightarrow^{222}$Ra
decay and initiated a search for the
$^{232}$Pr$\rightarrow^{230}$Ra decay. Our study of the excited states of $^{224,226,228,230}$Ra was focused on the properties of collective states.

The analysis of the results obtained
leads one to the conclusion that the ground-
states of radium isotopes and some neigh-
bouring nuclei from the N=136 region possess a non-zero octupole deformation.

2. Experimental techniques

Sources of francium isotopes were pro-
duced in a spallation reaction of $^{238}$U
induced by 600 MeV protons from the CERN
Synchrocyclotron. The targets were of the
UC$_2$-graphite cloth type$^2$ and contained
about 20 g of uranium. The nuclides were
obtained as mass-separated ion beams from the
ISOLDE II on-line separator$^3$. A selected
beam was collimated in order to reduce con-
tamination from adjacent masses, and de-
lected onto a movable tape system, working
in a start-stop mode, to carry the activity
away from the collection point to the de-
tectors.

The $\gamma$-ray singles and coincidence
measurements were performed simultaneously with two Ge(Li) detectors of 32 and 74 cm$^3$
active volume and an energy resolution
(FWHM) of 1.8 and 2.1 keV at 1332 keV, re-
spectively. In addition, multispectrum
analysis experiments were performed in order
to determine the half-life of the stronger
$\gamma$-lines. Additional experimental details
have been described elsewhere$^4$.

3. Experimental results and
the individual decays

Most of the transitions observed in our investigations were placed in the indi-
vidual decay schemes based on the results of the coincidence experiments and on energy
fits. Since complete data on the decay of
$^{224,226}$Fr has recently been made avail-
able$^5$, only the construction of the $^{228}$Fr
decay scheme is presented here.

Total transition intensities were de-
termined from $\gamma$-ray intensities and the-
etical conversion coefficients$^6)$. The $\beta$-
branches resulted from intensity balances
based on the assumption that the ground-
state of $^{228}$Ra is not fed in $\beta$ decay of
$^{228}$Fr. The $\log f$ values were determined
using the half-life of 39±1 s, ref.$^7$), the
"$g$"-tables of ref.$^8$) and $Q_\beta$ value of
3480 ± 660 keV. This $Q_\beta$ value results from
the difference of the mass excess values of
$^{228}$Fr, ref.$^9$), and $^{230}$Ra, ref.$^{10}$).

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3.1. The $^{224}$Fr-$^{224}$Ra and $^{226}$Fr-$^{226}$Ra decays

The decay schemes of $^{224}$Fr, $^{226}$Fr were published elsewhere 5) and will be reviewed here only briefly. The interpretations of the low-energy levels in $^{223}$Ra and $^{225}$Ra nuclei are presented in figs. 1 and 2, respectively.

Besides the known ground-state K$^m$=O$^+$ band, the K$^m$=O$^-$ band and a second K$^m$=O$^+$ band, the K$^m$= 1$^+$ states have been identified in $^{223}$Ra and $^{225}$Ra at 1052.9 and 1048.6 keV, respectively.

Fig. 1 Collective excitations in $^{223}$Ra

Fig. 2 Collective excitations in $^{225}$Ra

3.2. The $^{228}$Fr-$^{228}$Ra decay

Most of the transitions observed in the $^{228}$Fr decay could be placed into a level scheme of $^{228}$Ra comprising 36 excited states. Of those only the first state ($I^m=2^+$) was known previously 11). Eleven of these states are grouped into the ground-state band, the K$^m$=O$^-$ band with its head at 474.1 keV and two excited K$^m$=O$^+$ bands with heads at 721.1 and 1041.9 keV. The partial decay scheme of $^{228}$Fr is shown in fig. 3. The complete data will be published elsewhere 12).

Fig. 3 Low-energy part of the decay scheme of $^{228}$Fr. Transitions which have been confirmed by the coincidence measurements are marked by dots; the other transitions have been placed on the basis of energy fits. The intensities of the transitions given in parentheses are absolute intensities.
3.3 The $^{230}$Fr,$^{230}$Ra decay

Based on results from the multispectrum analysis experiment, the $\gamma$-transitions of 57.4 ± 0.1, 129.0 ± 0.1, 192.4 ± 0.1 and 710.5 ± 0.5 keV have been assigned to mass 230. The time-decay curves of these $\gamma$-rays are shown in fig.4. The half-life of T$_{1/2}$ = 20 ± 1 s obtained for $^{230}$Fr in this way is somewhat shorter than the value of 30 s predicted by the gross theory of beta decay.[3]. The observation of the Ra KX-rays which confirms the $2^+$-assignment, and $\gamma$-lines at 129 and 192 keV in the coincidence spectra, enabled us to introduce new levels in $^{230}$Ra at 57.4, 186.4 and 378.8 keV. These are interpreted as the $2^+$, 4$^+$ and 6$^+$ levels, respectively.

According to this interpretation the moment-of-inertia parameter $A$ for the $K^+=0^+$ ground-state and $K^+=0^+$ bands should be the same, but this is remarkably different from what is experimentally observed. This difference can, however, be explained by a strong Coriolis interaction of the $K^+=0^+$ with the $K^+=1^+$ bands unobserved prior to the present study. The experimental results concerning $^{224}$Fr, $^{226}$Fr decays[4,5] provide the possibility for checking the above assumption.

![Fig.4 Decay curves for selected $\gamma$-rays of $^{230}$Fr.](image)

Fig.4 Decay curves for selected $\gamma$-rays of $^{230}$Fr.

4. Discussion

It is known (see fig.5) that the $K,J^2=0^+,1^-$ states in Ra, Th and U nuclei from the N=136 region occur at an unusually low-excitation energy. The new excited state in $^{226}$Ra at 474.1 keV extends this systematics. On the basis of the experimental results, a non-zero ground-state octupole deformation has been considered[1] to explain the special features of nuclei in this region.

![Fig.5 Excitation energies of known $K,J^2=0^+,1^-$ (solid lines) and $K,J^2=0^+,0^+$ (dashed lines) states in Ra, Th and U nuclei (data are from this work; see also ref.1)).](image)

Fig.5 Excitation energies of known $K,J^2=0^+,1^-$ (solid lines) and $K,J^2=0^+,0^+$ (dashed lines) states in Ra, Th and U nuclei (data are from this work; see also ref.1)).

If the $A$-parameter of 7.43 keV for the $K^+=0^+$ band (compared to 14.06 keV for the ground-state band) in $^{226}$Ra (fig.1) is due to Coriolis interaction with the $K^+=1^+$ band with its band head at 1052.9 keV, then the experimental coupling matrix element would have an absolute value of 77 [I (I+1)]$^{1/2}$ keV. By assuming that the energies of the $1^-$ levels of the $K^+=0^+$ and $K^+=1^+$ bands in $^{226}$Ra at 253.7 and 1048.6 keV (fig.2), respectively, are perturbed by this interaction, an experimental coupling matrix element of 67 [I (I+1)]$^{1/2}$ keV results. These values can be compared with the theoretical values$^{[4]}$ of $<H^2>=-69 [I (I+1)]^{1/2}$ keV for $^{224}$Ra and $<H^2>=-55 [I (I+1)]^{1/2}$ keV for $^{226}$Ra. The calculations were performed under the assumption that the $A$-parameters for two unperturbed octupole bands are both equal to that of the ground-state band. The experimental coupling matrix elements are in qualitative agreement with the theoretical values. As emphasized in ref.[1], this theoretical estimate is not expected to have a quantitative validity. These data favour the interpretation of the $K^+=0^+$ ground-state and $K^+=0^+$ bands in $^{224,226}$Ra as being connected with a non-zero ground-state octupole deformation.

In conclusion, a brief summary of the experimental results which support the concept of non-zero ground-state octupole deformation in Ra, Th and U nuclei in the N=136 region is presented.
(i) The energy splitting of of $K''=0^+$
ground-state and $K''=0^-$ bands is small
(the ammonia molecule can be used as
simple model).

(ii) The rotational states in the $K''=0^+$
ground-state and $K''=0^-$ bands can be
described by the same moment-of-inert-
tia parameter $A$.

(iii) The energy ratios of the excited $0^+$
and $0^-$ states are much higher than
2.0 expected for harmonic two-phonon
octupole vibrational states and even
higher than the value of 2.7 for an
infinite square-well potential.

In addition, it is probable that the very
low HF (hindrance factor) of the $\alpha$-
transitions feeding the $K'',J''=0,1^{-}$ states\footnote{1)}
are connected with this interpretation.

Recently, a stable octupole deformation
has been obtained for nuclei in the Ra
and Th region in theoretical calcula-
tions\footnote{15)}.

References

1) W. Kurcewicz, E. Ruchowska, J. Żylicz,
N. Kaffrell and N. Trautmann,
Nucl. Phys. A304 (1978) 77, and
references quoted therein

2) L. C. Carraz, S. Sundell, H. L. Ravn,
M. Skarestad and L. Westgaard,
Nucl. Instr. 158 (1979) 69

3) H. L. Ravn, L. C. Carraz, J. Denimal,
E. Kugler, M. Skarestad, S. Sundell
and L. Westgaard,
Nucl. Instr. 139 (1976) 267

4) W. Kurcewicz, E. Ruchowska,
N. Kaffrell, T. Björnstad and G. Nyman,
IKMZ-Report 80-1, Institute of Nuclear
Chemistry, University of Mainz (1980)

5) W. Kurcewicz, E. Ruchowska,
N. Kaffrell, T. Björnstad and G. Nyman,

6) F. Rösel, H. M. Fries, K. Alder and
H. C. Pauli,
Atomic Data and Nucl. Data Tables 21
(1978) 291

7) H. L. Ravn, S. Sundell, L. Westgaard
and E. Roeckl,

8) B. S. Dzhelepov, L. N. Zyryanova and
Yu. P. Suslov,
Beta processes (Science Press, USSR,
1972)

9) M. Ephèrre, G. Audi, C. Thibault,
R. Klapisch, G. Huber, P. Touchard
and H. Wollnik,

10) A. H. Wapstra and K. Bos,
Atomic Data and Nucl. Data Tables 19
(1977) 177

11) Table of Isotopes, 7th edition, eds.
C. M. Lederer and V. S. Shirley
(Wiley, N. Y., 1978)

12) E. Ruchowska W. Kurcewicz,
N. Kaffrell, T. Björnstad and G. Nyman,
to be published

13) K. Takahashi, M. Yamada and T. Kandoh,
Atomic Data and Nucl. Data Tables 12
(1973) 101

14) A. Bohr and B. R. Mottelson,
Nuclear structure, vol. II
(Benjamin, Massachusetts, 1975)

15) A. Gujarov, B. Nerlo-Pomorska and K. Pomorski,
Contribution to this Conference,
Section-heavy and very heavy elements
PIONIC PROBES FOR EXOTIC NUCLEI

Kamal K. Seth
Northwestern University, Evanston, IL 60201, USA.

Abstract

With the advent of meson factories such as LAMPF, powerful new tools have been added to the list of those used in the study of exotic nuclei far from the valley of stability. These new tools are reactions involving pions in the incident and/or outgoing channels. The most useful, and so far the most used of these reactions are the pion double charge exchange reactions, both \((\pi^+, \pi^-)\) and \((\pi^-, \pi^+)\). The \((\pi^+, \pi^-)\) reaction has been successfully used to study \(T_z=3\) nucl. \(\Delta I=1\) such as \(^{18}\)C and \(^{26}\)Ne, and the \((\pi^-, \pi^+)\) reaction has been used to study \(T_z=2\) nuclei such as \(^{12}\)O, \(^{16}\)Ne, \(^{24}\)Si and \(^{32}\)Ar, and \(T_z=1\) such as \(^{36}\)Zn. Perhaps the most exciting aspect of these reactions lies in the fact that they can be used to study excited states of exotic nuclei and nuclei which are slightly unbound. An example of the latter is provided by the recent identification and mass measurement of \(^{6}\)He. Even more exotic systems such as \(^{14}\)H and \(^{15}\)H, which are of great astrophysical interest, are the subjects of current investigations. Recently the \((\pi^+, p)\) reaction has been used to identify and study \(^{6}\)He and \(^{15}\)H.

I. Introduction

Almost immediately after the discovery of nuclear analog states\(^1\), in \((p, n)\) single charge exchange reactions, Drell, Lipkin and de Shalit\(^2\) speculated on the possibility of double charge exchange (DCE) via \((\pi^+, \pi^-)\) reactions. Ericson\(^3\) immediately recognized the potential of pion DCE reactions, particularly \((\pi^+, \pi^-)\) in reaching exotic nuclei and studying their properties. Gilly\(^4\) at CERN actually tried to look for the exotic nuclei, \(^{11}\)n, \(^{11}\)H, \(^{11}\)Be, and \(^{10}\)B by means of \((\pi^+, \pi^-)\) DCE reactions as early as 1965. His efforts were unsuccessful, primarily due to the very poor intensity (and resolution) pion beams available to him. Only with the ushering of the era of "industrial revolution" in pion physics and the construction of "pion factories" did Ericson's dream become practical. If we define a figure of merit for DCE experiments as \(M=\text{Flux}/(\text{energy resolution})\) one can see how large an improvement had to take place. For the EPICS channel at LAMPF today, \(M=[2 \times 10^7 \text{p}^{-1}/\text{sec}] / 0.2 \text{MeV} = 10^9 \text{p}^{-1} / (\text{sec MeV})\), whereas at CERN in 1965, Gilly had to flight with \(M=[2 \times 10^5 \text{p}^{-1}/\text{sec}] / 15 \text{MeV} = 10^7 \text{p}^{-1} / (\text{sec MeV})\). It is amazing what a factor 10\(^7\) advantage can do!

In my talk today I will mainly describe the studies of exotic nuclei by pion double charge exchange. True to my announced topic I will also describe some of the very recent attempts we have made to use the \((\pi^+, p)\) reactions for studying exotic nuclei. All the \((\pi^+, p)\) reactions and experiments I will talk about were done at the EPICS channel at LAMPF. The main bulk of the data is from the Northwestern University group\(^5\).

Historically the first mass measurement by a DCE reaction was done at the LEP channel at LAMPF by Burman et al.\(^6\). The measurement was by-product of a reaction study on \(^{16}\)O and yielded a rather crude measurement of the mass excess for \(^{16}\)Ne(\(\Delta\)M=24.4+ 0.5 MeV). All subsequent measurements have been made at the EPICS channel, which we describe below.

II. THE EPICS FACILITY AT LAMPF

The Energetic Pion Channel and Spectrometer facility (Fig. 1) at LAMPF consists of a four-dipole channel which provides a vertically momentum dispersed (-4cm horizontal x 20 cm vertical) beam at an extended target at the center of a vacuum scattering chamber. The outgoing particles are analyzed by a QQD00 magnetic spectrometer. The three quadrupole (QQD0) produce a 1:1 image of the target on a set of four pairs of position sensitive drift chambers (FI-F4) at the entrance of the spectrometer dipoles (D5-D6). Four position sensitive multiwire proportional counters (R1-R4) at the focal plane of the spectrometer detect the analyzed particles. The \(x, y, \theta, \phi\) information at the entrance and the exit of the spectrometer allows soft-ware trajectory reconstruction and thus enables one to obtain energy loss spectra on-line. Particle identification is done by time of flight between a thin scintillation detector (SI) at the entrance of the spectrometer dipoles and the trigger scintillation counters \(S_2\) and \(S_3\) at the "focal plane". Additional electron rejection is done by a Freon-gas threshold Cerenkov counter (C).

\(\text{(Fig. 1. Schematic of the experimental setup.)}\)

Fig. 2 illustrates a typical particle identification spectrum. We note that it is this extremely clean particle identification which is responsible for most background-less spectra observed in our experiments.

One of the major shortcomings of the usual experimental arrangement at EPICS is the fact that the incident particle and elastic scattering flux incident on the front chambers \((\text{FI-F4})\) make it impossible to go to very forward angles. Since most DCE reactions tend to be forward peaked, this limitation was found to be very costly in beam time. After the first few DCE experiments at EPICS, the modification shown in Fig. 1 was installed. It essentially consists of a vertical C-magnet across the scattering chamber. This deflects the primary particles \((\pi^+, \pi^-)\) for example) away from the front chambers while the oppositely charged particles \((\pi^+, \pi^-)\) of interest head towards the chambers and the spectrometer dipoles. With this magnet it has been possible to take excellent data at small as small as \(\theta^\circ\).

*) Research supported in part by the U.S. Department of Energy
Before discussing some examples of our measurements, let me give you a statement of my own feelings about the role of pion induced reactions in the pursuit of nuclei far from stability. Because of the limitations which I have described above, pion induced reactions can never be used for "mass-production" of such nuclei, as is possible with several other techniques discussed at this conference. These reactions must be used only in particularly difficult cases. Our own approach has been just this. We have used these reactions only when more standard techniques have failed. For future measurements, for example, we cannot readily think of other techniques for measuring masses of $^{14}$Be and $^{40}$Ti. Even then it is becoming increasingly difficult to convince reluctant PAC's to approve the long beam times needed for these measurements. Patiently, we try and try again!

III. Some Experimental Results

T$_e$=3 Nuclei

a) $^{18}$C: Our interest in masses of exotic nuclei started with $T_e$=3 nucleus, $^{18}$C. Since earlier attempts to measure the mass of this particle-stable nucleus by means of heavy-ion DCX reactions had been unsuccessful, we attempted to populate it in the reaction $^{16}$O($^\pi$, $^\pi$)$^{18}$C. The attempt was quite successful (see Fig. 3). Using the reaction

$$^{180}(\pi^-,\pi^+)C$$

$^{12}$C($^\pi$, $^\pi$)$^{13}$B, whose Q-value is known accurately we obtain the mass excess for $^{18}$C as 24.91 ± 0.15 MeV. The errors could be easily improved to the ±0.5 keV level if the experiment were repeated today. What would be even more interesting is to determine if the 2$^+$ excited state which lies at ±2 MeV as the data suggest and as Khadikar and Kame$^{10}$ predict in their Hartree-Fock calculations of this nucleus. An experiment designed to study the excited state spectrum of $^{18}$C is currently on the approved list at LAMPF."

Fig. 3. Spectrum for the reaction $^{180}(\pi^-,\pi^+)C$

$^{12}$C($^\pi$, $^\pi$)$^{13}$B, whose Q-value is known accurately we obtain the mass excess for $^{18}$C as 24.91 ± 0.15 MeV. The errors could be easily improved to the ±0.5 keV level if the experiment were repeated today. What would be even more interesting is to determine if the 2$^+$ excited state which lies at ±2 MeV as the data suggest and as Khadikar and Kame$^{10}$ predict in their Hartree-Fock calculations of this nucleus. An experiment designed to study the excited state spectrum of $^{18}$C is currently on the approved list at LAMPF."

b) $^{26}$Ne: This stable nucleus was studied for the same experimental reasons as $^{18}$C. However, our own experimental technique had considerably improved since the $^{18}$C experiment. The beam sweep magnet, shown in Fig. 1 had been installed and it had become possible to make the measurement at $\theta = 5^\circ$. We measured the mass of $^{26}$Ne via the reaction $^{24}$Mg($^\pi$, $^\pi$)$^{26}$Ne and used the $^{12}$C($^\pi$, $^\pi$)$^{14}$Be reaction once again as calibration. The $^{26}$Ne spectrum is show in Fig. 4. The energy resolution realized in this measurement was about 250 keV and the mass excess for $^{26}$Ne was determined as 0.44 ± 0.07 MeV."

An interesting feature of the spectrum in Fig. 4 is the presence of a relatively strong excited state at ±3.75 MeV. Since $\theta = 5^\circ$ one does not expect appreciable excitation of any states
other than those with \( L = 0 \) angular distributions, this state is assigned \( \Omega^u = 0^+ \).

\(^{26}\text{Ne}\) has \( Z = 10, N = 16 \). Both these nucleon numbers are expected to become magic for 2:1 strong deformations\(^{13}\) (see Fig. 5), and one may conjecture\(^{14}\) about the extent to which strong competition between spherical and deformed \( 0^+ \) states may exist in such a nucleus\(^{14}\).

c) \(^{14}\text{Be}\): This, lightest of the known, stable \( \tau = 3 \) nuclei, can be studied by DCX reactions. Detraz\(^{15}\) has attempted to study the \(^{40}\text{Ca}(^{14}\text{C}, ^{14}\text{Be})^{40}\text{Ti}\) reaction, but had no success in identifying \(^{14}\text{Be}\). This appears to be at least partly due to the very negative \( Q(\approx -33\text{MeV}) \) for this reaction. We have proposed\(^{16}\) to measure the mass of \(^{14}\text{Be}\) by means of the reaction \(^{12}\text{C}(\pi^-, \pi^+)^{14}\text{Be}\). Unfortunately we have not yet succeeded in convincing the LAMPF PAC that this is an important measurement. We propose to try again.

\[ T = 5/2 \text{ Nuclei} \]

\(^{9}\text{He}\): The odd-isotopes \(^{5}\text{He}\) and \(^{7}\text{He}\), though particle unstable, turn out to be far less unbound than was suggested on the basis of the masses of adjoining even isotopes of helium. Their widths are also small. For \(^{5}\text{He} \text{ (g.s.)} \) \( r = 0.6 \text{ MeV} \), for \(^{7}\text{He} \text{ (g.s.)} \) \( r = 0.16 \text{ MeV} \). Therefore, although the systematics of adjoining masses suggested that \(^{9}\text{He}\) might be unbound by 2.5 to 3.8 \text{ MeV}, we conjectured that it might also turn out to be more bound and therefore have an identifiable width. Accordingly, we studied the reaction \(^{9}\text{Be}(\pi^-, \pi^+)^{9}\text{He}\). The resulting spectrum is shown in Fig. 6 along with the 3-body phase space for the break-up into \(^{6}\text{He} + n\). The peak corresponding to \(^{9}\text{He} \text{ (g.s.)} \) is clearly identifiable at the end of the phase space. The width of this peak is \( = 1 \text{ MeV} \), which is equal to our experimental energy resolution. The mass excess we obtain is \( 40.81 \pm 0.12 \text{ MeV} \) which corresponds to being unbound for single neutron emission by \( 1.14 \pm 0.12 \text{ MeV} \). This is 2.4 \text{ MeV} more bound than obtained from a local application of the transverse Garvey-Kelson relation, using the experimental mass of \(^{6}\text{He}\). We note that the experimental mass of \(^{9}\text{He}\) is also smaller by 1.85 \text{ MeV} than its Garvey-Kelson prediction, using the same \(^{6}\text{He}\) mass. In other words, \(^{8}\text{He}\) appears to be about 2 \text{ MeV} less bound than it would have to be in order to be consistent with \(^{7}\text{He}\) and \(^{6}\text{He}\).
$^7$H: From time to time there has been speculation about the possible existence of $^7$H. Since it has the same neutron structure as particle-stable $^9$He (1s 1/2, 1p 3/2 completely full), and has one less proton, one wonders whether it comes close enough to stability to be identifiable. For this purpose we have studied the reaction $^7$Li ($^-$, $^-\pi$)$^9$He. The resulting spectrum is shown in Fig. 7. It is clear

![Graph showing the reaction $^7$Li ($^-$, $^-\pi$)$^9$He](image)

Fig. 7. Spectrum for the reaction $^7$Li ($^-$, $^-\pi$)$^9$He.

that all we see is phase space. There is no identifiable bump anywhere, and we put the upper limit of <3 nb/sr for the production cross section if $^7$H is not unbound by more than 5 MeV with respect to the break-up channel $^3$H + n + n + n + n. This upper limit for the production cross section is a factor 30 lower than the one established recently by Evseev et al. in a recent experiment done at SIN.

The interesting feature of the continuum spectrum in Fig. 7 is that it does not at all fit with phase space predictions for the break-up channels, $^3$H + n + n + n + n (not shown, much steeper rising than any shown), $^4$H + n + n + n, or $^6$H + n. On the other hand, it is in remarkable agreement with the phase space results for $^4$H + n + n breakup. While this doesn't permit one to claim that $^7$H exists, it does suggest that the possible stability of $^7$H should be seriously examined. Indeed, it was precisely this motivation which prompted us to look for reactions in which $^7$H could occur as part of two-body final state. Such a reaction is $^6$Li ($^-$, $^-\pi$)$^9$H. With a little help from Prof. Bethe, we were given the opportunity to study it. In the following we present the results from this experiment.

($^-\pi$, $^p$) Reactions

It is not clear at this point as to what extent the ($^-\pi$, $^p$) reaction can be considered as a one-step direct reaction. Since the nuclear charge in this reaction changes by two units, at least two nucleons in the nucleus need to be involved. In a simple picture the incident $^-$ would be absorbed on a nucleon pair, for example, a n-p pair, and change it into a p-p pair. The large amount of energy-momentum transfer would be accomodated by ejecting one of the protons while the other sits on the high momentum tail of the wave function of a nuclear state. This kind of a reaction mechanism would automatically lead to very small cross sections. Small cross sections are therefore the rule for transitions to discrete nuclear states in nuclei near stability in ($^-\pi$, $^p$) reactions (or their time-reversed ($^p$, $^-\pi$) reactions), and it is not at all obvious if ($^-\pi$, $^p$) reactions leading to discrete states in exotic nuclei would have any measurable cross sections. To examine this serious experimental question we first studied the reaction $^9$Be ($^-\pi$, $^p$)$^{10}$He.

The experimental spectrum for $^9$Be ($^-\pi$, $^p$)$^{10}$He is shown in Fig. 8. The $^9$Be(g.s.) is clearly seen at the expected energy (200 keV). The cross section, $\sigma(20^\circ) = 43 / 7$ nb/sr is not too small either. It appears that the ($^-\pi$, $^p$) reaction has no great difficulty in reaching exotic nuclei. This gives us the hope that if $^7$H exists we should have a good chance of seeing it in $^6$Li ($^-\pi$, $^p$)$^9$H reaction.

![Graph showing the reaction $^9$Be ($^-\pi$, $^p$)$^{10}$He](image)

Fig. 8. Spectrum for the reaction $^9$Be ($^-\pi$, $^p$)$^{10}$He at $T(\pi^-) = 125$ MeV, $\theta = 20^\circ$.
Before passing on to $^5$H we wish to make an observation concerning the phase space observed in the $^3$Be($\pi^-,\pi$)$^3$He reaction. We find that the observed continuum cannot be fitted with any combination of multi-body phase space which involve only particle-stable helium nuclei like $^6$He, $^4$He or $^3$He. What is absolutely needed in order to explain the bump in the 5-10 MeV excitation energy region is a contribution which can only be provided by the break-up channel, $^4$He + n. This means that even though $^4$He is particle unstable, its nearly bound nature enables it to make an explicit contribution to the phase space.

$^5$H: The experimental data and its theoretical interpretation bearing on the possible existence of $^5$H up to 1965 is well reviewed in two articles, the first by Baz, Goldanskii and Zeldovich$^{21}$ and the other by Argan et al.$^{22}$). These reviews concluded that in all likelihood particle-stable $^5$H does not exist. All attempts to search for the $\beta$-activity of $^5$H were uniformly unsuccessful.$^{21}$ Several low energy experiments in which particle-unstable $^5$H could be detected, were subsequently attempted. However these suffered from severe limitations. For example, a study of the $^5$H($\pi$,p) reaction, for which the threshold triton energy is ~1 MeV could only be done with a 22.25 MeV triton beam.$^{22}$ It showed an enhancement indicating a $^5$H(g.s.) unbound against decay into $^3$H + n + n by only 1.8 MeV. A search for the mirror nucleus $^3$Be using the $^3$He($^3$Be,n)$^3$He reaction$^{20}$ led to the conclusion that $^5$H is unbound by at least 2 MeV. A direct, but much more difficult search by means of the reaction $^6$Be($\alpha$,p)$^6$Li$^{2+}$ to no clear evidence for a narrow state corresponding to $^5$H. Two studies of the very promising reactions

$$\pi^- + ^3\text{Li} \rightarrow ^5\text{H} + d$$

and,

$$\pi^- + ^6\text{Li} \rightarrow ^5\text{H} + p$$

were attempted with stopping pions.$^{25,26}$ These experiments were done under rather primitive conditions with ~$10^4$ pions/sec beams and range spectrometers of extremely limited capabilities and led to very non-conclusive results. After a very critical study of all the experimental literature, we reached the conclusion that no definitive experiment exists in the published literature to date which can rule out a $^5$H ground state which is unbound by one or two MeV only and which therefore may have an identifiable width of ~1 MeV or so.

In view of the above history of experiments on $^5$H and our very provocative result from the $^7$Li($\pi^-,\pi^+$) experiment indicating the existence of at least a very strong final state interaction in the ($lp + 4n$) system, we did our present study of the

$$\pi^- + ^6\text{Li} \rightarrow ^5\text{H} + p$$

reaction.

The results of our experiment are shown in Fig. 9. This very high statistics experiment (1 count ~ 0.2 mb/sr) gives us a smooth, featureless spectrum in which no enhancements of widths ~5 MeV can be discerned anywhere. One can only hope to deduce what one can from a very careful analysis of the phase space. In Fig. 9 we show a plot of the phase space corresponding to the 4-body final state, $p + ^3\text{H} + n + n$. Over a 30 MeV missing mass region, from ~25 MeV to 55 MeV this phase space fits the data excellently (within ~3%). However, it shows large deviations from the data in the 0-20 MeV region. These deviations are at least as large as a factor two at ~10 MeV. This is better seen perhaps in Fig. 10, in which the vertical scale is linear. If

![Fig. 9. Missing mass spectrum for the $^6$Li($\pi^+,p$)$^5$H reaction at $\theta = 20^\circ$.](image)

![Fig. 10. Missing mass spectrum for the $^6$Li($\pi^+,p$)$^5$H reaction at $\theta = 20^\circ$.](image)
the 4-body phase space is subtracted from the data we get a residual peaked structure centered around 11 MeV as shown in both figures 9 and 10. This structure has a centroid at \( 11 \pm 1.5 \) MeV and a half width of \( \approx 14 \) MeV. Without a detailed theory for this reaction all we can say is that if this structure is \(^5\)H it is unbound by \( \approx 11 \) MeV instead of \( \approx 2.7 \) MeV as suggested by systematics.

We can also state with confidence that we find no evidence for a 2 or 3 MeV unbound state. If it exists its cross section must be well under 10 nb/sr.

\[ T_2 = -2 \text{ Nuclei} \]

The main interest in these nuclei lies in completing isospin quintets and in determining how well the IMME formula with no cubic terms works. The nuclei \(^{12}\)C, \(^{12}\)O, \(^{16}\)Ne, \(^{20}\)Mg, \(^{24}\)Si and \(^{56}\)Ca have been previously studied by means of \(^{16}\)O, \(^{9}\)Be reactions by Tribble et al.\(^{17,20,23,21}\) and Rokelis et al.\(^{25}\). All \( T_2 = -2 \) nuclei up through \(^{40}\)Ti can also be reached very conveniently by \( (\pi^+,\pi^-)_{DCX} \) reactions on self conjugate targets. Burleson et al.\(^{22}\) at LAMPF have indeed measured several of these. The results, which are summarized in Table 1, agree with those of refs. 27-31. No significant deviations from the quadratic IMME have been found\(^{22,33}\).

### Table 1. Summary of Results for Pion Induced Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( T_2 )</th>
<th>Mass Excess (MeV)</th>
<th>( T(\pi^-) ) (MeV)</th>
<th>Production ((\pi^+)) nb/sr</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^7)Li((\pi^+,\pi^-))(^7)H</td>
<td>5/2</td>
<td>no evidence</td>
<td>192</td>
<td>(15) ( \pm 3 )</td>
<td>39</td>
</tr>
<tr>
<td>(^9)Be((\pi^+,\pi^-))(^9)Be</td>
<td>5/2</td>
<td>40.81(12)</td>
<td>192</td>
<td>(15) ( \pm 10 )</td>
<td>39</td>
</tr>
<tr>
<td>(^{14})C((\pi^+,\pi^-))(^{14})Be</td>
<td>3</td>
<td>324.91(15)</td>
<td>162</td>
<td>(11) ( \pm 10 )</td>
<td>9</td>
</tr>
<tr>
<td>(^{18})O((\pi^+,\pi^-))(^{18})C</td>
<td>3</td>
<td>0.44(7)</td>
<td>162</td>
<td>(6) ( \pm 10 )</td>
<td>12</td>
</tr>
<tr>
<td>(^{26})Mg((\pi^+,\pi^-))(^{26})He</td>
<td>3</td>
<td>27.80(10)</td>
<td>180</td>
<td>(5) ( \pm 50 )</td>
<td>39</td>
</tr>
<tr>
<td>(^{12})C((\pi^+,\pi^-))(^{12})O</td>
<td>2</td>
<td>32.56(5)</td>
<td>180</td>
<td>(5) ( \pm 50 )</td>
<td>32</td>
</tr>
<tr>
<td>(^{16})O((\pi^+,\pi^-))(^{16})Ne</td>
<td>2</td>
<td>24.05(5)</td>
<td>180</td>
<td>(5) ( \pm 50 )</td>
<td>32</td>
</tr>
<tr>
<td>(^{24})Mg((\pi^+,\pi^-))(^{24})Si</td>
<td>2</td>
<td>10.88(5)</td>
<td>180</td>
<td>(5) ( \pm 50 )</td>
<td>32</td>
</tr>
<tr>
<td>(^{28})Si((\pi^+,\pi^-))(^{28})S</td>
<td>2</td>
<td>-2.18(5)</td>
<td>180</td>
<td>(5) ( \pm 50 )</td>
<td>32</td>
</tr>
<tr>
<td>(^{40})Ca((\pi^+,\pi^-))(^{40})Ti</td>
<td>2</td>
<td>-4.32(10)</td>
<td>291</td>
<td>(5) ( \pm 10 )</td>
<td>39</td>
</tr>
<tr>
<td>(^{9})Be((\pi^+,\pi^-))(^9)Be</td>
<td>2</td>
<td>31.60(10)</td>
<td>125</td>
<td>(20) ( \pm 10 )</td>
<td>39</td>
</tr>
<tr>
<td>(^{6})Li((\pi^+,\pi^-))(^6)He</td>
<td>3/2</td>
<td>44.5(15)</td>
<td>125</td>
<td>(20) ( \pm 10 )</td>
<td>39</td>
</tr>
</tbody>
</table>

The level of accuracy obtainable presently in the determination of masses by pion DDX experiments is about \( \pm 50 \) keV. At this level it does not seem too profitable to push the study of the masses of \( T_2 = -2 \) nuclei by DDX experiments any further. Of the only two missing nuclei in this series, \(^{28}\)S can be reached by \(^{16}\)O, \(^{9}\)Be reactions, whereas \(^{40}\)Ca can not. We have therefore proposed\(^{31}\) the measurement of this mass by the \( ^{40}\)Ca(\(\pi^+,\pi^-\))\(^{40}\)Ti reaction, but have so far not received approval to proceed.

Unbound \(^7\)B

Our interest in \(^7\)B was aroused by Guy Pać who has been studying the shift in the apparent position of peaks when they are unbound and have finite widths and when they ride on large phase space continua.\(^{35}\) The mass of \(^7\)B had been measured earlier by McGrath, Cerny and Norbeck\(^{36}\) by means of the reaction \(^{16}\)O(\(^9\)He, \(^{4}\)He)\(^7\)B at \( T(\pi^-) = 50 \) MeV. They had measured a mass excess of \( 27.94 \pm 0.10 \) MeV and a width \( \Gamma = 1.4 \pm 0.2 \) MeV. The measurement had one major weakness. The outgoing \(^{6}\)He spectrum could only be followed about 4 MeV into the continuum, and this made it quite difficult to understand the phase space continuum and to untangle its effects. A 7% impurity of \(^{13}\)C in the target also added to the problems. Their analyzed spectrum is shown in Fig. 11. The authors concluded that there was no evidence for a \(^{6}\)He + p break-up and used a 4-body phase-space, corresponding to \(^{9}\)Li + p + p break-up, to analyze their data.

We have studied the reaction \(^7\)Li(\(\pi^+,\pi^-\))\(^7\)B at \( T(\pi^-) = 180 \) MeV and \( \theta = 5^\circ\). The resulting \( \pi^- \) spectrum is shown in Fig. 12. The \(^{40}\)Ca(\(\pi^+,\pi^-\))\(^{40}\)Ti reaction, which has a Q-value within 500 keV of that for the \(^7\)Li(\(\pi^+,\pi^-\))\(^7\)B reaction, was used for calibration. The broad peak corresponding to \(^7\)B(g.s.) transition is clearly visible in Fig. 12 and the continuum can be followed for at least 15 MeV before the spectrometer acceptance begins to cut it down. Unfortunately, in spite of our much better delineation of the phase space, we find ourselves no better off in understanding it. We can clearly rule out a 5-body phase space corresponding to \(^{9}\)He + 3p break-up since it would rise much too fast, but we are unable to fit the observed continuum with any combination of 3-body and 4-body phase space either. In fig. 13 we show the results of our efforts to fit the data with allowed, pure phase space contri-
Fig. 12. Missing mass spectrum for the reaction $^7\text{Li}(\pi^+,\pi^-)^7\text{B}$.

\[ T(\pi^-) = 180 \text{ MeV} \]
\[ \theta = 5^\circ \]

Fig. 13. Missing mass spectrum and phase space curves for the $^7\text{Li}(\pi^+,\pi^-)$ reaction.

\[ T(\pi^-) = 180 \text{ MeV} \]
\[ \theta = 5^\circ \]

It is obvious that things do not work, particularly near the threshold for $^6\text{Be} + p$ break-up. Evidently, the particle instability of both $^6\text{Be}$ and $^5\text{Li}$ leads to phase space which is substantially different from that calculated by assuming as though they were stable. Since a proper calculation of this pseudo-phase space seems to be impossible for the present, and since the shape of our continuum is quite well defined, we have made the most plausible shape reconstruction under the peak as shown in Fig. 12 and analyzed the residual structure remaining after the subtraction of this phase space 'background'. The structure has a clear peak corresponding to $^7\text{B}$ (g.s.). We obtain the mass excess for it as 27.80±0.10 MeV and the width $\Gamma = 1.2$ ±0.2 MeV. These results are fully consistent with those of McFarth et al.\(^{39}\) Our data indicates the presence of a narrower structure at an excitation of ~1.5 MeV. However the statistics are poor and the 'background' construction is somewhat arbitrary. We cannot therefore claim the existence of an excited state with any confidence.

It is worth pointing out that the mass excess predicted for $^7\text{B}$ using the $M(T_2) = a + bT_2 + cT_3^2$ form of the isobaric mass multiplet equation and the masses of the $J = 3/2^-$, $T = 3/2$ states in $^7\text{Be}$, $^7\text{Li}$ and $^7\text{He}$ is 27.99±0.08 MeV.\(^{37}\) This barely overlaps with our result. The conclusion that the coefficient, d of the $T_3^2$ term is zero is therefore only marginally consistent with our data.
$^{58}\text{Zn}$: The masses of all zinc isotopes down to $^{48}\text{Zn}$ are known. $^{57}\text{Zn}$ is known to be a $\beta$-delayed proton emitter and its mass has been inferred indirectly by measurements of $\beta$-end point energies. However, no convenient means have yet been found to measure the mass of $^{57}\text{Zn}$. We have measured this mass now by $^{54}\text{Ni}(\pi^+,\pi^-)^{58}\text{Zn}$ reaction. Since DCX analog cross sections have minima at $T(\pi^+) = 160$-200 MeV, and rise again at higher energies, we chose $T(\pi^-) = 291$ MeV for our experiment. Even then a target of 0.97 gm/cm$^2$ had to be used in order to obtain the spectrum shown in Fig. 14. A mass excess of $-42.32\pm 0.10$ MeV was obtained. This result is to be compared with the predictions listed in Table II. It is in quite reasonable agreement with predictions based on the transverse Garvey-Kelson relation.

IV. CONCLUSIONS, PROSPECTS FOR FUTURE

In 1970 when we wrote our first proposal for pion-induced double charge exchange at LAMPF, we made the foolish statement in it that DCX was not possible with conventional nuclear projectiles, but we did go on to state in a wiser footnote that the above statement was true only as long as heavy-ions were not yet considered conventional. In the meantime, as we all know, heavy-ions have become quite conventional and DCX reactions with $^{18}\text{O}$, $^{15}\text{C}$, and even $^{48}\text{Ti}$ beams have been tried. Unfortunately however, these heavy-ion induced DCX experiments continue to suffer from low cross sections and large backgrounds, and have not been successful in reaching exotic nuclei with large negative $Q$-values. Thus, at the present, pion-induced DCX reactions appear to be the only viable ones for these studies. Not only can they be used to determine ground-state masses rather accurately ($\pm 25$ keV appears to be possible with some hard work), but excited states and sometimes their $J^*$ can be quite directly determined. Similarly, the $(\pi^+,\pi^-)$ reaction, whose analog would be a reaction of the type $(n,p)$, appears to be the only possible one of its type presently. $(\pi^+,\text{He})$, and even more exotic reactions are clearly on the horizon.

In my talk I have tried to show that pion-in-

![Fig. 14. Missing mass spectrum for $^{58}\text{Ni}(\pi^+,\pi^-)^{58}\text{Zn}$ reaction.](image)

**TABLE II. SUMMARY OF EXPERIMENTAL RESULTS WITH PREDICTIONS**

<table>
<thead>
<tr>
<th>NUCLEUS</th>
<th>EXPERIMENT</th>
<th>MASS EXCESS (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{6}\text{He}$</td>
<td>M, GHT, LZ, BLM</td>
<td>44.5(15)</td>
</tr>
<tr>
<td>$^{7}\text{He}$</td>
<td>M, GHT, LZ, BLM</td>
<td>40.81(12)</td>
</tr>
<tr>
<td>$^{14}\text{Be}$</td>
<td>M, GHT, LZ, BLM</td>
<td>41.72**</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>M, GHT, LZ, BLM</td>
<td>24.91(15)</td>
</tr>
<tr>
<td>$^{18}\text{O}$</td>
<td>M, GHT, LZ, BLM</td>
<td>0.44(7)</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>M, GHT, LZ, BLM</td>
<td>27.80(10)</td>
</tr>
<tr>
<td>$^{22}\text{Ne}$</td>
<td>M, GHT, LZ, BLM</td>
<td>32.06(5)</td>
</tr>
<tr>
<td>$^{24}\text{Ne}$</td>
<td>M, GHT, LZ, BLM</td>
<td>24.05(5)</td>
</tr>
<tr>
<td>$^{25}\text{O}$</td>
<td>M, GHT, LZ, BLM</td>
<td>10.65(8)</td>
</tr>
<tr>
<td>$^{28}\text{Si}$</td>
<td>M, GHT, LZ, BLM</td>
<td>0.09</td>
</tr>
<tr>
<td>$^{32}\text{Ar}$</td>
<td>M, GHT, LZ, BLM</td>
<td>-2.18(5)</td>
</tr>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>M, GHT, LZ, BLM</td>
<td>-12.65</td>
</tr>
<tr>
<td>$^{50}\text{Zn}$</td>
<td>M, GHT, LZ, BLM</td>
<td>-42.32(8)</td>
</tr>
</tbody>
</table>

sult is often twenty counts and one final number. It is therefore prudent to use these techniques sparingly, to study only those specially exotic nuclei which can be reached or have not been successfully reached by any other techniques. For such special cases we will just have to try harder, and again and again if necessary, to communicate the excitement of this fascinating field to the larger community of nuclear physicists, of which the PAC's are a part.

REFERENCES

2. S.D. Dreil, H. Lipkin, and A. de Shalit, as quoted in ref. 2 below.
18. We are very thank ful to Prof. M.M. Block for calculation of relativistically invariant phase space for multi-body break-ups.
39. Kamal K. Seth, et. al., to be published.

DISCUSSION

K. Blower: Can you see in your experiments the width of the A-resonance state which might change for nucleons within nuclear matters?

K.K. Seth: Pion DCX would be a very expensive way of looking for the modification of the free A in nuclear matter. We see it only indirectly in our excitation curves for analogous DCX where a broad minimum is seen at the (3,3) position. Much better delineation of the (3,3) resonance in nuclear matter has been done in measurements of pion total cross sections on nuclei.

M. Berken: The (3C, 14O) double-charge exchange reaction has cross section one to two orders of magnitude larger than the (π, π') ones. But their measurements were performed on target nuclei lying in the stability valley: Do you have an idea of the dependence of (π, π') cross section with the Q when one is going on the side of the valley?

K.K. Seth: I am not an expert on (3C, 14O). I have however talked to the experts both at Los Alamos (Peng et al.) and Orsay (Détraz et al.) and they tell me that these cross sections fall precipitously with increasing negative Q. For a reaction like that to 1Be, the Q is almost ~40 MeV. I am told that there is very little hope at the presently available 1C energies to make such excision off the stability valley. You can not draw any conclusions from the Q=3 to 5 MeV experiments done so far at Los Alamos. We of course have enough energy in our (π, π') experiments so that a ~40 MeV Q value is no problem. The cross sections show no noticeable decrease.

C. Détraz: As reported in a communication to this conference (Naulin et al.) we have observed double charge heavy ion reactions at the AP Tandem: the (16O, 3C) reaction confirms the mass you obtained. It has a 40 nb per sr, which indeed made it just possible with a thick target. As for the 1Be mass, we plan to use the similar (14C, 1Be) reaction, but of course do not know if the cross-section will still remain on the good side of feasibility.

P.L. Reeder: Previous papers on 3H have been titled "search for 4H", "Another search for 4H" and "Still another search for 4H". Do you have a title for your paper on 3H?

K.K. Seth: Yes, the title will be: The Last Word on 3H.
Abstract

Excitation functions and angular distributions are presented for single and double charge exchange reactions measured in the scattering of $^{48}$Ti from $^{12}$Ca. Relatively large cross sections have been found (up to 10 mb/sr) for these reactions with the isobaric analogue states clearly populated. The data follow well DWBA predictions with isospin terms (t=1) in the interaction.

1. Introduction

Recently the importance of the double charge exchange (DCX) reaction in exploring fundamental nuclear properties has been demonstrated. Such reactions allow for the production via an isobaric analogue transition of proton-rich nuclei far from the line of stability. Also, since two nucleons are involved DCX will be sensitive to two-nucleon short-range correlations. The original motivation for studying this reaction came from ($^p$, $^n$) scattering where there are now available a wide body of experimental data involving light and medium heavy target nuclei. Since DCX processes are accompanied by an isospin change of two units, heavy ions are besides protons the only suitable projectiles by which DCX can be studied. At present there exists little data for heavy ion induced DCX. The cross sections for DCX reactions leading to discrete final states are small (typically < 20ub/sr) and up to now there exists no theoretical model which provides a consistent interpretation of the observed cross sections.

The DCX process proceeds only on nucleli with neutron excess because of the Pauli principle and should preferentially excite isobaric analogue states of the projectile and target. With this in mind and the availability of suitable beams and targets we have initiated a study of single charge exchange (SCX) and DCX using the scattering of $^{48}$Ti from $^{12}$Ca targets.

2. Experimental Details

The experiments reported here were performed using the UNILAC facility at GSI Darmstadt. Beams of $^{48}$Ti, typically 5 pNa, bombarded target foils that were evaporated onto carbon backings (20ug/cm$^2$). Some contamination (< 1%) of the targets by heavy metals (Fe, Zr and Ta) was observed, although this does not affect the results presented. The reaction products were detected by the QQQQ magnetic spectrometer and normalization between runs was obtained using a surface barrier detector placed at a fixed scattering angle. To ensure scattering angle accuracy the position of the beam spot on the target was checked several times. Signals from the spectrometer and monitor detector were recorded event-by-event onto magnetic tape and data reduction was performed subsequently offline.

Cross sections were measured at the following incident energies and scattering angles: $E_{\text{LAB}} = 226$ MeV ($Q_{\text{LAB}} = 250$°), $E_{\text{LAB}} = 288$ MeV ($Q_{\text{LAB}} = 165$°) and $E_{\text{LAB}} = 385$ MeV ($Q_{\text{LAB}} = 70$, 85, 115, 130°). The highest energy measured is three times the Coulomb barrier and the resolution of the energy spectra was $\Delta E/E = 1\%$. Absolute cross sections were obtained by normalizing to optical model predictions employing the optical potential of Wastyn et al. used to fit $^7$Ar + $^{12}$Ca elastic scattering data in the same energy region.

A typical example of the many reaction products in the quasi-elastic (QE) region ($Q = 40$ MeV) is shown in a $Z$ - $A$ plot in fig. 1. With a resolution in atomic number $Z/\Delta Z = 79$ and a mass resolution $A/\Delta A = 160$ the different reaction products are clearly identified. In particular the SCX and DCX events for $A = 48$ are indicated in fig. 1 where the respective horizontal and vertical lines cross in the direction of the arrows. Figure 2 shows a projection onto the $Z$ axis, where in the upper-part events in the deep inelastic (DIC) region of the spectrum ($Q < - 40$ MeV) are shown, while in the lower part events corresponding to the quasi-elastic region ($Q > 40$ MeV) are indicated. It is seen that most of the SCX and DCX cross section is quasi-elastic in origin, indicating the predominance of a direct interaction mechanism to these channels.

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**) Supported by Gesellschaft für Schwerionenforschung.
†) Physics Department, University of the Witwatersrand, Johannesburg, South Africa.
‡‡) Institute of Modern Physics, Academia Sinica, Lanshow, Peoples Republic of China.
3. Results and Discussion

Energy spectra of the two possible routes for SCX and DCX for quasi-elastic events ($Q > -40$ MeV) are shown in figs. 3 and 4, the $x$-axis refers to the excitation energy in the exit channel indicated. The SCX channel $^{48}$Ti $\rightarrow ^{48}$Sc seen in the upper part of fig. 3 is notably different from the alternative SCX reaction $^{48}$Ti $\rightarrow ^{48}$V of fig. 4. In the former, besides a lower yield generally, the cross section appears to be concentrated in excitation energies $< 15$ MeV. While in the latter, the main bulk of the yield lies somewhat higher in excitation between 8 and 20 MeV. The isobaric analogue states $^{48}$Ca $\rightarrow ^{48}$Sc ($E_X = 0$ MeV) and $^{48}$Ti $\rightarrow ^{48}$V ($E_X = 3.0$ MeV) are shown by arrows in the upper part of figs. 3 and 4, respectively (note that there is no corresponding analogue state for the recoil nucleus). As can be seen there is a clearly resolved peak in the energy spectra indicating some enhancement to these states. The double isobaric analogue states of the DCX channels $^{48}$Ca $\rightarrow ^{48}$Ti ($E_X = 16.6$ MeV) and $^{48}$Ti $\rightarrow ^{48}$Cr ($E_X = 17.1$ MeV) are indicated in the lower part of the energy spectra. A clustering is apparent for the latter but, however, a complete absence of events is noticed for the former.

The corresponding cross sections for SCX ($Q > -20$ MeV) and for DCX ($Q > -40$ MeV) are shown in figs. 5 and 6, where in fig. 5 the cross section at the grazing angle as a function of energy is plotted and fig. 6 shows the angular distribution measured at the highest bombarding energy. A particular exit channel with an effective Q-value, $Q_{eff}$, that is close to zero will be more favoured than one very much different from
zero where,

$$Q_{\text{eff}} = Q + \Delta E_C + \Delta E_L.$$

$Q$ is the ground state Q-value of the reaction and $\Delta E_C$ and $\Delta E_L$ are the differences in the Coulomb and centrifugal potential energies between the entrance and exit channels at the nuclear touching distance, respectively. From these simple physical arguments it is expected that the transition through $^{48}\text{Ti} \to ^{48}\text{V} \to ^{50}\text{Cr}$ should be more strongly populated than $^{48}\text{Ti} \to ^{46}\text{Sc} \to ^{48}\text{Ca}$. This indeed appears to be the case where the former route is on average a factor of 3 or 4 times stronger than the latter. The SCX and DCX cross sections rise steadily with incident energy and have a remarkably high value at the more forward angles of the angular distribution. Indeed, the trend of the SCX and DCX follows very well distorted wave Born approximation predictions involving isospin terms ($I, T$) in the interaction. Of course, the possibility of sequential nucleon transfer leading to the SCX and DCX channels should not be overlooked and this possibility is being investigated further.

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**Fig. 3** Energy spectra for SCX (upper) and DCX (lower) for quasi-elastic events.

**Fig. 4** Energy spectra for SCX (upper) and DCX (lower) for quasi-elastic events.

**Fig. 5** Excitation function for SCX (upper) and DCX (lower) reactions at the corresponding grazing angle (the lines drawn are there to guide the eye only).


Fig. 6 Angular distribution for SCX (upper) and DCX (lower) reactions.

4. Outlook

We are presently analyzing the wealth of data taken to construct angular distributions and excitation functions for the various reaction products. To enlarge the angular distribution we added measurements at two more angles, 9.75°LAB and 14.50°LAB at the highest incident energy, 385 MeV, and we also looked for the corresponding reactions with a 48Ti beam onto a 28Mg target. These data are in the process of being analyzed. The SCX and DCX processes are being treated in distorted wave Born approximation where the transition amplitude contains effective interactions from shell-model wave functions and the nucleon-nucleon term involves only t.t contributions.
PRODUCTION OF NUCLEI FAR FROM STABILITY BY FRAGMENTATION OF HIGH ENERGY HEAVY IONS

T. J. M. Symons

Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720

Abstract

The application of relativistic heavy ion beams to the production of nuclei far from stability is discussed. Production cross sections obtained using 40Ar and 48Ca projectiles accelerated by the LBL Bevalac are presented together with the first results of half life measurements made using an extension of these techniques.

1. Introduction

For nearly forty years, accelerators and techniques for the production of nuclei far from stability have evolved together. From earliest, pioneering studies using low energy electrostatic machines to the present generation of isotope separators, introduction of a new accelerator has almost always been followed by its application to the study of some region of the table of isotopes. The incredible variety of techniques presented at this conference provides the most eloquent testimony to the ingenuity of the physicists involved.

In the next decade, this symbiotic relationship is almost certain to undergo a severe test. Increasingly, nuclear physics research is being concentrated at a small number of expensive facilities, leading to a much more intense competition for beam time. This is a situation in which very low cross section experiments will have to compete especially hard in order to survive. Furthermore, it is not only the number of accelerators but also their nature that is changing. In the United States, for example, the most ambitious construction projects are either for electron accelerators, which have no obvious application to this field, or high energy heavy ion machines whose usefulness for this purpose is by no means clear. Thus, while proposals for such accelerators almost always emphasize their appropriateness for the study of nuclei far from stability, investigation of the basic reaction processes and construction of suitable apparatus is only just beginning.

For this investigation there are two straightforward approaches that can be taken. The first is to bombard a heavy target repeatedly for spallation products exactly as is done with proton beams at isotope production facilities such as ISOLDE at CERN. In this application it is hoped that the greater excitation energy and heat deposited in the target nucleus by the heavy ion beam will lead to larger production cross sections for very exotic isotopes. At the present time it seems that the use of light nuclear beams such as 3He may indeed be advantageous in certain applications. However, for heavier beams than this, there seems to be no clear advantage since any increase in cross section is more than compensated for by the lower beam intensities that are normally obtained.

The second application of high energy heavy ion accelerators is to invert the reaction process by accelerating the heaviest beam available and bombarding a light target. One then observes the projectile fragments. As we shall see, under favorable circumstances this method has kinematical advantages that can outweigh the problem of low beam intensity. Indeed, at the LBL Bevalac, we have already obtained significant results even though the beam intensity available is six orders of magnitude less than that obtained from a typical high energy proton accelerator.

In this paper, we shall discuss the fragmentation process and its application to production of neutrons rich light nuclei. We shall then describe our recent development of the technique to measure β decay lifetimes and finally discuss some of the experiments that we may expect to be performed at the new accelerators.

2. Production Mechanisms

At low energies (E/A ≤ 20 MeV/nucleon) many processes contribute to the total reaction cross section in heavy ion collisions. Of these, three that have found widespread application for production of unstable nuclei are fusion-evaporation reactions, deep inelastic scattering and two body transfer reactions. However, as the bombarding energy is increased, the cross section for all these processes decreases rapidly. There are many reasons for this: Firstly, the time scale of the reaction is much shorter, reducing the mean field effects and increasing the importance of nucleon-nucleon scattering. Secondly, as the relative velocity of the two ions increases, it is no longer possible to match the velocity of a nucleus or light cluster and transfer it from one nucleus to the other. Thirdly, in a central collision, so much energy is available that the two nuclei completely dissociate rather than fusing together.

For peripheral reactions much of the cross section goes instead into nuclear fragmentation in which the nucleus breaks up into several pieces, usually one or two complex fragments and several nucleons and light clusters. The inclusive properties of this process have been extensively studied at high energies (E/A ≥ 200 MeV) and it is known that there is relatively little momentum transfer between target and projectile and that the fragments are produced moving close to the beam velocity at zero degrees in the laboratory. The exact nature of the reaction process, and in particular the importance of direct break
up, is still controversial, but we should note that the abrasion-ablation model is able to make reasonable predictions of the cross sections.\(^5\)

3. Experimental Measurement of Production Cross Sections

The high velocity of the fragments leads to three particular experimental advantages of the fragmentation process. These have been discussed elsewhere but are of such importance that they can be restated here:

(i) Since both projectile and fragment are moving at high velocity in the laboratory, it is possible to use thick targets. For example a 1 gm cm\(^{-2}\) Be target is appropriate for the fragmentation of \(^{48}\)Ca at 200 MeV/nucleon. This is between two and three orders of magnitude thicker than would be used in a typical deep-inelastic reaction. At higher energies than this even thicker targets would be appropriate.

(ii) Since the reaction products are produced in a narrow cone close to 0° in the laboratory, it is possible to collect almost the full reaction cross section in a spectrometer of quite modest acceptance. At 200 MeV/nucleon bombarding energy a spectrometer of 1 mea acceptance will accept greater than 30% of the cross section even in unfavorable cases.

(iii) Since they are all moving at the same velocity, magnetic analysis alone suffices to separate isotopes according to their A/2 values. This means that exotic species are readily separated from the more abundantly produced ones and that the detectors only have to handle relatively low count rates.

The experiments described here were carried out using the zero degree spectrometer of the Lawrence Berkeley Laboratory Bevalac. Beams of \(^{40}\)Ar and \(^{48}\)Ca were accelerated to 205 and 220 MeV/nucleon respectively and used to bombard C and Be targets of 900 mg cm\(^{-2}\). The arrangement of the apparatus is shown in figure 1 and comprises the target and then a spectrometer consisting of a quadrupole doublet and two dipole magnets followed by a large (~7m x 3m) vacuum tank. In all the experiments described here, the fragments were detected in air outside a thin vacuum window. The fragments were double focused by the quadrupole in the focal plane of the spectrometer and detected by a semi-conductor detector telescope.

This telescope comprised two 500 \(\mu\) thick, 6 cm diameter, position sensitive Si(Li) detectors for horizontal and vertical position measurement followed by 12, 5 mm thick, 5 cm diameter, Si(Li) detectors for energy loss measurements. Finally, the telescope was backed by a plastic scintillator for rejection of light particles punching through the silicon.

The maximum beam intensity available was of the order of \(4 \times 10^7\) particles/beam pulse (~10\(^7\) particles/second) which is very small in comparison to a typical low energy nuclear physics experiment. Accurate beam monitoring was achieved with a variety of scintillators and an ion chamber. Two scintillators were mounted directly in the beam, one of which counted individual beam particles. For the other, the photomultiplier tube leakage current was digitized using a current to frequency converter. This is valuable at intensities greater than measurable by direct counting. For the very highest intensities, scintillator telescopes measured the flux of secondary particles scattered from the target. Unfortunately, the beam intensity can show considerable variations from pulse to pulse. For this reason, all the monitor scalers were read out via QMOR and written to magnetic tape after every beam pulse.

The combination of the spectrometer and focal plane telescope provides a system capable of two independent measurements of the particle mass and charge. First, the particles are identified by the energies deposited in the Si(Li) detectors. For each detector in the stack, a particle identification signal (\(\text{P}_1\)) is calculated using the formula

\[
\text{P}_1 = \left[ (E_1 + \Delta E_1)^n - E_1^n \right] / S_1 = M^{-1} x^2
\]

where \(\Delta E_1\) is the energy that is lost in the 1st detector, \(E_1\) is the total energy deposited in subsequent detectors up to the stopping detector, \(S_1\) is the thickness of the 1st detector, \(n\) is a parameter which varies from element to element but is usually \(\approx 1.78\), and \(M\) and \(Z\) are the particle mass and charge respectively. The \(I_1\) signals are then combined to form a weighted mean and \(\chi^2\) function defined by

Fig. 1 Experimental layout for detection of fragments of 212 MeV/nucleon \(^{48}\)Ca.

- 669 -
\[ \chi^2 = \sum_{i=1}^{s-1} \left( \frac{I_i - \bar{I}}{\varepsilon_i} \right)^2 \]

where \( \varepsilon_i \) is the area on each \( I_i \). This error is derived by assuming a certain detector resolution and differentiating the identification function appropriately. The mass resolution is improved considerably by rejecting particles with large values of \( \chi^2 \). This eliminates not only events that misidentify due to fluctuations in the energy loss, but, most importantly, those that react in the detectors. At these energies \( \approx 30\% \) of the incident particles will react in the silicon.

Secondly, the total energy, \( T \), deposited in the telescope is combined with the particle deflection, \( D \), in the spectrometer to form a second particle identification signal

\[ PI = \frac{k}{T} - T_{2\sigma} = M/\sigma^2 \]

where \( k \) is the spectrometer calibration constant. These two functions may be combined to calculate the charge and mass of the fragment unambiguously.

The results obtained from such an analysis are shown in fig. 2, which contains the mass spectra for 8 elements produced in the \( ^{48}\text{Ca} \) bombardment. In each case a 30\% \( \chi^2 \) cut and a total energy cut have been applied as well as a cut on charge. Fourteen new isotopes were identified from the data shown in this figure in addition to the two observed in our previous experiment using an \( ^{40}\text{Ar} \) beam. The new isotopes observed in heavy ion fragmentation are

\[ ^{22}\text{Ne}, \ ^{26}\text{F}, \ ^{28}\text{Ne}, \ ^{33,34}\text{Mg}, \ ^{35,36,37}\text{Al}, \ ^{38,39}\text{Si}, \ ^{41,42}\text{P}, \ ^{43,44}\text{S} \text{ and } ^{44,45}\text{Cl}, \]

each of which at least 10 counts have been observed. In view of the very low beam intensities, these results are encouraging for the application of similar techniques at new accelerators such as the MSU and GANIL coupled cyclotron facilities. These machines will have very much larger beam intensities in just the energy range that we have been considering.

In figure 3, which shows the table of isotopes for the lighter elements, we see that we are already within one or two units of the limit of stability for all elements up to \( ^{39}\text{Ca} \). Whether this limit in fact can be reached with reasonable intensity is, of course, a sensitive function of the rate at which yield drops with increasing mass number. In figure 4, we compare the cross sections for the production of Sodium isotopes by heavy ion fragmentation and by spallation as measured by Klapisch and co-workers at CERN. The first point to notice is that the trend of the cross section as a function of mass number is almost identical in the two cases even down to the pronounced odd-even effects that can be seen. This gives confidence that one can extrapolate from present heavy ion data to predict the yields for nuclei at the limit of stability. It is
In a test of this technique at the Bevalac we used a new telescope layout illustrated in figure 5. The 5 cm detectors used previously have been replaced by 6 7cm diameter position sensitive detectors.

![Diagram of telescope layout]

Fig. 4 Comparison of production cross sections for Na isotopes produced in the $^{48}$Ca + $^9$Be, $^{40}$Ar + C and $p + ^{238}$U reactions.

important, also, to note that the cross section for $^{48}$Ca fragmentation is almost an order of magnitude greater than that for $^{40}$Ar for the most neutron rich nuclei. This is obviously related to the larger neutron number in the former case and some further increase in cross section can be expected when heavier beams are used.

4. Half Life Measurements

Although identification of a new isotope is in itself a useful measurement, especially at the limits of stability, it is obviously desirable to measure the physical properties of the nucleus under consideration. For this reason we are now starting a program to measure the $\beta$ decays of unstable nuclei formed via heavy ion fragmentation.

As we have discussed above, the isotopes produced in heavy ion fragmentation have a range of the order of several centimeters of silicon. They also have a considerable dispersion in range due to the spread in energies of the fragments. This makes the preparation of a $\beta$ source a non-trivial matter since the isotopes are distributed through the stopping material.

However, in our application the stopping material is itself an excellent $\beta$ detector and this problem can be overcome by detecting the $\beta$ electrons in delayed coincidence in the telescope stack. Furthermore, the great difference in range between different isotopes at the same magnetic rigidity then becomes an advantage since one has true isotope separation within the detector telescope.

![Detector stack]

Fig. 5 Experimental layout for detection of delayed coincidences.

also fabricated at LBL. The position sensitivity is valuable since it allows a correlation to be made between the position of the incident heavy ion and the decay electron. Two 800 $\mu$m thick trigger detectors were mounted in front of the stack.

The complete detector stack is shown in figure 6.

![Detector stack consisting of 2 800 $\mu$m detectors and 6 7 cm x 5 mm position sensitive detectors]
Since the energy deposited by the heavy ion in a detector is of the order of 1 GeV and that deposited by a $\beta$ electron is of the order of 1 MeV some attention has to be paid to the electronics used as illustrated schematically in figure 7. The analog signals (3 per detector) from the position sensitive detectors are split after the preamplifier into low and high gain channels. All the analog channels are then fed to CAMAC ADCS for digitizations. In the test run a total of 38 amplifier channels were used. This could be considerably reduced by use of gain switching in the preamplifier.

The low gain signals are also fed to a hardware particle identifier which produces an output using a power low approximation just as is done in analyzing the detector signals in the computer. The output of this identifier is also digitized and read into the computer. The CAMAC crate is connected to a microprogrammable branch driver (MBD) which passes data by direct memory access to a PDP 11/34 computer for analysis and storage on magnetic tape. When a low gain event is read from CAMAC, the program running in the MBD examines the ADC values and determines the stopping detector. It then compares this and the particle identifier signal with limits that are downloaded from the PDP 11/34, to determine whether the event represents a suitable stopping isotope; the read out and decision takes $\approx 600$ $\mu$s. If the event is accepted as a valid stopping event then an output pulse is used to set a flip/flop which changes the trigger mode of the system to a two fold coincidence between any pair of position sensitive detectors in high gain. This pulse is also fed to the accelerator control room and interrupts the beam extraction for the remainder of the spill thereby reducing the beam background. This is accomplished within 2 ms allowing measurement of half-lives as short as 5 ms. The high gain mode remains enabled until the system is reset at the start of the next spill.

In this first test, an $^{40}$Ar beam of 250 MeV/nucleon was used. Unfortunately, the beam intensity available was only $10^6$ particles/second so that the yield for a very neutron-rich isotope was reduced by approximately two orders of magnitude below that of the $^{48}$Ca experiments described above. However, this beam intensity was adequate to determine the feasibility of the experiment and to learn the technical problems involved.

Some preliminary analysis of a small subset of the data has now been carried out. In figure 8, we show the software PI spectrum for charge 13 events stopping in detector 5 in one of the runs. Two peaks can be resolved which are $^{31}$Al and $^{32}$Al respectively. The delay time until the first candidate $\beta$ event is plotted for each of these peaks in figure 9. The decay curves are very different in the two cases. Preliminary analysis of the $^{31}$Al curve shows a half life of 630±40 ms, in good agreement with the published value 644±25 ms. In contrast, $^{32}$Al shows a very much faster component with a half life of the order of 40 ms. This half life was
previously unknown. In these spectra no attempt has been made to reduce background by demanding consistency between the positions of the heavy ion and $\beta$ candidates, nor has any $\chi^2$ cut been made on the PI spectrum, so some further background suppression can be expected in the final analysis. This preliminary experiment has produced very encouraging results and we believe that with larger beam intensities, the technique can be used to measure a large number of half lives in a relatively short time.

5. Conclusions

In the coming year the upgraded Bevalac, accelerating all ions up to Uranium and the MSU coupled cyclotron are expected to operate. We believe that fragmentation reactions to produce nuclei far from stability will play a role at these and other such facilities. First there will be experiments performed using secondary beams. At the highest Bevalac energies ($E/A > 1$ GeV/nucleon) the fragments are so well focused that they can be prepared into a secondary beam thereby extending the study of heavy ion collisions to systems with unusual neutron to proton ratios. As one example the possibility of studying electromagnetic properties of nuclei in this way has already been discussed by Berman et. al.

Secondly, mass measurements will be attempted. A recoil mass spectrometer, incorporating a dipole and velocity filter is being constructed at Michigan State University and is expected to have a mass resolution of a few MeV.

For our own programme at the Bevalac, we hope to continue along two fronts exploiting the unique features of this machine namely the very high energies and heavy beams that will be available. If the Bevalac upgrade is successful, we believe that beam time for a further isotope search will be justifiable, this time using a broad range detection device at the HISS spectrometer. This would allow simultaneous measurement of isotopes with different $A/Z$ values and would greatly increase the efficiency of our technique. We also plan to proceed with development of the half life measurements to make a systematic study of half lives in the mass 30-50 region. Systematic studies of many nuclei can yield useful information both for nuclear structure and for astrophysics.

In the introduction to this paper we questioned the applicability of high energy heavy ion accelerators to this field. Our experience at the Bevalac leads us to believe that this question does indeed
have a positive answer. If the physics interest justifies it, then high energy heavy ion beams can certainly be expected to play a role in the study of nuclei at the limits of stability and experimental physicists will continue to exercise the ingenuity of experimental design that has served this field so well for the past 40 years.

6. Acknowledgements

The production cross section experiments were carried out by the authors of references 1 and 2, to all of whom this writer is greatly in debt for their advice and help.

The $\beta$ decay experiments were performed by H. J. Crawford, M. J. Murphy, G. D. Westfall and this author.

The author is especially indebted to J. T. Walton and H. Sommer for painstaking efforts to fabricate the large area positive sensitive detectors.

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References


DISCUSSION

I. Bergström: In your first part of your talk you showed slides which indicated mass information but you did not comment about the possibility of getting Q-values? How do your measurements compare with the pion charge exchange measurements which is seldom talked about and which indeed gave Q-value information?

T.J.M. Symons: First, the mass information that we obtain from the Si(Li) detector telescope is only sufficient to resolve neighbouring isotopes, not to measure their masses. In this respect, our technique is inferior to the pion charge exchange measurements. However, our production cross-sections are very much higher enabling us to study nuclides further from stability.

W. Benenson: At what energy will the fragmentation process become useful, for example, for $^{39}$Ar? Is it 25 MeV/A?

T.J.M. Symons: I believe that measurements with heavy ion beams can be made at any energy. However, at 25 MeV/nucleon one would probably not call it fragmentation. In order to have the very high efficiency that I have described, 100 MeV/nucleon is a minimum energy.

J.N. Ayto: Would it be possible to extract information on beta-decay energies with this technique?

T.J.M. Symons: Yes, of course. The only problem is the amount of beam time that will be required to make a useful measurement. I suspect that this is not justified at the Bevalac with our present beam intensities.

G. Herrmann: Would you expect that with this method one would have access to heavy, neutron-rich nuclei beyond the fission product region?

T.J.M. Symons: We would certainly have access to the fission product region. Whether we could go beyond it, I do not know. Also, rather different detection techniques would be required.
THE COLD FRAGMENTATION OF $^{234}\text{U}$ IN $^{233}\text{U}$ ($n_{th',f}$)

P. Armbruster


U. Quade, K. Rudolph

Technische Hochschule Darmstadt, D-61 Darmstadt, Fed. Rep. of Germany

W. Engelhardt
Technische Hochschule Karlsruhe, D-75 Karlsruhe, Fed. Rep. of Germany

F. Gönnewein, H. Schrader
Institut Max von Laue - Paul Langevin, F-38042 Grenoble, France

Abstract

The transformation of the uranium nucleus into a separated two fragment configuration has been found to be possible without appreciably heating the fragments via intrinsic excitation or deformation. A small part of the fragmentations in thermal neutron induced fission proceeds with a release of mutual kinetic energy of the fission fragments, which is not far from the total Q-value of each fragmentation. 1 permille of all fragmentations occur with an excitation energy smaller than 7 MeV, an excitation energy of the fragments not larger than the excitation energy of the fissioning nucleus after thermal neutron capture.

Experimental Method and Results

This is a report on an experimental investigation of the cold fragmentation of $^{234}\text{U}$. $^{233}\text{U}$ targets of 40 µg/cm² thickness were exposed to a thermal neutron flux of $\approx 7 \cdot 10^{11}$ neutrons/cm²s at the High Flux Reactor of the ILL, Grenoble. The fission fragments of the reaction $^{233}\text{U}$ ($n_{th},f$) were mass and energy separated within micro-seconds, using the fission product separator "LOHENGRIN" of the ILL. The separation occurs as a function of mass over ionic charge A/q and of the velocity v of the fragments. The mass yields were measured with an ionization chamber.

Since "LOHENGRIN" provides mass separated beams at constant kinetic energy E, it is possible to use an absorber at the exit slit of "LOHENGRIN" in which a mass separated fragment loses a certain amount of energy $\Delta E(Z)$ according to its nuclear charge Z. We used a parylene-absorber and measured with the ionization chamber the rest energy $E_r = E - \Delta E(Z)$. With this "degrader-rest-energy technique", which is complementary to a $\Delta E$ measurement, it was possible to determine the nuclear charges in the light group of fission products at all masses and energies present. The large sensitive area and the good nuclear charge and energy resolution of the detector system allowed measurements of isotopic yields down to $10^{-5}$ and of mass yields down to $10^{-6}$ of the absolute fission yield.

Fig. 1a shows mass distributions of light fragments selected at kinetic energies of 114.1 MeV, 116.1 MeV, and 118.1 MeV. Measurements in steps of 1 MeV for light fragments in the energy region between (112-119) MeV have been made. Fig. 1b gives the maximum possible kinetic energies of light fission fragments using the mass formula of Møller and Nix. Measurements of isotopic yields are available up to $E = 112$ MeV, for selected chains up to $E = 114$ MeV. The yields are absolute fission yields given as dY/dE * dE. Fig. 2 gives as examples the energy dependence of the chains A = 90 and A = 100. We fitted second order polynomials to the logarithmic yields. The finite energy resolution of 50.5 MeV has been unfolded in the yields evaluated. It is an important but still minor correction even for the lowest yields measured. The energy resolution is limited mainly by the target thickness and energy dispersion of the spectrometer over the entrance slit of the ionization chamber. At an absolute level of $10^{-2}$ all masses in the mass range A = 79-104 were detected, about 25% of the chains were even detected having yields less than $10^{-6}$.

If the excitation energy of the two fragments is smaller than the neutron binding energy (1-7 MeV), primary yields are measured. As mass and atomic number are conserved the determination of the mass and the atomic number of one fragment allows the identification of the pair of fragments $(A_Y = 234 - A_Z; Z_Y = 92 - Z_Z)$. In addition from momentum conservation in the nuclear breakup a calculation of the total kinetic energy $E_{kY}$ of the fragment pair from the kinetic energy $E_{kX}$ of one fragment can be done $E_{kY} = E_{kX} (1 + A_Y/A_Z)$. Fig. 3 compares the experimentally determined $E_{kY}$ values at the $10^{-5}$ chain yield level with a calculated Q-value. Q is the mean of the Q values of a given mass split into different nuclear charges as determined by the new mass tables of Møller and Nix, weighted with the independent yields as measured at kinetic energy $E_X < 112$ MeV and extrapolated into the range of high kinetic energies $E_X > 112$ MeV, $Q = \Sigma_i Q_i \cdot Y_1(Q_i)$. The difference $Q - E_{kY} = E*$, which is the excitation energy of the reaction is given in Fig. 4 as a function of the mass split. In almost all cases even mass splits are more excited.

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Fig. 1a: Mass yields for cold fragmentation of $^{235}$U at 3 energies of the light fission fragments.

Fig. 1b: Maximum kinetic energies for light fragments calculated from $Q$-values, together with the corresponding $E_{\text{max}}$ from $Q$-values. The cuts chosen for the mass yields of Fig. 1a.

Fig. 2: The mass yields at $A = 90$ and $A = 100$ as a function of the kinetic energy of the light fragment (see the logarithmic scale).

----- measured
..... resolution corrected

Fig. 3: Total kinetic energy $E_{\text{TK}}$ at $Y(A) = \int Q \, dY/dE \, dE = 10^{-5}$ in comparison to the $Q$-values as a function of the mass ratio. The isotopes of even elements with independent yields larger than 90% and the odd-odd nuclei with yields larger than 50% are indicated.

Fig. 4: Excitation energy $E^* = Q - E_{\text{TK}}$ at $Y(A) = \int Q \, dY/dE \, dE = 10^{-5}$ as a function of the mass ratio.
than odd ones. Low values for $E^*$ are observed within the range of A ≈ 92 where the highest mass yields in the light fission product group are known to exist. Unless there is a failure of the mass formula not taking into account properly the onset of deformation in the mass range A > 100 or the shell effect at N = 82 in the complementary fragment, the coldest fragmentations are found for mass splits with a broken N = 82 shell.

The maximum possible kinetic energies of light fission fragments can also be deduced from the calculated Q-values, using momentum conservation (Fig. 1b). They are given to show the cuts connected to the light fragment energies chosen in the mass yield measurements presented in Fig. 1a.

The independent yield measurement at 112 MeV in the region of cold fragmentation allows a first direct determination of the odd-even effect (Y_o - Y_e)/Y_o in the neutron yields. A value of 11% is found for neutrons as an average over the mass range, which compares with 46% as measured for protons. The extrapolation of independent yields from measurements at high fission yields ($E = 108$ MeV) into the range of cold fragmentation gives values of 10% and 40%, respectively. In the following we take mean values from the two determinations. We interpret (following Ref. 9) that about 11% of the fragmentations are unaffected by neutron pair breaking, whereas 43% of the fragmentations are unaffected by proton pair breaking. Even at low excitation energies, fragments with broken pairs prevail.

**Discussion of Results**

The fact of reduced pairing is seen directly from Fig. 4. The excitation energy of even-mass chains is larger than of odd-mass chains. For the difference an average value of (1.0 ± 0.2) MeV is found for the mass range considered. Its origin is the contribution of the pairing energy to the Q-values, which cannot be realized in the case of broken pairs. Taking an odd-even term in the Q-values, e.g. in the tabulation of evaporated fragments, gives an increase in the observed excitation energy in even chains, which is given by $\Delta^* = 2A Y_{uu}$. With the experimental value $Y_{uu} = 0.24 ± 0.02$, that is 24% of the yield in even chains is found in odd-odd nuclei, we get $\Delta^* = (1.0 ± 0.1)$ MeV as non-realized pairing energy in good agreement with the excitation energies of odd and even mass chains.

The persisting pairing can be seen directly from Fig. 3. It manifests itself in sequences of nuclei, as $^{86-96}$Se, $^{85-95}$Kr, and $^{54-95}$Sr, which carry nearly all the yields of the chains. No comparable sequence is found for even neutron numbers. The small probability of neutron pairing is demonstrated by the high yield of $^{95}$Sr and $^{95}$Kr. An odd mass isotope successfully competes with its even neighbours, which are unable to take advantage of the neutron pairing energy.

The charge distribution of fission products is determined by the minimum potential energy of the scission configuration.4 The optimum charge values for most of the chains would be noninteger values. The energy necessary to change from the optimum charge values $Z_{opt}$ on the minimum of the potential energy surface to the actual integer charge value is $\Delta E^*/MeV = 1.6 (Z-Z_{opt})^2$. In favourable cases, as in the chain A = 82, the energy available for even-even break-up is reduced by 1.6 MeV, thus leading to a higher yield of odd-odd $^{22}$As than its even-even neighbouring isobars. On the average in the mass range considered, the excitation energy bound by non-optimum charge values is 0.4 MeV. Pair breaking and quenched charge values averaged over all chains contribute to the excitation on the average (0.4 + 1.0/2) MeV = 0.9 MeV.

The gross features of the strong yield variations demonstrated in Fig. 1 may be understood from the Q-value systematics. The peaks in the $114.1$ MeV yield distribution are due to nuclear structure effects. Shell effects are clearly seen. The peak at A = 100 belongs to a fragmentation into nearly doubly magic $^{135}Te$ and the soft nucleus $^{95}Sr$, which may profit from the N = 50 deformed shell.7 The peak at A = 90 may be understood from the deformed shell at N = 88, and the set-in of deformation at N = 88 for $^{14}Na$. The peak at A = 84 is caused by the N = 50 shell in $^{84}Se$.

The peak structures demonstrate that the system is able to take advantage of a few MeV in the reaction Q-value. At low intrinsic excitation energies finally the gain of Q-values by shell effects determines the production yields. Systems stabilized by shell effects are found as reaction products at this level of intrinsic energy predominantly. The predominance is lost for $E^* > 10$ MeV.

However, as Fig. 4 demonstrates, the phenomenon of cold fragmentation is a general one found for all masses in the range A = 80 - 104. Having subtracted from the average experimental excitation energy (3.8 ± 2.0) MeV the energy bound by pair breaking and the integer charge values not meeting the minimum potential energy condition, an excitation energy of (2.9 ± 1) MeV is found in the two fragments at the 10-2 chain yield level. This value includes the excitation energy ($B_T - B_p$) = 1.1 MeV of the system at the saddle point. The excitation energy generated by the necking-in process may be estimated to range in the mass range considered between (0 - 5) MeV with an average value of about (1.8 ± 1) MeV.

Converting the measured $E_{ MK}$-values into effective separation distances, we obtain values between (15 - 16) fm. These distances are ± fm larger than in2. The peak at two touching spheres calculated with $r_p = 1.17$ fm. From the elongation of the configuration at the second saddle point12 the corresponding separation distance between the charge centers may be estimated to be 14 fm. The
breaking of the nucleus in cold fission is a necking-in process with a very small increase in the separation distance.

How a necking-in may be accomplished with low energy dissipation is a completely open question. Possibly collective modes such as the giant quadrupole resonance of the configuration at the second saddle point could be involved in initiating the nearly cold transition to a two fragment system. A fast collective necking-in mode with $\Gamma \lesssim 2$ MeV corresponding to times larger than $3 \times 10^{-12}$ s would meet the energy rates and allow for pair breaking as deduced from the experiment.

Conclusions

(1) About $10^{-3}$ of all fission events have excitation energies smaller than 7 MeV. At a yield level of $5 \times 10^{-4}$ fragmentations with excitation energies less than 1 MeV are found.

(2) The structure in the mass yields for cold fragmentation is determined from the Q-value systematics and the potential energy surface of the scission configuration. For excitation energies smaller than 10 MeV closed shell nuclei dominate the yield.

(3) In the range of cold fragmentation, variations as small as 1 MeV in the intrinsic excitation energy drastically change the mass yields.

(4) The lowest excitation energies are observed for the fission products within the range A $\sim$ 92, which are the most abundant masses of the light fission products. At the lowest excitation energy, nuclei with odd atomic numbers prevail.

(5) The flow of nuclear matter past the second saddle point is predominantly transverse. The necking-in process proceeds with a creation of only a few MeV of intrinsic energy. In nearly all fragmentations broken neutron pairs are found, whereas in about 50% of all cases proton pairs remain unbroken. The matter flow may be predominantly carried by neutrons, and it destroys at least partially the superfluidity of the system.

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References

2) Signarbieux et al., to be published in Journal de Physique Letters
3) E. Moll et al., Nucl. Instr. and Methods 123 (1975) 615
4) U. Quade, K. Rudolph and G. Siegert, Nucl. Instr. and Methods 164 (1979) 435
6) U. Quade et al., to be published; U. Quade, private communication
8) W.D. Myers, Droplet Model of Atomic Nuclei, IFI Plenum Data Company (1977)
10) P. Armbruster, Nucl. Physics A140 (1979) 385
11) E. Monnand and B. Fogelberg (1976) Proc. 3rd Int. Conf. on Nuclei far from Stability, Cargèse, p. 503
DISCUSSION

J.B. Wilhelmy: You have shown a picture of touching fission fragments for the cold fragmentation. Is this consistent with the Coulomb energy required with this configuration? Do we need some distortion energy in the fragments to obtain an energy balance?

P. Armbruster: The fragmentation $^{102}$Zr/$^{133}$Te needs, if you convert the Q-value into a separation distance of the charge centres, a deformation of the fragments. Assuming $^{133}$Te spherical $^{102}$Zr should be deformed with an axis ratio of 2:1. The deformation energy needed for this deformation is assumed to be small, as the nuclear $^{133}$Te is assumed to be a soft one.

D.C. Hoffman: Can you really say for certain that the highest total kinetic energy is for $Z = 52$, $N = 82$ ($^{133}$Te) and $Z = 40$, $N = 60$ ($^{120}$Zr) rather than for $^{135}$Sn (doubly magic) and $^{102}$Mo?

P. Armbruster: We have determined the isotopic composition of this $A = 100$ as a function of the kinetic energy of the light fragment. At high values of $E_x$ the yield of $^{102}$Zr becomes 100%, that is the partner must be $^{133}$Te.

K. Bleuler: Is it still right to maintain that the two fission products have the same temperature?

P. Armbruster: This assumption is still made, but can be proved experimentally only indirectly. The measured excitation energies are the sum of deformation energy + collective and intrinsic modes of excitation. How to calculate the temperature from the excitation energy measured is not known. Moreover, at the small energies in cold fission the temperature may not be defined at all. The energy is distributed across the fragments according to the levels available in the fragments.

J.R. Nix: Your larger even-odd effect for protons relative to that for neutrons presumably arises because the small neutron skin and Coulomb polarization freezes in the proton distribution slightly sooner than the neutron distribution. At this point the temperature-dependent pairing gap $\Delta(T)$, upon which the even-odd effect depends exponentially, is larger for protons than for neutrons, as illustrated in this figure:

![Diagram](image)

Furthermore, the presence of an even-odd effect means that the excitation energy at scission is very low, which rules out high-dissipation theories for describing thermal-neutron-induced fission.

J. Theobald: Our question is, if fission fragments can be in their ground states in the scission configuration. If the peak region between the nascent fragments is neutron rich, one has to describe neutrons by complicated wave functions. The neutrons remain hot with many pairs broken, while the protons get frozen in the nascent fragments conserving partially the proton pairs. This picture depends on course on the adiabaticity of the fission process.

P. Tondeur: I would like to suggest a schematic explanation of the larger amount of neutron pair breaking in cold fission. Consider the pairing strength $G$ usually taken $\sim A^{-1}$. Protons, already separated in the two fragments, as well as most of the neutrons, should feel the larger pairing strength corresponding to the larger $A$, whereas the part of the neutrons still belonging to the whole fissioning nucleus should feel a smaller $G$, so their pairs would be more easy to break. The same conclusion is obtained by considering $\Delta \sim A^{-1/2}$: nucleons in the neck -- probably mainly neutrons -- are expected to be less paired than those who already belong to one of the fragments.
A NEUTRON MULTIPLICITY TECHNIQUE FOR IN-BEAM $\gamma$-SPECTROSCOPY ON NEUTRON DEFICIENT NUCLEI

J. Roth, L. Cleemann, J. Eberth, T. Heck, W. Neumann, M. Nolte
Institut für Kernphysik der Universität zu Köln, Germany

R.B. Piercey, A.V. Ramayya, J.H. Hamilton
Vanderbilt University, Nashville, USA

1. Introduction

Studies of nuclei far from stability are one of the present frontiers in nuclear physics. These investigations permit us to pursue the degrees of freedom of the nuclear many body system and their interplay over a long chain of isotopes providing a sensitive test of nuclear models developed from spectroscopic data in the valley of stability. On the other hand very exotic nuclei were produced recently and rare decay processes like $\beta$-delayed $\alpha$, p and n emission could be studied in detail.

Most experimental data of nuclei far off stability were taken with sophisticated and still improving mass separators installed at high flux reactors and at various types of particle accelerators. This data enlarged our knowledge of the properties of ground states and long lived isomers, their decay modes and the nuclear structure of low spin states in the daughter nuclei, but in-beam data on the produced residual nuclei are rather scarce.

In this contribution we present an improved method for in-beam $\gamma$-spectroscopic investigations of very neutron deficient nuclei using $(\alpha, x\gamma np)$ reactions with target and projectiles for which $N-Z$. In such a reaction the resulting compound nucleus predominantly will evaporate charged particles which produces residual nuclei near the line of stability, while the cross sections for evaporation of neutrons leading to neutron deficient residual nuclei are small. Therefore an efficient neutron-$\gamma$ coincidence technique seems to be the adequate tool to separate these neutron channels from the competing charged particle channels.

2. Experimental setup and results

To get a high coincidence rate we used a 10 cm thick cylindrical neutron scintillation detector of 35 cm diameter filled with NE 213. The detector is divided into four optically tight segments each driven by an independently working ultrafast photomultiplier. Neutron detection in the presence of $\gamma$-rays makes an $n-\gamma$ discrimination inevitable as neutron detectors are usually sensitive to all kinds of radiation. It is well known that the scintillation decay time of some scintillators depends on the type of radiation. This is the base for the pulse shape discrimination (PSD) we used. Our PSD was developed by Betz et al. which seemed to be the best tool for this purpose even nowadays. The possible count rate is $5 \times 10^5$ pps per segment and the average neutron efficiency of the system for neutrons evaporated from a compound nucleus is estimated from several measurements to be greater than 0.6. The neutron pulses are fed into a multiplicity logic which is adjusted to the desired multiplicity. The output pulses are used in a fast coincidence circuit with the $\gamma$ pulses.

The first application for this system is to suppress $\gamma$-rays from non neutron exit channels. As one does not only suppress photopeaks but also the correlated compton events one gets a much better peak to background ratio for the neutron exit channels. The spectra look much cleaner as one can see in fig. 1 and even very weak neutron reaction channels come out of the background.

![Graph](image_url)

**Fig. 1** Neutron multiplicity gated singles spectrum of the reaction $^{58}$Ni + $^{19}$F

n-\gamma separation error is about 1 : 2000. The average neutron efficiency of the system for neutrons evaporated from a compound nucleus is estimated from several measurements to be greater than 0.6. The neutron pulses are fed into a multiplicity logic which is adjusted to the desired multiplicity. The output pulses are used in a fast coincidence circuit with the $\gamma$ pulses.

The first application for this system is to suppress $\gamma$-rays from non neutron exit channels. As one does not only suppress photopeaks but also the correlated compton events one gets a much better peak to background ratio for the neutron exit channels. The spectra look much cleaner as one can see in fig. 1 and even very weak neutron reaction channels come out of the background.
The second important application of the system is to restrain the number of possible exit channels. The fact that the detector is divided into four parts allows to determine the multiplicity of the evaporated neutrons which helps to identify the residual nuclei. Going from the 0-fold to the 1-fold spectrum the photopeaks from non neutron reactions are nearly suppressed while the peak to background ratio of the peaks correlated with neutron events is enhanced. Going from 1-fold to 2-fold spectrum the lines with a neutron multiplicity greater than one are enhanced over the one neutron reaction channels. The same statement is plotted by means of the reduction factor in fig. 2 and fig. 3. The reduction factor is defined as the line intensity in the 0-fold spectrum divided by the line intensity in the 1-fold spectrum or line intensity in the 1-fold spectrum divided by the intensity in the 2-fold spectrum respectively. As we have a finite number of neutron detectors and the system efficiency is less than 100% we get a reduction of countrate for each multiplicity and the reduction factors are inversely proportional to the multiplicity. Going from 0-fold to 1-fold we get a factor greater than 100 for charged particles and a factor below 10 for neutron channels. Going from 1-fold to 2-fold we get a factor of -15 for one neutron channels and a factor of -14 for two neutron channels.

Although the reduction factors depend on the geometry of the experimental setup, on the recoil velocity of the compound nucleus, on the lifetimes of the nuclear levels and on the multiplicity the separation of the reduction factors for different multiplicities is great enough to discriminate the neutron multiplicity unambiguously.

Because of the great efficiency this system is a universal tool and can easily be combined with nearly all kinds of nuclear measurements. Within the last year we applied it with success in neutron gated...
γ-angular distributions and excitation functions. The crucial test for such a method is its applicability to a n-γ-γ coincidence. The experimental setup and an example of a n-γ-γ coincidence measurement are shown in fig. 4 and fig. 5. A lifetime measurement by means of recoil distance measurement with a piezo regulated plunger has been performed as well. Fig. 6 shows spectra for several distances. Even eγ coincidence measurements with a mini-angle spectrometer with neutron multiplicity condition have been performed easily on 76Ge, 74Kr and 72Kr. Results of all these measurements on 74Kr can be found in another contribution to this conference.

Many test measurements in the mass region A = 40 - 110 proved the universal applicability of this method. So for example fig. 7 and fig. 8 show two spectra for the production of very neutron deficient nuclei. Fig. 7 shows a neutron multiplicity gated spectrum of the reaction $^{58}\text{Ni} + ^{12}\text{C}$. The charged particle channels are nearly suppressed. From the reduction factors we learn that the other lines have neutron multipli-

Fig. 5 Example for a n-γ-γ coincidence measurement of the reaction $^{58}\text{Ni} + ^{19}\text{F}$ with a gate on the 456 keV 2'→0' transition of $^{74}\text{Kr}$.

Fig. 6 Recoil distance measurement of the reaction $^{58}\text{Ni} + ^{19}\text{F}$ at four distances between target and stopper. Time of measurement for each distance = 7 h.

Fig. 7 Neutron multiplicity gated singles spectrum of the reaction $^{58}\text{Ni} + ^{12}\text{C}$. Time of measurement 8 h. Explanation see text.

$^{58}\text{Ni} + ^{12}\text{C} \rightarrow ^{76}\text{Ge} + ^{6}\text{As}$

$^{58}\text{Ni} + ^{12}\text{C} \rightarrow ^{76}\text{Ge} + ^{6}\text{Ge}$
city one. All xpy candidates in this reaction are still unknown so that identification is only possible by means of additional measurements for example a coincidence with charged particles which is subject of our recent test. The next picture shows a nice example for the separation of neutron channels in the mass region > 100.

In summary the versatility and high efficiency of the system made us sure that this technique will be a standard tool in the future to get access to very neutron deficient nuclei where conventional γ-spectroscopic methods failed.

1) L.M. Bollinger, G.E. Thomas, Rev. Sci. Instr., 32 (61) 1044
2) P. Betz et al., Nucl. Instr., 119 (74) 199
3) L. Cleemann et al., Nucl. Instr. 156 (78) 477
4) W. Neumann et al., Nucl. Instr., 164 (79) 539
† Supported by BMFT

DISCUSSION
I. Bergström: You showed a neutron multiplicity trigger γ-spectrum where my bare eye could just resolve the 8+_1 6+_1 transition. How were you then able to see the 20+_1 18+_1 transition?
J. Eberth: Firstly, by summing the coincidence spectra of the lowest five transitions of the ground state band. Then, for all new lines showing up in this spectrum, which indeed had rather low intensities, at least five gates were set passing the line under consideration. By this procedure a consistent set of coincidence spectra was achieved resulting in the shown level scheme. One should mention that the low background of the neutron-gated γγ coincidence spectra helps very much to identify weak transitions.

Fig. 8 Neutron multiplicity gated singles spectrum of the reaction $^{32}$Mg + $^{19}$F. The marked peaks are transitions in $^{108}$Sn. Total time of measurement: 6 h.

To extend the system to multiplicities greater than four and to increase the efficiency for the higher multiplicities we are going to enlarge the number of neutron detectors by four additional but separate scintillators, so that all in all we have a sensitive area of 1453 cm$^2$ around the target approaching 4π geometry. The remaining holes in this geometry essentially are filled by three Ge(Li) detectors. The fact that the Ge(Li) detectors themselves are surrounded by the liquid scintillators leads to another possible application of the system. As the neutron detectors have a reasonable efficiency for γ-rays and the PSD gives out the γ-information too we can use the system as anticompton shield as well. First tests let us look forward quite
Abstract

The meson factories such as the Los Alamos Meson Physics Facility have made possible high flux medium energy proton beams that can be used for spallation reactions to produce macro quantities of unstable isotopes. Targets of over 10 g/cm² can be exposed to total fluence approaching 1 A-hour resulting in spallation yields in the 0.01-10µg range for various nuclear targets and potential instabilities found in nuclear structure studies. With the use of hot cell facilities, chemical processing can isolate the desired material and this coupled with subsequent isotope separation can result in usable quantities of material for nuclear target applications. With unstable isotopes as target materials, conventional nuclear spectroscopy techniques can be employed to study nuclei far from stability. The irradiation and processing requirements for such an operation, along with the isotope production possibilities, are discussed. Also presented are initial experiments using a 148Gd (t₁/₂ = 75a) target to perform the (p,τ) reaction to establish levels in the proposed double magic nucleus 154Gd.

1. Introduction

Study of nuclei far from stability is usually accomplished using conventional targets with exotic reactions and/or sophisticated detection techniques. The major exception to these conventional targets has been in the study of the properties of the heavy actinides for which reactor-based production programs have provided sufficient materials for targets as heavy as 247Am. With the advent of the high intensity meson factories such as LAMPF, a new possibility has emerged for the production of macro quantities of off-stability isotopes using spallation reactions to provide nuclear target materials. The Los Alamos Meson Facility, on a routine basis, now provides beams of 500-600 µA of 800 MeV protons. The major purpose of the facility is to produce pions and muons in various production targets, but following this production a substantial amount of the primary proton beam is still available. Through irradiation facilities located at the beam stop area, spallation reactions can be performed on a variety of target materials. For this to be a viable operation, the capabilities and expertise for the handling and chemical processing of the intensely radioactive samples have to be available. To produce targets for further nuclear studies, the chemically separated samples have to be, in general, isotopically separated onto suitable backings for nuclear reaction studies. With these combined technology capabilities, it then becomes possible to reach nuclear regions far from stability by using conventional nuclear spectroscopy probes with their intrinsically high efficiency and resolution. To date, we have begun initial steps to develop these capabilities and, as a demonstration of the technique, have produced a 148Gd target (t₁/₂ = 75a). With this target we have performed the 148Gd (p,τ) 148Gd reaction to study the low lying levels in the interesting nucleus 148Gd.

2. Irradiation and Processing

To make use of the large beam available in the LAMPF beam stop area, an extensive isotope production program was begun with the emphasis on medical applications. There are clinical requirements for a large variety of specific radioactive isotopes for diagnostic and therapeutic application. Often it is desirable to produce large quantities of a relatively long lived isotope which can then serve as a "cow" or generator for some shorter lived isotope which is used in nuclear medical applications. With this procedure radioactive compound labeling can be obtained, if required, and a controlled specific radiation dose can be administered. For these purposes it is necessary to be able to produce macro quantities of the primary isotopes of interest. To this end an irradiation facility was constructed at the LAMPF beam stop and is schematically illustrated in Fig. 1. The constraints on this facility are that it be able to withstand the intense proton beam and provide convenient access to enable remote easy target insertion, exchange and servicing. This "stringer" facility allows the insertion of up to 9 target assemblies for simultaneous irradiation. Each of the targets is water cooled with a flow rate of ~60 liter/min to enable dissipation of the 30-50 kilowatts of power delivered by the beam. A photograph of a standard target assembly is shown in Fig. 2. The total thickness is 38 mm, and the primary housing is constructed of aluminum with a thickness in the irradiation region of 6 mm. A copper block is inserted into this irradiation window, and it contains the target material. In general the targets can be up to 12 mm thick and 25 cm² in area. The large area is required since the beam substantially diverges when it goes through the pion production targets and

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Fig. 1 Schematic representation of the remote irradiation facility at LAMPF. Up to nine targets can be irradiated at one time. Each is water cooled with a flow rate of ~60 liter/min.

- 684 -
continues to diverge through small angle scattering throughout the stringer target assembly.

A typical irradiation cycle of LAMPF is ~4 months during which time 1/2 A-hr of proton beam will be delivered to the stringer irradiation facility. During this period, targets will be inserted and removed as required for production of specific isotopes. In general, these irradiations result in intensely radioactive target assemblies with initial activity levels in the hundreds or thousands of Röntgen range. The assemblies are loaded into a special can made of enriched 239Pu and transported to a hot cell facility located some 5 km from LAMPF. In this facility the targets are removed from the can and disassembled for chemical processing. All standard chemical procedures can be remotely carried out within the hot cell area. Once the desired isotopes are extracted, they can be packaged in a form suitable for shipment to medical facilities. This extensive capability also permits the possible isolation of desired isotopes for nuclear studies as well.

3. Isotope Production

The initial feasibility studies of producing targets from isotopes made at LAMPF have concentrated on the spallation products formed with protons on Ta targets. Ta is an essentially monoisotopic metal and has excellent thermal properties for exposure to the high flux beam. Since it is a heavy element, the spallation process concentrates production into a broad range of neutron deficient isotopes throughout the rare earth region. Figure 3 shows some experimental data and a calculated cumulative spallation yield cross section for 540 MeV protons on Ta using an inter-nuclear cascade model followed by statistical evaporation. The model reproduces the general shape and magnitude of the measured distribution, but the important point to note is that there is substantial cross section for production of neutron deficient isotopes throughout the rare earth region. With an irradiation of a target of 10g/cm² with a total fluence of 0.5 A-hr of protons, a cross section of 1 mb results in production of ~100 µg of product.

The spallation yield is maximized for neutron deficient isotopes as indicated in Fig. 4. The average primary mass produced in the reaction is displaced by 5-10 neutrons from the line of beta stability toward the neutron deficient side. Of course, the distribution is quite wide having a c of about 2.2 for a given mass chain. This provides independent yields to a substantial number of isotopes and thus, to some extent, can overcome shielding effects associated with beta stable isotopes blocking the cumulative chain. In this production region several isotopes are of potential interest for targets for nuclear structure studies. For ease of handling the initial efforts will concentrate on the long lived α-emitting rare earths 144Sm ($t_1 = 10^4$ a), 148Gd ($t_1 = 75$ a), 152Gd ($t_1 = 1.8 \times 10^5$ a) and 153 Dy ($t_1 = 70$ a). Of these the most interesting are 148Sm and 148Gd since the $(p, t)$ pick up reaction can be used to study the closed $N=82$ shell. The nucleus 148Gd has received considerable attention recently due to its apparent double closed shell structure and in the next section we discuss our first results with the radioactive target 148Gd to produce and study this isotope.

Other isotopes of potential use are indicated in Fig. 4. Of these, two deserve special mention.
Fig. 4. Portion of a chart of the nuclides. The dashed line is the line of beta stability, and the solid line indicates the average product for a given mass formed in the proton induced spallation of $^{181}$Ta. The cross hatched boxes indicate isotopes of potential interest for target preparation. Also shown are production cross section intervals.

The first is $^{146}$Gd which has a relatively short half life of only 48.3 days. Since this is a presumed doubly closed shell nucleus various inelastic and direct reaction probes should provide corroboration for this assignment. Adequate quantities of this isotope can in principle be isolated. The most recent Gd extraction from an irradiated Ta target (Table I) had over 100 μg of this isotope at the end of bombardment. However, even a target containing only 5 μg of the isotope will have a disintegration rate of 100 milliradu and, therefore, require adequate shielding for handling purposes. Another isotope of high interest is $^{178m2}$Hf. This 31 year isomer is at an excitation energy of 2.4 MeV but, most importantly, has a spin of 16$. The nuclear structure properties associated with high angular momentum are currently an active area of research. Theoretical speculation concerning yrast traps and shape changes for nuclei of high angular momentum$^5$ has resulted in extensive experimental programs to study these regions. Our recent irradiation of 11.9 g/cm² of Ta with 0.565 A-hr of protons has resulted in the production of over 40 μg of the $^{178m2}$Hf high-spin isomer. With this as a starting material, Coulomb excitation studies using heavy ion projectiles should be able to reach the highest identified nuclear spin states. There is substantial effort being expended on the development of the so called "spin spectrometers" or "crystal balls" for measuring γ-ray multiplicities utilizing large NaI arrays. The availability of $^{178m2}$Hf would permit an extension in the use of this sophisticated equipment into unique areas.

There are still substantial problems to be overcome before $^{178m2}$Hf becomes readily available for nuclear structure studies. To obtain a suitable target the chemically isolated Hf fraction has to be isotopically separated. Since Hf is a refractory element, the efficiency for this separation might be low unless extensive ion source development is performed. Also, even though the production yield of the isomer is acceptably large, the production of the stable ground state is much larger. The cascade calculations estimate that the ground state yield will be ~150 times as large as that measured for the isomer (Table II). Even at this impurity level it

| TABLE II |
| Mass | 172 | 175 | 178m2 | 178 |
| $t_\gamma$ (a) | 1.87 | 0.19 | 31. | Stable |
| Yield t=0 (μg) | 6220. | 5290. | 41. | (6000) |

may be possible to use this target material in Coulomb excitation studies by exploiting the higher total γ-ray energy released associated with the isomer when compared with the ground state. An attractive area of research for this isomer is exploring the possibility of performing multiple step selective photoionization with laser systems. A high resolution tunable dye laser could be used to resonantly excite the unique hyper-fine level splitting associated with the isomer. This coupled with a high intensity laser could then be used to selectively photoionize the isomer permitting, in principle, isomer separation.

In addition to isotopes produced with spallation reactions on Ta there is interest in several light elements. Production targets of Cu, V and Si have been irradiated in the primary proton beam. For these lighter elements the lower charged particle Coulomb barrier results in more equivalent proton and neutron emission. The yields are, therefore,

| TABLE I |
| Mass | 166 | 148 | 151 | 153 |
| $t_\gamma$ (a) | 0.13 | 75. | 0.33 | 0.66 |
| Yield t=0 (μg) | 115. | 300. | 206. | 179. |
not as skewed toward the neutron deficient region. Figure 5 presents this lighter element region and indicates isotopes of interest. Table III summarizes these isotopes and indicates the production yield expected in a typical LAMPF irradiation cycle (~4 months). In all cases 10^6-10^8's of µg are

![Fig. 5. Portion of a chart of the nuclides emphasizing the lighter element region. Dashed line is the line of beta stability. Labeled open boxes are primary irradiation targets for proton induced spallation reaction, while the cross hatched boxes represent isotopes of interest for secondary target preparation.](image)

### TABLE III

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Target</th>
<th>Production/Cycle (µg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60^Fe</td>
<td>Cu</td>
<td>20-200</td>
</tr>
<tr>
<td>44^Si</td>
<td>V</td>
<td>20-200</td>
</tr>
<tr>
<td>32^Si</td>
<td>V</td>
<td>30-300</td>
</tr>
<tr>
<td>26^Al</td>
<td>Si</td>
<td>50-500</td>
</tr>
</tbody>
</table>

Production of Light Isotopes

expected, and this should be adequate feed material to produce usable nuclear targets. Properties associated with these isotopes can yield information regarding the nucleosynthesis process in stars and the processes involved in supernova explosions. Through the use of the (t,nHe) reaction information can be acquired on the low lying 1^+ levels and thus some insight for the Gamow-Teller decay strength, which is important for understanding isotopic production in nucleosynthesis and in supernova. The extension of these studies to the most neutron rich isotopes is important and, therefore, measurements on 44^Fe (3 x 10^8's) is of special interest. The (t,p) reaction on 60^Fe would provide an extension of available information on level structure for the nuclear synthesis codes.

The (p,y) measurements on 26^Al (7.3 x 10^8's) are also of astrophysical interest. Recent measurements of 26^Mg in meteorites has led to discrepancies in the theories of nucleosynthesis and the origin of the solar system. By directly measuring the (p,y) cross section on this isotope the nature of this apparent discrepancy can be investigated. Studies on 44^Ti (47a) can provide insight into level structures in this region and are also important for nucleosynthesis systematics. Another unique isotope for study is 32^Si (~650a). This very neutron rich isotope permits examination of the nuclear region which bridges the gap between the deformed s-d shell and the closed N=20 neutron shell. Using the (s,n) and (t,n) reactions this region could be investigated in detail.

For each isotope to be studied, chemical processing techniques have to be perfected for operation in remote hot cells to efficiently extract microgram quantities from up to kilogram samples. In general these chemically isolated products have to be isotopically separated onto thin target backings. This requires development of ion source technology and the availability of a separator which can safely handle the radioactive feed material and be adequately decontaminated following the separation. As a long term development, shorter lived isotopes will become more attractive for potential target material. This will necessitate rapid handling throughout the processing and coordination with accelerator scheduling to maximize the usefulness of the target.

4. Initial Experiment: 134^Gd(p,t)168^Gd

The nucleus 146^Gd has received considerable attention recently because of its supposed doubly closed shell character. It has, like 132^Sn and 208^Pb, a high lying 1^+ first excited state. Because 146^Gd lies too far from the line of beta stability to be examined by normal light ion particle transfer, it has been studied only through γ-ray and conversion electron measurements following xn reactions and by two proton transfer using heavy ions and the (He,n) reaction. In order to complement the xn studies and to improve the resolution obtainable with the two proton transfer reactions we have prepared a 148^Gd (t,He) 75a target and performed the 148^Gd(p,x) 144^Gd reaction.

The target material was produced by spallation reactions on a 22 g/cm² Ta target. The primary beam energy of 800 MeV protons was degraded to the 400-700 MeV range through various production targets placed before our target. This was a relatively early exposure at LAMPF with the irradiation carried out during 1978 when the average beam current was on the order of 100 mA. An integral beam fluence of ~5.6 x 10^14 no/hr was seen by the target. The tantalum was transported to a hot cell facility for chemical processing. It was dissolved in a 6:1 HNO₃:mixture, and the rare earth group was isolated from the bulk solution by adding a lanthanum carrier and precipitating the rare earth fluorides. The rare earths were placed back in solution and separated from each other by using standard cation exchange chromatography with c-hydroxysisobutrylic acid as the column eluant. The chemically extracted gadolinium fraction was assayed to contain 9.8 µg of 144^Gd. A 1 µg carrier of natural Gd was added to the solution and then precipitated as a wet hydroxide. The precipitate was shipped to Lawrence Livermore National Laboratory where it was converted to an oxide and isotonically separated. The 144^Gd was collected on a 40 µg/cm² carbon foil into a normal spot size of 2 x 2 mm². The target was returned to Los Alamos where a thickness determination was performed using 14C elastic scattering, which gave only a limit of <16 µg/cm².

Using the three stage capability at the Los Alamos Van de Graaff facility we used 24 MeV protons to perform the (p,t) reaction. Assuming the ground state cross section of the reaction on 134^Gd to be the same as the previously measured 134^Ce(p,t) 132^Ce, a thickness of 6 µg/cm² was obtained. The triton spectra were recorded using a Q30 spectrometer.
having a 1 meter position sensitive helical wound
detector located at the focal plane. Figure 6 pres-
ent a spectrum obtained at a scattering angle of
25°. Even with this very thin target a nine point
angular distribution was measured for all states
below 2.5 MeV. Experimental results and the corre-
sponding DWBA fits are shown in Fig. 7 for three
different levels. One important result from these
measurements is that no excited states lie below
the 1.575 MeV level, thus corroborating previous
studies and supporting the double magic character
of this nucleus. The DWBA analysis of this level is
consistent with an L=3 assignment, but we do not
feel it is sufficiently unique to firmly establish the
spin from this analysis. The level at 1.980 MeV
is established as an L=1 transfer and is consistent
with assignment as a 2° level made through difficult
threshold analysis in an 144Sm(n,2ny)146Gd measure-
ment15). In the normal γ-ray cascade this level is
not a member of the yrast band and is thus not pop-
ulated. With our light ion direct reaction tech-
nique the assignment of this important level is
clearly established. The level at 2.173 MeV has the
distinctive signature of an L=0 transfer and is in
agreement with the recent assignment based on xn,
conversion electron measurements15). This level is,
however, not the pairing vibration state since it
contains less than 10% of the ground state strength.
Figure 8 presents a level scheme for the low lying
levels in 146Gd as deduced from our (p,t) measure-
ments along with previous assignments from xn stud-
ies.

The results of the present experiment clearly
show that useful nuclear reaction results can be
obtained on targets as thin as ~10 μg/cm² using
light ion reactions and a high resolution spectrome-
ter. Irradiation using higher beam fluences can
potentially provide orders of magnitude more material
for target preparation. We anticipate that this
will open new regions for significant physical
measurements in previously inaccessible areas.

5. Acknowledgements

We would like to thank R. J. Prestwood for che-
micai assistance in preparation of the Gd, and R.
J. Dupzyk for isotopic separation at the sample.
This work was done under the auspices of the United
States Department of Energy.

Fig. 6 A portion of the triton spectrum from the
reaction 144Gd (p,t) 146Gd.

Fig. 7 Angular distribution for three levels in
146Gd. The solid lines are DWBA fits with the
indicated transferred angular momentum.

Fig. 8 Deduced level scheme for low energy states
in 146Gd. Assignments from the current
(p,t) investigations are indicated on the
right, while previous assignments based on
(xn,μ and e') are on the left.

References
1. H. C. Britt, Physics and Chemistry
of Fission 1979, (International
Atomic Energy Agency, Vienna)


DISCUSSION

F. Roecki: What are the overall efficiencies you obtained in mass separating gadolinium and hafnium?

J.B. Wilhelmy: For the gadolinium efficiencies as high as 60% have been obtained. However, in the case of the preparation of our target on a thin carbon backing the collection was ~ 15%. For hafnium we have not determined an efficiency as yet but for the chemical homolog Zr we have obtained ~ 5-10% collection efficiencies.

W. Benenson: Can you tell us how dangerous and radioactive the actual targets are?

J.B. Wilhelmy: For the 154Gd target we have used, the activity was ~ 20-30 μCi and since this is a low energy alpha emitter it is relatively easy to handle. We do however hope to make a target of 154Gd which has only a 38-day half life. In this case a target containing 5 μg of material will have an activity level of ~ 100 mCi and this requires more caution in handling. We do have experience in working with similar activity levels in actinide element targets where we have not encountered undue difficulties.

R.A. Naumann: As an indication of the feasibility of using radioactive targets of moderately short half-life for triangular spectroscopy, I can report that we have been carrying out experiments at Princeton using 300-cay berkelium 249 in collaboration with the Livermore National Laboratory. The targets were isotope separated at Livermore and transported and used at Princeton without problems.

J.B. Wilhelmy: We have had similar experience at Los Alamos.

F. Kleinheinz: The 0.16 MeV 0+ state in 154Gd as discussed by Julin et al. [Phys. Lett. 94B (1980) 123] is predominantly the proton 0+ level, and therefore quite expected to be only weakly seen in (p,t). It also would be most attractive to determine the masses of 154,155,156,157Gd from transfer studies with this target, and to obtain neutron single particle strengths.
NUCLEAR TRANSFER SPECTROSCOPY USING RADIOACTIVE TARGETS†

R. A. Naumann, R. Dewberry, R. T. Kouzes
(Princeton University)
R. Hoff, H. Börner, R. G. Lanier, L. Mann, G. L. Struble
(Lawrence Livermore Laboratory)

Abstract

The feasibility and techniques for carrying out transfer spectroscopic experiments with radioactive targets having half lives down to a fraction of a year are reviewed. The use of such radioactive targets is illustrated by recent studies of the spectroscopy of $^{155}$Sm, $^{177}$Lu and $^{247}$Bk using (p,t) transfer spectroscopy.

1. Introduction

The specificity of charged particle transfer spectroscopy applied to shorter lived isotopic targets affords many interesting possibilities for detailed examination of the structure of nuclei lying off the stability line. Two developments make possible such experimental investigations: first, the availability of high flux reactors or the high current beams at the meson factories and, second, the development of the highly efficient thermal ion sources used to prepare the isotopic targets. The latter technology has been particularly developed by Johnson's group11 at the Livermore National Laboratory and by Raiko12 and his collaborators at Dubna.

The activity levels involved in such investigations are not prohibitive. For example, a 2 microgram target occupying dimensions 5 mm x 2 mm corresponds to a thickness of 20 µg/cm², a target thickness quite adequate for precision nuclear spectroscopy using current apparatus.

If one considers the disintegration rate for such a 2 microgram quantity of a pure isotope with mass 150, one finds the activity levels are quite acceptable from the point of view of preparation and manipulation at the spectrograph as shown in the table below.

<table>
<thead>
<tr>
<th>Half Life (years)</th>
<th>Activity Level (millicurie)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10³ years</td>
<td>5x10³</td>
</tr>
<tr>
<td>1 year</td>
<td>5</td>
</tr>
<tr>
<td>1/3 year</td>
<td>15</td>
</tr>
</tbody>
</table>

With the availability of such radioactive targets numerous interesting prospects unfold among which are the investigations of the level structures of transuranium nuclei, odd-odd nuclei using two nucleon transfer spectroscopy and the structure of nuclei in the vicinity of shell closures such as occur near $^{29}$Ni$_{12}$ or $^{15}$Cd$_{8}$.

$^{23}$Bk

To illustrate some of these we have chosen three studies completed at the Princeton University Q30 Spectrograph.

†) Work supported by the United States Department of Energy and the National Science Foundation.

The first figure shows the identification of the rotational band based on the Nilsson 7/2+ [633] proton state in Berkelium 247 using the (p,t) reaction with 320 day Berkelium 249 as a target.

![Fig. 1 Levels in $^{247}$Bk$_{152}$ from the (p,t) reaction on 320 day $^{249}$Bk$_{154}$.](image)

The latter is exceptional among the odd A Berkelium isotopes in having a 7/2+ ground state. This ground state has been previously assigned as the [633] state. We observe the (p,t) reaction specifically populates 6 members of the rotational band in Berkelium 247 which corresponds to the ground state of Berkelium 249. The specificity of the (p,t) reaction and the close similarity of the 7/2+ [633] states in both Berkelium 247 and 249 is shown by the absence of evidence for population of any other states in $^{247}$Bk.

Figure 2 displays the triton spectra observed in the (p,t) reaction on a target of 90 year Samarium 151, a nucleus lying in the shape transition region with 89 neutrons.

![Figure 2](image)
Fig. 2 Levels in $^{149}\text{Sm}$ from the $^{151}\text{Sm}$ (p,t) reaction.

the $L = 0$ angular distributions observed in the stripping reaction.

The possibility of employing radioactive odd-odd nuclei as targets is particularly intriguing both because of the scarcity of these nuclei among the naturally occurring species and also because the specificity of certain transfer reactions permits the relationship of states occurring in two nearby odd-odd nuclei to be established.

Figure 3 shows the states in odd-odd lutetium 174 populated by the (p,t) reaction using an enriched sample of naturally occurring odd-odd lutetium 176.

One rotational band (with rotational members at 715, 922 and 1142 keV) is populated; the prominent 7-2 quasiparticle band head is located by these studies at 523 keV. On the basis of the $L = 0$ angular distribution and the intensity observed for the 523 keV state we are able to assign this band in lutetium 174 as the two neutron hole analog of the ground state band known in lutetium 176 having the same two quasiparticle configuration for the odd neutron and proton in both product and target. The relatively strong population observed for the second 7-state at 320 keV, however, indicates that, in the case of the (p,t) reaction in odd-odd nuclei less perfect overlap occurs between the ground state of the target and the product.

We conclude that the relatively greater effort involved in preparing radioactive targets for selected charged particle transfer investigations is rewarded by spectroscopic results for nuclei lying off the stability line which cannot be achieved using other techniques presently available.

References


THE DECAYS OF NEUTRON DEFICIENT $^{103}$In AND $^{102}$In

R. Beraud $^+$, J. Tréherne $^+$ $^{++}$, A. Charvet $^+$, R. Duffait $^+$, A. Ensailem $^+$, J. Genevey $^+$ $^{++}$, A. Gizon $^+$ $^{++}$, J. Gison $^+$ $^{++}$, M. Meyer $^+$

$^+$ IPN (IN2P3), 69622-Lyon-Villeurbanne, France
$^{++}$ ISN (IN2P3), 38026 Grenoble, France

Abstract

Using an on-line mass isotopic separator operating on nuclear reactions induced by heavy ions, $^{102}$In ($T_{1/2} = 24 + 4$ seconds) has been identified for the first time. Gamma-rays observed in the decay of $^{102}$Cd were compared with previous in-beam experiments on $^{101}$Cd and $^{102}$Cd. The partial level scheme deduced for $^{102}$Cd has been included in the systematics of ground bands of the even cadmium isotopes.

1. Introduction

This paper deals with the investigation of the short-lived very neutron-deficient isotopes of indium in the vicinity of $^{103}$In, the spherical double closed shells far from stability which always represents an exciting experimental challenge. It is interesting to study the lighter cadmium nuclei reached by the indium's decays to extend the experimental systematics available on the heavier ones and to compare the situation to the theoretical predictions. Indeed, in this region, constrained Hartree-Fock calculations including pairing correlations and performed with the SKIII Skyrme effective force have been used to determine the deformation energy curves of $^{98-102,106-110}$Cd. With this description, $^{100}$Cd appears spherical and the even heavier cadmium present a small prolate deformation. Then, from self-consistent calculations, the neutron and proton quasi-particle states are extracted at equilibrium deformations and injected in a rotor-plus-quasi-particle model to describe the odd-A cadmium nuclei. The development of several bands as the $h_1/2$, $g_7/2$ and $d_5/2$ ones is predicted. Moreover, these calculations do not predict a prolate-oblate shape coexistence at low energy for odd-A isotopes.

Experimentally, the in-beam gamma-ray spectroscopy applied to heavy-ion reactions is a classical tool to investigate neutron-deficient isotopes. Unfortunately, the very neutron deficient compound nuclei reached present a complicated deexcitation, with many evaporation exit channels. More or less collective structures are easily identified in the final nuclei but, in general, from excitations functions, their Z and A identification is ambiguous.

If the cross-section of the final products is not too low, the on-line mass separation is a powerful technique to identify the isotopes by a few low-energy excited states and also to observe isomers which could be eventually correlated to a shape transition.

As experimental in-beam results were available in our laboratory on $A = 103, 102$ $^{2)}$ chains a complementary study has been undertaken with online isotopic separation for a Z determination. It is reported in this paper.

2. Experimental technique

The experiments were carried out using the 5-10 MeV/nucleon heavy-ion beams from the Grenoble variable energy cyclotron and the mass separator operating on-line. The details concerning this new possibility will be described elsewhere but few points typically related to the indium separation are reported here.

The Hier-Bernas-Charvet type ionization ion-source of the magnetic separator $^{3)}$, with a vertical arc perpendicular to the extracted ion-beam direction, has been modified to use the recoil of the nuclei produced in the target by the heavy-ion reaction. A photography and a schematic view of the modified ion-source are presented in figures 1 and 2, respectively.

Figure 1 - Photography of the ion-source
For the production of indium isotopes, the best results have been obtained with a natural molybdenum target (roughly 5 mg x cm^{-2} thick) placed in the front of a graphite catcher (Papier N from Carbone Lorraine, 0.15 - 0.3 mm thick), operating with 800 nA to 3 mA ¹⁴N⁺ beams delivered by the accelerator. The catcher was heated at a temperature of 1600-1700°C to diffuse out the recoiled isotopes inside the ionization chamber. The extraction of indium has been carefully studied on ¹⁰⁶In produced by ¹⁴N beams on natural molybdenum targets. Then, on the basis of the Alice Code predictions, the production of ¹⁰³,¹⁰⁴In has been improved at different beam energies for both the ⁹²Mo + ¹⁶O and the ⁹²Mo + ¹⁴N reactions. The latter reaction was found to be the most efficient at 80 MeV for ¹⁰³In and at 86 MeV for ¹⁰⁴In respectively. These productions have been compared with the ones obtained at Isocele 2, with light particle projectiles (figure 3).

The mass separated products were collected and transported in front of detectors. The identification of the isotopes was mainly based on the γ and X-ray singles measurements with intrinsic Ge detectors. The half-lives were determined by a classical multi-spectrum analysis consisting of 8 time subgroups (2K channels each).

Figure 3 - Productions of indium isotopes

- Sn + p 210 MeV
- Sn + ³He 270 MeV
- Sn + α 218 MeV
- Ag + ³He 270 MeV

Isocèle II Grenoble

3. Experimental results

3.1. The ¹⁰³In isotope

Before this investigation, ¹⁰³In was the highest known indium isotope, identified at Louvain by Jeunesse et al. The present experiment, a half-life of 1.0 minute has been found, in good agreement with the previous one (T₁/₂ = 1.08 ± 0.11 minute). In addition, several new γ-rays have been assigned to the ¹⁰³In → ¹⁰³Cd decay (Table 1). The strongest lines correspond to the ones at 188 keV, M1 (7/2⁺ - 5/2⁻) and 720 keV, E2 (11/2⁻ - 7/2⁻) already placed in ¹⁰³Cd by in-beam investigations on the ⁹⁶Mo(¹⁴C, 3ny) reaction ⁵. Up to now, the other new transitions have not been unambiguously inserted in the ¹⁰³In → ¹⁰³Cd decay scheme and complementary coincidences measurements have to be performed on ¹⁰³In separated samples after the energy improvement.
of the Grenoble accelerator. Nevertheless, combining these preliminary data with in-beam results the most probable spin assignment for $^{103}$In is 9/2.

3.2. The $^{102}$In isotope

In the multispin analysis performed on the $^{102}$Cd decay at a beam energy of 86 MeV, in addition to the well-known $\gamma$ lines of the $^{102}$Cd $\rightarrow$ $^{102}$Ag $\rightarrow$ $^{102}$Pd decay, four new $\gamma$-rays at 776.8, 861.4, 593.0 and 396.5 keV have been found to decay with an average half-life $T_{1/2} = 24 \pm 4$ seconds, as shown in figure 4. Relative intensities of the gamma transitions have been reported in Table 1.

Due to the presence of an enormous amount of K-X lines associated with the $^{102}$Ag $\rightarrow$ $^{102}$Cd decay (Ag/In production ratio $>10^3$), K-X rays characteristic of Cd element have not been observed. Nevertheless the four lines never seen before belong necessarily to the $^{102}$In $\rightarrow$ $^{102}$Cd decay for the following reasons. The $A = 102$ mass chain starts at the indium element through the $^{92}$Mo $\rightarrow$ $^{14}$N reaction and these lines have also been observed in in-beam experiments leading to the excited states of $^{102}$Cd produced in the $^{92}$Mo $\rightarrow$ $^{12}$C reaction at 50 MeV and the $^{102}$pd $\rightarrow$ $^{3}$He reaction at 35 MeV. In these cases their intensities are in agreement with those of the $\gamma$-rays of the daughter activity (Cd $\rightarrow$ Ag) measured after the beam cut-off.

From $\gamma$-$\gamma$ coincidences and angular distribution measurements performed in-beam\(^{11}\), the 776-861-503 keV transitions form a $\Delta I = 2$ cascade and connect the $0^+$, $2^+$, $4^+$, $6^+$ excited levels (figure 5). Due to the relative intensities of the $\gamma$-rays in both in-beam and decay experiments, the 776.8 keV transition is placed at the bottom of the sequence but the reversed order (861-776) is not excluded.

According to the observed cascade, the spin of the $^{102}$In identified by isotopic separation should be $> 5$.

Table 1 : Relative gamma-ray intensities observed in the $^{102}$In and $^{103}$In decays.

<table>
<thead>
<tr>
<th>$^{102}$In</th>
<th>$^{103}$In</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\gamma$</td>
<td>$I_\gamma$</td>
</tr>
<tr>
<td>156.6</td>
<td>10</td>
</tr>
<tr>
<td>396.5</td>
<td>12</td>
</tr>
<tr>
<td>593.0</td>
<td>30</td>
</tr>
<tr>
<td>776.8</td>
<td>100</td>
</tr>
<tr>
<td>861.4</td>
<td>96</td>
</tr>
<tr>
<td>(923.7)</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4 - Decay curves of the $\gamma$-lines ascribed to the $^{102}$In $\rightarrow$ $^{102}$Cd decay.

Figure 5 - Partial decay scheme of $^{102}$In $\rightarrow$ $^{102}$Cd

4. Discussion

Using the new ground state band identified in $^{102}$Cd, the systematics of the $2^+$, $4^+$ states in even cadmium nuclei can be extended (figure 6). A sudden rising of these levels is found in $^{102}$Cd in comparison with the heavier isotopes and indicates an important decrease of the deformation. This observation is in agreement with the Hartree-Fock calculations performed on these even cadmiums\(^{11}\). Indeed, from this treatment, the $\beta_2$ parameter associated with a prolate deformation varies from $\beta_2 = 0.17$ in $^{110}$Cd to $\beta_2 = 0.10$ in $^{102}$Cd. The quadrupole moments have not been measured for these lighter even cadmiums and the prolate shape is only confirmed.
Figure 6 - Systematics of the $2^+$ and $4^+$ levels in light even Cd nuclei.

experimentally by the characteristics of the collective structures observed by in-beam spectroscopy in the neighbouring odd-A isotopes $^5$).

Another theoretical approach has been made for the $^{102}$Cd nucleus in the frame of a shell model calculations around the doubly closed shells $^{100}$Sn isotope $^6)$. A very good agreement is observed for the calculated and experimental $^2$) ground bands and also for a second $6^+$ level identified at 2561 keV in the $^{112}$Mo($^{12}$C, $2n$) reaction.

References


DISCUSSION

A. C. Miller: We have measured hyperfine structures and isotope shifts for the sequence of Cd-isotopes between 102 ≤ A ≤ 120. Extracting deformation from our data we see a gradual decrease in deformation approaching lower neutron numbers consistent with what you have shown.

J. Eberth: I would like to comment on your statement that it is difficult to study $^{112}$Cd by in-beam $\gamma$-spectroscopy. We have investigated the reaction $^{112}$C + $^{11}$Be with the neutron multiplicity technique which I presented in my talk of this morning. As you see from the transparency in the two-fold neutron gated $\gamma$-spectrum there are two weak neutron exit channels enhanced, namely the $2n$-channel to $^{100}$Cd and the $p2n$-channel to $^{111}$Ag. All transitions assigned by your work to $^{107}$Cd can be identified with a good peak-to-background ratio. The 861.1 keV transition has about twice the intensity of the 776.6 keV line in our spectrum. As there is no evidence for a doublet, 861.1 keV might be the energy of the ground state transition and 776.6 keV the $4^+ + 2^+$ transition. But still one has to be careful if the 861.1 keV line has not partially to be assigned to $^{111}$Ag which we will prove by a n-$\gamma$-$\gamma$ coincidence measurement.

W. Andrae: A confirmation of many two-quasiparticle assignments in $^{108}$Cd are the five new isomers in the nanosecond region we found recently in reactions with $^{18}O$ on the Rutgers tandem.

J. Staehel: I do not yet see how you get your evidence for triaxiality in Ba-isotopes; are you sure that it is not possible to reproduce your data by coupling an odd particle to a $\gamma$-unstable core?

A. Gison: I can only say that we have used a special model to reproduce our in-beam measurements and that we know that different models are able to do the same thing.
APPLICATIONS OF NUCLEAR DATA ON SHORT-LIVED FISSION PRODUCTS

G. Rudstam, P. Aagaard, K. Aleklett, and E. Lund
The Studsvik Science Research Laboratory,
S-611 82 Nyköping, Sweden

Abstract

The study of short-lived fission products gives information about the nuclear structure on the neutron-rich side of stability. The data are also of interest for various applications both to basic science and to nuclear technology. Some of these applications, taken up by the OSIRIS group at Studsvik, are described in the present contribution.

1. Introduction

By now, many aspects of the properties of nuclei far from stability have been studied in great detail, and a multitude of experimental results have evolved. Apart from the inherent interest of these results for the understanding of nuclear structure in these regions of the nuclidic chart, the data collected are also very valuable for other branches of science and technology. The aim of the present contribution is to show how data for short-lived fission products find their way into other fields, both fundamental and technical ones.

Many of the applications of a technical nature are connected in one way or another to the problems arising from the use of nuclear power. Quite generally one may state that an extensive knowledge about the properties of all the fission products, the short-lived ones included, is indispensable from the simple fact that these radioactive nuclei are produced in large quantities in the nuclear power stations. An obvious requirement ought to be that the properties of this waste from the power production should be known in detail. Apart from this aspect a few specific fields may be mentioned where the OSIRIS group at Studsvik is involved, namely

- the evaluation of the power developed in nuclear fuel by decaying fission products (essential data: decay properties, especially half-lives and average beta and gamma energies, fission yields);
- the effective delayed-neutron energy spectrum in nuclear fuel (essential data: half-lives, neutron branching ratios, and neutron energy spectra of individual delayed-neutron precursors, fission yields);
- the independent-yield pattern of fission products (essential data: half-lives, presence of isomers, branching ratios of gamma-rays used in the measurements of abundances).

There are also fields within basic science where the knowledge about the properties of short-lived fission products is of great value. One such field is related to experiments using antineutrinos from reactors. For the interpretation of these experiments the energy spectrum of the antineutrinos must be known. The origin of the antineutrinos is the beta decay of the fission products in the fuel which means that the energy spectrum can be evaluated from the decay data and abundances of these fission products. In particular, the data on those products with high Qβ-values are of interest since it is these nuclides which are responsible for the important high-energy part of the antineutrinos.

Another field of application of decay data of strongly neutron-rich nuclei is the theory of nucleosynthesis. The rapid process of element build-up, for example, follows a path displaced far out on the neutron-rich side of stability. The nuclei actually taking part in the process are almost entirely out of reach for experimental techniques of today. Nevertheless, a detailed knowledge about the decay properties of the most neutron-rich nuclides available for study forms an important basis for extrapolations to regions still further away from stability.

A common feature for all the applications mentioned here is that efforts are required which systematically explore wide ranges of nuclides.

2. The decay heat problem

The importance of knowing the heat developed in nuclear fuel elements by decaying fission products is very great. The reason for this is obvious. It is impossible to stop the fission process in a reactor rapidly, but it is impossible to stop the decay of the fission products. The power developed in this decay is considerable amounting to about 10% of the total reactor power at equilibrium. This represents a very large power output, and in case of a loss-of-coolant accident it might well melt the fuel with a disastrous evolution of radioactivity as a result unless emergency cooling is quickly put into force. The knowledge about the decay power is indispensable both for judging the results of serious accidents and for designing emergency cooling systems. The economic impact is also great because the heat generated will, at the end, determine the maximum running power permissible for a given reactor type.

The decay power can be determined integrally, but such determinations have the weakness that the results are strictly valid only for the experimental conditions used during their determination. A more general method is the summation method where the contributions from the individual fission products are added together, weighted according to the abundances of the fission products in the fuel. It is here where the knowledge about nuclear
properties comes in. For these summations we need to know

1) the half-lives of all nuclides concerned (including long-lived isomers),

2) the branching to different isomeric states in the daughter, and branching to neutrons for delayed neutron precursors,

3) the average beta and gamma energies.

In addition, the fission yields and neutron capture cross sections are needed for calculating the abundances. As soon as we have this set of data at hand, however, the decay heat can be evaluated for any irradiation conditions and fuel composition.

In the evaluation of the decay heat the short-lived fission products have a special importance. They have usually a large total disintegration energy, and many of them are situated close to the peak of the charge dispersion curves. Consequently, they will be responsible for a large contribution to the decay heat during a limited time after the shutting down of a reactor.

2.1 Average beta energies

It is possible to evaluate the average beta energy from the decay scheme of a nuclide provided that all beta branches, and shapes of these branches, are known. This situation is not very frequent. A more straightforward method is to measure the gross beta spectrum from as low an energy as possible up to the end-point, and then to evaluate the average energy of this spectrum with due account taken of the part falling below the low-energy experimental limit. This method is independent of any assumptions concerning, for instance, the kind of beta transitions taking place. This has been done at OSIRIS\(^2\) using the following computer-controlled sequence of steps

a) collection of the beam corresponding to the desired mass for a predetermined time,

b) movement of the sample to a measuring position,

c) simultaneous recording of beta and gamma spectra for a predetermined time with a Si(Li)-detector system for the beta particles and a Ge(Li)-detector for the gamma-rays,

d) waiting for a predetermined time,

e) repetition of steps (c) and (d) a given number of times, normally with different measuring and waiting periods,

f) repetition of (a) - (e) a given number of times to acquire counting statistics,

g) repetition of (a) - (f) with an aluminium absorber placed between the sample and the beta detector to measure the gamma effect in this spectrometer.

Using the gamma measurements of typical peaks to determine the relative abundances of the different isobars in the samples, the set of beta spectra, corrected for gamma effect and background, could be decomposed into isobaric components. These in turn were transformed into electron energy spectra using the response function of the beta spectrometer and, finally, the average beta energies were deduced.

The method described has been used to determine the average beta energy of 36 fission products. This is only a small part of the actually known radioactive fission products, which is about 400, but as many of the measured ones belong to the most important fission products their combined contribution to the total beta effect is about 30\% at cooling times between 0 and 100 seconds after stopping a reactor. For a further set of 39 nuclides results from an earlier beta strength study carried out at OSIRIS\(^2\) have been used to evaluate the average beta energy. Apart from these fission products and those with known decay schemes from which the average beta energy can be determined, there still exist about 130 nuclides known to be fission products but for which no measurements exist. Approximate values of average beta energies for these nuclides have been obtained using the assumption that the beta strength is proportional to the level density\(^2\).

Putting all data from the four groups of fission products - those with directly measured average energies, those with energies evaluated from decay scheme, those with energies deduced from beta strength measurements, and those with energies determined by the extrapolation procedure - together and combining them with other kinds of decay and fission yields, we are now in the position to determine the beta part of the decay heat for any irradiation history and fuel composition. An example is given in Fig. 1 where the data can be compared with results from an integral measurement\(^3\). Apparently, the agreement is excellent. Also the uncertainties of the two types of determinations are very similar (in the case of the OSIRIS results we have evaluated the uncertainties from the errors of the decay data and the fission yields). The figure also shows results from a summation calculation using the ENDF/B-IV data library\(^4\) which are in less good agreement with experiments.

It may be of interest to note that for long irradiations the average beta energy, average gamma energy, decay constants, and fission yields give similar contributions to the uncertainty of the decay heat values. Of much less importance are the errors of the delayed-neutron branching ratios and neutron capture cross sections\(^5\).
Fig. 1. The quantity cooling time multiplied by beta power (in MeV/fission x s) versus cooling time. Open circles with error staples (± one standard deviation): OSIRIS work\(^6\). Closed circles: Experimental results from Ref.\(^3\). Solid curve: Summation calculation using ENDF/B-IV\(^3,4\). Fuel: \(^{235}\)U.

2.2 Average gamma energies

For the average gamma energy the situation is somewhat easier than for the corresponding beta energy since we are not concerned with spectral shapes. In fact, what is needed is a set of gamma energies and their absolute branching ratios. If one wants to count the effect of conversion electrons and X-rays apart, conversion coefficients must also be part. One source of error may be, however, that our table of gamma energies may not be complete. Referring to the "Pandemonium" discussion\(^6\) we note that a substantial part of the gamma-rays may be missing. If these gamma-rays should be grouped in certain energy regions this will lead to an error of the average gamma energy, which is hard to estimate. Therefore, direct measurements of the gross gamma spectrum using a low-resolution spectrometer such as Na\(_I\) should be worth while, and we are planning such a project at Studsvik. The technique would then be similar to that for the average beta energy.

Another difficulty with the average gamma energy is that the absolute branching ratios are often much less precise than the relative ones. Therefore, an attempt to determine accurately and on the absolute scale the branching ratio of one of the gamma-rays is often called for.

It may be noted that the results of the experimental beta strength study\(^2\) can be used to deduce values of the average gamma energy. Furthermore, the extrapolation procedure to unmeasured cases, used to evaluate beta energies, is also applicable to the gamma energies. Results from such determinations are found in a laboratory report\(^7\).

2.3 Applications of average energies within basic science

It may seem strange that quantities such as average values of the beta and gamma energies emitted in the decay of nuclei can have any importance for basic science. Nevertheless, we would like to point out two fields which may profit from these measurements. In the first place, the average beta energy is an excellent check-point for level scheme constructors who have to reach a result which yields an average beta energy in agreement with the directly measured one. Secondly, the average energies are useful for dynamic theories of nucleo-synthesis where the energy developed by radioactive decay of the nuclides in the "r-process" must be taken into account\(^8\). In this case extrapolations have to be used as few of the very neutron-rich nuclides taking part in the process are available for experiments. Direct measurements of cases as far out on the neutron-rich side of stability as possible will provide valuable check-points for the extrapolation procedures or the theoretical calculations which one has to rely upon.

3. Delayed neutrons

3.1 Branching ratios

It is well known that the delayed neutrons are very important for running a reactor. Their number is less than \(1\%\) of the average number of neutrons emitted per fission, but their time distribution is essential for controlling the reactor. Consequently, practically all the data we collect on delayed neutrons from fission products are of value for nuclear technology. At the present time there are 67 precursors with known half-lives and delayed-neutron branching ratios. For about half of them, with only few exceptions including all the important cases, i.e. those with high fission yields and large branching ratios, we also know the shape of the neutron energy spectrum.

A check of the completeness of our delayed-neutron data can be obtained by comparing the neutron yield expressed as number of delayed neutrons obtained per \(10^4\) fissions with recommended values (from a number of integral measurements). For
$^{235}$U thermal fission summing the neutrons using $P_n$-values from Ref.\textsuperscript{9}) and the new fission-yield evaluation ENDF/B-V\textsuperscript{10}) gives a neutron yield of 173±6 n/10\textsuperscript{4} f. The recommended value is 162.1±0.5. For $^{239}$Pu thermal fission the corresponding values are 69±4 and 62.8±3.8. In both cases the values obtained by summation of precursors data are about two standard deviations higher than the recommended values. This discrepancy is not very grave, still it indicates that some $P_n$-values may be too high. For most precursors where $P_n$-values have been determined independently at several laboratories, the agreement is now very good, but there are a few important cases with only one published value. These cases should be checked by independent measurements.

It may be noted that the uncertainty of the summed yield is the same as that of the recommended value for $^{239}$Pu. This situation is quite general as shown in Ref.\textsuperscript{9}). Thus we can with confidence use the set of data for individual precursors for evaluating macroscopic properties in any nuclear fuel.

3.2 Delayed neutron energy spectra

The shape of the delayed-neutron energy spectrum, and its time variation, is of great importance for reactor kinetics, especially for fast reactors\textsuperscript{12}). By now, we know the shape of the neutron spectra for 29 precursors. Since most of the important precursors are among those with known spectra, the missing spectra only correspond to a minor part of the delayed-neutron effect at equilibrium, e.g. 13 % in the case of $^{235}$U thermal fission. Therefore, we can construct the composite spectrum, and its time variation, from the known spectra, expecting it to approximate well the true energy spectrum except perhaps at very low and very high energy when the experimental data are less complete.

From the beginning of the studies of delayed neutrons it has been customary in reactor physics to divide the precursors into six half-live groups, with half-lives around 55, 22, 6, 2, 0.6, and 0.2 s. Although we know that all these groups except the first one ($^{87}$Br) are complex the reactor physicists still wish to keep this six-group division, probably because their computer programmes are written to take only six groups into account and because this limitation is sufficient for an adequate description of the delayed-neutron effect. We have at Studsvik, as part of our applied programme, constructed energy spectra corresponding to the six neutron groups. The results can be compared with integral measurements for groups 2-4 in Figs. 2-4. The comparison concerns thermal neutron fission of $^{235}$U. The agreement is, on the whole, quite good. This indicates that similar spectra can confidently be constructed for any other fissile material. In fact, it turns out that these spectra depend very little on the actual fissile nuclide.

![Fig. 2. Delayed-neutron Group 2. Solid curve: Energy spectrum, normalised to unity, from OSIRIS work\textsuperscript{9}). The uncertainty (± one standard deviation) has been indicated at 50 keV intervals. Dashed curve: Energy spectrum, normalised to unity between 100 and 1200 keV, from Ref.\textsuperscript{13}). Dash-dot curve: Energy spectrum, normalised to unity between 100 and 1200 keV, from Ref.\textsuperscript{14}).](image-url)
Fig. 3. Delayed neutron Group 3.
Solid curve: Energy spectrum normalized to unity, from OSIRIS work\textsuperscript{9}). The uncertainty (2 one standard deviation) has been indicated at 50 keV intervals.
Dashed curve: Energy spectrum, normalized to unity between 100 and 1200 keV, from Ref.\textsuperscript{13}.
Dash-dot curve: Energy spectrum, normalized to unity between 100 and 1200 keV, from Ref.\textsuperscript{14}).

Fig. 4. Delayed-neutron Group 4.
Solid curve: Energy spectrum, normalize to unity, from OSIRIS work\textsuperscript{9}). The uncertainty (2 one standard deviation) has been indicated at 50 keV intervals.
Dashed curve: Energy spectrum, normalized to unity between 100 and 1200 keV, from Ref.\textsuperscript{13}.
Dash-dot curve: Energy spectrum, normalized to unity between 100 and 1200 keV, from Ref.\textsuperscript{14}).
4. Fission yields

The fission yield is not a nuclear property, but is an inordinately high quantity for applications of nuclear properties to nuclear technology. It is quite strange that the fission yield pattern after 40 years of study still is not known with any acceptable accuracy even for 235U thermal fission. At the light peak measurements begin to assemble thanks to results from facilities such as LOHENGRIN and HIAWATHA, but at the heavy peak and at the windows into the yield measurements are scarce. For this reason we have started a project at OSIRIS aiming at determining yields of as many as possible of the fission products obtained there. Since these fission products correspond to about 96% of the total fission yield, a very complete mapping of the yield surface is within reach.

4.1 Experimental technique

One inherent difficulty in yield studies using ISOL-systems is the correction for the decay between production and measurement. Such correction requires knowledge about the delay in the system. Following Winsberg we have chosen to represent the delay by a function giving the probability p(t|dt for a delay between t and t + dt. It can be shown18,19 that the delay can be described by two parameters, one for the diffusion through the target material or the desorption from the target surface, whichever happens to be time-decisive, and the other for the delay in the gaseous volume of the ion source. In the OSIRIS integrated target-ion source the influence of the latter parameter is negligible for nuclides with half-lives above 1 second, but has to be taken into account for shorter half-lives. This leaves one parameter to be determined for each element. Some results are given in Table 1 in terms of a "half-life" corresponding to the time it takes to reduce the content of isotopes of a given element to half its original value (assuming desorption to be time-controlling) for the particular conditions used at OSIRIS (1500°C, uranium on graphite cloth). It is seen that this release half-life varies widely from element to element. It is in the order of a few seconds for zinc, gallium, silver and indium, 1–2 minutes for bromine, krypton, tin, antimony, iodine, and xenon, about 7 minutes for rubidium and cesium and 15 minutes for tellurium.

Table 1

<table>
<thead>
<tr>
<th>Element</th>
<th>&quot;Half-life&quot;, s</th>
<th>Element</th>
<th>&quot;Half-life&quot;, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>7.7±3.1</td>
<td>Indium</td>
<td>3.2±0.3</td>
</tr>
<tr>
<td>Gallium</td>
<td>6.0±1.9</td>
<td>Tin</td>
<td>210±10</td>
</tr>
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<td>Bromine</td>
<td>190±20</td>
<td>Antimony</td>
<td>190±20</td>
</tr>
<tr>
<td>Krypton</td>
<td>120±10</td>
<td>Tellurium</td>
<td>900±50</td>
</tr>
<tr>
<td>Rubidium</td>
<td>390±10</td>
<td>Iodine</td>
<td>53±7</td>
</tr>
<tr>
<td>Silver</td>
<td>21.2±1.4</td>
<td>Xenon</td>
<td>58±3</td>
</tr>
<tr>
<td>Cadmium</td>
<td>140±20</td>
<td>Cesium</td>
<td>470±40</td>
</tr>
</tbody>
</table>

Using the delay parameters the fission yields are now being determined for a large range of fission products. It should be borne in mind that there is still another factor coming into play, namely the overall separator efficiency, defined as the probability that an atom in the gaseous phase of the discharge chamber will be collected in the measuring position. Apart from a small mass effect20 the efficiency should be the same for all isotopes of the same element, but large variations may occur from element to element. Therefore, relative isotopic yields are easily obtained whereas absolute yields require a special determination of the absolute yield of one of the isotopes for each element, for instance by radiochemical techniques.

At the present time we have analyzed our data for the isotopes of the elements iodine, xenon, and cesium. For these elements absolute yields determined radiochemically are available for normalization21–24. The remaining elements mentioned in Table 1 are being analyzed. In addition, we plan to carry out complementary studies of those elements which can be obtained by the CF4-method25, i.e. strontium, yttrium, zirconium, barium, lanthanum, cesium, and praseodymium. After this work we expect to have a very complete picture of the yield distribution for 235U thermal fission. It would then be very interesting to carry out a similar study for thermal fission of 239Pu and 239Pu and for fast fission of 238U.
5. Antineutrino energy spectra

Reactors are useful as sources of antineutrinos formed in the decay of the fission products. For the interpretation of the experiments carried out with this kind of source it is important to know the energy spectrum of the antineutrinos. It is therefore tempting to evaluate this energy spectrum from our improved knowledge about the properties of the fission products. Here again special emphasis may be put on nuclides far from stability which have high fission yields and, moreover, possess high $Q_\beta$-values and therefore are responsible for the high-energy part of the antineutrino spectrum.

At OSIRIS we have carried out such an evaluation\(\textsuperscript{26}\), giving results such as the spectrum shown in Fig. 5 as a band corresponding to a confidence range of \(\pm\) one standard deviation. This work was completed in 1979. Since then two other analyses have appeared\(\textsuperscript{27,28}\). They are also plotted in Fig. 5. They essentially fall within the limits of error of the OSIRIS result indicating a good agreement between these three analyses. Nevertheless, the high energy end of the spectrum is still very poorly known. It is important because the antineutrino induced reactions often have a strong energy dependence, and therefore a special study of the decay of fission products with very high $Q_\beta$-values and yet a reasonably high yield is recommended.

6. Other applications

It is probable that the ISOL-facilities, when the needs for physical investigations are filled, will pass into a phase of increasing applications to other branches of sciences and technology.

As far as nuclear technology is concerned more investigations of the properties of fission products may be called for in connection with the development of more advanced systems. Above all, however, the value of the ISOL-technique for the production of radioactive sources of various kinds and for various purposes is expected to increase. Its great advantage is the collection of strongly active samples can be done almost fully automatic and with little radiation hazards. Furthermore, the collection can be made on any backing and with small or variable penetration and almost point-like samples of high purity can be made.

![Diagram](attachment:image.png)

Fig. 5. Number of antineutrinos per MeV per fission for $^{235}$U irradiated for $10^7$ s. The results from the OSIRIS work\(\textsuperscript{26}\) are shown by the solid curves which correspond to $\pm$ one standard deviation from the mean values. Spectra from refs.\(\textsuperscript{27,28}\) with error limits indicated at odd or even mass number, are shown as dotted and dashed lines, respectively.
References

1) K. Aleklett and G. Rudstam, Average beta-ray energies of short-lived fission products, to be published.


COMPARATIVE YIELDS OF ALKALI ELEMENTS AND THALLIUM FROM URANIUM IRADIATED WITH HIGH-ENERGY PROTONS, $^4\text{He}$ and $^{12}\text{C}$


The ISOLDE Collaboration, CERN, Geneva, Switzerland

Abstract

Mass-separated ion beams of the alkali elements Na, K, and Fr, and of the element Tl were produced by bombarding a uranium target with 600 MeV protons, 890 MeV $^4\text{He}^{2+}$, and 936 MeV $^{12}\text{C}^{4+}$. Isotopic production yields are reported. In the case of the $^{12}\text{C}$ beam these are thick target yields. Absolute cross-sections for the proton-beam data were deduced by normalizing the delay-time corrected yield curves to measured cross-sections. For products farthest away from stability the $^4\text{He}^{2+}$ beam generally gives the highest yields.

1. Introduction

The present work was initiated by the new possibilities of accelerating heavy ions at the CERN Synchrocyclotron (SC). In addition to the 600 MeV proton and 930 MeV $^4\text{He}^{2+}$ beams, the SC is also able to accelerate $^{12}\text{C}^{4+}$ ions to an energy of 860 MeV. Since neutron emission usually is favored relative to the emission of charged particles, the heavy-ion reactions may be suitable for the production of a variety of very neutron-deficient nuclides of 2 higher than the target element. The purpose of the present experiment was, however, to investigate the production of nuclei lighter than the target and to see if the more complex projectiles have higher cross-sections so as to broaden significantly the isotopic-yield distributions.

A survey of comparative yield measurements for the elements Na, K, Tl, and Fr, produced by bombardment of 12 g U/cm$^2$ targets, was carried out at ISOLDE. The $^{12}\text{C}$ ions are completely stopped in such thick targets, and therefore these measurements are thick target yields. Relative to protons and $^4\text{He}$, the effective target thickness is thus reduced considerably. Here we shall discuss some aspects of the utilization of heavy ions for the production of rare nuclear species.

2. Experimental techniques

Data for the available projectiles at ISOLDE from the CERN 212 cm Synchrocyclotron are summarized in Table 1. The beam intensities were measured by a secondary emission chamber which was calibrated against the reaction $^{17}\text{Al}(\alpha,\text{xnyp})^{21}\text{Na}$. The reaction products separated in the ISOLDE electromagnetic mass separator were brought through a beam-handling system onto a movable aluminized mylar tape. The collected activity was transferred to a thick, 40 mm diameter, 4 mm plastic scintillator, where the β-particles were counted. The detection efficiency of this detector was measured by means of standard β sources. The 4π plastic scintillator was also used for the Tl isotopes, which decay by isomeric transition or electron capture. In these cases, the absolute yields are estimated to be uncertain by a factor of 2 to 3 owing to the different efficiency of the β detector. For the relative yields for the different projectiles are, however, not affected. For the detection of α-particles, silicon surface barrier detectors were used either placed in the beam behind a carbon collector foil or in combination with a tape-transport system. The neutron-rich nuclides, which are characterized by the emission of β-delayed neutrons, were identified with a 4π neutron detector calibrated with a 49 g sample of uranium. For a few nuclides the gamma-rays were measured with a 17% Ge(Li) standard efficiency detector. The observed counting rates were corrected for decay losses by using the formula presented by Bjørnstad et al. in order to obtain the saturation yields. To eliminate the effect of short-time variations in the bombarding beam intensity and the separator efficiency, most of the yields were obtained as ratios between two adjacent masses. The determined saturation yield ratios were then normalized to one absolute yield measurement for each element.

3. Results

The presented production yields from the proton and $^4\text{He}$ irradiations are normalized to a beam intensity of 1 pμA and a target thickness of 10 g U/cm$^2$, i.e. thin target yields. Since the $^{12}\text{C}$ beam is completely stopped in the target, its saturation yields are thick target yields normalized to 1 μA. The proton-beam results are shown in Figs. 1-4. The isotopic distributions, shown in these figures, reveal within the experimental accuracy no structure due to odd-even effects. The Fr and Tl yields have their maxima at the neutron-deficient side of stability as expected for spallation products. The yields for Na and K are peaked at the neutron-rich side, but closer to the stability line in accordance with the fragmentation model. The yields from the $^4\text{He}$ and $^{12}\text{C}$ irradiations are presented in Figs. 5-12 as ratios to the proton-induced yields. The presented distributions will be further discussed in Section 4. The yields depend very strongly on the performance of the actual target-ion source system and, in order to keep the experimental conditions approximately the same, the presented data for p and $^4\text{He}$ were obtained by using the same target unit. The performances of various targets due to temperature differences mainly affect the short-lived nuclides because of their strong sensitivity to decay losses in the target. Occasionally 10-100 times higher yields have been observed for these nuclides. This means that precise cross-section measurements are difficult to

### Table 1

Summary of beam data at the ISOLDE target

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Beam intensity (pμA)</th>
<th>Incident beam energy (MeV)</th>
<th>Energy loss in target (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>3</td>
<td>600</td>
<td>30</td>
</tr>
<tr>
<td>$^4\text{He}^{2+}$</td>
<td>0.5</td>
<td>890</td>
<td>200</td>
</tr>
<tr>
<td>$^{12}\text{C}^{4+}$</td>
<td>0.1</td>
<td>936</td>
<td>936</td>
</tr>
</tbody>
</table>

* a) 1 pμA = 1 particle microampère = 6.24 × 10$^{12}$ particles/s.

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1) Present address: Department of Nuclear Chemistry, University of Oslo, Oslo, Norway.
2) Present address: Department of Physics, University of Helsinki, Helsinki, Finland.
3) Present address: Lawrence Berkeley Laboratory, Berkeley, Calif., USA.
perform at an on-line separator like ISOLDE but it is very suitable for relative yield measurements. It may, however, be interesting to estimate approximate cross-sections far away from stability, since it is very difficult to get this information from other techniques than on-line measurements. In order to obtain absolute formation cross-sections, the saturation yields have to be corrected for decay losses in the target. The parameter \( \mu \) for the diffusion mechanism(s) in solids, described in Garza et al.,\(^{16}\) was fitted to the experimentally measured diffusion curve for Na, thus giving a value of 0.02 s\(^{-1}\). Earlier results from on-line measurements\(^{17}\) show that the same \( \mu \) value is roughly applicable also for K and Fr. The diffusion time for Tl was not measured for the actual target system, but earlier experiments have shown that it is much longer than for the alkalis and therefore the Tl yields were not corrected for delay in the target. The delay-corrected yields were then related to cross-sections measured by radiochemical methods\(^{18,19}\). The cross-sections given in Figs. 2 and 4 are determined to a precision of a factor of 2 to 3, depending on the uncertainties in the delay-time corrections and the normalization of cross-sections.

4. Discussion

For the fragmentation product Na, the yield ratios in Figs. 5-6 show that both \(^3\)He and \(^{12}\)C give a higher yield at the neutron-deficient as well as the neutron-rich side of the distributions. The higher yields are tentatively understood in terms of higher energy deposition in the target nucleus. For production purposes the \(^3\)He beam will become even more attractive in the near future because a beam intensity of the same order as the proton beam is within reach at the SC. An unexpected high yield was observed for \(^4\)Na with \(^{12}\)C as projectile. To investigate if this could be attributed to the reaction \(^{12}\)C on carbon in the target, a separate experiment with \(^{12}\)C on a pure graphite target was performed. The result obtained was in agreement with integration of the 30 to 80 MeV \(^{12}\)C data\(^{14,15}\), showing that the \(^4\)Na is produced near the end of the range of the beam in the target. This experiment points to the possibility of performing such reactions in thick targets, which may be interesting in order to produce neutron-deficient nuclei in the region \(Z < 20\) where suitable high-temperature targets for proton and \(^3\)He bombardments are hard to find. In the \(^{12}\)C experiment a small contribution at masses \(A > 24\) was also observed, originating from reactions with the Ta target container.

The ratios for the fragmentation product potassium, K, are shown in Figs. 7-8. The trend of higher yields from the \(^3\)He and \(^{12}\)C irradiations is not as pronounced as for Na, but still there is a gain in yield at both the neutron-deficient and neutron-rich sides of the beam in the target. This experiment points to the possibility of performing such reactions in thick targets, which may be interesting in order to produce neutron-deficient nuclei in the region \(Z < 20\) where suitable high-temperature targets for proton and \(^3\)He bombardments are hard to find. In the \(^{12}\)C experiment a small contribution at masses \(A > 24\) was also observed, originating from reactions with the Ta target container.

For the deep spallation product Tl, higher yields are expected when using \(^3\)He or \(^{12}\)C as projectiles instead of protons, because the higher total energy transferred to the system favours the evaporation of many particles. The effect is shown in Figs. 9-10. The experimental ratio illustrated in Fig. 9 shows that the yields for \(A < 187\) are 10 to 100 times higher from \(^3\)He than from protons. When using \(^{12}\)C instead of protons as projectiles the effect is not so pronounced but still there is a gain in yield, as shown in Fig. 10. The measurements of the Tl isotopes were not extended to the neutron-rich side of stability because of contamination from the isotopic Fr isotopes.

In the case of the close spallation product Fr, Figs. 11-12, the higher bombarding energy of the \(^3\)He and \(^{12}\)C beams disfavours the yields. This is analogous to the case where the proton energy is increased from medium to high energy, where the cross-section decreases for close spallation products but increases for deep spallation fragments\(^{20}\) in the fission region the cross-section is rather unaffected by the higher bombarding energy in agreement with observations for Cs and Rb isotopes produced in 910 MeV \(^3\)He irradiations\(^{21}\). For the most neutron-deficient nuclei, shown in Fig. 11, there is a gain by using \(^3\)He as projectiles, while nuclides closer to stability are disfavoured. This gives, because of contamination from neighbouring masses in the separator cleaner conditions when studying nuclear properties in the very-light Fr isotopes. The low ratio shown in Fig. 12 is not only a consequence of the reaction mechanism but also an effect of the small effective target thickness for \(^{12}\)C, while the proton and \(^3\)He yields are thin target yields.

During the \(^{12}\)C experiment an attempt was made to produce elements heavier than the target. The effort was to produce \(^{236}\)Am isotopes by irradiating \(^{12}\)C-graphite cloths by \(^{12}\)C, which involves a transfer of three protons to the target nucleus. In this experiment a thermal ion source was used. The detection system was optimized to measure both alpha and fission-fragment energies. The most typical characteristic of the Am isotopes would be spontaneous fission, but no such events were observed. It is possible that relatively high-temperature stable Am compounds were formed, thus preventing the release of Am from the target. However, some weak alpha peaks were observed in the expected region of energy for Am. Assigning these alpha peaks to Am, an estimated upper limit of 30 nb for the production of \(^{237}\)Am could be made, which roughly agrees with the data obtained by a low-energy \(^{12}\)C beam\(^{22}\).

The present work shows that the results obtained with the \(^3\)He beam are very encouraging and higher production yields are established, especially for the deep spallation and fragmentation products. For production purposes the \(^3\)He beam will become even more attractive with the planned higher beam intensity. The \(^{12}\)C beam seems to offer no advantage for production of elements lighter than the target. The higher energy available does not compensate for its low intensity and shorter range as compared to \(^3\)He and protons.

References


17) The ISOLDE Collaboration, The $^{87}$Rb beta-strength function, to be published in Phys. Lett. B.

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**Fig. 1** Production yields of Na isotopes. Filled circles are normalized saturation yields (see text). The $P_0$ values used are normalized to the new $P_0$ value for $^3$Li of $(50 \pm 4)$%. The cross-section scale on the right-hand axis is normalized to 0.19 mb measured$^{17}$ for $^{22}$Na. This scale applies to the decay-corrected yields (open circles) according to the text. The points at masses 33 and 34 are within parentheses because the correction for the daughter activities is not taken into account.

**Fig. 2** Production yields of K isotopes. See caption of Fig. 1. The $P_0$ values used are taken from Ref. 17. The cross-section scale is normalized to 0.35 mb for $^{40}$K, assuming the same cross-section at the maximum of the yield distribution as that measured$^{13}$ for Sc.

**Fig. 3** Production yields of Ti isotopes. See caption of Fig. 1. No decay correction is applied to the points (see text). The letters m and g indicate the metastable and the ground state, respectively. The same detection efficiency as for beta particles was used.

**Fig. 4** Production yields of Fr isotopes. See caption of Fig. 1. The cross-section scale is normalized to 0.20 mb measured$^{13}$ for $^{212}$Fr. The error bars are from the uncertainties in the $\mu$ value and the normal temperature variations of the target.
Fig. 5  Ratios of the $^3$He to the proton-induced saturation yields of Na isotopes normalized to the same beam intensity.

Fig. 6  Ratios of the $^{12}$C to the proton-induced saturation yields of Na isotopes normalized to the same beam intensity.

Fig. 7  Ratios of the K isotopes. See caption of Fig. 5.

Fig. 8  Ratios of the K isotopes. See caption of Fig. 6.

Fig. 9  Ratios of the Tl isotopes. See caption of Fig. 5. For the letters m and g see caption of Fig. 3.

Fig. 10  Ratios of the Tl isotopes. See caption of Fig. 6. For the letters m and g see caption of Fig. 3.
Fig. 11  Ratios of the Fr isotopes. See caption of Fig. 5.

Fig. 12  Ratios of the Fr isotopes. See caption of Fig. 6.
ON-LINE SEPARATION OF REFRACTORY HAFNIUM AND TANTALUM ISOTOPES AT THE ISOCLELE SEPARATOR

C.F. Liang, P. Paris, G. Bastin, C.S.N.S.M. ORSAY
J. Obert, J.C. Puteaux, I.P.N. ORSAY.

ABSTRACT:

By chemical evaporation technics, neutron deficient Hafnium nuclei have been on-line separated at the ISOCLELE facility, from the isotopic rare-earth elements, in the metal-fluoride $\text{HfF}_3^+$ ion form. Half-lives of 162-165Hf have been measured. Similarly, Tantalum has been selectively separated on the TaF₄⁻⁻ form.

It is well known that the presence of halogens and oxygen increases the separation efficiency of refractory elements forming volatile halides or oxides. This effect has been used for example to separate the short life fission products in the gaseous phase with controlled $\text{O}_2$/WCl₅ mixing in the transport $\text{N}_2$ gas (1), or to separate the Zr, Nb elements by reaction with metal-chloride vapours ($\text{NaClO}_3$) as impurity in the carrier $\text{N}_2$ gas (2).

In the case of on-line mass separation, the chemical reaction in the ion-source was first observed by Ravn and al. (3) who reported the production of $\text{BaF}^+$ ion at ISOLDE. The fluorine originated from impurities in the target or the material of the ion-source. At the Orsay-ISOCLE on-line separator, in an attempt to separate the La, Ba, Cs isobars, we developed this method by controlled feeding of $\text{CF}_4$ gas in our target ion-source system. Very pure neutron deficient La sources were obtained in the $\text{LaF}_2^+$ form with a very weak mixing of Ba and Cs isobars (4).

According to the same principle, we searched to separate the refractory $\text{Hf}$ (valence 4) which form a volatile and stable fluoride compound $\text{HfF}_4$.

2. EXPERIMENTAL PROCEDURE AND RESULTS

The target, inside the ion-source, was constituted by 2 grams of anhydrous Ytterbium fluoride powder put in a cylindrical container. A continuous gas support for fluorination to favour the formation of $\text{HfF}_3$ at the surface of the $\text{YbF}_3$ powder was supplied by introduction of $\text{CF}_4$ vapour through a small Mo tube connected at the bottom of the container. The target was bombarded by 1 $\mu$A 280 MeV $^3\text{He}$ beam from the I.P.N.-Orsay synchrocyclotron and heated progressively by an auxiliary heating system.

The neutron deficient Hf isotopes were formed by $\text{Yb} (\text{^3He,n})$ reactions. The maximum temperature of the ion source was about 1200°C. In these conditions, we obtained an important $\text{YbF}_3^+$ stable beam (~1.5 mA). The isotope identification was based upon single high-resolution spectra with coaxial Ge(Li) and X-rays intrinsic Ge detectors. The multispectrum analysis was performed for half-life measurements. On the masses $A=162$ $A=168$, the $\gamma$ spectra showed an important isobaric mixing of $\text{Hf}$, $\text{Lu}$, $\text{Yb}$ and $\text{Tm}$. This mixing remained also on the $A=179$ ($\text{MP}^+$) and $A=186$ ($\text{MP}^+$) masses.

While on the masses $A=57$, we obtained, as expected, very pure $\text{HfF}_3^+$ ion, the rare-earth families (valence 3) in this case were negligible. For illustration, figure 1 shows the first spectrum of the eight ion spectra of a multi spectrum analysis on the mass $A=164-167$. Half-life measurements were performed on the decay curves of $\text{K}_{\gamma}$ Lu peaks (figure 2-5) and four isotopes (162-165 Hf) unknown up to now were identified.

![Figure 1: Spectrum Hf$^{164}$ → Lu$^{164}$ → Yb$^{164}$](image-url)

First spectrum of the 8 multispectrum analysis (one minute measurement for each after a 4 minutes collection time).
Very recently, we attempted to exploit the same principle for selectively separating Tantalum (valence 5). Ta isotopes were produced by (3He,xn) reactions on a Lutetium metal powder target continuously fluorinated by a CF₄ vapour flow. We obtained TaF₄ with a rather good yield at a lower target temperature than for the above reported Hf separations. Unknown 163-164-165pa isotopes were observed and analyses of the corresponding half-life measurements are in progress.

REFERENCES:
(2) G. Herrmann, Arkiv. for Fysik, 36, n°14 (1966) 111.
A NEW ELECTROSTATIC ON-LINE COLLECTION-SYSTEM

J.P. Dufour, R. Del Moral, A. Fleury, F. Hubert, Y. Llobador, M.B. Mauhourat
C.E.N. Bordeaux-Gradignan, France

R. Bimbot, D. Gardès, M.F. Rivet
I.P.N. Orsay, France

Abstract

The working conditions of a new on-line electrostatic collection system are presented. The main characteristics are high efficiency (reaching 20%) and short delay time (down to the millisecond). The salient features of specific devices for measurements of absolute cross sections, recoil range distributions and angular distributions are given.

1. Introduction

The collection method presented here is of a non selective type. This method is not to be compared with the biggest high performance recoil spectrometers but better must be considered as a necessary complement of existing devices.

Our work has been to complete and modify the already known off-line electrostatic collection in order to realize on-line detection. It appears that the transport and the deposit of the activity on the surface of a detector can be easily performed with small devices. There is some relationship of this method with the helium-jet technique as the total efficiencies are comparable (the transport delay time being nevertheless one order of magnitude shorter in our devices). But the main advantages of the electrostatic collection are simplicity, lightness and the possibility of a precise selection both in recoil energy and angular distribution. Then, known reaction mechanisms (fusion, deep inelastic ...) as well as new ones, that may occur in the range 20-100 MeV/n, can be studied by this method and this both for the exotic nuclei production and mechanism study per se.

2. Principles and off-line tests

All electrostatic experiments rely on two main basic principles: i) the recoiling nuclei are stopped in a gas, ii) at the end of the path an electrostatic field is applied. When the velocity vanishes (about $10^{-7}$s after the nuclear interaction) the field ensures, in most of the cases, the presence of a remaining charge on the nuclei. An electric force is then created and provides the transport of the activity on a catcher, or in front of a detector.

The experimental devices built on these principles have been, up to now, focused on off-line measurements in which nuclei are first electrostatically deposited on parallel plates and then handly or mechanically transported in the detection area (see Fig. 1). Differential range of fission fragments and evaporation residues were studied with such devices. In the case of exotic isotope collection, there was only one group (Ghiorso et al.) using this technique with on-line detection (discovery of element 103). At this time (twenty years ago) many experimental points remained obscure in the application of the main principles. Especially the total efficiency and the transport time were not measured. Furthermore the influence of important parameters such as the beam quality and intensity, the gas nature and pressure, the chemical properties of the collected nuclei, were only partially or not at all known.

![Fig. 1 Apparatus for differential range measurements by electrostatic collection (taken from Harvey[3]).](image)

2.1. Measurements of the Ion mobility in light gases

The ion velocity in an homogeneous electric field is well known when the species concerned are He$^+$/He, N$_2^+$/N$_2$ ... i.e., for particular cases where ions come from the gas itself. We have then studied the ion mobility $\mu$ of 214Po in N$_2$ and He. The pressure range was 0.02 to 1 bar and the electric field was varied correspondingly from 10$^3$V m$^{-1}$ to 10$^5$V m$^{-1}$. The 214Po$^+$ ions came from a 224Ra source and were transported along parallel field lines up to the surface of an alpha detector. The three parameters $P$ (pressure), $E$ (electric field) and $d$ (transport length) were varied and the loss of nuclei due to radioactive decay during the transport was determined for each ($P$, $E$, $d$) value; other sources of experimental loss than decay rate were measured to be negligible. All results are well reproduced by the following formula which gives the mean velocity $v$:

$$ v = \frac{E}{\mu} $$

with $\mu = (2.2 \pm 0.2) \times 10^{-4}$ in N$_2$ and $(4.1 \pm 0.4) \times 10^{-4}$ in He, if $v$, $E$ and $P$ units are $\text{m}^{-1}$, $V \text{ m}^{-1}$, and barn respectively. The width of the distribution is more difficult to obtain but can be roughly estimated to be half the mean value. One must notice that if the total transport length remains of the order of 0.1 to 1 m, the transport time can be as short as 1 ms. ($P = 50$ mbar, $E = 4 \times 10^5$V m$^{-1}$). An important point is then to minimize the distance between the stopping point of the nuclei and the detector.

2.2. The electrostatic field line configurations

The velocity is limited in the gas by the fluid friction. So there is no significant kinematic force perpendicular to the electric one. For the same reason, a magnetic field has a negligible effect if the pressure is greater than 1 mbar. So, trajectories of ions are directed by the electrostatic field lines.
Fig. 2 Schematic view of the electrode configuration in an "In beam" collection

2.2.1. Boundary conditions determined by metallic electrodes

In this classic case the Laplace equation completely solves the problem. Within the restriction of non-crossing field lines it is possible to find an electrode disposition establishing the field along an arbitrary given line. In Fig. 2 is illustrated a standard case where the mean path is a straight line in the lower part and a circle in the upper part.

An important property of the $\nabla \cdot B$ equation is that if the geometry of the electrodes is given, the relative intensity of the field along a field tube is determined by the section of this tube. This implies that in a focusing configuration as displayed on Fig. 2, the electric field is much lower in the convergent part. The total transport time is consequently increased and reaches 10 ms (in standard conditions) for this system.

2.2.2. Devices including insulators

If a continuously ionizing source (such as a beam or a radioactive source) is present in the electric field the equation $\nabla \cdot p(E) = 0$ is of an integral type. The charge density $p(E)$ is determined by the movement and recombination of the created free charges, themselves conditioned by the electric field.

We tried with some success to impose, in addition to the potential condition, a volume condition by the mean of an insulator (Fig. 3). On the surface of the insulator the charge density reaches an equilibrium state. The normal component of the electric field vanishes. Thus this boundary condition defines a field tube when potential constraints fail to do so. The system shown in Fig. 3 is charge equilibrated in a time varying from several minutes in presence of a $10^4$ alpha s$^{-1}$ source to few milliseconds when a beam goes through the device.

This system fails in two cases: i) if the ionizing source is too weak, ii) if the number of energetic ions directly implanted in the insulator is too high, for example, in the first degrees around the beam direction.

Fig. 3 Electrostatic device using a massive insulator
3. In beam collection of fusion residues and recoil range measurements

We have used the device shown in Fig. 2. The target and the Ni window are in the vicinity of the collection zone and have the same applied voltage as the lower plate. The detection being limited to alpha spectroscopy, the background is very low (less than 1 event/hour MeV$^{-1}$) above 3 MeV when the surface barrier detector is placed behind a metallic screen and well protected from multiple scattering. This latter point justifies the circular field line created in the upper part by a succession of 17 electrodes. The nuclei are deposited onto the surface of the detector which defines the ground potential and constitutes the last electrode. The resolution is there still good, typically 30 keV with a 450 mm$^2$ detector. With this system we found optimum conditions for detecting isotopes with half-lives greater than 1 s which were:

P = 250 mbar of N$_2$, V = 5 kV, beam intensity: 5 x 10$^{10}$ part s$^{-1}$. The total efficiency (including the detection efficiency) is then 2% in the case of rare earth and francium isotope production.

This device enabled us to discover (in 1979) a new isotope $^{184}$Pb$^{18}$ formed in the heavy ion fusion reaction (40Ca + 148Sm). The large detection efficiency (45%) allowed us to make $\alpha$-$\alpha$ time delay coincidence between the new alpha line 6620 keV and the known 6120 keV line of 180Hg. These parent-daughter relationships are of great interest, as emphasized by Hofmann et al. for the velocity filter, in the identification of new isotopes detected by non-selective collection methods.

For shortest half-lives the operating conditions must be changed, the pressure and voltage being reduced (100 mbar, 2.5 kV). The total efficiency is only 1% for a 5 ms half-life (214Pu).

We must emphasize that the crossing of the beam through the device strongly reduces the efficiency since its value is 50% in off-line tests and corresponds to the detection geometry.

3.1. Recombination and space charge effects

The ionization created by an heavy ion beam in a gas (at pressure about 100-1000 mbar) is very high, but the separation of these charges by an electric field is small due to the recalling field existing between positive ions and negative species. So recombination is a dominant mode. The ionization current between two parallel plates can be estimated by taking into account the equation of mobility (Eq. 1) for ions and electrons.

One finds that J, the density of the extracted current is given by the following equation:

$J = k \ln \left( \frac{I_{BEAM}}{P \cdot d^2} \right)$

where $k = 3$. This current evacuates about two to four orders of magnitude less charges than those created by the beam. So the probability for a recoiling charged nucleus to be collected before neutralization is very small if it stays in the plasma. Fortunately the collision induced reionization occurs with a great probability and extraction from the plasma of long-life isotopes such as $^{153}$Dy has been experimentally found to be in between 40%-100%.

In addition to this effect, in the interaction zone, the space charge regime has also a great influence in the transport. Inside a positive charge cloud moving under the influence of a primary electrostatic field, a repulsive component appears when the local charge density is too high. This effect is responsible of an important loss on the edges of the electrodes during the transport of the activity to the detector.

3.2. Measurements of recoil range distributions

All effects correlated to the space charge are of a particular importance when the aim of the electrostatic collection becomes to give a correct view of the recoil range distributions through an homogeneous field. Fig. 4 exhibits the system we have successfully tested first with a low energy fusion reaction and afterwards with the very energetic $^{12}$C beam of CERN.

Previously experimenters checked carefully the symmetry between the beam and the two parallel plates. The space charge study shows that behind an apparent symmetry in the electrodes, the mobility of electrons and ions are so different ($\mu(e^-) \approx 10^3 \mu(+)$) that charge densities and electric fields exhibit strong differences between the elec-

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Fig. 4 Apparatus for differential range measurements by on-line electrostatic collection

- 713 -
tronic and ionic collection zones. An important consequence is that the potential of the metallic parts placed in the beam such as Ni window or target must have an applied potential close to the cathode one. Otherwise we have noticed a loss of collection for small ranges (less than 3 cm), and some authors* mentioned a short-range tail due to a distortion in the collection.

4. Addition of a gas flow to the electrostatic collection

A system like the one in Fig. 1 does not guarantee that the efficiency is independent of the half-life over a wide range. This is a problem to measure absolute cross-sections. In order to suppress multiple reionizations and recombinations as well as to compel the total transport time to be as small as possible, we used a system mixing a gas flow and an electrostatic collection (Fig. 5).

It must be noticed that this technique is quite different from the helium-jet for two reasons: 1) the gas flow is insured by a small ventilator (power = 20 W, dimension: $\phi$ 80 mm) instead of a big pump, 2) the total flow rate of the evacuated gas in the collecting chamber is quite high: $10^5$ cm$^3$ s$^{-1}$ whatever the pressure is in the range 20-100 mbar. In an He-jet system the total flow rate is $10^2$ cm$^3$ s$^{-1}$ in the high pressure chamber if the operating pump evacuates $10^3$ m$^3$ s$^{-1}$ at a $10^{-2}$ mbar pressure in the vacuum chamber. The high flow rate insures the total removing of the gas receiving the activity in less than 20 ms (This time could still be easily lowered with a more powerful ventilator).

We measured the same efficiency for two isotopes whose half-lives were 30 ms and 150 ms (source tests). In on-line tests we found for a 36 s half-life ($^{213}$Fr) an efficiency twice the value for a 5 ms half-life ($^{214}$Fr). These results are consistent with the mechanical characteristics.

Fig. 5 Combination of a gas flow with the electrostatic collection

Fig. 6 Alpha spectrum obtained with an equal efficiency for all half-lives of the produced isotopes (from $^{151}$Tb, $T_{1/2}$ = 17 min to $^{155}$Lu, $T_{1/2}$ = 70 min)
of the ventilator predicting a total transport time in the range 10-15 ms.

This point is very crucial in the interpretation of results obtained with the $^{12}$C beam at 1 GeV at CERN. It appears on Fig. 6 that exotic nuclei as far from the stability line as $^{157}$Hf ($T_1/2 = 120$ ms) and $^{159}$Lu ($T_1/2 = 70$ ms) could be seen; and we can state that the non-detection of more exotic isotopes is only due to a too low production yield since $^{156}$Hf ($T_1/2 = 25$ ms) and $^{158}$Ta ($T_1/2 = 37$ ms) have half-lives greater than 20 ms.

The electrostatic design is arranged with the gas flow in order to insure that: 1) near the target and during the transport, electric forces are small compared to fluid forces, 2) near the detector the force situation is reversed by expending the gas while the electric field is enhanced in a focussing configuration. The total efficiency is entirely controlled by recombinations occurring in the plasma zone. All neutralized atoms are lost for the further electrostatic deposit on the detector. The intensity of the extracted current can be approximated by the following expression:

$$ J = k \mu \frac{v_0 d P}{P} \left( \frac{v_0 d P}{\mu} \right)^2 $$

(3)

where $v_0$, $d$ and $V$ are the gas velocity, the electrode separation and the electrode voltage respectively. The extracted current only slightly changes when the beam intensity or energy or nature is varied. On the contrary, the total number $N_p$ of ion-electron pairs is strongly dependent on these parameters:

$$ N_p = \alpha I_{beam} P \frac{dE}{dx}(E) $$

(4)

de(E) being the stopping power of the beam in the gas. The efficiency proportional to the ratio $J/N_p$ is then given by the following relation if $V < \frac{v_0 d P}{\mu}$:

$$ \frac{J}{N_p} = k' \frac{2}{v_0} \mu d \times I_{beam} \times \frac{dE}{dx}(E) $$

(5)

The better conditions for this system are energetic beams (low $dE/dx$), low intensity beams and high fluid velocity. So we have obtained a total efficiency of 15% using the $10^{10}$ part $s^{-1}$ $^{12}$C beam at 1 GeV (transport efficiency $\approx 45\%$). The counting rate is almost independent of the beam intensity above $10^{10}$ part $s^{-1}$, increasing by a factor of two for a tenfold increase of the beam intensity.

An interesting development of this system could be its use behind an electromagnetic recoil separator, even a crude one, as a residual $10^7$-$10^9$ part $s^{-1}$ beam would not hinder the collection.

5. Out of beam collection and on-line angular distributions

The crossing of the beam through the collecting section is the only cause of the problem appearing in the system presented just before. We have then developed devices in which the beam is out of the electrostatic field. As the number of diffused particles can reach $10^8$ part $s^{-1}$ without any influence on the collection, the forbidden solid angle is reduced to the beam emittance, that is less than $1^o$ aperture.

The system shown on Fig. 7 is only an example of this kind of disposition. The target and the beam are in a vacuum chamber while the collecting chamber is reduced to a little cell in which the electrostatic field is used to focalise the activity onto the detector. The background is very low, since the direct scattering cannot reach the detection zone (Fig. 8). The total efficiency has been measured to be in the range 20%-40% and the conditions of the collection appear to be very similar to off-line conditions. The time transport is therefore given by the velocity measured in off-line tests. The efficiency of collection is about 100% for the charged recoiling nuclei. But depending on the chemical nature of the collected nuclei, on the stopping gas and on the electric field, a fraction of the entering ions is neutralized in the last part of the slowing down path. Due to the exclusion of the plasma, a further reionization of neutral atoms is impossible. The proportion of $^4$He or $^0$ charge states in the $\mu$-keV energy range is not well known. Experimental data$^{(2,6)}$ indicate that in $^2$H,$^2$He,$^2$H$_2$, most of the elements remain still charged at the end of the

![Fig. 7 The on-line angular distribution "detector"

![Fig. 8 Alpha spectrum obtained at 7° and 20° in the laboratory system in the reaction of $^{12}$C at 1 GeV on $^{18}$Ta]
stopping path: the exceptions are rare gases and halogens which are mainly neutralized. In the case of rare earths our measurements indicate a 40% greater probability for the 1+ charge state than for the 0 one. If the stopping gas has a too low ionization potential (Ar, CH₄, ...) the situation may become very different and even elements having a low ionization potential like Cs may be almost totally neutralized12).

We have up to now obtained on-line angular distributions of neutron-deficient isotopes produced in the reactions of the CERN 12C beam on heavy targets. A typical spectrum is shown on Fig. 8. This kind of differential measurements has not yet been achieved in a wide angular range (2°-90°) by any other method and corresponds to one of the most promising configuration of the electrostatic collection. Similar systems well suited for isotope production, fusion or deep inelastic reactions, are now developed with the goal to collect all nuclei emitted outside a forward cone having a 1° aperture.

6. Conclusion

The electrostatic collection presents very interesting characteristics. This method is simple, versatile and can be used for different purposes: absolute cross sections measurements, recoil range distributions, angular distributions. The high efficiency (reaching 20%) and the short delay time (down to the ms) allowed exotic nuclei detection. The electrostatic transport in gases offers two methods of focalisation: the gas flow and the electric field itself in which the mean delay time is of the order of 10 ms and could be easily lowered to 1 ms.

It is important to notice that the rapid methods of collection are not universal. For example the recoil spectrometers only collect the fusion residues with high efficiency. In other cases (Lohengrin, Josef) an additional low collection (multicapillary He-Jet system, tape transport) is useful. The other very quick methods as mass spectrometry are restricted to some elements, alkalines for example, and hardly detect half-lives shorter than 100 ms when the mass of the isotope exceed 100. The high efficiency collection in the 5 ms-100 ms half-life range, almost independent of reaction mechanism and collected elements, is especially important since in many cases the last known exotic isotopes have precisely half-lives about 100 ms.

References

5) J. Gilat and J.M. Alexander, Phys. Rev. 136 (1964) 1298
TRIPLE FOCUSING RECOIL SEPARATOR CARP AT RCNP

S. Morinobu, I. Katayama
Research Center for Nuclear Physics, Osaka University, Suita, Osaka 565 Japan.

H. Nakabushi
Department of Physics, Osaka University, Toyonaka, Osaka 560 Japan.

Abstract

A reaction product mass separator (CARP) which is now being constructed for use with the AVF cyclotron at RCNP is described. This device is intended to separate unallowed recoiling products in nuclear reactions from the primary beam and to analyze them according to their charge-to-mass ratio. The use as a mass-spectrograph or as a mass-separator is available according to the experimental requirements. The solid angle and the energy range of acceptance will be 10 msr and 20%, respectively.

1. Introduction

The heavy-ion induced reactions have offered in the past decade a variety of unique tools in the experimental investigations of nuclear structures and nuclear interactions. The multiplicity of their reaction channels has helped many of the studies to access new phenomena which would not be observed with light ion beams. However, the multiplicity of the reaction channels itself has often made the experiments quite complex and as such has hampered the results therefrom to be fully informative. To identify final channels one has to determine the proton number $Z$, the mass number $A$ and possibly also the kinetic energy $T$ of the reaction products. The difficulty usually arises in the determination of $Z$ and $A$, which has so far proven the rather poor resolution of the identification technique by the particle detectors, especially for medium weight or heavy products. Another important problem in the heavy-ion induced reactions is that the detection of the products has often to be carried out in a shower of undesired background particles. This is particularly so when one observes the fusion products which are emitted preferentially in the forward direction i.e., close to or in the high flux of incident beams and dirty particles.

The last problem has been greatly relaxed in the velocity filter systems at GSI$^1$ and BNL$^2$ by electromagnetically separating the products from the primary beams and transporting them onto the detector. Such systems have proved to be quite useful in studying fusion products emitted in the beam direction but the devices themselves do not have any resolving power for $Z$ and $A$.

Since the path of an ion in an electromagnetic field is determined by the charge-to-mass ratio $q/m$ and the energy $T$ (or equivalently the momentum $p$), it is indeed possible to have a separation system which possesses resolving power for $q/m$ as well. The separator of this type will certainly provide us with a mean to directly determine $A$ but not $Z$ of the reaction products. It should be noticed however, that if a definitive determination of $A$ is achieved, then it at the same time helps us considerably also to determine $Z$ by the use of the other existing methods based on the detection of the particles or of the accompanying radiations. The largest merit of this type of separator is that the reaction products are mass-separated and hence will be detected without being masked by the large amount of products of the prevailing channels, if any. This fact will make it feasible to observe such low cross section events as, for example, the production of nuclei beyond the proton drip line.

From these view points, we have chosen to construct at RCNP an electromagnetic device which focuses the reaction products directly from the target onto the detector site with $q/m$ dispersion. In the following, a brief description will be given of this device which is named CARP (Charge-to-mass Ratio Analyser for Reaction Products) and now being constructed for use with the heavy-ion beams from our AVF cyclotron. The CARP will have a solid angle of about 10 msr and an energy range of acceptance of 20% (FWHM).

We are expecting it to act as a mass analyzer in the reaction mechanism studies and as a mass separator in the decay spectroscopic works especially for the medium weight or heavy nuclei. The separators similar in concept separators are also currently under construction at Daresbury$^3$ and MSU$^4$.

2. Basic Considerations

Before describing the design of the CARP, we briefly touch on the available reactions at RCNP and the behaviour of the recoiling products to get a practical idea about the separator.

Up to now, the heavy-ion beams of relatively light mass ($A \leq 22$) are available at the energies of $E/A \sim 10$ MeV from our AVF cyclotron. (The ion source developments for still heavier beams are actively in progress.) At this beam energy, the dominant reactions are fusion and transfer reactions. The latter includes the so-called deep-inelastic collisions also.

The cross section is the maximum in the fusion reaction and the recoil energies $T$ imparted to the product nuclei are also the largest. This is the main reason why this reaction has been most successfully used in the experiments with existing separators$^4,5$. In our case, the $A = 20$ beam ($E/A = 10$ MeV), for instance,
will produce the $A = 50 \sim 200$ fusion products of $T = 80 \sim 200$ MeV with cross sections of several hundred mb or less. They are preferentially emitted in the forward direction. The angular and energy spread of the recoils are expected to be around or less than 100 mr and 10%, respectively, depending on the possible evaporation of light particles.

The transfer reaction may be characterized by the relatively small cross sections and small product energies. The emission angles are usually large typically around 90°. In the $A = 5$ transfer reaction, for example, on the $A = 100$ target with the same beam as in the above, a 30° deflection of the projectiles will result in a 80° emission of the products with energies around 10 MeV. In this case, the kinematic energy shifts of the products are so large as $(1/T)\partial T/\partial q \gtrsim 0.8$, which brings about an energy spread of 8% within the angular range of 100 mr. The cross section is expected to be less than several tens mb/sr and rapidly decreases as the projectile deflection angle increases i.e., the product emission angle decreases.

The nuclei produced in these reactions progress through and emerge out of the target with various ionic charges, which have close connection to the necessary size of the separator. Fig. 1(a) shows the mean (equilibrium) charge $q$, which was calculated from the empirical formula by Nikolaev and Dimitriev\(^6\), as a function of the energy. It may be seen that typically a value of $q = 10 \sim 25$ is expected in our case, depending mainly on the product energy. The collection efficiency of the separator with $q/m$ dispersion is partly determined by the fraction of the products at the charge state of $q = q$. Assuming a gaussian shape for the charge state distribution, the fraction may be estimated from the width formula\(^7\) as shown in fig. 1(b). The expected yield at the mean charge state is 20 % 30%. In the separator of present concern, the rest of the fraction may be the expence for requiring mass resolving power.

Another factor which may have a large influence on the collection efficiency is the multiple scattering of the products in the target, which causes additional spread in the emission angles. From the estimation\(^6\) shown in fig. 2, one may conclude that for the fusion products of $T \gtrsim 15$ MeV, a target of 500 $\mu g/cm^2$ or larger in thickness can be used without the serious loss of intensity, provided the angular acceptance of the separator is set to around 100 mr.

![Mean angular spread due to multiple scattering of a particle with mass number $A$, atomic number $Z$ and kinetic energy $T$ in the solid materials of the same constituents.](image)

### 3. Experimental Requirements

There are two different ways of using the separator depending on the types of experiments to be carried out with it. As mentioned before, one is the use in the reaction mechanism study where measurements of both the energy and mass spectra of the products are desired to obtain. The information on the angular distribution is also important here. Another use is in the decay spectroscopic work which requires as many products as possible to be transported irrespective of their energy into a low background area. The measurements are usually performed at a fixed angle of the maximum cross section. In both types of experiments, the collection efficiency should of course be as large as possible.

The CARP has been intended to meet these requirements in a single separator. An important problem arises here from the fact that there is a contradiction among
them in the availability of energy analysis. It is indeed possible to have a system which is dispersive both in energy and mass\(^9\). However, the energy dispersion would deteriorate the efficiency of the system in collecting the products in a small detection volume. The resulting expense in the product intensity is expected to be serious in the heavy-ion induced reactions where the energy spread due to kinematic effect and/or energy straggling of the products in the target is expected large as was partly discussed in the previous section. Therefore, since energy is the quantity which can most conveniently be measured by conventional detectors, it is the best way to have the separator possess the energy focussing rather than energy dispersive character.

There is also a difference in the use of the detection systems among the above two types of experiments. In the reaction study, one usually uses particle detectors which are less sensitive to the gamma or beta-ray background. Instead, as large a mass range as possible is required for the detectors to cover. In the decay spectroscopic works, on the other hand, the detectors are often for gamma or beta-rays and only one mass line is required to be transmitted. The only way to support these experiments with a separator will be to introduce two focussing positions in it, thereby separating the detector sites according to the experimental purposes. The focussing position for the reaction studies may be at a rather short distance from the last optical device of the separator possibly at the sacrifice of low background level, but a focal plane with mass dispersion should exist there. For the decay studies, the focal length should be long enough to allow the detector site to be shielded by appropriate materials. The focal plane may not necessarily be present there but a "focal point" for one mass should be present. The angular distribution measurements in the former will also become available if the vacuum chamber is made separable between these two focussing positions.

4. System Descriptions

Based on the discussions presented in the preceding sections, we adopted the followings for the design guides of the separator:

(i) The separator should be mass dispersive but not energy-dispersive.
(ii) The mass resolving power should be \(m/\Delta m > 500\) to allow heavy product nuclei to be resolved.
(iii) The angular range of acceptance should be wide in both the median and transverse planes to cover emission angles of the fusion products i.e., \(\Delta \theta\) and \(\Delta \phi \approx 100\) mr.
(iv) The energy range of acceptance be \(\Delta E/T \approx 20\%\) or larger to prepare for the large kinematic and energy straggling effects.
(v) The maximum energy accessible be \(T \approx 80\) MeV for the relatively light medium-weight particles at the equilibrium charge states.

(ii) Two operation modes giving two different focussing positions should be available. They may be called the short arm and long arm modes according to the different focussing lengths. Preferably, a good focal plane be available in the short arm mode.

In order to achieve a mass dispersive device, one usually has to combine two different types of dispersive elements i.e., magnetic dipoles and electric deflectors. The so-called Wien filter\(^10\) consisting of the crossed electric and magnetic fields also has a dispersive character. However, it is not always possible to produce a magnetic field of a necessary strength in a rather wide pole gap containing electrodes and we have not chosen to use the filter in our separator.

The idea of the dimensions of these devices and the necessary field strengths may be obtained from fig. 3, where the electric and magnetic rigidities of the particles are shown for the equilibrium charge states given in fig. 1. One may note that the magnetic rigidity has a little dependence on the energy and does not exceed 10 Kgm for the reaction products of present concern. The value is easily accessible with a rather small magnet having a mean radius of around 1 m or less. By contrast, the electric rigidity increases with energy and the slope becomes larger for the lighter mass particles. If one sets an upper limit of

\[
\begin{align*}
\text{(a)} & \\
A & = 50 \ Z = 25 \quad A = 150 \ Z = 65 \\
A = 200 \ Z = 80
\end{align*}
\]

\[
\begin{align*}
\text{(b)} & \\
A & = 200 \ Z = 80 \quad A = 150 \ Z = 65 \\
A & = 100 \ Z = 45 \\
A & = 50 \ Z = 25
\end{align*}
\]

Fig. 3. Electric rigidity (a) and magnetic rigidity (b) of a particle at the equilibrium charge state. The mass number, atomic number and kinetic energy of the particle are denoted by \(A, Z\) and \(T\), respectively.
the field strength achievable in vacuum at, say, around 20 kV/cm, it will result in that the electric deflector should have a curvature of a few to several meters to cover a wide enough range of the particle energy. In our case, the length of the system had to be less than 10 m to fit into the available experimental area, which restricted the electrode radius to no longer than 4 m. In practice, taking also the cost into account, the mean radii of the particle orbits in the electric and magnetic devices have been chosen to be 3 and 1 m, respectively.

Aside from the dispersive devices, there is a need for the employment of the separate quadrupole fields, if we require that two focusing positions be available. The use of such fields must follow the consideration to yield triple i.e., energy and doubly directional focus at both of the focal points. The achievement of a "good focal plane" at one focusing position (short arm mode) and a "good focal point" at the other (long arm mode) will further require corrective elements of the sextupoles and possibly also octupoles. They should preferably be devoted to the reduction of chromatic aberrations to obtain a wide range of energy acceptance.

Fig. 4 shows the adopted layout of the separator CARP, which may be abbreviated to a QDQ system, with Q, D and E being the magnetic quadrupole, magnetic dipole and electric deflector, respectively. For the economy of the system length, no intermediate focus was assumed between the two dispersive fields of D and E. The fields were simply arranged so that the directions of the particle deflections in them be opposite with each other to achieve zero dispersion in energy at the two focusing points F1 (short arm mode) and F2 (long arm mode). The order of the arrangement D and E was determined from the considerations to enable the angular distribution measurements in the largest angular range within the limited space of the experimental area. The selection of the focal points between F1 and F2 was made possible by switching on and off a weak quadrupole field between the fields D and E (not explicitly shown in fig. 4 but assumed in the element H2).

The optics calculations were performed with a computer code ORBIT4 which was especially developed in our group to enable the optimization of the optical parameters. The deflection angles of \( \phi_m = 55^\circ \) and \( \phi_e = 32^\circ \) in the elements D and E (see fig. 4) are the results of the detailed mapping of the phase space volume, which is a product of the solid angle and energy width of acceptance, in the \( \phi_m \phi_e \) plane. In this mapping, the strengths of the quadrupole fields and exit angle of the dipole were calculated for every combination of \( \phi_m \) and \( \phi_e \) under the constraint of yielding triple focus at the focal points. The general tendency was that the smaller \( \phi_m \) is and the larger \( \phi_e \) is, the larger the phase space volume becomes. However, the practical considerations on the system magnifications, resolutions, and space limitations forced us to make a compromise. The coordinates of the particle orbits obtained for the present system are shown in fig. 5. It may be seen that the quadrupole Q1 acts to taper the particle envelope in the transverse plane to fit through the gap (9 cm) of the magnet D, and Q2 to adjust the slopes of the particle orbits to meet at the focal points.

The second order calculations were mostly concentrated in making the focal line at the short arm mode focal point F1 perpendicular to the beam axis and furthermore in achieving triple focus over the practically whole length of it. In general the directional and energy focal lines (denoted as \( \alpha \)- and \( \gamma \)-focus line in fig. 4) deviate from each other and only intersect on the central trajectory. For this reason, the chromatic and geometric
aberrations in the median plane had to be dealt with separately. This apparently is an impossible work to do with only the curving parameters at the dipole field boundaries. We could approximately attain our aim by introducing three sextupole magnets (H1, H2 and H3 in fig. 4) together with the aid of the re-adjustment of the focussing length in the short arm mode.

In the present design, the relative angle of the two focal lines is made as small as 23° and hence practically in "a triple focal line" inbetween. The introduction of the sextupoles was also quite effective in the long arm mode in reducing the chromatic aberrations in the median plane. Those in the transverse plane were again minimized by re-adjusting the focal length but the relative angle of the two focal line remained at about 110° in this case.

The third order chromatic aberrations were finally treated for both the modes by admixing octupole components in these corrective sextupole and the first quadrupole (Q1) fields. The obtained specifications of the separator CARP are summarized in Table 1. The expected spectrum calculated by simulating the particle rays which are uniformly distributed both in emission angles and in energy are shown in fig. 6 for the two focussing modes of the short arm and long arm ones. The transmission in the short arm mode was found to vary by about 20% in the present simulation as one goes from the center to the edge of the focal line.

5. Summary and Application

The mass separator for reaction products CARP has been designed for use with the cyclotron at RCNP and is now under construction. This device has a structure which may be abbreviated to a QDEQ system and achieves triple i.e., energy and doubly-directional focus for two modes of operation. In one mode of operation, there is a good focal line of 20% mass width and in the other a focal point for one mass line at a reasonably long distance from the last optical device of the system. These facts together with the large solid angle of 10 msr will allow the use of the CARP both as a mass spectrograph in the reaction mechanism studies and as a mass separator in the decay spectroscopic works. The application to the in-beam spectroscopic study will also be feasible in both types of usages. Requiring also coincidences between the products on the focal plane and the radiations detected by other detectors will lead to the detailed understanding of the nuclear phenomenon under investigation. Fig. 7 illustrates the possible arrangements of the detectors currently being considered to cover these experimental purposes. To take the full advantage of the CARP, its support should be pivoted at the target center in as large an angular range as possible. In the present design, however, the range available is only -10° to 30° to the beam, which has resulted from the space limitations of the experimental area. We are expecting in the future that we will be able to transport the beam onto the target also from another direction, which allows the CARP to effectively reach

Fig. 5. Calculated trajectories of a particle with the central mass. The trajectories in the short arm mode are shown by dotted lines and those in the long arm mode by the solid lines.

YIELD (ARB.)

MASS SPECTRUM AT F1

YIELD (ARB.)

MASS SPECTRUM AT F2

Fig. 6. Calculated line profiles on the plane perpendicular to the central ray for the short arm mode (upper) and the long arm mode (lower). The mission angles and energies of the particles are assumed to be uniformly distributed within Δθ, Δθ ≤ 100 msr and ΔT/T ≤ 20%. The source width and height are 1.5 and 1.2 mm respectively. The optical transfer matrix elements in the second order approximation have been used. The numbers placed at the top of the peaks denote the relative values (%) of m/q ratio.
Table 1. Specifications of the CARP

<table>
<thead>
<tr>
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<th>short arm mode (F1)</th>
<th>long arm mode (F2)</th>
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the angles of up to 90° or larger.

The authors express their sincere thanks to Profs. H. Matsuda and H. Ikekami for their illuminating discussions and encouragements. They are grateful to Prof. K. Katori for his interest. Thanks are also due to Dr T. Matsuo who kindly allowed us to make use of the program TRIQ in developing our program ORBIT. The continuous encouragement of Prof. M. Kondo, the director of RCNP, is gratefully acknowledged.

References

11) The program ORBIT has been developed making use of a part of the program TRIQ; T. Matsuo, H. Matsuda, Y. Fujita and H. Wollnik, Mass Spectroscopy, 24 (1976) 19.

Fig. 7. Possible arrangements of the detection systems for the reaction products and other radiations, as expected in the practical experiments of various types.
DEVELOPMENT OF A GAS-JET COUPLED ISOL FACILITY WITH A $^{252}$CF SPONTANEOUS FISSION SOURCE

R. C. Greenwood, R. A. Anderl and V. J. Novick

Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho 83415, USA

Abstract

A mass separator at the INEL has been successfully coupled on-line to a source of $^{252}$Cf fission products via a He-gas jet transport arrangement using solid aerosols of NaCl as activity carriers. Initial tests of the ISOL system on-line to an $\sim 7 \mu g$ $^{252}$Cf source were conducted using gamma-ray spectroscopic measurements of the separated $^{138,139,140,141}$Ba and $^{142}$La activities. The measured transport efficiencies through the system of $<3\%$ and $<0.3\%$ for the Cs and Ba isotopes, respectively, are comparable with those of similar tests conducted at INEL with a hollow-cathode ion source alone coupled to the He-gas jet transport arrangement. Following these tests, a general survey of the mass-separated activities was conducted with the ISOL system on-line to an $\sim 600 \mu g$ source of $^{252}$Cf. Gross $\alpha$-activity was measured for samples collected at 73 mass positions. Gamma-ray spectra were measured with a Ge(Li) detector for 29 of the mass positions. These survey experiments demonstrated the production of significant fission product activity in mass regions which are not available at other ISOL facilities.

1. Introduction

An on-line mass separator has been developed at the INEL as part of a comprehensive program of nuclear structure studies of neutron-rich nuclides produced in the fission process. A unique feature of this ISOL facility is the use of $^{252}$Cf as the source of fission products. As illustrated in Fig. 1 of Ref. 1, the fission-product yield curve for spontaneous fission of $^{252}$Cf has a narrower valley region and significantly higher yields for isotopes with A $\geq$ 150 than those from the more conventional thermal-neutron fission in either $^{235}$U or $^{239}$Pu.

Because of the source strengths of $^{252}$Cf which we eventually anticipate using in this ISOL facility, it was necessary to locate the $^{252}$Cf in a hot cell, remote from the mass separator. This consideration has mandated the use of a gas-jet transport arrangement for coupling the $^{252}$Cf fission-product source on-line to the mass separator. Thus, because of the uncertainties concerning the potential for success of such a coupling scheme which existed at the time that this work was initiated, the first step in this development effort was to undertake an extensive series of tests with an $\sim 7 \mu g$ $^{252}$Cf source coupled on-line to an ion source test assembly, as discussed in Ref. 3. A version of the Siderius hollow-cathode ion source was selected for use in these initial studies because of the features of this ion source, high pressure and high temperature ($\geq 2000^\circ C$) operation, high ionization efficiency and small discharge volume, appeared to be most compatible with the gas-jet coupling scheme.

Results of these earlier tests$^3$ have been sufficiently promising to encourage our most recent efforts to couple the gas-jet transport directly to the mass separator. ISOL operation has now been successfully achieved. Initial experiments with this facility have involved a general survey of the elemental species separated using gross $\beta$-$\gamma$ scans and isotope identification from $\gamma$-ray spectral measurements, and determinations of absolute transport efficiencies through the ISOL system.

2. Ion-Source Gas-Jet Coupling Tests

A detailed discussion of the tests conducted with the $^{252}$Cf coupled on-line to an ion source test assembly has been given previously.$^3$ For completeness, however, we briefly review the results obtained in that phase of the work.

2.1 Test Assembly

The test assembly, which is schematically illustrated in Fig. 1, consists of a small $^{252}$Cf source, an aerosol generator and He gas-jet transport arrangement, a high-capacity Roots-pump system, and an ion source and beam formation/collection system. No mass dispersion stage was used for mass analysis of the ion beam.

An $\sim 7 \mu g$ source of $^{252}$Cf electrodedeposited (at Oak Ridge National Laboratory) on a platinum disc was used as the source of fission products for this work. The source, which is covered by an $\sim 1 \mu g/cm^2$ nickel window is located inside a $\sim 300 \text{ cm}^3$ source chamber which forms an integral part of the gas-jet transport arrangement. The He gas pressure of $\sim 2 \text{ atm}$ in the chamber is sufficient to thermalize the fission products which then rapidly attach themselves to the aerosols contained in the He gas stream.$^4$ Solid aerosols of NaCl were generally used in this work, although some tests were also conducted with aerosols of AgCl and Ag, produced in aerosol generator arrangements identical to that in Fig. 1 for NaCl. The fission products, produced...
attached to the aerosol particles, were transported to the skimmer chamber via a 5 m long Teflon capillary (0.86-mm i.d.). The skimmer hole dimensions of 1.5 mm and 3.0 mm, respectively, for the first and second flat-plate skimmers were chosen to provide 100% transmission at a 3° half-angle divergence of the aerosol stream into the rear of the anode region. The distance of the capillary exit to the first skimmer could be varied during the tests. The purpose of the second skimmer plate, although not allowing for true differential pumping in the interskimmer region, is to enable us to control the pressure in the interskimmer region by means of the bypass valve. In the final test assembly used, the DANYSIK Model 911A hollow-cathode ion source was extensively modified, as illustrated in Fig. 2, to better match the divergence properties of the aerosol stream, with the anode piece and extension tube being shortened and the internal radial dimensions being enlarged. The ion-beam formation system, illustrated in Fig. 1, extracts ions from the ion source at ground potential and accelerates and focuses them, using a three-electrode cylindrical Einzel lens, to a collector held at negative voltage.

2.2 Results from the test assembly

Since there is no mass dispersive element in the ion source test assembly, in order to assess the mass fractions separated we had to rely upon isotope identification from the gross spectrum of γ-rays of the fission products collected following extraction and focussing of the ion beam. Absolute separation efficiencies were obtained by comparing γ-ray line intensities in these spectra with the corresponding line intensities in the gross fission-product γ-ray spectra collected on a foil placed 5 mm from the exit of the capillary, in front of the first skimmer, from other experiments. It had been determined that the transmission efficiency of the He gas-jet transport arrangement approached 100%. To simplify this analysis, by reducing the complexity of the collected γ-ray spectra, collection times at the preskimmer and ion beam collectors were chosen to be 30 min, followed by a 5 min delay. For each experiment, a sequence of three 10-min long 4096-channel spectra were accumulated; measured with a 107-cm² coaxial Ge(Li) detector in a fixed geometry. In this way, only those fission products with half-lives ≥ 2 min contributed significantly to the measured γ-ray spectra. Of particular importance in the analysis of these data was the identification of γ-ray lines associated with those fission products whose precursors, in the decay of fission products along an A chain, had half-lives of less than a few sec. In such cases, because of the fission product hold-up time of < 10-15 s in the collection chamber, we could with some degree of certainty assign them as being the elemental species being ionized. In Table 1 we summarize the results of these experiments, with the estimated absolute separation efficiencies being given as a function of several parameters: (1) aerosol type (NaCl, Ag); (2) support gas (He, Ar, CCl₄); (3) arc power; and (4) anode material (Ta, Mo). Somewhat surprising to us at that time was the evidence from these data that ion beams of Mo/Tc and the rare-earth elements were being formed with reasonable efficiencies.

3. ISOL System Studies

3.1 The ISOL arrangement

As the next step in the development of a He gas-jet coupled ISOL facility, the gas-jet/skimmer/ion-source (Ta anode) arrangement successfully tested on the ion-source test assembly discussed in Sect. 2 above, was transferred, without modification, to the existing mass separator. [This electromagnetic separator is of an ISOLDE-I type, although with a 90° dispersion magnet.] However, since the ion source of this mass separator is operated at positive potential (typically +50 kV) rather than at ground potential, as in the test assembly, it was necessary to develop a high-voltage-isolation vacuum line to couple the skimmer chamber to the Roots pumping system; since we considered it desirable to operate the pumping system at ground potential. A complicating factor in designing this isolation line is that the operating pressure in the skimmer chamber is <200 mT. It is in this pressure regime that the probability for high voltage breakdown is maximized; i.e., the operating region is near the minimum of the Paschen curve for He. In order to overcome this problem, a high-voltage isolation section was developed, consisting of three stages and using specially-designed electrodes and insulator sections, with the voltages in the electrodes being determined by a voltage divider network. This isolation section, which has a total length of <0.5 m is seen in Fig. 3, which is a photograph of the He gas-jet coupled ISOL arrangement we employed in the present work.

![Fig. 2 Details of the skimmer/ion-source configuration for the He gas-jet coupled ion source.](image-url)

![Fig. 3 The He gas-jet coupled ISOL arrangement.](image-url)
Table 1. Absolute elemental separation efficiencies for He-jet-coupled ion source operated with Ta and Mo anodes, Ar and CCl4, support gas and NaCl aerosols.

<table>
<thead>
<tr>
<th>Element Separated</th>
<th>Ta Anode</th>
<th>CCl4(^a)</th>
<th>Ar-1(^b)</th>
<th>Mo Anode</th>
<th>CCl4(^c)</th>
<th>Ar-2(^d)</th>
<th>CCl4(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr</td>
<td>0.5</td>
<td>0.8</td>
<td>0.1</td>
<td>0.6</td>
<td>0.3</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Sr/Y</td>
<td>0.9</td>
<td>1.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>1.0</td>
<td>---</td>
</tr>
<tr>
<td>Mo/Tc</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.2</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Te</td>
<td>4.0</td>
<td>3.0</td>
<td>2.5</td>
<td>2.5</td>
<td>1.5</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Cs</td>
<td>0.9</td>
<td>1.9</td>
<td>0.3</td>
<td>0.4</td>
<td>1.2</td>
<td>1.7</td>
<td>---</td>
</tr>
<tr>
<td>Ba</td>
<td>0.5</td>
<td>1.5</td>
<td>0.2</td>
<td>0.5</td>
<td>1.4</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Ce</td>
<td>0.5</td>
<td>1.6</td>
<td>0.2</td>
<td>0.6</td>
<td>1.6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Ce/Pr</td>
<td>0.9</td>
<td>1.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.9</td>
<td>1.2</td>
<td>---</td>
</tr>
<tr>
<td>Pr</td>
<td>0.5</td>
<td>1.1</td>
<td>0.2</td>
<td>0.6</td>
<td>1.6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Sm</td>
<td>0.8</td>
<td>1.9</td>
<td>---</td>
<td>1.5</td>
<td>1.5</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

\(^a\) Arc power of 150 watts
\(^b\) Arc power of 130 watts
\(^c\) Arc power of 60 watts
\(^d\) Arc power for 170 watts
\(^e\) Arc power of 70 watts

While the initial tests of ISOL operation were performed with the \(\gamma\)-ray \(^{252}\text{Cf}\) fission source used with the test assembly, our most recent work has involved use of the two \(\gamma\)-300 \(\mu\)g \(^{252}\text{Cf}\) sources discussed in Ref. 1. Figure 3 of Ref. 1 shows the schematic relationship of the hot cell containing these sources to the mass separator. The gas-jet transport capillary used with the larger \(^{252}\text{Cf}\) sources has an i.d. of \(\approx\)1.1 mm and is \(\approx\)12-m in length.

Since the primary interest of these initial ISOL tests is to gain an understanding of the coupling of the He gas-jet transport arrangement to the mass separator, only a relatively simple tape-pull mass-collection system has been constructed to provide rapid access to collected separated mass fractions. This arrangement has proven to be satisfactory for the ISOL operational tests in that it allows mass fractions to be \(\gamma\) counted within 30 s from the end of collection.

3.2 Results from ISOL tests

Three separate sets of experiments have been performed to date with the ISOL system. In the first set of tests (Sect. 3.2.1 below) the \(\gamma\)-ray sample of \(^{252}\text{Cf}\) was utilized while for the latter two tests the two \(\gamma\)-300 \(\mu\)g \(^{252}\text{Cf}\) sources were used. All of the tests were conducted using the Ta anode, He/Ar support gas and an anode arc power of \(\approx\)180 watts (i.e., similar operating conditions to those of column 2 in Table 1).

3.2.1 Absolute separation efficiencies were obtained for the mass fractions \(138\) through \(142\) in this initial series of tests. These mass fractions were collected as a group on a single broad collector foil and \(\gamma\)-ray counted as a single group. Comparison of these \(\gamma\)-ray line intensities with those of the corresponding lines in the gross fission-product \(\gamma\)-ray spectrum obtained under identical running conditions at the preskimmer position yielded the following absolute mass separation efficiencies: \(^{136}\text{Cs}(\approx\)2.7%), \(^{137}\text{Cs}(\approx\)2.9%), \(^{138}\text{Ba}(\approx\)1.2%) and \(^{142}\text{Ba}(\approx\)2.8%) (each \(\approx\)0.3%). From these isotopic efficiencies we conclude that the absolute separation efficiencies obtained for Cs and Ba are \(\approx\)3% and \(\approx\)0.3%, respectively. These efficiency values are comparable with those shown in Table 1 obtained with the ion source test assembly.

3.2.2 Relative separation efficiencies as a function of the collected mass were obtained from gross \(\gamma\)-ray counts of individual mass fractions collected on the tape-pull arrangement. In these experiments, each mass fraction was collected for 5 min, with the gross \(\gamma\)-ray counting being started after a delay of 30 s. A total of 73 mass fractions ranging from A=88 to A=168 were surveyed in this manner. The results of this survey are shown in Fig. 4 with a fission-product yield curve for spontaneous fission in \(^{252}\text{Cf}\) being superimposed above the curve of relative mass separation yields. The separation-yield curve in Fig. 4 can only properly be viewed in a qualitative sense, as an indication of separation yields in general mass regions, since for an individual mass fraction the specific \(\gamma\)-ray count will be highly dependent on the decay properties of that particular A chain. Nevertheless, the general trends observed in Fig. 4 are somewhat interesting in that they indicate a rather broad distribution of elements separated. In particular, it is of interest to note, the relatively large separation efficiencies observed in the mass region centered around A=114 and the apparent confirmation of significant yields for rare-earth elemental separations.

3.2.3 Isotopic identification for some 29 of the mass fractions were obtained in a subsequent set of experiments by measuring the \(\gamma\)-ray spectrum from each of the mass fractions using a Ge(Li) detector. In these experiments, the results of which are summarized in Table 2, mass fractions
were collected for 5 or 10 min with y-ray counting beginning after a delay of as short as 30 s. In all cases, the y-ray spectral data provided un-
ambiguous information of the isotopic species de-
posited in each mass region. A number of rather
interesting conclusions can be inferred from the
data shown in Table 2. These are as follows:
- the strong peak in the mass yield curve at
  A=113 and 114 results from the separation of
  Pd;
- the isotopic identifications in the mass
  fractions 104, 107, 108 and 109 together with
  the mass separations efficiency data of Fig. 4
  provides definitive evidence for separation
  of Mo, Tc and Ru;
- the rare-earth elements are separated;
- for the lower Z rare earths, Ce and Pr at
  least, separation occurs in both the elemental
  and monoxide forms, with the ratio of oxide-
to-elemental yields being ~2.2.

4. References

1. R. C. Greenwood, R. J. Gehrke, J. D. Baker and
   D. H. Meikrantz, contribution to this conference.


3. R. A. Anderl, V. J. Novick and R. C. Greenwood,
   Proc. 10th EMIS Conf., to be published in Nucl.
   Instr. and Methods.

4. R. C. Greenwood, R. A. Anderl, R. J. Gehrke and
   p. 76.

5. A. Kjelberg and G. Rudstam (eds.), CERN 70-3

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Table 2. Isotopes in separated mass fraction
determined from y-ray spectral measurements.

<table>
<thead>
<tr>
<th>Mass fraction</th>
<th>Radioisotopes identified in fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td>94Sr (75 s)</td>
</tr>
<tr>
<td>104</td>
<td>104Tc (18.2 min)</td>
</tr>
<tr>
<td>107</td>
<td>107Ru (4.2 min) - 107Rh (21.7 min)</td>
</tr>
<tr>
<td>108</td>
<td>108Ru (4.5 min) - 108Rh (16.8 s)</td>
</tr>
<tr>
<td>109</td>
<td>109Rh (80 s)</td>
</tr>
<tr>
<td>111</td>
<td>111mAg (65 s)</td>
</tr>
<tr>
<td>113</td>
<td>113Pd (90 s) - 113Ag (69 s)</td>
</tr>
<tr>
<td>114</td>
<td>114Pd (149 s) - 114Ag (4.5 s)</td>
</tr>
<tr>
<td>116</td>
<td>116Ag (2.68 min)</td>
</tr>
<tr>
<td>132</td>
<td>132Sn (40 s) - 132Sb (2.8 min), 132Sb (4.2 min)</td>
</tr>
<tr>
<td>133</td>
<td>133Te (12.4 min)</td>
</tr>
<tr>
<td>136</td>
<td>136I (83 s and 46 s)</td>
</tr>
<tr>
<td>138</td>
<td>138Cs (2.9 min and 32.2 min)</td>
</tr>
<tr>
<td>139</td>
<td>139Cs (9.5 min)</td>
</tr>
<tr>
<td>140</td>
<td>140Cs (65 s)</td>
</tr>
<tr>
<td>141</td>
<td>141Ba (18.2 min) - 141La (3.9 hr)</td>
</tr>
<tr>
<td>142</td>
<td>142Ba (10.6 min) - 142La (93 min)</td>
</tr>
<tr>
<td>144</td>
<td>144La (40 s)</td>
</tr>
<tr>
<td>145</td>
<td>145Ce (3.7 min)</td>
</tr>
<tr>
<td>146</td>
<td>146Ce (14 min) - 146Pr (24 min)</td>
</tr>
<tr>
<td>149</td>
<td>149Pr (2.3 min)</td>
</tr>
<tr>
<td>154</td>
<td>154Pm (1.7 min and 2.7 min)</td>
</tr>
<tr>
<td>155</td>
<td>155Sm (22.4 min)</td>
</tr>
<tr>
<td>157</td>
<td>157Sm (8.0 min)</td>
</tr>
<tr>
<td>159</td>
<td>159Eu (18.1 min), 161Ba (18.2 min), 162Ba (10.6 min)</td>
</tr>
<tr>
<td>161</td>
<td>161Gd (3.7 min), 161Ce (3.0 min), 162Ba (10.6 min), 161Ba (18.2 min) ?</td>
</tr>
<tr>
<td>162</td>
<td>162Gd (9 min) - 161Tb (7.7 min), 164Ce (14 min) - 164Pr (24 min)</td>
</tr>
<tr>
<td>165</td>
<td>165Pr (2.3 min)</td>
</tr>
<tr>
<td>173</td>
<td>--</td>
</tr>
</tbody>
</table>
RAPID CONTINUOUS CHEMICAL METHODS FOR STUDIES OF NUCLEI FAR FROM STABILITY

N. Trautmann, N. Greulich, U. Hickmann, N. Kaffrell, E. Stender and M. Zendel
Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Germany

H. Gäggeler
GSI Darmstadt, D-6100 Darmstadt, Germany

K. Broden and G. Skarnemark
Department of Nuclear Chemistry, Chalmers University of Technology, S-41296 Göteborg, Sweden

D. Eriksen
Department of Nuclear Chemistry, University of Oslo, Oslo 3, Norway

Abstract

Fast continuous separation methods accomplished by combining a gas-jet recoil-transport system with a variety of chemical systems are described. Procedures for the isolation of individual elements from fission product mixtures with the multistage solvent extraction facility SISAK are presented. Thermochromatography in connection with a gas-jet has been studied as a technique for on-line separation of volatile fission halides. Based on chemical reactions in a gas-jet system itself separation procedures for tellurium, selenium and germanium from fission products have been worked out. All the continuous chemical methods can be performed within a few seconds. The application of such procedures to the investigation of nuclides far from the line of $\beta$-stability is illustrated by a few examples.

1. Introduction

Though extensive efforts have been made in the last years to study nuclei far from the region of $\beta$-stability, there are still many nuclides which remain to be discovered or whose decay properties are of interest but not known well enough. For the isolation of such short-lived nuclides from complex reaction product mixtures mainly mass separation\(^1\) or chemical procedures\(^2\) are suited. Most recent progress in both methods is due to developments and improvements of on-line separation techniques. The use of conventional mass separators with the advantage of a rapid and unambiguous isobaric separation is limited to elements for which suitable target-ion-source systems are available; e.g. non-volatile elements like Zr and Nb have low yields or are inaccessible by this method. Therefore, the emphasis in developing continuous chemical separation procedures, which are selective with respect to the atomic number, was put on those elements which cause problems in ISOL-systems.

On-line chemical separations can be accomplished by combining a gas-jet recoil-transport system\(^3\) with a variety of separation steps. The present paper describes its combination with the multistage solvent extraction system SISAK\(^4\) and with a thermochromatographic column where chemical selectivity is achieved by producing volatile species. Furthermore, approaches to achieve chemical separations in a gas-jet system itself are presented and the application of the various chemical procedures in nuclear spectroscopic studies is illustrated by a few examples.

2. Continuous chemical separation procedures

The gas-jet recoil-transport method\(^5\) has found widespread application as a rapid and efficient technique for transporting short-lived nuclides from the production site to detector systems or to separation facilities. In this method nucleation and reaction products recoiling out of thin solid targets are stopped in a gas containing clusters and the thermalized atoms sticking to these clusters are transported along with the carrier gas out of a stopping chamber through a capillary to a low-background area. The sticking process is rather unselective with regard to the mass and atomic number of the reaction products and in most cases mass separation\(^5\) or chemical steps have to be added.

The development and application of the continuous chemical separation methods described below were performed with neutron-rich nuclei from thermal-neutron induced fission of $^{235}\text{U}$ or $^{239}\text{Pu}$. Since gas-jets have mostly been used at accelerators, the techniques outlined in this paper are also applicable to products from charged particle induced reactions.

The fission products were produced by irradiation of 0.1–1 mg $^{237}\text{U}$ or $^{239}\text{Pu}$ targets in a thermal neutron flux of about $6 \times 10^{10}$ n/cm$^2$·s in one of the beam holes of the Mainz reactor. After thermalization in nitrogen containing clusters they were swept out through a 1 mm inner diameter polyethylene capillary.

2.1 Combination of a gas-jet with the solvent extraction system SISAK

The SISAK technique is based on continuous multistage solvent extraction procedures where the separation of the two phases is accomplished by specially designed centrifuges\(^6\). A set-up of four small centrifuges has been installed at the Mainz reactor and combined with a KCl/Np-jet\(^7\). This arrangement allows on-line nuclear spectroscopic studies on nuclides with half-lives down to about one second.

As an example Fig. 1 shows the separation of zirconium and niobium from a fission product mixture\(^8\) based on the solvent extraction with Alamine-336. The fission products carried by the gas-jet are dissolved in 1 M sulphuric acid in a static mixer. The gas-liquid mixture is then fed into a degassing unit, in which the carrier gas and more than 98% of the noble gases are separated from the aqueous solution and removed by suction. To enhance the degassing effect the temperature of the solution is kept at ~70 °C. In the first mixer-
centrifugal separator unit (C1) the aqueous phase is contacted with a 0.1 M solution of Alamine-336 in Shellsol-T (an aliphatic kerosene). The organic phase also contains n-dodecanol (5%) to prevent formation of a third phase. Zirconium and niobium are extracted with high yield (>80%) into the organic phase, probably as negatively charged sulphate complexes. Technetium and a few other fission products (like iodine) are extracted to a small extent (<5%).

In the second mixer-centrifuge step (C2) zirconium and niobium are back-extracted almost quantitatively by means of 0.3 M nitric acid, while technetium and most of the other contaminants remain in the organic phase.

After the back-extraction step hydrogen peroxide is added to the aqueous solution for the complexation of niobium, and 10 M nitric acid to increase the acidity so that the solution entering the third mixer-centrifugal separator unit (C3) consists of ~3 M nitric acid and ~1 M hydrogen peroxide. In C3 approximately 95% of the zirconium are extracted into an 1 M solution of HDEHP (dihydroxyethylidihydroxyphenyl phosphoric acid) in Shellsol-T whereas niobium as peroxide complex remains in the aqueous phase. In the organic phase only zirconium nuclides and their daughter products can be observed, together with a very small amount of iodine; the aqueous phase still contains some zirconium activity which is removed in a further extraction step with HDEHP (C4). The average delay times from the target site to the detectors (maximum countrate at the detector) are 7 and 9 for pure Zr- and Nb-fractions measured in the positions D(Zr) and D(Nb) of Fig. 1, respectively. The γ-ray spectra of the niobium fraction show no other γ-rays than those belonging to the nuclides 93-104Nb and their decay products. The zirconium chemistry has been used for γ(t)-coincidence measurements on 102Zr.

The chemical procedure for the separation of technetium from a 239Pu fission product mixture is shown in Fig. 2. Here, the fission products carried by the gas-jet are dissolved in a solution consisting of 0.1 M nitric acid and 0.1 M potassium bromate. The solution is heated to ~80 °C to accelerate the oxidation of technetium to the pertechnetate ion and to achieve a better separation from the fission product noble gases. In the first mixer-centrifugal separator step (C1) technetium is extracted into 0.05 M Alamine-336 in chloroform. Molybdenum and a small fraction of zirconium and niobium are co-extracted. In the next step (C2) technetium and traces of zirconium, niobium and molybdenum are back-extracted into 2 M nitric acid.

### Table 1 Continuous chemical separation procedures with SISAK

<table>
<thead>
<tr>
<th>Separated element</th>
<th>Production mode</th>
<th>Transport system</th>
<th>Studied nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Zn(n,p)Cu</td>
<td>Liquid ZnCl₂</td>
<td>60Cu, 70Cu</td>
</tr>
<tr>
<td>As</td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>To be used for 85As</td>
</tr>
<tr>
<td>Br</td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>86-89Br</td>
</tr>
<tr>
<td>Zr</td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>100Zr</td>
</tr>
<tr>
<td></td>
<td>Heavy-ion reaction</td>
<td>Gas-jet</td>
<td>To be used at GSI, Darmstadt</td>
</tr>
<tr>
<td></td>
<td>Heavy-ion reaction</td>
<td>Gas-jet</td>
<td>Test</td>
</tr>
<tr>
<td>Nb</td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>106-108Tc</td>
</tr>
<tr>
<td></td>
<td>Heavy-ion reaction</td>
<td>Gas-jet</td>
<td>To be used for 109-112Ru</td>
</tr>
<tr>
<td>Tc</td>
<td>239Pu; thermal fission</td>
<td>Gas-jet</td>
<td>116Pd</td>
</tr>
<tr>
<td>Ru</td>
<td>239Pu; thermal fission</td>
<td>Gas-jet</td>
<td>Test</td>
</tr>
<tr>
<td>Pd</td>
<td>239U; 14-Mev fission</td>
<td>Liquid</td>
<td>143-148La</td>
</tr>
<tr>
<td></td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>145-150Ce</td>
</tr>
<tr>
<td></td>
<td>235U; thermal fission</td>
<td>Gas-jet</td>
<td>147-151Pr</td>
</tr>
</tbody>
</table>

- 728 -
(or in some cases 0.8 M nitric acid; see below). In the third stage (C3) zirconium and niobium contaminations are removed by extraction with 0.5 M HDEHP in chloroform. The outgoing aqueous phase contains only technetium nuclides, their daughter products and a small Mo-contamination (< 1%).

\( \gamma(\gamma) \)-coincidence investigations on 106-108Tc were carried out by measuring directly the aqueous phase leaving C3. For \( \gamma(\gamma) \)-angular correlation measurements on 108Tc the system was modified in such a way that the technetium activity was back-extracted (in C2) into 0.8 M HNO\(_3\), and after C3 0.7 M sodium hydroxide was added. The resulting solution was pumped through a detector cell (length = 4 cm; diameter = 1 cm) filled with anion exchange resin which retains technetium for \( \approx 30 \) s under these conditions. The \( \gamma(\gamma) \)-angular correlation studies on 5 s 108Tc were made on an empty detector cell of the same dimension as in the case of 108Tc through which the aqueous phase from C2 was pumped with a flow-rate of \( \approx 10 \) ml/s. The measurements on neutron-rich technetium nuclides resulted \(^{9-11}\) in detailed decay schemes of 106-108Tc.

So far we have developed 12 different separation procedures\(^{9,12}\) with the SISAK system which are summarized together with their applications in Table 1. For the separation of arsenic a gas-jet with chemical selectivity (HCl-jet; see below) and a new, faster degassing unit with a hold-up time of \( \approx 0.3 \) s compared to \( \approx 2 \) s obtained with the former degasser was applied. With this arrangement one step separation is sufficient for the isolation of arsenic yielding in a total transport time of \( \approx 2.9 \) s (maximum countrate), determined by multiscaling of the arsenic fraction and operating the reactor in the pulse mode.

2.2. Combination of a gas-jet with a thermochromatographic column

In the combination of a gas-jet with a thermochromatographic column chemical selectivity can be achieved by producing volatile species in reactions with reactive gases which are swept by a carrier gas or in the vacuum through a tube with a negative temperature gradient and are deposited at temperatures correlated to the adsorption enthalpies and entropies of the volatile species. Fission products were used as a model for complex mixtures of elements and chlorides, bromides and iodides were chosen as volatile species.

A nitrogen gas-jet containing potassium chloride clusters is used to transport the fission products from the target area to the thermochromatographic system\(^{13}\) shown in Fig. 3. The clusters are stopped in a quartz-wool plug located in a quartz column with an inner diameter of 4 mm which is filled with quartz powder. The plug is heated to \( \approx 950 ^\circ \)C in order to destroy the clusters and to enable complete halogenation. Along the thermochromatographic column a negative temperature gradient of \( 18 ^\circ \)C/cm is established. After the column the gas passes through a charcoal trap which collects very volatile species and through a NaOH trap in which the halogenating agents are captured. To increase the flow rate through the thermochromatographic set-up an oil pump is placed behind the NaOH trap. For halogenation of the fission products a mixture of the reactive gas with nitrogen is fed into the column through a by-pass. The element distribution along the thermochromatographic column was measured after removal of the column from the oven by \( \gamma \)-ray spectroscopy. With HCl, HBr and HI quite similar thermochromatograms were obtained. As an example Fig. 4 shows the fission product distribution with HI in the carrier gas at a flow rate of 1.3 l/min and after an exposure time of 15 min. The alkaline earth elements are not volatilized under these conditions. The lanthanides are deposited at 750 \( ^\circ \)C and Rb and Cs are found at 660 \( ^\circ \)C. Molybdenum forms a rather broad zone with two peaks at 590 \( ^\circ \)C and 410 \( ^\circ \)C. Proceeding to the low temperature region,
particle size. In this trap, bromine, iodine and selenium activities are absorbed to 95% whereas fission products fixed on clusters pass through

\[ \text{Se, Br, I} \rightarrow \text{Fission products} \rightarrow \text{Capture An} \rightarrow \text{Tc, Kr, Br} \rightarrow \text{Pump} \]

\[ \text{Charcoal} \rightarrow \text{Pressure control} \rightarrow \text{Charcoal trap} \rightarrow \text{Heating} \rightarrow \text{Stopping chamber} \rightarrow \text{Detector} \]

Fig. 5 Set-up for the continuous separation of tellurium from fission products (not to scale)

with about 90% efficiency, accompanied by krypton and xenon activities. After this trap the gas mixture enters the reaction chamber consisting of a quartz spiral which is heated to 860 °C. At this temperature, the clusters are decomposed and volatile compounds of tellurium are formed. These compounds and the noble gases are transported through a capillary to a trap filled with charcoal. Tellurium is completely absorbed in this trap whereas the noble gases pass through. At the exit of this trap, a pump was placed to decrease transport time and to improve decontamination from noble gas activities. It should be mentioned that beyond 900 °C the decomposition of ethylene becomes vigorous as indicated by the formation of soot.

The set-up for the continuous separation of selenium from fission products is similar to the one used for tellurium (Fig. 5) except that the charcoal trap preceding the reaction chamber is replaced by two paper filters. In this filter, 99% of the activities attached to clusters are retained whereas selenium, the halogens and the noble gases pass through. Selenium and the halogens form volatile species in the reaction chamber but due to differences in the formation of the species and in the transport behaviour, selenium and the halogens can be separated from each other. The decay time between production of Te and Se at the target and their collection in the final absorption trap was determined to be 6 s for 50% of the saturation activity.

Both on-line gas phase procedures have been applied for investigations on the decay properties of the neutron-rich nuclides 85-87Se and 135-137Te by γ-ray singles and coincidence measurements14,15).

Highly volatile chlorides of germanium, arsenic and the halogens are formed from fission fragments recoiling into nitrogen containing hydrochloric acid as the reactive component and can be separated from each other on selective absorbents. Fig. 6 shows the arrangement for the continuous separation of germanium from fission products16). The reactive gas, a 1:20 mixture of hydrochloric acid and nitrogen and the volatilized fission products pass a small column (Trap 1) packed with quartz-wool to retain activities attached to clusters.

\[ \text{Me(gas)} \rightarrow \text{Detector} \rightarrow \text{Magnetic valve} \rightarrow \text{Stoping chamber} \rightarrow \text{Fission products} \rightarrow \text{Charcoal trap} \rightarrow \text{Heating} \rightarrow \text{Stopping chamber} \rightarrow \text{Detector} \]

Fig. 6 Experimental arrangement for the on-line separation and measurement of germanium isotopes

\(^{208}\text{F}\), an activator product of teflon, which is used as material for the stopping chamber in order to prevent corrosion, is permanently released and absorbed on quartz-wool, too. After this trap the gas enters a quartz spiral (Trap 2) which is coated at its inside with a silver layer and heated to about 800 °C. In this spiral the halogens are transformed to nonvolatile species and absorbed at the silver layer, whereas germanium, arsenic and the noble gases pass through. The following column (Trap 3) is filled with polystyrene beads saturated with HDEHP retaining the volatile arsenic compound almost quantitatively. The placement of a detector system close to the absorption position allows to measure short-lived arsenic activity on-line. Germanium chloride, passing this column, is collected in a charcoal trap (Trap 4) and its isotopes can be studied with a detector system placed there, as shown in Fig. 6. The noble gases are pumped off. The calculated transport time from target to detector is about 3 s and a transport yield of \( \approx 30\% \) results for carrier-free germanium. The method described has been used for decay studies16) on the neutron-rich germanium isotopes 26.8 s \(^{70}\text{Ge}\), 7.8 s \(^{71}\text{Ge}\) and 4.5 s \(^{72}\text{Ge}\).

3. Conclusions

The combination of gas-jet recoil-transport system with various chemical steps enables continuous separations of single elements from complex reaction product mixtures within a few seconds and, hence, offers an important approach for studies of nuclei far from the region of \( \beta \)-stability.
The continuous solvent extraction with the centrifuge system SISAK is applicable for the isolation of any element which can be distributed between two immiscible liquid phases. The gas-jet can be combined with thermochromatographic columns in a very simple way opening many possibilities for on-line studies on short-lived nuclides. Chemical reactions in a gas-jet system with reactive additives can be utilized for very fast on-line procedures for the isolation of certain elements.

The continuous performance is of importance in all measurements with low efficiencies such as delayed-neutron spectroscopy, γγ-coincidence, high energy γ-ray and γγ-angular correlation spectroscopy which require long-time operation in order to collect data of sufficient statistical quality. With regard to the time scale all the continuous procedures presented in this paper work in the second range. The future trends may be mainly directed towards the development of ultrafast chemical separations which should allow investigations on nuclides down to half-lives of milliseconds. Here the most promising way seems to be direct chemical reactions in a gas-jet recoil-transport system.

References

A LIQUID SALT TARGET FOR SELECTIVE PRODUCTION OF NEUTRON DEFICIENT ANTIMONY ISOTOPES

AT ISOLDE

O. Glomset\textsuperscript{a)}, T. Bjørnstad, E. Hagebo, J.R. Haldorsen and V. Hjaltadottir

Department of Chemistry, University of Oslo, Blindern, Oslo 3, Norway

and S. Sundell

ISOLDE group, EP-division, CERN, 1211 Geneva 23, Switzerland

Abstract

A target system designed for selective on-line mass separator production of neutron deficient antimony isotopes in high energy proton-induced spallation reactions is described.

The target material consists of tellurium dioxide (TeO\textsubscript{2}), potassium chloride (K\textsubscript{2}Cl\textsubscript{2}) and lithium chloride (LiCl) in the molar ratios 29:25:46. The mixture constitutes a eutectic with a melting point at 3475°C.

The material shows acceptable stability at vacuum conditions (10^{-6}-10^{-8} torr) during prolonged operation at 450°C. In vacuum chamber release tests of products from irradiated samples one finds that 50% of the antimony activity has evaporated after 2.6 min heating at 420°C, while there is practically no release of other elements (i.e. tin and indium). Thermo-chromatographic experiments show no deposit in quartz tubes of the released products in the temperature range 430°C to 20°C. The products are firstly condensed in a liquid nitrogen trap.

Careful tests of the target system were carried out at the ISOLDE-off-line isotope separator in order to estimate the best overall on-line running conditions.

Subsequently the target system was tested on-line at ISOLDE with 86 MeV/amu as the bombarding projectile (protons were not available at the actual time). Release yield curves and release delay times were recorded. At 420°C delay half-times of 2-6 min were found for antimony. No tin and indium were seen. This is in accordance with results from the vacuum chamber experiments. The production yield of, for instance 119-121Sb, with 2.5 μA 600 MeV proton bombardment of a normal size target of ~32g/cm², is estimated to ~2.5×10^{8} atoms/s.

1. Introduction

Over the last few years a considerable effort has been devoted to the development of an ISOL-target for selective production of indium, tin and antimony from spallation reactions induced by high energy protons. The scientific justification is obvious since these elements lie in the region of the magic number Z=50. Target materials containing elements with Z>52 are not ideal as the volatile reaction products Xe and I easily diffuse to the ion source and become ionized together with the elements of interest. This is for instance shown by Glomset and Hagebo for a cesium-containing target matrix. The interest therefore focused on matrices containing tellurium as target element.

Since indium, tin and antimony form volatile halides, halogen containing materials were expected to be possible candidates as target material. Early experiments have tested the release properties of telluriumtetra-chloride as a fine powder. However, in spite of promising results from vacuum chamber tests, on-line isotope separator experiments gave an average delay half-time of 18 min for the two elements antimony and tin.

The delay in powder matrices is mainly governed by the diffusion rate in the solid and/or the surface desorption rate. Higher rates are observed at increased temperatures. But a high vapor pressure of the target matrix itself may lead to considerable loss of material, which in turn may affect a proper operation of the ion source. The maximum permissible operating temperature for telluriumtetra-chloride was 100°C. Diffusion in liquids is generally much faster than in solids at comparable temperatures. In order to improve the release rate, a search has been conducted for a tellurium-containing halide system with sufficiently low vapor pressure above the melting point to ensure a stable operation of the mass separator. The preparation and performance of such a material at off-line and on-line conditions is reported in the present paper.

2. Off-line experiments

2.1 Vacuum chamber tests

2.1.1 Target material preparation

The system finally chosen as subject for further studies consisted of tellurium-dioxide (TeO\textsubscript{2}), potassium chloride (K\textsubscript{2}Cl\textsubscript{2}) and lithium chloride (LiCl) in the molar ratios 29:25:46 respectively. This mixture is reported to have a eutectic melting point at 347-359°C, and is prepared in the following way: After some hours storing of the very hygroscopic lithium chloride at 110-120°C to remove any trace of humidity, the three compounds are mixed, and pounded

\textsuperscript{a) Present address: Department for Health Physics, Rikshospitalet, Oslo 1, Norway.}
in a mortar. The mixture is then melted in a quartzship at approximately 800-900°C in dried nitrogen atmosphere, the mixture appears white-yellow and crystalline. It is hygroscopic, and is preferably stored in a desiccator. The melting point was measured to be 347±5°C in accordance with the literature value.

2.1.2. Target material preparation

Fig.1 gives the vapor pressure curves of the pure components in the mixture, and of the possible product compounds. At temperatures below some 450°C the matrix vapor pressure can still be kept below \(10^{-4}\) torr (which is necessary for a stable source). At this temperature the vapor pressure of the probable products are rather high. Hence, when the product compounds are present at the liquid surface, the evaporation is expected to be fast.

![Vapor pressure curves of the probable chemical reaction products of the spallation produced elements indium, tin and antimony.](image)

The thermal stability has been tested gravimetrically, and revealed an evaporation loss rate of less than 1 permille per hour for sample sizes of 2-3 g, a temperature variation in the range 390-470°C and a pressure of \(10^{-3}\) to \(10^{-4}\) torr. After 48 hours at 400°C, the mixture is still a liquid, thus underlining that the change in chemical composition is not pronounced during this period of time.

The reaction product release rate was tested in a vacuum chamber experiment. The probe nuclide was selected to be \(^{124}\)Sb (60.3d). Small samples of the mixture were irradiated with 600 MeV protons for 72 hours, and allowed to decay for 4 months. The samples were successively transferred to small graphite evaporation containers surrounded by tantalum for ohmic heating, and mounted between two electrodes in a vacuum chamber test bench. Heating intervals of 3 min were applied to the samples. The pressure was \(10^{-3}\) to \(10^{-2}\) torr and the temperature 400°C. The results of the Y-spectrometric measurements after each heating interval are summarized in Fig.2 which gives the fraction of activity left, \(F(t)\), as a function of the heating time.

![The fractional release of antimony (\(^{124}\)Sb) at 400°C as a function of the heating time.](image)

Liquid targets have previously been reported to show characteristic of a rather simple release behaviour, where the release process can be described by a single exponential term

\[ F(t) = e^{-\frac{t}{T}} \]  (1)

Here \(\nu\) is a constant believed to be related to the surface desorption step. This description does not, however, fit the data in Fig.2. It is necessary to introduce one extra delay component. About 10% of the totally produced antimony activity is ruled by this long component. The origin of this delay is not easily recognized. Somewhat speculative suggestions may be that the temperature is kept much lower here than in ref. s. 3, 9) and a liquid diffusor time may play a role. Besides, since this is a chemical target, the necessary chemical reactions for formation of the chlorides have to be completed before evaporation can take place.

However, by subtracting the log delay component from the data in Fig.2, a single exponential component can be fitted to the resulting points.

The delay half-time is defined as the time needed for evaporation of one half of the original activity. From the measured delay curve in Fig.2 one finds a gross delay half-time of \(t_{1/2} = 2.6\) min. The short component alone \(t_D = 2.3\) min, and the long component \(t_{1/2} = 30\) min.

2.1.3. Thermochromatography

Thermochromatographic experiments have been performed on the released products where internal parts of the oven consisted of pyrex glass or quartz tubes, and a linear temperature gradient between
420 °C and room temperature was established. The results show that 100% of the released products (both of Sb and Sn) were found in the liquid nitrogen-cooled part mounted at the outlet of the chromatograph. The activity of tin (117mSn) was, however, rather poor.

2.2. Isotope separation

On-line conditions has been simulated at the ISOLDE off-line isotope separator. The target and ion source arrangement used is described later.

Samples of 5-6 g of 600 MeV proton irradiated material were heated to 420 °C for about 30 min, and the separated activity collected on an end strip placed in the focal plane in the collector tank. Gamma-spectrometric measurements were performed on the target material before and after the separation, on the endstrip and on various parts of the target-ion source assembly. The results show that about 75% of the original antimony activity in the target is released. Only traces of antimony were found in the ion source internal parts. An ionization efficiency for antimony of 4.5-6 % has been derived. Small amounts of tin was also released from the target, but practically nothing reached the collector strip.

3. On-line experiments

3.1. Experimental

3.1.1. Target description

The general layout of the target is similar to the normal ISOLDE-targets. Due to the corrosive behaviour of the molten mixture the target container and the transfer line to the ion-source had to be made of quartz. The line is connected vertically onto the middle of the target container, bends then horizontally and vertically into the ionsource which is of the PENBIAD type. The target container is covered with an outer mantle of stainless steel, and the target is heated by passing DC-current through this mantle.

In order to avoid too high transfer of unwanted species from the target to the ion source the transfer line has to be kept relatively cold. This is achieved by shielding the line against radiative heat from the target and the ion source by stainless steel screens, and by a water-cooled copper-tress on the line. The system is illustrated in Fig.3.

3.1.2. The bombarding beam

The bombarding particle available at the CERN synchrocyclotron for these experiments was the 86 MeV/amu C-ion. This beam does not give optimal conditions due to its short range (see below) and high ionizing effect. The later will result in breaking of chemical bonds and local overheating, thus producing higher vapor pressure than expected during proton irradiation. The high vapor pressure will in turn lower the ionization yield and disturb the extraction optics. It was found appropriate to work with a beam intensity of 5-10^10 particles/s.

3.1.3. Production yield measurements

Since the projectile has Z=6, it is possible to form products with higher atomic number than that of the target element in appreciable amounts. Production yield measurements of Sb, I and Xe isotopes are presented. The two latter results from proton transfer reactions from the 12C-ion, and will normally not be observed in proton irradiations.

Indium and tin isotopes were not observed.

The mass separated beam from the ISOLDE on-line isotope separator was collected on the aluminized side of a movable thin plastic tape, and the source subsequently transferred into detection position 50 cm away. All the yield measurements were performed by γ-ray spectroscopy using a Ge(Li)-detector with standard electronics connected via CAMAC to a HP-computer. A 4g-lead detector was utilized for optimizing the separator parameters on each mass. The data were stored on magnetic tape, and subsequently analyzed by the computer code GAMANAL.

3.1.4. Delay-time measurements

The ideal nuclide for on-line delay time measurements should be long-lived compared to the delay time in question so that decay-corrections can be neglected. It be shielded in order to avoid parent corrections and have reasonably high production yield giving sufficient counting statistics. The best candidate among the antimony isotopes according to these criteria is 117mSb (16 min., 60.4 min).

These measurements were performed with the same experimental setup as described in the preceding section. The structure of the time-sequence for the different operations is illustrated in Fig.4. The collection time and sample transport are controlled by electronic "flip-flops" driven by a crystal.
clock. The counting after each collection is manually started on a light signal. The error in starting point is estimated to be less than 0.5 s, and hence without any practical importance. All the γ-ray spectra were stored on magnetic tape, and subsequently analyzed by the HP-computer code ISANUT.

3.2. Results and discussion

3.2.1. Production yield of antimony isotopes

The yields are calculated as the production yields (in the collector thank) at saturation by the formula

\[ Y = \frac{S \cdot \lambda}{\varepsilon_Y \cdot t_{\text{coll}} \cdot (1 - \exp(-\lambda t_{\text{col}})) \cdot \exp(-\lambda t_d) \cdot (1 - \exp(-\lambda t_{\text{count}}))} \]

where

- \( S \) = the total net integral in the γ-peak
- \( t_d \) = decay time
- \( t_{\text{coll}} \) = collection time
- \( t_{\text{count}} \) = counting time
- \( \varepsilon_Y \) = absolute counting efficiency at the energy \( E \)
- \( \varepsilon_T \) = beamline transport efficiency (=80%)
- \( I_Y \) = branching ratio of the γ-line

Here the collection, decay and counting times were preselected for each nuclide. The absolute counting efficiency was determined using a calibrated source of \(^{152}\)Eu, and the decay scheme information was taken from various issues of "Nuclear Data Tables" and from "Table of Isotopes". The quoted errors are composed of the statistical error in the net number of given by the code GAMANAL (\( \sigma_e \)), an overall error of 5% in the efficiency curve (\( \sigma_{\varepsilon_Y} \)) and 10% in the beamline transport efficiency (\( \sigma_{\varepsilon_T} \)).

The yields are illustrated in Fig.5 and listed in Table 1 together with some physical and experimental parameters. Also shown in Fig.5 is the estimated yield curve for the (at present) full "C"-beam intensity of \( 3 \times 10^5 \) particles/s.

3.2.2. Production yields of xenon and iodine isotopes

The xenon and iodine isotopes produced in proton transfer reactions are detected simultaneously and their production yields are derived. All the Xe-yields are calculated by the formula (2). The results are given in Fig.6. Of the measured I-isotopes the only one that can be directly \(^{122}\)I, calculated by the formula (2) is \(^{122}\)I. The yield for \(^{122}\)I is calculated from the observed \(^{55}\)Fe activity. For the masses 117, 118 and 119 a correction has to be made (although rather small) for the growth from the corresponding Xe-mothers both during collection and counting. (eqn.3)
Table 1. Production yields of Sb-isotopes by $^{12}$C$^+$-irradiation (5.10$^{10}$ part/s) of a Te-based (17 atom%) target with thickness 32 g/cm$^2$.

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<th>Mass</th>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$ (abs)</th>
<th>$t_\gamma$</th>
<th>$t_{coll}$</th>
<th>$t_{count}$</th>
<th>Number of counts</th>
<th>Prod. yield</th>
<th>Average prod. yield</th>
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$$Y_2 = \frac{S \cdot \lambda_2}{\lambda_2 \cdot \lambda_1 \cdot (1-exp(-\lambda_2 t_{coll})) \cdot exp(-\lambda_2 t_d)} \cdot \frac{1}{(1-exp(-\lambda_2 t_{coll}))}$$

$$Y_1 = \frac{\lambda_2 \cdot (1-exp(-\lambda_1 t_{count}))}{\lambda_2 \cdot \lambda_1 \cdot (1-exp(-\lambda_2 t_{count})) - 1}$$

$$Y_1 \cdot \left[ 1 - \frac{\lambda_2}{\lambda_2 \cdot \lambda_1} \cdot \frac{1}{(1-exp(-\lambda_2 t_{coll}))} \right]$$

$$Y_1 \cdot \left[ 1 - \frac{\lambda_2}{\lambda_2 \cdot \lambda_1} \cdot \frac{1}{(1-exp(-\lambda_2 t_{coll}))} \right]$$

The subscripts 1 and 2 means the mother and daughter nuclides respectively. The results are given in Fig. 6.

3.2.3. Estimate of the production yield of the antimony isotopes with a full intensity proton beam

When the $^{12}$C$^+$-ions pass through the quartz wall of the target container, they are totally stripped of electrons into $^{12}$C$^+$-particles. By means of Fig. 7 (which gives the range of $^{12}$C$^+$-ions in different elements) $^1$, the range of these particles in the target mixture is estimated to be ~2.7 g/cm$^2$ (the glass wall of the target container degrade the particle energy to ~80 MeV/amu). The total target thickness is calculated by $d_m = \frac{k \cdot w}{V} \cdot \frac{w}{V}$, where $w$ is the length of the target = 12 cm, $W$ is the total weight = 27 g and $V$ is the volume of the melt = 10 cm$^3$. This gives $d_m = 32 g/cm^2$. Accordingly, only the first 1/12 of the total target thickness contributes to

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the activity production.

For 600 MeV protons the target can be considered as thin, and the whole length contributes equally to the production of the measured isotopes. If the production rate of the measured isotopes from $^{12}$C$^-$ bombardment is constant over the carbon-ion range (rough estimate) and the reaction cross section for $^{12}$C$^-$-bombardment and protons are equal then the yields increase by a factor of 1.12 for 1 mA p as compared to 1 part $^{12}$C. An additional factor of 2.5 is gained by increasing the beam current to 2.5 mA p (the maximum permissible onto an ISOLDE-target at present).

The measured production yields of the antimony isotopes then have to be multiplied by a factor of $3.75 \times 10^{-3}$ to arrive at the estimated production yields from 600 MeV proton bombardment with a maximum beam intensity of 2.5 mA. The results are shown as curve IV in Fig.5.

### 3.2.4. The delay time of antimony

The statistics obtained in the 1.5 min counting intervals was rather poor, and the only $\gamma$-lines possible to use for the delay-time calculations are the 1293 keV and the 511 keV annihilation radiation peaks. The latter is practically free from general background. Neither do the two nuclides $^{116}$Xe and $^{118}$Xe disturb. The measured delay curves after "beam off" are given in Fig.s 8a and b. However, the nuclide $^{116}$Sb has two isomers with half-lives of 16 min and 60 min. Both contribute to the two $\gamma$-lines, and this must be taken into account when making the decay correction of the measured delay curve. The contribution from the 60 min isomer in the 1293 keV (with $I_{1293} = 100\%$) at constant production rate is calculated from other $\gamma$-lines with known relative intensities, belonging only to this isomer, i.e., 99 keV(3%), 407 keV(42%) and 542 keV(52%). The shape of the decay curve could then be established, and the proper corrections made in the delay curves. The resulting delay curves are shown (dashed) in Fig.s. 8a and b.

While the vacuum chamber delay curve (section 2.1.2) expresses the remaining (or fractional) activity in the sample after heating, denoted $T(t)$, the presently derived curves result from a differential measurement of the released activity, denoted $f(t)$:

$$f(t) = \frac{\delta T(t)}{\delta t}$$  \hspace{1cm} (4)

The vacuum chamber curves can be fitted with a sum of two exponentials, and only about 10% of the total amount of produced antimony nuclides are ruled by the long delay component. Supposing the same delay properties in on-line experiments, a long component will be depressed in the resulting delay curves, and appear as a level hardly distinguishable from the general background (within the counting statistics). However, the delay can not be expected to be identical in vacuum chamber and on-line experiments, and the present curves also show a much more
pronounced long component which may be due to relatively slow adsorption and desorption processes on the moderate temperature quartz surfaced in the target container and transfer line. The short component is, however, still appreciable, and the derived half-time values of 2.4 min and 2.8 min (for the 1293 keV and 511 keV peaks, respectively) are in accordance with the vacuum chamber results. The errors are estimated to be ±50%.

4. CONCLUSION

The tellurium-based melted mixture has been thoroughly tested both in vacuum chamber and off-line isotope separator experiments. A target made of this mixture was also tested on-line under especially unfavorable conditions, (short range and high ionization density).

The target material has survived the tests in good shape.

The reason for not observing tin and indium in the mass separator experiments is not fully examined yet. However, two circumstances may be contributing: low vapor pressures and formation of chemical sidebands. The relatively low vapor pressures of the probable chemical reaction products (see Fig.1) counteracts an efficient release from the target. On the other hand off-line results show that part of the tin is released (possibly as SnCl4), but can not be recovered at the Sn-mass on the collector strip. Chemical sidebands are often formed in isotope separators. Unpublished ISOLDE results show that addition of fluorine or chlorine-containing compounds in small quantities to the target matrix leads in several cases not only to an increased production rate at the proper mass M, but to still higher rates at sidebands like MF and MF2, or MCl and MCl2. Sidebands with a still higher number of ligands may be formed and separated, depending upon the stability of high oxidation states of the central atom.

Such sidebands have not been checked in the present work.

As we believe that the target material will stand a 2.5 μA proton beam, the estimated yields in Fig.5 establish that this target/ion source combination may be a useful ISOLDE production target. It is not unlikely that the delay time of ~2.5 min can be improved somewhat in proton irradiations, since a more uniform temperature can be achieved in the target melt. This opens up possibilities to extend the research into the poorly known region beyond 117Sb. Spin and magnetic moment measurements with the on-line ABMR technique require, at present, yields in the range 10^-11-10^-12 atoms/s, while laser spectroscopy with the collinear technique [12] can make use of beams down to 10^4 atoms/s.

Recent interest at ISOLDE in performing Mössbauer studies on-line with the mass separator, has been expressed [3]. Experiments are already performed using 119In. The same low energy γ-transition of 23.87 keV follows the decay of 119Sb, which can now be produced clean and in good quantities.

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References

15) ISOLDE internal computer code.

20) C. Ekström, private communication, 1980.


24) G. Weyer, proposal for Mössbauer experiments at ISOLDE, presented at the open ISOLDE meeting, December 1978.
COMPETITION BETWEEN NEUTRON AND CHARGED PARTICLE EMISSION FROM COMPOUND NUCLEI AROUND $A = 150$

R. Kossakowski, J. Jastrzębski, Z. Preibisz, P. Rymuza and W. Skulski
Institute of Nuclear Research, 05-400 Swierk, Poland
S. André, J. Genevey, A. Gizon, J. Gizon and V. Barci
Institut des Sciences Nucléaires, IN2P3, USMG, 38026 Grenoble-Cedex, France.

Abstract

Cross sections of reaction products from the interaction of 5.10 MeV/nucleon $^{12}$C, $^{14}$N and $^{16}$O ions with targets of mass around $A = 150$ are investigated using gamma ray detection techniques. The competition between various reaction channels in which from 0 to 4 charges are removed from the compound nucleus is studied as a function of excitation energy of the compound nucleus (CN) and of the distance of the CN from the stability line. The experimental data are compared with the predictions of the evaporation model using the ALICE code.

1. Introduction

The principal limitation for the production of very neutron deficient nuclei in heavy ion reactions is due to the increasing probability of charged particle emission when either the excitation energy of the compound nucleus, or its distance from the stability line, increase. Although qualitative features of the competition between neutron and charged particle emission are quite well understood, there is a very limited amount of quantitative experimental data. This competition was previously investigated by Stephens et al.\(^1\). In this work an effective proton binding energy including the Coulomb barrier was determined in a number of reactions and a simple relationship between proton to neutron evaporation rates, binding energies and nuclear temperature was established. More complete evaporation calculations were performed by Winn et al.\(^1\).\(^2\).

In the present work we investigate the production cross sections of final nuclei, observed in light-heavy ion induced reactions on a number of targets with mass around $A = 150$. Gamma ray techniques were employed. The compound systems formed in these reactions span a large region of nuclei in respect to the stability line. Varying projectile energies, we were able to deduce the relative importance of the charged particle emission (as compared to the neutron emission alone) as a function of excitation energy of the compound nucleus (CN) and the distance of the CN from the stability line. Some part of the data presented in this communication has been published before\(^3\).

2. Experimental method

The $^{141}$Pr, $^{144}$Sm, $^{147}$Sm, $^{150}$Sm, $^{152}$Sm and $^{154}$Sm targets, 10-20 mg/cm$^2$ thick, were irradiated with $^{12}$C and $^{14}$N ions and $^{141}$Pr target also with $^{16}$O ions from the variable energy cyclotron at ISN, Grenoble. The incident energy was varied between 71 MeV and 110 MeV for $^{12}$C ions, between 68 MeV and 145 MeV for $^{14}$N ions and between 100 MeV and 130 MeV for $^{16}$O ions. Only part of the collected data has been evaluated so far.

The gamma rays were detected with a 10-15% efficiency Ge(Li) detector, placed at 55° in respect to the beam axis at a distance of about 10 cm from the target. The gamma ray spectra were measured in coincidence with the beam burst.

![Fig. 1](image)

**Fig. 1** K-shell ionization cross section for target elements with 37 ≤ $Z ≤ 57$ and $^{12}$C, $^{14}$N and $^{16}$O projectiles in an universal representation. The abscissa represents the scaled projectile velocity and the ordinate the reduced cross section. The experimental cross sections of Refs. 8, 9 are corrected for polarization in conjunction with the binding effect\(^1\), relativistic effect\(^2\) and Coulomb deflection\(^1\). The continuous line is the $F_K (\eta_K/(\langle S_K \rangle)^2)$ function calculated from the PWBA and tabulated in Ref. 10. The energies of ions from the present work correspond to $\eta_K/(\langle S_K \rangle)^2$ between 0.05 and 0.10. See Refs. 10, 11 for the meaning of symbols used in this figure.
between bursts, and immediately after the beam shut-off.

For a given target-projectile-energy combination the relative cross sections for the production of final nuclei were deduced basing on in-beam transition intensities leading to the ground or low lying states of these nuclei as well as from radioactive transitions (corrected for recoils) measured between beam bursts and after the beam shut-off. The energies and branching ratios of the radioactive gamma transitions were taken mainly from Ref. 4. The available literature data on the in-beam transitions were catalogued in order to facilitate the attributions.

The excitation functions and absolute cross sections were obtained using the target K X-rays measured simultaneously with the gamma rays in each run. This normalization method was previously employed for lighter ions (3, 6) where the K-shell ionization cross sections are relatively well known or may be reliably calculated (7). In order to test whether the calculations may give reliable K-shell ionization cross sections for heavier projectiles the available experimental data from Refs. 8, 9 were compared with the calculated cross sections obtained from the plane-wave Born approximation (10) (PWBA) with a number of corrections (11-13). Fig. 1 shows these data in a universal representation in which the reduced cross sections are plotted against the reduced bombarding energy and compared with calculations. The experimental data exist for projectiles of a similar atomic number as employed in the present work but for slightly lighter targets. Although the calculated curve deviates slightly (up to 20%) from the experimental data, at the present stage we use the calculated K-shell ionization cross sections for normalization purposes.

Fig. 2 Distribution of the cross section for the $^{12}$C + $^{144}$Sm reaction at 110 MeV bombarding energy (103 MeV mean energy at the half thickness of the target). The cross sections are given in mb. The relative errors are between 10% and 20% for values exceeding 30 mb.

3. Results

From the experiment we determined the distribution of the cross section among almost all the residual nuclei with $\delta \geq 10$ mb. Fig. 2 shows an example of such a distribution in the $^{12}$C + $^{144}$Sm reaction at 110 MeV incident energy. The compound nucleus, $^{156}$Er, is the farest from the

Fig. 3 Fraction of the total observed cross section for different values of the removed charge (isotopic yield) as a function of excitation energy of the compound nucleus $^{156}$Er.
Fig. 4 Fraction of the total observed cross section for different values of the removed charge as a function of the distance of the compound nucleus from the stability line. Data points, for a fixed excitation energy (78 MeV), were obtained from the interpolation of results similar to those shown in Fig. 3. The $N/Z$ of the stability line is obtained from the abundance weighted $N/Z$ values of stable, even-even nuclei.

Fig. 5 Absolute values of the total observed cross section and of the $(\text{H}, \text{xn})$ channel cross section as a function of the distance of the compound nucleus from the stability line for $E^* = 78$ MeV.

Fig. 6 Average removed charge and average removed mass as a function of the distance of the compound nucleus from the stability line for $E^* = 78$ MeV. The error bars of the $\Delta A$ values are smaller than data points.
Fig. 7 Average removed mass as a function of the excitation energy of the compound nucleus.

stability line (among systems investigated in this work). The total observed cross section of 1379mb is distributed here among 19 final products.

The relative contribution to the total observed cross section of various reaction channels in which from 0 to 4 charges were removed from the CN (isotopic yield) is shown in Fig. 3. From similar data the relative contribution of various channels was deduced as a function of the distance of the compound nucleus from the stability line and is shown in Fig. 4. It is seen that for the excitation energy of 78 MeV about 70% of the observed cross section goes into (III, x) products in case of 164Er, whereas this fraction drops to 10% for the 156Er compound nucleus.

The absolute values of the total observed cross sections and of the (HI, x) channel cross section are shown in Fig. 5 for the 78 MeV excitation energy. We see that at this excitation energy the (HI, x) channel would have a negligible cross section for a compound nucleus with K/Z difference of -0.18 (e.g. 154Er).

The average values of the removed charge (ΔZ) and mass (ΔA) for the same excitation energy are presented in Fig. 6. The extrapolation of the experimental data suggests that even at this rather high excitation energy the ΔZ value should be close to zero at the stability line. This may indicate that the incomplete fusion mechanism is of no major importance in the energy range studied in the present work. (However, see also the following section).

Finally, in Fig. 7 the average removed mass is presented as a function of the excitation energy of the compound nucleus. The slope of a straight line fitted to the data points of Fig. 7 is 12.6 ± 0.7 MeV/mass unit. No deviation from a straight line, which would indicate a substantial emission of fast particles, is discernable within the experimental errors.

4. Discussion

The experimental data of the previous section were compared with the evaporation model using the code ALICE [13]. The calculations were performed using Myers-Swiatecki Lysekil liquid drop masses with no pairing and no shell correction. The s-wave approximation with a liquid drop moment of inertia was chosen. The absolute values of the calculated cross section were normalized to the observed cross section using a multiplicative factor which was close to 0.8.

The comparison of the experimental data with the evaporation calculations is shown in Figs. 8-10. It is seen that the ratios of the calculated over the experimental values of the cross section and of the average values (ΔZ and ΔA) change smoothly both as a function of excitation energy and of the distance from the stability line. The calculated average evaporated mass is systematically about 10% lower than the ΔA of Fig. 7 in the whole energy range. For all but 156Er compound nuclei the code seriously underestimates all channels with charged particle emission in comparison with the (HI, x) channel. (In the 156Er case only ΔZ = 4 channel is strongly depressed in the calculation). It was thought that a part of this discrepancy, at least for the ΔZ = 2 and ΔZ = 4 channels, may perhaps be accounted for by the presence of other than complete fusion processes. In order to investigate this possibility the calculation was performed using the "Sum Rule Model" of Wilczyński et al. [17] with the same parameters as in Ref. 17. At the highest energies

Fig. 8 Comparison of the observed mass and charge distribution of the reaction products from the 12C + 144Sm reaction with predictions of the evaporation model. The experimental data (open rectangles) are deduced from Fig. 2. Calculated cross sections (solid bars) are obtained with the code ALICE, with parameters described in the text and after the normalization of the total calculated cross section to the total observed cross section. The energy spread in the target is taken into account in the calculation.
employed in this work the calculated cross section for the emission of fast $\alpha$ particles (the strongest non-equilibrium channel) was as high as $1/3$ of the observed cross section for the $\Delta Z = 2$ products. However, the model does not account for the substantial cross section of the $\Delta Z = 1$ and $\Delta Z = 4$ products and for the relatively slow variation of the cross section of the $\Delta Z = 2$ products with the incident energy.

Therefore, taking into account the results discussed in connection with Figs. 6 and 7, we conclude that the ALICE code underestimates the reaction channels in which one or more charged particle is removed from the compound nucleus. However, in view of the $^{150}$Er result, this conclusion may be not valid very far from the stability line.

Fig. 10. Comparison of the average removed mass and charge as a function of the excitation energy (for the $^{12}$C + $^{141}$Pr reaction) and distance from the stability line (for $E^* = 78$ MeV, experimental data of Fig. 6) with the predictions of the evaporation model. See also caption to Fig. 8.

Fig. 9. Comparison of the isotopic yields as a function of the excitation energy (for the $^{12}$C + $^{141}$Pr reaction) and distance from the stability line (for $E^* = 78$ MeV, experimental data of Fig. 4) with the predictions of the evaporation model. The error bars are only from the experimental data. See also caption to Fig. 8.
5. Summary and conclusions

Employing the gamma ray detection techniques we were able to determine the distributions of the cross section among all the residual nuclei with $\Delta>10$ mb for many target-projectile-incident energy combinations. These data allow us to follow in a quantitative way the competition between various reaction channels in which from 0 to 4 charges are removed from the compound nuclei of different excitation energy or different distance from the stability line. It was shown that, for a fixed excitation energy of the compound nucleus, the cross section of the $(\bar{H},xn)$ channel and the average removed charge change linearly with the distance of the compound nucleus from the stability line. Within the energy range investigated in this work, the average removed mass also exhibits almost linear dependence on the excitation energy of the compound nucleus and is independent of the position of the compound nucleus in respect to the stability line.

The evaporation calculations performed with the code ALICE show a moderate agreement with the experimental data. With the options used in this work the code underestimates the reaction channels with charged particle emission in comparison with the $(\bar{H},xn)$ channel. Only part of this effect may be attributed to the presence of the incomplete fusion reactions.

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References

EMISSION OF LIGHT CHARGED PARTICLES AT $Q^0$ IN HEAVY ION - INDUCED REACTIONS


Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, USSR

Abstract

Spectra of light particles emitted at $Q^0$ were measured in reactions induced by $^{16}$O, $^{20}$Ne, $^{22}$Ne and $^{40}$Ar ions on $^{48}$Ti, $^{197}$Au, $^{181}$Ta and $^{238}$U targets. Incident energies were in the range 5-10 MeV/A. Almost all the spectra extend in energy to the vicinity of the two-body kinematic limit.

Heavy ion reactions involving light charged particle emission have recently attracted the attention of both experimenters and theoreticians. Among these reactions, the process involving the emission of energetic light charged particles is of special interest.

As shown earlier,$^{1,2}$ the interaction of two complex nuclei can be accompanied by emission of a large number of $\alpha$-particles whose formation cross section makes up a considerable part of the total reaction cross section. It has been observed experimentally that the yield of energetic $\alpha$-particles increases significantly compared with that expected from calculations using the evaporation model of compound nucleus decay.$^3$ In this case most of the projectile energy is carried away by $\alpha$-particles whose angular distribution is observed to be strongly forward peaked.

The $\alpha$-particle energy spectra measured at an angle of $Q^0$ in different reactions induced by the $^{22}$Ne ions are presented in fig. 1. From the data obtained it follows that the $\alpha$-particles having velocities above the projectile velocity are formed with a noticeable cross section. The estimate of "nuclear temperature" $T$ made assuming that the dependence of the cross section on the emitted particle energy $E$ is describable by the relation $\sigma(E) = 11.95 \cdot 10^{-3} \frac{E}{T}$, where $B$ is the effective barrier and $E$ is the temperature, shows that $T$ is a factor of about 3 higher than the compound nucleus temperature. This difference increases with increasing projectile energy. Another should be noted that in all cases the maximum $\alpha$-particle energy is only by several MeV lower than the maximum possible energy which can be carried away by the $^8$He nucleus and which is determined by the conservation laws under the assumption of the two-body nature of the process. The emission of the heavier particles ($^6$He, $^6_2$H, $^7_1$H, $^{7_1}$He) with relatively high probability has been observed in all the reactions investigated. To study the process involving the emission of light charged particles we used targets made of various elements ($^{48}$Ti, $^{197}$Au, $^{16}$O, $^{181}$Ta, $^{238}$U) and the $^{16}$O, $^{20}$Ne, $^{22}$Ne and $^{40}$Ar ion beams with an energy of 5-10 MeV/nucleon. Energy spectrum measurements were carried out at $Q^0$ by using a magnetic spectrometer. Light particles were detected and identified by means of a semiconductor $\Delta E-E$ telescope placed in the focal plane of a magnet. The energy spectra of light charged particles for the reaction $^{22}_{\text{Th}}^3_4$Ne are shown in fig. 2. These spectra have well pronounced maxima in the exit channel. It is also seen that the cross section for forming the isotopes of a given element increases as their binding energy grows. Another important peculiarity of these spectra is the fact that almost all of them reach the maximum possible energy calculated on the basis of the law of conservation of energy and under the assumption of the two-body nature of this process. Apparently an exception is the spectrum of the $^8$He nuclei, which has the form of a narrow distribution with a FWHM of no more than 10 MeV. Thus, as shown earlier, in the given case of emission of energetic particles, the fast particle emitted at the initial stage of the reaction carries away practically the entire thermal energy while the residue, formed at the following stage, with mass $(A_1 + A_2 - A)$, where $A$ is the mass of the particle emitted, will possess minimum excitation energy. We shall not consider the mechanism of such a process, which needs a thorough theoretical analysis and would only like to note some aspects of using reactions of this type to produce nuclei with uncommon properties.

First, as noted above, we have shown earlier for reactions involving fast $\alpha$-particles that these reactions can lead to the production of nuclei with almost zero excitation energy. The cross sections of such processes, as follows from the spectra measured for non-fissioning nuclei, can amount to $10^{-31} - 10^{-32}$ cm$^2$. Therefore it is evident that the reactions involving the emission of energetic charged particles, especially $^8$He and $^{16}$O, are a promising method for synthesizing new heavy and superheavy nuclei. In certain cases the energy spectra are cut off 5-8 MeV before the kinematic limit. This difference can be determined by the residue rotational energy, which may produce a few dozens of the $^8$He units in the grazing collision of nuclei. This problem needs a detailed consideration too, and experiments are currently underway to measure the angular momentum of the residual nuclei after the emission of fast charged particles. The availability of rotational energy in residual nuclei can lead to another important trend -- the production of rapidly rotating "cold" nuclei. In this respect reactions involving the emission of energetic protons may prove to be the most advantageous ones. Finally, the relatively high yield of different isotopes in these reactions can lead to the formation of various neutron-rich nuclei, e.g. the $^{16}$He nuclei, the problem of synthesizing which has recently been raised in nuclear physics again. Extrapolations of formation cross sections for He isotopes according to the $Q_{99}$ systematics which describe well the yield of all $Q_{99}$ isotopes of these reactions, give values of $10^{-33}$ cm$^2$ for the formation of the $^{22}$Ne nuclei in the most favorable reaction $^{48}$Ti$^{22}$Ne.

Thus reactions involving the emission of energetic light particles in the interaction of two complex nuclei with moderate energies constitute a new type of nuclear reactions, which, in all likelihood, reflect the cumulative effect and should be elucidated theoretically. The use of these reactions may prove efficient in synthesizing nuclei in uncommon states.
Fig. 1. Spectra of $\alpha$-particles at $0^\circ$ obtained from reactions induced by $^{22}\text{Ne} (178 \text{ MeV})$ on different targets.
Fig. 2. Spectra of different light isotopes emitted at 0° in the reaction \( ^{22}\text{Ne}(178\text{MeV}) + ^{232}\text{Th} \). The arrows indicate the maximum energy allowed for these ions if the process is a two-body one. For \( \alpha \)-particles the Coulomb barrier is also indicated by an arrow.

References

2) V. V. Volkov et al., JINR E7-12411 Dubna, 1979
DYNAMICAL ANALYSIS OF FISSION-ISOMER HALF-LIVES

A. Lukasiak and A. Sobiczewski
Institute for Nuclear Research, Hoza 69, PL-00-681 Warszawa, Poland

A. Baran and K. Pomorski
Institute of Physics, The Maria Sklodowska-Curie University, Luslin, Poland

Abstract

Microscopic dynamical analysis of the fission half-lives of even-even fission isomers is performed. No adjustable parameters are used. The calculated half-lives as well as barrier heights are in a good agreement with experiment for lighter nucleides but they are too small for heavier ones.

1. Introduction

In a series of papers\(^1,2\), we analysed the spontaneous-fission half-lives \(T_{\text{sf}}\) of even-even nuclei. The goal was to see if it was possible to reproduce the experimental values of \(T_{\text{sf}}\) and of the barrier heights by microscopic calculations without use of any free parameters.

The answer to the question is yes. A condition for that is a dynamical character of the calculations, i.e. an account of the complex tensorial nature of the inertia of a nucleus with respect to the fission mode. In static calculations (e.g. ref.\(^3\)), which treat the inertia as a scalar function, there was always the need to use adjustable parameters to obtain a reasonable agreement with experiment.

The goal of the present paper is to extend the microscopic dynamical analysis of refs.\(^1,2\) to the half-lives of the fission isomers.

2. Description of the calculations

The calculations are performed in the same way as in ref.\(^2\).

The probability of fission in unit time is assumed to be a product of a number of assaults of a nucleus on the fission barrier in this time and the probability of the penetration through the barrier for a given assault. The number of assaults on the barrier per unit time is assumed the same as in the ground state, corresponding to the \(h\omega = 1\) MeV energy of the vibration that leads to fission. The probability of the penetration through the barrier is calculated in the WKB approximation. The fission trajectory is found by minimization of the action integral in a multidimensional deformation space. The trajectory starts from the second minimum of the potential energy (lowest state of the isomer), in distinction to the fission in the ground state\(^2\), for which it starts from the first minimum of energy. Deformations of multipolarity 2, 3, 4, 5 and 6 are taken into account. The potential energy is calculated by a standard macroscopic-microscopic method. The macroscopic part is taken from the droplet model\(^4\), while the shell correction (calculated by the Strutinski method) is based on the Nilsson model with the \("As242\) parameters\(^5\). The inertia tensor is calculated by the cranking method.

3. Results and discussion

Let us first look at the results obtained for the ground state.

The results for the half-lives \(T_{\text{sf}}\) are shown in fig.1, taken from ref.\(^2\). We can see that the experimental values of \(T_{\text{sf}}\) for 40 nuclei\((Z=2-104)\) are reproduced with an average accuracy of about 1.7 orders, i.e. within a factor of 50. This is a similar accuracy as obtained in the static analysis using one adjustable parameter\(^3\). The largest discrepancy appears for the heaviest elements and mostly on the neutron-rich side. This is not surprising as the parameters of the Nilsson model on which the calculations are based, have been adjusted (long time ago\(^6\)) to properties of nuclei around uranium and plutonium.

The parameters of the fission barrier are given in fig.2, also taken from ref.\(^2\). These are the heights of the first barrier \(E_A\), second minimum \(E_\gamma\) and the second barrier \(E_B\), all calculated with respect to the first minimum. The experimental values are taken from ref.\(^6\). We can see that for the heaviest nuclei both theoretical barriers are too small, but also \(T_{\text{sf}}\) are, in general, too small. For the heaviest nuclei, the second barrier is too small, but the first is much too large. For these nuclei, the theoretical half-lives \(T_{\text{sf}}\) are higher than the experimental ones. Thus, we can roughly say that when the theoretical barrier is too large (small), so is the half-life \(T_{\text{sf}}\). This indicates that the calculated inertia, on which \(T_{\text{sf}}\) depends approximately as much as on the barrier, is about right.

The isomeric half-lives \(T_{\text{is}}\), calculated in the present paper, are given in fig.3. The experimental points are taken from ref.\(^7\). We can see that the isomeric half-lives \(T_{\text{is}}\) are less satisfactorily reproduced by the calculations than the ground-state lifetimes \(T_{\text{sf}}\). The calculated \(T_{\text{sf}}\) are, in

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\(^+\) Present address: Technische Universität München, Garching, Fed. Rep. of Germany
Fig. 1. Logarithms of the calculated (theor) and experimental (exp) ground-state half-lives $T_{sf}$, given in years, as functions of the neutron number $N$.

Fig. 2. Calculated and experimental heights of the first saddle point ($E_A$), second minimum ($E_0$) and second saddle point ($E_B$) of the ground-state fission barrier, as functions of the neutron number $N$.

Fig. 3. Logarithms of the calculated (circles) and experimental (full squares) isomeric half-lives $T_{sf}^m$, given in seconds, as functions of the neutron number $N$.

generally, smaller than the experimental values. For 10 nuclei, for which the experimental values are known, the average discrepancy is about 3.1 orders. Also the theoretical systematics (i.e., the dependence of $T_{sf}$ on the neutron number $N$) differs from the experimental one.

One may expect that the too low theoretical $T_{sf}$ are due to the too low fission barriers. In fact, fig. 2 shows that the isomeric fission barrier, equal to the ground-state second barrier $E_B$ minus the energy of the second minimum $E_{II}$, is too small for all the three nuclei for which $E_{II}$ is known and allows one to expect even more too small barriers for Pu isotopes, heavier than those for which $E_{II}$ is known.

To see directly the reason why the calculated $T_{sf}$ for Pu decrease so fastly with increasing neutron number $N$, we show in fig. 4 the microscopic barriers for $N=142$, 144, 146, 150. We can see that the highest barrier is obtained for $N=144$ and that the barrier fastly decreases with increasing $N$. This illustrates a rather strong correlation between the systematics of $T_{sf}$ and the systematics of the barriers. The calculated effective inertia does not show such correlation with $T_{sf}$.

It can be seen in fig. 3 that the calculated $T_{sf}^m$ privilege the neutron number $N=144$ (while experiment gives an advantage
Fig. 4. Calculated isomeric fission barriers for isotopes of Pu.

\[ e^\sqrt{\hbar \omega} \]

\[ \text{neutrons} \]

\[
\begin{array}{c|c|c}
[N_n,\Lambda] & K^\pi & \text{neutrons} \\
\hline
[990] & 1/2^- & \\
[853] & 7/2^+ & \\
[615] & 11/2^+ & \\
[871] & 1/2^+ & \\
[741] & 3/2^- & \\
[734] & 9/2^- & \\
[622] & 5/2^+ & \\
\end{array}
\]

\[ \text{7.4} \]

\[ \text{144} \]

\[ \text{7.2} \]

\[ [862] 5/2^+ - \]

\[ [512] 3/2^- - \]

\[ [505] 11/2^- - \]

\[ [510] 1/2^- - \]

\[ [752] 3/2^- - \]

\[ \text{7.0} \]

Fig. 5. Nilsson levels for neutrons at a deformation (\( \epsilon = 0.60, \), \( \epsilon_4 = 0.06 \)) around the second minimum.

to \( N=146 \), cf. also ref.\(^8\)). The reason is that the Nilsson spectrum, used by us, shows a shell at \( N=144 \) for the deformation corresponding to the second minimum. The spectrum is shown in fig. 5.

4. Conclusions

The following conclusions may be drawn from our study:

(i) The analysis of the ground-state and isomeric half-lives and of the barrier heights indicates that the calculated inertia of a nucleus is about right. Thus, a discrepancy in the half-life seems to be mainly associated with the discrepancy in the barrier height.

(ii) The isomeric fission half-life \( T_{Ff} \) is a sensitive function of the fission-barrier height. For example, a 0.5 MeV change in the height changes \( T_{Ff} \) by about 1.5 orders. Thus, \( T_{Ff} \) supplies a subtle test for the potential energy of a nucleus at large deformations and in this way also for its internal (single-particle) structure at these deformations.

(iii) Dynamical microscopic calculations with no free parameters reproduce the experimental \( T_{Ff} \) better than static calculations, although the latter use adjustable parameters. An average disagreement obtained in the static calculations\(^7\) for 6 isomers of U and Pu is about 3.0 orders, while it is only about 1.0 order in the present dynamical calculations.

(iv) Still, although smaller than in static calculations, the discrepancy is rather large. For all 10 even-even isomers, for which experimental \( T_{Ff} \) are presently known, the average discrepancy between the micro-
scopic dynamical results and experimental ones is about 3.1 orders. We associate this discrepancy with the too low isomeric-fission barriers calculated by us. This suggests a need for a modification of the single-particle Nilsson scheme at large deformations, especially for heavy nuclides.

References


4) W.D.Myers, Droplet model of atomic nuclei (IFI/Plenum, New York, 1977).


INVESTIGATION OF ISOTOPES WITH $Z \geq 100$

Gesellschaft für Schwerionenforschung m.b.H. (GSI) D-6100 Darmstadt, Postfach 110541

K. Güttner, B. Thuma
Universität Gießen, D-6300 Gießen

D. Vermeulen, C.-C. Schn
Technische Hochschule Darmstadt

Abstract

Evaporation residues from fusion reactions of $^{48}$Ar, $^{70}$Ti, and $^{84}$Kr with isotopes of Pb and Bi respectively were investigated with a newly developed method of in-flight velocity separation and implantation into position sensitive surface barrier detectors. Our experimental method permits the investigation of a decaying or spontaneously fissioning nuclei with lifetimes down to $10^{-6}$ s and formation cross sections below 1 nb.

Experimental results on the production of isotopes of $^{71}$Pm, $^{144}$Sm, $^{140}$La, $^{104}$Pd, $^{105}$Pd, and the first observation of element 107 by a decay are presented. The possibility to form cold compound nuclei close to the fusion barrier is discussed in the view of recent experimental results.

1. Introduction

The well established techniques used so far for the identification of short lived nuclei with $Z \geq 100$ from heavy ion fusion reactions, as the He-jet, rotating drums or moving tapes have been developed to a high state of perfection and hence approached the limits of their possibilities. Their main restrictions are due to the fact that the nuclei to identify have to be stopped in the gasflow or solid material before they are moved to the detector positions. Short halflives which become of increasing importance for the most heavy and unstable nuclei can only be detected at a limit of some tenths of seconds with the He-jet or some parts of milliseconds with the rotating drum, the latter one being only applicable to reaction products undergoing spontaneous fission.

Moreover in the stopping process useful information from the reaction kinematics as angular and velocity distributions cannot be used to their full extent. Hence an in-flight separation seems to be the most suitable experimental method to separate the evaporation residues from the projectile beam. The in-flight separated nuclei are implanted into position sensitive surface barrier detectors, where they are identified by their a decay or spontaneous fission.

We have developed this experimental technique during the past five years at the velocity filter SHIP and applied it to the investigation of the heaviest nuclei.

2. Velocity Separation of Evaporation Residues

For complete fusion the velocity of the resulting compound nucleus follows from momentum conservation:

$$V_C = V_P \frac{M_P}{M_C}$$

$M_C$ is the mass of the compound nucleus $M_P$, $V_P$ are mass and velocity of the projectile. The compound nucleus moves in beam direction. As it is heated in the fusion process, neutrons, protons and/or a particles are evaporated. In our case only neutron emission is important due to the low excitation energy of the compound systems and the high Coulombwall of the nuclei with $Z \geq 100$.

For isotropic particle evaporation the average velocity of the evaporation residues equals that of the compound nucleus. In the evaporation process and by scattering in the target velocity and angular distributions are spread.

Reaction products from other binary reactions, as fusion-fission or transfer cannot move with the velocity of the evaporation residues. In beam direction transfer products move with a velocity close to that of the elastic scattered target nuclei, which is $2V_C$. They can only reach $V_C$ by multiple scattering.

3. Separation and Identification Techniques

SHIP$^1$ principally operates like the Wien velocity filter, however it has spatially separated electric and magnetic fields (fig.1). For efficient suppression of background from scattered projectiles or products from nuclear reactions other than fusion, SHIP has two filter stages. Two quadrupole triplets focus the evaporation residues onto the velocity slit and the detector position respectively. The selected velocity range is determined by the variable velocity slit after the first stage. It is normally $\leq 5\%$. The reaction products have highly excited electron shells and consequently cover a wide ionic charge distribution, SHIP accepts a maximum of $\leq 15\%$. A thin carbon foil $8$ cm downstream the target equilibrates the charge distribution $20$ ns after formation of the evaporation residue to avoid losses due to exotic charge states from converted transitions. The solid angle of acceptance is $2.7$ mrad, separation time $2\,\mu$s.

Fig.1: The velocity filter SHIP.
A schematic graph of our setup is shown in fig. 2. Target thickness is monitored by Rutherford scattering. The separated evaporation residues pass a large area time-of-flight detector before they are implanted into a position sensitive surface barrier detector. From flight time and energy of the incoming ions a rough mass estimation is possible. By an anticoincidence between time of flight and the surface barrier detectors, decays in the detector can be discriminated from incoming particles. The system is completed by a $\gamma$-X-ray detector. The time of flight detector was only dispalyable in the $^{57}$Ti and $^{58}$Cr irradiations.

![Fig. 2: Experimental setup.](image)

Symmetric fission of the compound nuclei can be detected with a simple time-of-flight energy measurement in our target chamber. We used the micro-bunches of the UNILAC beam of less than 1 ns width for timing and a surface barrier detector for energy measurement.

The position sensitive detector system consists of an array of seven position sensitive surface barrier detectors with a total area of 2 000 mm². Fig. 3 shows a two dimensional plot of the spatial distributions of $\alpha$ decays from a certain de-excitation channel. The detectors are position sensitive in vertical direction. The horizontal position is given by the detector number. The horizontal distribution across the single detectors is smeared out artificially for better presentation. The active detector area is reduced by the fringes of the single detectors to 80 %. SHIP is operated with velocity dispersion in the detector plane, so the horizontal position of implantation is determined by particle velocity. Ions with average velocity will be implanted in the central detector. The projections of horizontal and vertical distributions of the evaporation residues are also plotted.

![Fig. 3: Intensity distribution of $^{162}$W from the reaction $^{95}$Mo on $^{110}$Cd on the detector array (horizontal distribution across each detector artificial).](image)

The efficiency is calculated with a Monte Carlo program including the recoil of evaporated neutrons on the evaporation residue, energy loss and scattering in the target, the ionic charge distribution of the evaporation residues and the ion optical properties of SHIP. With the detector array we calculate $(22-26)\%$ for evaporation residues in the discussed reactions. As the evaporation residues are implanted close to the detector surface, about $50 \%$ of the emitted particles escape, the sensitivity is then $(11-13)\%$. Suppression of the projectile beam is typically $10^{-6}$ to $10^{-8}$ integrated over the whole energy spectrum.

Unknown $\alpha$ emitters can be identified via $\alpha-\alpha$ mother-daughter correlations, using the position sensitivity of the detector. All decays originating from a certain implanted evaporation residue have to occur at its position of implantation within the detector resolution. For all ions impinging the detector and all decays energy, position, and time are listed on tape. Offline all events within a certain position and time window are evaluated. The time intervals between implantation and first decay or subsequent decays are taken for half-life determination, which is performed with the maximum likelihood method. Correlation time is limited by random correlations.

8. Experimental conditions

Monoisotropic targets of $^{206,207,208}$Pb and $^{209}$Bi were irradiated with $^{40}$Ar, $^{50}$Ti, or $^{58}$Cr. Average beam intensities were $10^{12}$ sec$^{-1}$, target thickness around 0.7 mg/cm². The specific projectile energies were close to fusion barrier and about 4.85 MeV/u.

To withstand high beam intensities the targets were covered with carbon films of 0.03 mg/cm² and mounted on a wheel, which rotates synchronously to the accelerator pulsing. During subsequent beam bursts of 5 ms followed by 15 ms intervals eight consecutive targets are moved across the beam axis, with a velocity of 1 cm/ms.

9. $^{40}$Ar on $^{206,208}$Pb irradiations

The investigation of $^{95}$Mo isotopes from fusion of Ar and Pb is a good starting point to enter the region of the heaviest elements. Targets near the double magic $^{208}$Pb allow the production of cold compound systems, formation cross sections are in the nanobarn region, the dominating decay modes are $\alpha$ decay or spontaneous fission, and half-lives range from ms to s. These experimental conditions are also expected for the heavier nuclei.

Moreover special de-excitation channels have been investigated carefully by various authors: $^{208}$Pb($^{40}$Ar,3n)$^{206}$Pb), and $^{206}$Pb($^{40}$Ar,2n)$^{204}$Fm. With our experimental setup, observation of all de-excitation channels is possible for the first time.

In $^{208}$Pb irradiations we observed the isotopes $^{244,246}$Fm. The $\alpha$ decaying isotopes $^{246,248}$Fm were identified by their decay energies, their half-lives, and by correlations to daughter decays, the spontaneous fissioning $^{244}$Fm by its half-life. In this experiment the finding of the 2n de-excitation channel by Oganesian et al. 81), who only observed the spontaneous fission of $^{248}$Fm was confirmed. From our data we can plot an integral excitation function for isotopes formed via neutron evaporation (fig. 4). From theoretical considerations we expect, that the maximum of this excitation function coincides roughly with the fusion barrier obtained from the
measurement of compound fission. The position of the barrier can be described by an effective Coulomb radius. Schulte\(^1\) obtained \(r_{\text{eff}} = 1.44\ \text{fm}\) in agreement with that of Oganesian\(^2\)'s value of \(r_{\text{eff}} = (1.44 \pm 0.01)\text{fm}\). Both values were taken from compound fission. The maximum of the excitation function (fig.4) corresponds to \(r_{\text{eff}} = (1.22 \pm 0.02)\text{fm}\).

![Fig.4: Integral excitation function for \(^{40}\text{Ar}\) on \(^{208}\text{Pb}\), error bars indicate statistical error. The absolute error for the cross section is a factor of two, for energy \(\pm 2\ \text{MeV}\).](image)

Our results confirm the suggestion of Oganesian to obtain cold heavy compound nuclei from fusion reactions making use of the favourable Q-value of the double magic \(^{208}\text{Pb}\).

Irradiating \(^{206}\text{Pb}\) with \(^{40}\text{Ar}\) we found the new isotopes \(^{243}\text{Fm}\) and its daughter decay \(^{239}\text{Cf}\). Fig.5 shows an a-spectrum without correlation conditions but taken between the UNILAC beam bursts, the irradiation time was 20 h, the projectile dose \(8 \times 10^{16}\). The spectrum shows the decay assigned to \(^{243}\text{Fm}\) and the daughter decays \(^{239}\text{Cf}\) which could also be correlated (Table 1). The measured cross section is \((1.3 \pm 0.1)\text{nb}\).

![Fig.5: Alphaspectrum for \(^{40}\text{Ar}\) on \(^{206}\text{Pb}\), taken between UNILAC beam bursts.](image)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy/keV</th>
<th>(T_{1/2}/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{256}\text{Ti})</td>
<td>(8\ \text{keV})</td>
<td>((8.1 \pm 1.3) \times 10^{-3})</td>
</tr>
<tr>
<td>(^{255}\text{Ti})</td>
<td>(8\ 726\ \text{keV})</td>
<td>(1.4 \pm 0.6)</td>
</tr>
<tr>
<td>(^{247}\text{Md})</td>
<td>(8\ 428)</td>
<td>(2.9 \pm 1.7)</td>
</tr>
<tr>
<td>(^{243}\text{Fm})</td>
<td>(8\ 546)</td>
<td>(0.10 \pm 0.08)</td>
</tr>
<tr>
<td>(^{239}\text{Cf})</td>
<td>(7\ 63)</td>
<td>(39 \pm 37)</td>
</tr>
</tbody>
</table>

Table 1.

Isotopes from \(^{40}\text{Ar}\) and \(^{50}\text{Ti}\) irradiations. Error for decay energies \(\pm 25\ \text{keV}\), half-life for 68% probability.

The spectrum also shows a decays from transfer products. From comparison of our data to those of Nitschke we calculated that transfer products are suppressed by SHIP to more than three orders of magnitude. Our experiments show that they have the same velocity as the evaporation residues. As discussed in sec.1 this can only be explained by scattering processes.

Comparison of our cross sections, which are strongly dependent on our efficiency calculations, to experimental data from Guggeler\(^1\), Nitschke\(^2\) and Oganesian\(^2\) show good agreement, and indicate the reliability of our calculations, even for the region of the heaviest nuclei, where most of the parameters necessary for the ion optical calculation are extrapolated.

6. \(^{50}\text{Ti}\) on \(^{209,208}\text{Pb}\) irradiations

One interesting aspect to investigate element 104 is the systematics of spontaneous fission halflives for even-even nuclei, which changes abruptly between No and 104 (fig.6). According to experiments from Oganesian\(^3\) the enhancement of halflife at the Na52 subshell disappears. For the isotope \(^{256}\text{Ti}\) on this subshell one could expect an effect of about four orders of magnitude.

![Fig.6: Systematics of experimental spontaneous fission halflives for even-even nuclei (filled square: investigated at SHIP).](image)
We irradiated $^{208}$Pb targets with (4.75-5.15) MeV/u. At the lowest energies the 1n channel was identified by observation of the well known a decay of $^{259}$No, which could also be correlated to $\alpha$ decays of $^{259}$No. With increasing projectile energy the expected $\alpha$ spontaneous fission activity, assigned to $^{259}$No, appeared. The width of the excitation function is about 10 MeV (fig.7), so we can exclude that the spontaneous fission activity originates from a transfer. Another proof is the agreement of our measured cross section to that given by Oganesian, which is about 6mb in both cases.

![Excitation function for $^{50}$Ti on $^{208}$Pb](image)

**Fig.7:** Excitation function for $^{50}$Ti on $^{208}$Pb (see also fig.4).

Another assignment of the decay than that given by Oganesian would mean the absence of the 2n channel, as we do not observe other decays, which could be assigned to the isotope $^{256}$No. Our halflife of (8.1 ± 0.3) ms (fig.8) is in good agreement to that measured by Oganesian. At the highest energies we observed spontaneous fission events with seconds halflife, which might belong to the isotope $^{259}$No and indicate the 3n channel.

![Logarithmic distribution of time distances between implantation and decay of $^{256}$No.](image)

**Fig.8:** Logarithmic distribution of time distances between implantation and decay of $^{256}$No.

This isotope also can be formed in the reaction $^{208}$Pb ($^{50}$Ti,2n)$^{256}$No. We irradiated $^{208}$Pb with the optimum energy for the 2n channel, which is known from the preceding experiment and observed $\alpha$ decays and also spontaneous fission (Table 1).

So we have good arguments to prove the assignment of the observed spontaneous fission activity as proposed in ref. 3. Fig.9 shows the integral excitation function for the $^{208}$Pb irradiations, from which we take an effective Coulomb radius of (1.42 ± 0.02) fm for the maximum of the excitation function, in agreement to the result from $^{40}$Ar on $^{208}$Pb irradiations.

![Integral xn excitation function for $^{50}$Ti on $^{208}$Pb](image)

**Fig.9:** Integral xn excitation function for $^{50}$Ti on $^{208}$Pb (see also fig.4).

### 7. $^{50}$Ti on $^{209}$Bi irradiations

In irradiations of $^{209}$Bi with $^{50}$Ti we expect the formation of $^{258}$,259Bi. The isotope $^{257}$Bi is of special interest: In irradiations of $^{54}$Cr on $^{209}$Bi to produce element 107 Oganesian et al. (14) observed two spontaneous fission activities. One with a halflife of (1-2)ms was assigned to $^{259}$Bi, the other one with 58 was explained by an unobserved decay of $^{257}$Bi leading to $^{259}$Bi, which was assumed to undergo spontaneous fission with the corresponding halflife. From the relative intensities of observed spontaneous fission events in both cases, for $^{259}$Bi as well as for $^{259}$Bi strong $\alpha$ decay branches were postulated.

We irradiated $^{209}$Bi with $^{50}$Ti beams between 4.65 MeV/u and 4.95 MeV/u with an integral ion dose of 10$^{16}$ per energy. The 2n channel was observed at 4.65 MeV/u and 4.95 MeV/u by decay chains from $^{257}$Bi ending in the sequence $^{294}$Md-$^{294}$Es. Due to the 50% detector efficiency, most of them are incomplete. At 4.92 MeV/u we found the decay chain of fig.10, in which decays of 8940 keV and 8760 keV are correlated to the known transition of $^{294}$Md. The statistical error probability of this chain is less than 10$^{-3}$. So we can assign the decays to the isotopes $^{257}$Bi and $^{293}$Es. The chain in fig.10 represents the decay pattern of a single implanted nucleus of $^{257}$Bi, therefore we have to consider that the given decay energies and time distances scatter around the exact values of $\alpha$ decay energies and halflives.

- 758 -
Fig. 10: Decay chain observed in $^{50}\text{Tl}$ on $^{209}\text{Bi}$ irradiations, 2 n channel.

At 4.75 MeV/u we observed decay chains, two examples of which are shown in fig. 11. For the odd-odd nuclei $\gamma$ decay as well as electron capture could be observed. The electron capture decay of $^{258}\text{Bi}$ would lead to the spontaneous fissioning of $^{258}\text{Bi}$.

Fig. 11: Decay chain observed in $^{50}\text{Tl}$ on $^{209}\text{Bi}$ irradiations, 1 n channel.

The decay characteristics of the Lr and 105 isotopes from the n channel are, up to our present state of data evaluation for $^{258}\text{Bi}$ two decay energies, 9182 keV and 9073 keV and (3.3 ± 0.7) s half-life, for 254 Lr the decay energy 8459 keV, and the half-life (16 ± 4) s. The decay chains end in known transitions of $^{254}\text{No}$, $^{250}\text{Fm}$ or $^{250}\text{Md}$.

The errors of the decay energies are ± 35 keV. Half-life may be corrected in the course of further data evaluation, as yet to be done only the most significant events have been analysed, for instance those correlated to daughter decays or with short time distances to the evaporation residues.

We observed 12 spontaneous fission events with a half-life of (3.0 ± 0.3) s one at 4.65 MeV/u, 3 at 4.75 MeV/u, 7 at 4.85 MeV/u and one at 4.95 MeV/u. The maximum cross section is about 0.7 nb in good agreement with Oganesian et al., who measured 0.8 nb (4).

8 $^{54}\text{Cr}$ on $^{209}\text{Bi}$ irradiation, Element 107

As pointed out in the previous section Oganesian and coworkers observed a spontaneous fission activity of (1-2) ns in irradiations of $^{209}\text{Bi}$ with $^{54}\text{Cr}$, which they assigned to the isotope $^{267}\text{Tl}$, they postulated a strong $\alpha$ decay branch of this isotope.

Table 2. Decays observed in $^{50}\text{Tl}$ and $^{54}\text{Cr}$ on $^{209}\text{Bi}$ irradiations. The error for decay energies is ± 35 keV. The half-life is for 60% probability.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy/keV</th>
<th>$T_{1/2}$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{267}\text{Tl}$</td>
<td>10 376</td>
<td>(4.7 ± 2.3) x 10^{-3}</td>
</tr>
<tr>
<td>$^{258}\text{Bi}$</td>
<td>9 189</td>
<td>3.3 ± 0.7</td>
</tr>
<tr>
<td>$^{257}\text{Bi}$</td>
<td>9 049</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>$^{254}\text{Lr}$</td>
<td>8 459</td>
<td>16 ± 4</td>
</tr>
<tr>
<td>$^{253}\text{Lr}$</td>
<td>8 824</td>
<td>2.6 ± 4</td>
</tr>
</tbody>
</table>

Preliminary data

Fig. 12: Correlation between evaporation residues and decays for $^{54}\text{Cr}$ on $^{209}\text{Bi}$.
Fig. 12 shows a plot of position and time correlations between evaporation residues, characterized by an energy exceeding 17 MeV and a time-of-flight signal, and daughter decays, characterized by an energy between 7 MeV and 14 MeV, and an anticoincidence to the time-of-flight detector. The time window is 200 ms, the position window ± 0.5 mm. The time distances between implantation and a decay for the 10.4 MeV events range from (1-13) ms, that of the 9.7 MeV event is 165 ms. The half-life of the short lived events is 4.7 ms (fig. 13).

![Graph](image)

**Fig. 13**: Logarithmic time distribution of events from fig. 12.

The difference in mother energy signals between the average of the background from target-like recoils with an average of 14 MeV and the 18 MeV events corresponds to the mass difference between Bi and the fissioned system, if the velocity is normal, as checked by the time of flight measurement.

One of the observed events is correlated to a decay chain ending in $^{250}$Fr, two of them ended in $^{250}$Fm decay and one ends in $^{250}$Md. The decay chains are partly incomplete, as in the average half of the particles, emitted from the evaporation residues implanted close to the detector surface, escape the detector.

An example of a complete decay chain is shown in fig. 14, the results of the irradiations are collected in table 2. The a decay energy of $^{262}$Tb has been measured to (10176 ± 35) keV. One of the observed decays connected to a correlation chain has an energy of (9.70 ± 0.05) keV and its most probable half-life differs considerably from that of the other decays. In this case we have to consider that the evaporation residues are implanted into the detector close to its surface hence the possibility that not the full energy of an a decay is measured, cannot be excluded. For our case the probability for a decay with degraded energy between 9 and 10 MeV is less than 5%.

At 4.85 MeV one spontaneous fission with a time distance of 4.3 s to the implantation of the evaporation residue was observed.

The cross section calculated from our counting rates is of the order of 0.2 mb, the integral dose of irradiation was $1.2 \times 10^{14}$ particles.

![Decay Chain](image)

**Fig. 14**: Alpha decay chain of element 107.

### 9. Discussion

Our experimental results show that the use of targets near the double magic $^{208}$Pb makes it possible to form cold compound nuclei for the heaviest systems known up to now. The effective Coulomb radius of $(1.42 \pm 0.02)$ for which the integral excitation function for evaporation residues has a maximum did not decrease even for our heaviest projectile $^{54}$Cr. So we can hope to produce even heavier evaporation residues with low excitation energies.

The identification of the isotopes $^{255,256}$Tb by their spontaneous fission and their assignment $^{13}$ is supported by our results. The change in spontaneous fission half-life systematics when leaving the actinide region, as found by Oganesian et al. and calculated by Randrup et al. $^{15}$ could be confirmed.

The assignment of the spontaneous fission activity observed in the $^{242}$Bi on $^{242}$Bi irradiations is not facilitated by our experimental results, as we have to take into account the in-channel possible source for this activity. The isotope $^{250}$Tb is not likely to undergo spontaneous fission itself. The hindrance factors for spontaneous fission between even-even and odd mass nuclei are expected to be of about the same order as they are between odd mass and odd-odd nuclei $^{18}$. From this point of view the odd-odd $^{250}$Tb is not expected to undergo spontaneous fission decay. The predicted $\alpha$ decay half-life of $^{250}$Tb is 16 s $^{17}$, so this isotope could have a strong electron capture branch, which would lead to the spontaneous fissioning $^{250}$Po, with a half-life of tens of milliseconds. Consequently, the fission events would be observed with the longer half-life of $^{250}$Tb. $^{251}$Tb however is expected to fission as interpreted by Oganesian et al. Our opinion is that the spontaneous fission activity in $^{242}$Bi on $^{242}$Bi irradiations could originate as well from the 1n as from the 2n channel as we observed it together with an $\alpha$ decay from $^{250}$Tb as well as from $^{251}$Tb.

Our experimental results show the first observation of $\alpha$ decays of element 107, assigned to the isotope $^{262}$Tb by $\alpha$-$\alpha$ correlations to known transitions of various isotopes. Spontaneous fission of this odd-odd isotope is not expected. The one spontaneous fission event we observed may belong to a daughter decay, as its lifetime agrees with those measured in the $^{242}$Bi on $^{242}$Bi irradiations. Electron capture of $^{262}$Tb leading to the
spontaneous fissioning \( ^{262}\text{Hf} \) can be excluded from &
half-life predictions. The odd mass nucleus, \( ^{261}\text{Hf} \) &
which might be formed by 2 neutron evaporation could
not be found, possibly due to the low excitation energy
at the compound systems produced.

One other important result of our experiments is
that the nuclei formed in the chosen target
projectile combinations need no extra energy above
the Coulomb barrier to undergo fusion. So we have
a new hope, to reach the island of superheavy nuclei
by cold fusion of \( ^{48}\text{Ca} \) and \( ^{249}\text{Cm} \).

It is expected that fusion of very heavy systems is
limited by Coulomb disruptive forces. This process
can be characterized by the scaling factor
\( (Z^2/A)^{\text{eff}} \). From the presented results as well as
from the data of Schmidt et al.\(^{10}\) &
no enhancement of the barrier, e.g. no reduction of the effective
Coulomb radius is measured even for \( (Z^2/A)^{\text{eff}} \) values
exceeding that for \( ^{40}\text{Ca} \) on \( ^{249}\text{Cm} \) (Fig.15). With an
effective Coulomb radius of 1.40 fm the excitation energy
of the compound system at the fusion barrier has
the unexpected low value of 28 MeV. As
reasonable cross sections can be expected also below
the barrier\(^{10}\), there is some hope that the
formation of a superheavy evaporation residue
is possible by evaporation of one neutron with
\( (4.7-4.9)\text{MeV/v} \) projectile energies.

\[ \frac{48}{249} \text{Ca} + \frac{249}{\text{Cm}} \]

Fig.15: Effective radius parameter in dependence of
\( (Z^2/A)^{\text{eff}} \), circles: Vaz and Alexander\(^{10}\),
triangles: Schmidt et al.\(^{10}\), squares: this work.

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References:
1. G. Münzenberg, W. Faust, S. Hofmann,
Meth 161(1979)65
2. C.C. Sahm, H. Schulte, D. Vermeulen, J. Keller,
H.-G. Clerc, K.H. Schmidt, F.P. Heßberger,
3. S. Hofmann, W. Faust, G. Münzenberg,
W. Reisdorf, P. Armbruster, K. Güttner, H. Ewald;
Z. Phys. A291(1979)53
4. W. Faust, G. Münzenberg, S. Hofmann,
W. Reisdorf, K.H. Schmidt, P. Armbruster; Nucl.
Instr. Meth 166(1979)397
5. K.H. Schmidt, W. Faust, G. Münzenberg,
H.-G. Clerc, W. Lang, K. Fiehler, D. Vermeulen,
A518(1990)253
6. J.M. Nitschke, R.E. Leber, M.J. Nurmin,
A. Ghiorso; Nucl. Phys. A313(1980)236
7. H. Gäßiger, A.S. Iljinov, G.S. Popko,
Phys. A289(1979)415
8. G. Münzenberg, S. Hofmann, W. Faust,
P.P. Heßberger, W. Reisdorf, K.H. Schmidt,
T. Kitahara, P. Armbruster, K. Güttner, B. Thuma,
D. Vermeulen, submitted to Z. Phys. A
10. K.H. Schmidt, P. Armbruster, F.P. Heßberger,
G. Münzenberg, W. Reisdorf, C.C. Sahm,
D. Vermeulen, H.-G. Clerc, J. Keller, H. Schulte
to be published in Z. Phys.
12. Yu.Ts. Oganesian, Yu.E. Penionzhkevich,
K.A. Gavrilov, Kim De En; JINR P7-7863, Dubna
(1974)
E. Penionzhkevich, M.P. Ivanov, Yu.P. Tret'yakov;
Int. Conf. on Nuclei far from Stability, Cargese,
Corsico (1975)542
14. Yu.Ts. Oganesian, A.G. Demin, N.A. Danilov,
G.N. Flerov, M.P. Ivanov, A.S. Iljinov,
N.N. Kolesnikov, B.N. Markov, V.M. Plotko,
15. J.Randrup, C.F. Tsang, P. Möller, S.G.
16. W.J. Swiatecki; Phys.Rev.100(1955)937
17. N.N. Kolesnikov, A.G. Demin, Communication JINR
PG-9421, Dubna(1975)
18. W.J. Swiatecki, preprint LBL/10911, Berkeley
(1980)
preprint (1980).
DISCUSSION

J.B. Wilhelm: Do you get any information on total kinetic energy release for this very heavy element fissions from summing in your crystal?

G. Münzenberg: This is a very big problem we thought about, because first of all our surface barrier detectors are more useful for detecting $\alpha$-decay with good resolution. That means they have comparatively high resistance. On the other hand, you know always one of the fission fragments is leaving the detector so we have only a very small chance that both fragments are stopped in the same detector. That means if both are going just passing close to detectors surface. If you remember the figure of the detector system, you realize those long big detectors. They were really mounted for detecting the second fragment. I think up to our present state of art we are not able to have such a good energy resolution for the total kinetic energy.

W.-D. Schmieder-Ott: In your titanium experiment when you produce elements 105 and 104 you have to decide whether the 104 is spontaneous fissioning. Will there be a possibility to measure this spontaneous fission in anticoincidence with capture X-rays.

G. Münzenberg: This is one possibility we think about but you have several technical problems: one is comparatively long coincidence time of about 10 to 50 milliseconds and so you have to work at a very low level of background. We think about it and we hope that we will be able to do it once. The problem is not the efficiency, it is just the background.

R.K. Shelton: You have seen many new isotopes. I wonder if the additional isotopes and the additional systematics makes it possible for you to say whether or not one should really find a much longer lived region at $Z = 100$ and $N = 184$?

G. Münzenberg: We see no trends, everything is quite normal.

D.C. Hoffmann: You say you check the alpha systematics and for 107 it seems not inconsistent. Can you say anything more about agreement with the alpha decay of 105, for example, and what you observe in 107?

G. Münzenberg: The Q alpha systematics for the very heavy elements is somewhat difficult I would say, the reason being that some very important points are missing.

A. Sobisamaki: Concerning your data on the fission half-life $T_f$ for the nucleus $^{254}$U, which supports the change in the systematics of $T_f$ obtained by the Dubna group at $Z = 104$, I would like to add that theoretical results also give a support for such change. This was already discussed in Cargèse, but since then we made some improvements in the calculations. As a result, the calculated half-lives somewhat altered, but the change in the systematics remained.

G. Münzenberg: I think in respect to this comment it will be very interesting to have some spontaneous fission of some even-even nucleus of element 106 because then you get the trend of the new systematics and this could be done with our instruments because the half life is expected to be some tens of microseconds.
HEAVY ACTINIDE PRODUCTION IN THE REACTIONS OF \(^{238}\text{U} + {^{238}\text{U}}\) and \(^{238}\text{U} + {^{238}\text{Cm}}\)

H. Gääggeler, M. Schädel, W. Brüche, J. V. Kratz, K. Sümmerer and G. Wirth

N. Trautmann, P. Peuser, G. Tittel and R. Stakemann
Institut für Kernchemie, Universität Mainz, D-65 Mainz, Fed. Rep. of Germany

G. Herrmann
Gesellschaft für Schwerionenforschung mbH, D-61 Darmstadt and
Institut für Kernchemie, Universität Mainz, D-65 Mainz, Fed. Rep. of Germany

E. K. Hulet and R. W. Lougheed
Lawrence Livermore Laboratory, University of California, Livermore, California, USA

J. M. Nitschke
Lawrence Berkeley Laboratory, University of California, Berkeley, California, USA

R. L. Hahn and R. L. Ferguson
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Abstract

Experiments on the production of heavy actinides up to mendeleevium from the reactions between \(^{238}\text{U} \) on \(^{238}\text{U} \) and \(^{238}\text{U} \) on \(^{238}\text{Cm} \) are summarized. We find that independent of the system and the bombarding energy an average of about 4 neutrons is emitted from the primary fragments implying average excitation energies of 30 to 40 MeV in the heavy fragments. An intercomparison of our data with results obtained with lighter particles like \(^{40}\text{Ca} \), \(^{88}\text{Kr} \) and \(^{136}\text{Xe} \) on \(^{238}\text{U} \) and \(^{244}\text{Cm} \) targets, respectively, shows increased formation cross sections for heavy actinides with \(^{238}\text{U} \) as projectile. In addition, for the \(^{238}\text{U} + {^{238}\text{U}}\) reaction cross sections for americium shape isomers were determined. Deduced isomer-to-ground-state ratios are about lower as compared to light particle induced reactions. With a simple model estimates of production rates for very heavy elements up to \(Z=104\) have been performed for the reactions of \(^{238}\text{U} \) on \(^{244}\text{Cm} \), \(^{244}\text{Cf} \) and \(^{254}\text{Es} \) targets.

1. Introduction

Heavy actinides have so far been produced either by n-capture processes followed by \(\beta\)-decay or by heavy-ion reactions with relatively light particles (As40). An alternative way has been opened by studies of the interactions between very heavy ions. This approach is based on a novel type of nuclear reactions, the damped collisions, in which both interacting nuclei stick together in a dinuclear system for a short time, dissipate kinetic energy and angular momentum, exchange nucleons and separate again. The transfer of many nucleons seems an attractive method of synthesizing very heavy and neutron-rich actinides and possibly of superheavy elements\(^{1}\). If the dispersions in excitation energies and angular momenta in these collisions are sufficiently broad, then the partial cross sections contained in the low-energy and low-angular momentum tails may be high enough for the production of detectable amounts of highly fissile transfer products such as heavy actinides.

In this contribution we report on the production of the heavy actinides plutonium (\(Z=94\)) through mendeleevium (\(Z=101\)) in the reactions \(^{238}\text{U} \) on \(^{238}\text{U} \) and \(^{238}\text{U} \) on \(^{244}\text{Cm} \) carried out at the UNILAC accelerator. The results are based on the balance of diffusion model calculations together with empirical fission systematics in order to learn about the rare reaction channels that lead to the formation of heavy fragments at the lowest possible excitation energies. Based on some simple assumptions calculations of production rates for heavy elements up to \(Z=104\) have been performed for the reactions of \(^{238}\text{U} \) on \(^{244}\text{Cf} \) and \(^{254}\text{Es} \) targets in order to shed some light onto future possibilities for the production of new neutron rich isotopes of very heavy elements by damped collision processes.

2. The reaction of \(^{238}\text{U} \) with \(^{238}\text{U} \)

2.1 Results at \(E \leq 7.5\) MeV/u

Bombardments of thick metallic \(^{238}\text{U} \) targets were performed with 7.5 MeV/u \(^{238}\text{U} \) projectiles\(^{2}\). All reaction products are stopped in the target. After bombardment the targets were chemically processed in order to obtain different element fractions up to fermium (\(Z=100\)). These final samples then were assayed for \(\alpha\)- and spontaneous fission decay over several months. The results obtained for the heavy actinides Pu through Fm are shown in Fig.1a. The cross sections represent mean values for the energy range 7.5 MeV/u down to the interaction barrier (B=9.1 MeV/u). For comparison cross sections for the reactions of \(^{136}\text{Xe} + {^{238}\text{U}}\) and \(^{88}\text{Kr} + {^{238}\text{U}}\) are shown (Fig.1b) for the same incident energy of 7.5 MeV/u. The net production rates are significantly larger with \(^{136}\text{Xe} \) than with \(^{88}\text{Kr} \) as projectile. Due to the very negative Q\(_{\text{fg}}\) values involved in the \(^{88}\text{Kr} \) and
$^{136}$Xe on $^{238}$U reactions an equally large mass transfer at the same kinetic energy loss (TKEL) as in the $^{238}$U + $^{218}$U reaction should result in products with considerably lower excitation energies ($E^*$), since $E^* = E_{TKEL} + Q_{eg}$. This should drastically increase the production rates for highly fissile actinides. However, the observed opposite trend has to be considered as evidence for a much smaller primary yield before fission with the projectiles $^{84}$Kr and $^{136}$Xe relative to $^{238}$U. This is expected on the basis of the phase space available above the minimum potential energy surface (PES). In Fig. 2 for the systems $^{136}$Xe on $^{238}$U and $^{218}$U on $^{238}$U the $Q_{eg}$-values and the potential energy for the most probable mass fragmentations are shown as function of the product charge. Obviously, shell effects manifest themselves in pronounced minima in the PES. According to Schmidt and Wolschon$^6$ and Grossmann$^7$ the very flat PES for $^{238}$U + $^{238}$U with a minimum near $Z=102$ and $Z=82$ strongly influences the early development of the interacting system. Therefore, large mass transfer is favoured with relatively small dissipated energies. For the early development of the $^{136}$Xe + $^{238}$U system, the dissipated energy per exchanged nucleon is 2 to 4 MeV higher than with the $^{238}$U projectile due to the higher energy required for particle-hole excitation which accompanies the exchange of nucleons$^6$.

As discussed elsewhere$^3$ we can describe the measured isotope distributions $Y(Z, A_p)$ of a given actinide element by starting from a narrow primary fragment distributions $Y_1(Z, A_p)$ around the centroid $A'_p$ by taking into account multiple chance fission in the neutron evaporation chain as

$$Y(Z, A_p) = \sum_{i=1}^{k} \left( \frac{\Gamma_n}{\Gamma_n + \Gamma_F} \right)^i Y_1(Z, A_p) \frac{\Gamma_F}{\Gamma_n + \Gamma_F} \frac{d\sigma}{dE} p(x_i) dE. \quad (1)$$

$A'_p$ is obtained by potential energy calculations, $\Gamma_n/(\Gamma_n + \Gamma_F)$, the relative neutron decay width is taken from an empirical formula$^8$. $p(x_i)$ gives the probability for the evaporation of $x_i$ neutrons from the fragment at fixed excitation energy $E^*$ as extracted from ALICE code calculations, and $d\sigma/dE$ accounts for the dispersion in excitation energy which has assumed to be of Gaussian shape.

This analysis led us to conclude that a minimum energy dissipation is required for a given charge transfer and to take care of this by introducing an energy cutoff. Such a cutoff is expected from one-body dissipation models which assume that energy dissipation occurs essentially

Fig. 1a: Cross sections for the formation of heavy actinides in the reaction of 7.5 MeV/u $^{238}$U projectiles with thick $^{238}$U targets. (The curves are drawn to guide the eye).

Fig. 1b: Intercomparison of formation cross sections for heavy actinides from the reactions of 7.5 MeV/u $^{84}$Kr, $^{136}$Xe and $^{238}$U projectiles with $^{238}$U targets.
through the exchange of nucleons. Thus, the minimum number of exchanged nucleons required to produce a given product gives rise to a minimum amount of dissipated energy. With this assumption the position and width of the experimental distributions were well reproduced but the absolute cross sections calculated were too high by one order of magnitude. This discrepancy may be explained i) by shell effects or ii) by lower I\(_n\)/I\(f\) values as compared to the empirical systematics due to angular momentum effects or iii) by non-statistical processes leading to non-equilibrated states in the exit channel. Assumption i) may be correlated with the simultaneous formation of a nearly magic light fragment with Z=82 or Z=126 which does not take up much excitation energy and leads, hence, to an increased depletion by fission for the heavy fragments. Assumption ii): Based on the rotating liquid drop model, I\(n\)/I\(f\) can be expressed by

\[
\frac{I_n}{I_f} = \frac{I_n}{I_f} = \frac{1}{1 + \left(\frac{I_2}{I_{1\text{lim}}}\right)^2}
\]

where I_{1\text{lim}} is a limiting angular momentum which is a function of the temperature of the nucleus and its moments of inertia in the ground-state and at the saddle point. Assuming an evaporation cascade of four neutrons and fragment spins as deduced from diffusion model calculations, we obtain a reduction of about one order of magnitude for the production rates. Assumption iii): The theoretical approach is valid only if the fragments in the exit channel are fully quillibrated. However, it has been shown that for very heavy fragments from the reaction of U+U such an assumption might no longer be valid. Fragment deformations leading to shapes outside the appropriate saddle point might be associated with these large charge transfers.

2.2 Excitation functions for heavy actinides

In order to learn about the lowest excitation energy bins populating surviving heavy actinides additional thick target irradiations were performed. The incident energies were 6.49 MeV/u (1.06X/E/B), 6.84 MeV/u (1.12X/E/B) and 8.65 MeV/u (1.41X/E/B). Within experimental error all results show the same behavior: The centroids and widths of the measured isotope distributions do not depend on the incident energy. This observation supports the assumption that independently of the projectile energy surviving heavy actinides are produced at low energy transfers.

From these thick target cross section values excitation functions were extracted from the differences in the production rates between 8.65 and 7.50, 7.50 and 6.84, 6.84 and 6.49 and 6.49 and 6.13 (interaction barrier) MeV/u. All these excitation functions behave similarly with a steep increase in cross section up to about 6.8 MeV/u and a relatively flat decrease at higher energies. The widths of these asymmetric excitation functions are about 150 MeV (FWHM, lab). As an example, Fig. 3 shows the results for californium integrated over all isotopes. Such a shape can be used as a guide to the eye.

![Fig. 2: Left hand side: Ground-state Q-values, Q_{gg}, for the formation of heavy fragments in transfer reactions between 136Xe and 238U projectiles with 238U targets. Right hand side: Minimum of the potential energy surface vs. charge number of the heavy fragment in the same reactions and normalized to the entrance channel as described in Ref. 13.](image)

![Fig. 3: Integral cross sections for californium from the reaction of 238U on 238U as function of the bombarding energy. The solid curve represents a theoretical prediction (see text). The dashed curve is drawn through the experimental data to guide the eye.](image)
reproduced with the idea of a constant ex-
citation energy bin being responsible for
the production of surviving actinides. The
solid line in Fig. 3 shows a calculation of the
excitation functions for californium
isotopes as function of the uranium energy.
This curve was obtained with the following
assumptions: i) the excitation energies of Cf
fragments can be deduced from the ex-
citation energies of the complementary
light fragments (see Ref. 13), ii) the Q-
value dispersion has a width of 100 MeV
(FWHM)3 iii) there is an energy cutoff of 350
MeV9 and iv) the production of surviving Cf
product can be extracted by the 4 n
evaporation channel. Their fission proba-
bilities were taken from the empirical
systematics of Sikkeland et al.9 Fig. 3
demonstrates that the shape of the experi-
mental excitation function can well be
reproduced with these simple assumptions.
However, the absolute values again disagree
with the experimental ones by about a fac-
tor of ten and the same reasons discussed
above may account for that discrepancy.

2.3. Production of americium shape isomers

Shape isomers have so far been pro-
duced in light particle induced reactions
with 2MeV or in photo-induced
reactions. An interesting result of such
studies is the isomer-to-groundstate ratio,
i.e. the relative probability for produc-
tion of the nucleus in the first and second
well. From such data information about the
heights of the first and the second fission
barrier can be extracted. For the 14 ms
isomer 242Am this ratio was found10 to be
about 4x10^-4 independent of the reaction
and the projectile energy. The heaviest
projectile which was used in these studies
was 11B at an energy of 60 MeV which
brings a maximum angular momentum of 15 \( \hbar \)
into the system. For the present studies a
rotating wheel system13 was applied to
measure the production cross section for
americium shape-isomers. In this system
the reaction products recoiling out of a
rotating target wheel are caught in a
second rotating system consisting of a stack
of thin catcher foils. During irradiation
these catcher foils are continuously ro-
tated into shielded positions where they are
exposed to stationary fission-track detec-
tors positioned on both sides of each ro-
tating foil. This allows the detection of
spontaneous-fission activities by the
production of fission-fragment tracks in
one or both adjacent plastic foils and the
measurement of their half-lives via the de-
crease of the fission-track density along
the direction of rotation. Furthermore,
the range of the fissioning species in the
changer material can be obtained from the
track distribution associated with subse-
quent catcher foils and the angular dis-
tribution of the fissioning species from
the radial track distribution within the
detector foils facing each catcher foil.
From the measured range and angular dis-
tributions excitation functions may be ex-
tracted.

The experiments revealed two activities
that can be attributed to the fission
isomers 244Am\(^{m}\) (\( T_1/2 = 1.0 \) ms) and 242Am
\(^{m}\) (\( T_1/2 = 14 \) ms).

The mean production cross sections be-
 tween 7.5 MeV/u and the interaction barrier
obtained for the 14 ms 242Am\(^{m}\)
cross section is plotted as extracted from
the measured range and angular distribu-
tions within the catcher foil stack. Again,

![Graph](image)

Fig. 4: Differential cross sections \( d\sigma/dE \)
for 242Am from the reaction of 238U \( ^{238}\text{U} \).
circles: ground-state yields
squares: fission-isomer yields

a similar shape is observed as already
measured for heavy actinides in the ground-
state (see Fig. 3) with a maximum at about
6.6 MeV/u and a width of about 150 MeV
(FWHM). In order to determine the isomer-
to-groundstate ratio the cross sections for
this nuclide in the groundstate were de-
duced by a radiochemical analysis of the
activity collected in the catcher foils.
Since the groundstate of 242Am could not be
determined directly due to its short half-
life of 16 hours, the 242Am yield was ob-
tained by a graphical interpolation between
the neighbouring 241Am and 243Am yields
accessible by \( \alpha\)-spectroscopy. In the upper
part of Fig. 4 the excitation function for
242Am (total yield) is shown. From the two
curves of Fig. 4 the isomer-to-ground-state
ratio can be obtained as 4x10^-5. This ratio
does not vary with the uranium projectile
energy which again supports the assumption
that a constant excitation energy and angu-
lar momentum bin is responsible for the po-

culation of surviving highly fission products.

The value of 4x10^-5 for the isomer-
to-groundstate ratio measured in the $^{234}\text{U} + ^{235}\text{U}$ interaction is one order of magnitude below that found for any other reaction. The most reasonable explanation might be the higher excitation energies and angular momenta involved in fully damped reactions between very heavy ions. However, the excitation energy can hardly be considered to reduce significantly the isomer-to-groundstate ratio: In a recent work[14] this ratio was measured for $^{242}\text{Am}$ in photo-induced reactions with bremsstrahlung energies between 13 and 80 MeV and was found to remain constant within this energy range. More realistic is an attribution of the lowered isomer-to-groundstate ratio to the increased nuclear spin in the $^{238}\text{U} - ^{238}\text{U}$ reaction. This can be expected because of the different moments of inertia at the deformations of the first and second fission barrier saddle points. The rotational energy which has to be added to the potential energy for zero angular momentum reduces the height of the second fission barrier more drastically than for the first barrier. Therefore, the probability for the population of the nucleus in the second well should decrease with increasing angular momentum. A crude estimate of the isomer-to-groundstate ratio as function of the angular momentum can be obtained from eq. (2) by introducing two limiting angular momenta $l_{\text{lim}}$ (A) and $l_{\text{lim}}$ (B) for the first (A) and second (B) fission barrier, respectively. In Fig. 5 isomer-to-groundstate ratios for $^{242}\text{Am}$ for light particle-induced reactions[15] are shown together with the value measured in this work as a function of the estimated average spin. The upper curve was obtained assuming a rigid rotor-like behaviour of the americium fragments. The rigid body assumption should be approached in the limit of both large temperature and large deformation. However, our value from the $^{234}\text{U} + ^{238}\text{U}$ reaction can be better fitted with the cranking model[16] which is based on single-particles energies and wave functions at a given deformation. The better agreement with the latter model may be seen as additional evidence for the expectation that the isomer-to-groundstate ratio is mainly determined in the last neutron evaporation step, i.e., at a low nuclear temperature.

In conclusion, it seems that measurements of isomer-tercgroundstate ratios for shape-isomers produced by different heavy ion reactions might be a useful tool to investigate the influence of angular momentum on the double-humped fission barrier.

3. The reaction of $^{238}\text{U}$ on $^{248}\text{Cm}$

3.1 Experimental

Thick metallic $^{248}\text{Cm}$ targets were bombarded with $^{238}\text{U}$ projectiles in order to study the production of very heavy actinides and to search for long-lived superheavy elements[17]. The targets were prepared by evaporation of 3.2 to 7.5 mg/cm$^2$ $^{248}\text{Cm}$ metal on 4.5 mg/cm$^2$ thick molybdenum foils. These $^{248}\text{Cm}$ thicknesses were sufficient to degrade the beam energy from 7.4 MeV/u to near or below the Coulomb barrier, which, in turn, results in a physical integration of most of the broad excitation functions for the heavy actinides (see Fig. 3). Since such targets contain a spontaneous fission activity of about $10^9$ events per day special precautions were required as described elsewhere[18].

During the experiments up to $3 \times 10^{15}$ particles were accumulated. All interesting products emitted within a laboratory angle of 55$^\circ$ were stopped in a copper catcher, which was chemically processed after the end of bombardment with a procedure similar to that used in the $^{238}\text{U} + ^{238}\text{U}$ experiments.

3.2 Cross sections at E = 7.4 MeV/u

The formation cross sections for isotopes of the elements californium (Z=98) through mendelevium (Z=101) are shown in Fig. 6a. They represent mean values between the $^{238}\text{U}$ projectile energy of 7.4 MeV/u and the interaction barrier (B=6.3 MeV/u). The cross sections for Fm, Es and Cf increase by three to four orders of magnitude with the heavier target $^{244}\text{Cm}$ as compared to $^{238}\text{U}$ (see Fig. 6b). This is obviously due to the trivial fact that the cross sections for damped collision products decrease steeply for increasing number of excited nucleons, and that the number of nucleons to be transferred in order to make Cf through Fm is much smaller if $^{248}\text{Cm}$ is used instead of $^{238}\text{U}$. In Fig. 6b are also plotted experimental cross sections obtained for the reactions of $^{48}\text{Ca} + ^{248}\text{Cm}$(19) and $^{136}\text{Xe} + ^{248}\text{Cm}$(20). As for heavy ion induced reactions on $^{238}\text{U}$ targets, the system with the

---

**Fig. 5:** Isomer-to-groundstate ratios for $^{242}\text{Am}$ from light particle induced reactions (circles) and the reaction $^{238}\text{U} + ^{238}\text{U}$ (square) as function of the estimated nuclear spin. The two curves show theoretical predictions based on different assumptions about the moments of inertia (see text).
The heaviest projectile $^{238}$U reveals again the highest cross sections. However, in the $^{238}$Cm case a quantitative intercomparison may be somewhat ambiguous because different incident energies were used for the three systems. In any case, the higher cross sections for the $^{238}$U + $^{248}$Cm system is again in qualitative accordance with the PES (see Fig. 7). The $^{238}$U + $^{248}$Cm system exhibits a very flat surface with a minimum near $Z_h=108$ (and $Z_1=80$) which favors the exchange of nucleons at low dissipated energies. On the contrary, the $^{40}$Ca + $^{248}$Cm or the $^{136}$Xe + $^{248}$Cm systems find themselves trapped in a pocket centered near the injection point which hinders the systems to spread out at the very beginning of the interaction.

Fig 6a: Cross sections for the formation of heavy actinides in the reaction of 7.4 MeV/u $^{238}$U projectiles with thick $^{248}$Cm targets. (The curves are drawn to guide the eye)

Fig 6b: Inter-comparison of formation cross sections for heavy actinides from the reactions of:

- Squares: $^{238}$U + $^{248}$Cm
  (E ≤ 7.4 MeV/u)
- Triangles: $^{40}$Ca + $^{248}$Cm
  (E ≤ 5.6 MeV/u)
- Circles: $^{136}$Xe + $^{248}$Cm
  (E ≤ 6.4 MeV/u)
- Crosses: $^{238}$U + $^{238}$U
  (E ≤ 7.5 MeV/u)

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Fig. 7: Left hand side: Ground-state Q-values, Qgs, for the formation of heavy fragments in transfer reactions between $^{136}\text{Xe}$, $^{48}\text{Ca}$ and $^{238}\text{U}$ projectiles with $^{28}_{\text{Cm}}$ targets. Right hand side: Minimum of the potential energy surface vs. charge number of the heavy fragment in the same reactions and normalized to the entrance channel as described in Ref. 13.

3.3 Intercomparison of the $^{238}\text{U}+^{238}\text{U}$ and $^{238}\text{U}+^{28}_{\text{Cm}}$ data

For an intercomparison of our experimental cross sections for the heavy actinides between the systems $^{238}\text{U}+^{238}\text{U}$ ($E \leq 7.5$ MeV/amu, see Fig. 1) and $^{238}\text{U}+^{28}_{\text{Cm}}$ ($E \leq 7.4$ MeV/amu, see Fig. 6) we assume the primary yields for a given (xp,yn)-nucleon transfer to be the same in both reactions. This assumption is based on experimental data of the much less fissible projectile-like fragments Po (Z=84) and At (Z=85), which were found to have the same cross sections within error limit for both systems. Then, we can approximate the ratios of cross sections $\sigma(U+U)/\sigma(U+Cm)$ for a given channel by the ratio of the fission probabilities using angular momentum independent values such as the empirical values of Sikkland et al. 4): inherent in this approach is the assumption that modifications by excitation energy and angular momenta cancel out to a good approximation. The only remaining variable in such a procedure is the number of emitted neutrons $x_i$. Starting from the yields for Am ($\Delta Z=3$) through Bk ($\Delta Z=5$) in the $^{238}\text{U}+^{238}\text{U}$ system (see Fig. 1) we calculated cross sections for Es ($\Delta Z=3$) through Md ($\Delta Z=5$) in the $^{238}\text{U}+^{28}_{\text{Cm}}$ reaction for given values of $x_i$. The results are shown in Fig. 8. Accordance between experimental data and calculated values is obtained for an average $x_i$ of about 4 implying average excitation energies in the heavy fragments of 30 to 40 MeV. This is entirely consistent with the earlier findings for the $^{238}\text{U}+^{238}\text{U}$ reaction (see section 2.1). It confirms, that the reaction mechanism is very nearly the same for both combinations. These estimates again indicate that the excitation energy distribution decreases very steeply below about 30 MeV so that $0 \text{n}$ and $1 \text{n}$ channels are essentially absent.

4. Estimates for formation cross sections for very heavy actinides in the reactions of $^{238}\text{U}$ on $^{248}_{\text{Cm}}$, $^{256}_{\text{Cf}}$ and $^{254}_{\text{Es}}$

Based on the method outlined in section 3.3 a crude estimate of formation cross sections for very heavy elements produced in damped collisions between $^{238}\text{U}$ projectiles incident on the heavy actinide targets $^{248}_{\text{Cm}}$, $^{256}_{\text{Cf}}$, and $^{254}_{\text{Es}}$ was performed. The calculations were done on the basis of the experimental $^{238}\text{U}+^{238}\text{U}$ data of Fig. 1a, assuming an average of 4 neutrons to reflect the main evaporation channel of the heavy fragments (see Fig. 8). The estimates are shown in Fig. 9. These plots represent thick target values for an incident energy of 1.25E/B. For the $^{238}\text{U}+^{248}_{\text{Cm}}$ system the calculation has been extended up to lawrencium (Z=103). It should be
Fig. 9: Estimated cross sections for heavy actinides from the reactions of $^{238}$U projectiles with $^{246}$Cm, $^{249}$Cf and $^{254}$Es targets (for details see text).

noted that beginning with fermium, the calculations extend beyond the heaviest known isotopes, $^{259}$Fm, $^{260}$Md, $^{259}$No, and $^{260}$Fr. For nobelium (Z=102) the maximum yields are predicted for $A = 259/260$ with estimated cross sections of about 1 nb.

For the $^{238}$U+$^{249}$Cf system, the formation cross sections should increase much compared to $^{238}$U+$^{246}$Cm due to the increased proton number of the target. However, since the target is relatively neutron-depleted, the maxima of the isotope distributions are situated in already well-known regions. Therefore, one should be quite pessimistic about this combination as a tool for producing new neutron-rich isotopes of highly-fissile heavy elements.

Even though $^{254}$Es could be prepared only with low target thicknesses due to its high radioactivity and its very restricted availability, the combination of $^{238}$U on $^{254}$Es might offer a novel way of producing new neutron-rich lawrencium isotopes (see Fig. 9). The maximum of the calculated distribution is centered at $A = 261$ which is a so far unknown isotope. However, its production cross section of about 10 nb is not very promising.

In conclusion, the data obtained with the projectile $^{238}$U clearly exhibit increased yields for the formation of very heavy actinides compared to combinations with lighter ions. This is of importance for the main goal of this project, the synthesis of superheavy elements through damped collisions.

Promising might be the choice of quasi-elastic reactions. Such reaction channels have recently been shown to give relatively high cross sections for so far unknown neutron-rich lanthanide isotopes. However, an application of this reaction type to very heavy elements would limit future explorations to the neighbourhood of the target isotope.

References
1) see e.g. G. Herrmann, Nature (London) 280, 543 (1979)

- 770 -


17) G. Herrmann, these proceedings.


ATTEMPTS TO SYNTHESIZE SUPERHEAVY ELEMENTS - A STATUS REPORT

G. Herrmann
Institut für Kernchemie, Universität Mainz, D-6500 Mainz, and

Abstract
A status report is presented on attempts to synthesize superheavy elements by complete fusion reactions and by damped collisions between heavy nuclei. Although these efforts remained negative so far, experimenters may still feel encouraged to continue with their attempts because the potential of heavy-ion fusion and transfer reactions has not fully been exhausted to date.

1. Introduction
Those of you who have attended the first conference of this series held in 1966 at Lysekil may remember the paper by H. Meißner\textsuperscript{1} in which he showed that the next proton shell closure beyond lead (Z=82) should occur not too far from the heaviest synthe
tical elements, at atomic number 114 and not at 126 as previously believed. This is one of the key papers which caused a tremendous research activity on superheavy elements. The second one is the paper by W. D. Myers and W. J. Swiatecki\textsuperscript{2} published in the same year where it was pointed out that the stabilising effects of proton and neutron shell closures should be strong enough in some regions beyond the explored periodic table to produce fission barriers comparable to or even greater than that of uranium.

The first detailed theoretical investigations\textsuperscript{3-5} of nuclear properties revealed the topology of an island of relatively stable nuclei due to shell closures at atomic number 114 and neutron number 184. First estimates indicated half lives comparable to or even longer than the age of the earth for nuclei in the centre of the island. Thus, superheavy elements could even exist in nature, and many groups felt encouraged to search for such elements in terrestrial and extraterrestrial samples. First, negative results were published 1969 by S. G. Thompson et al.\textsuperscript{6} who also reported the first attempt to synthesize superheavy elements by fusion of \textsuperscript{248}Cm with \textsuperscript{40}Ar to form a compound nucleus of element 114. A review written in 1974 contains already 329 references\textsuperscript{7}.

In the following status report, I shall focus on attempts to synthesize superheavy elements in the laboratory but shall skip the search in nature since there will be a contribution to this conference from the Dubna group\textsuperscript{8} which made the strongest efforts in this direction over many years. For a more detailed discussion of relevant questions the reader is referred to review articles, e.g. ref.\textsuperscript{9}.

2. Nuclear and chemical properties
Let us first consider briefly the nuclear and chemical properties of superheavy elements. For spontaneous fission decay the maximum stability is expected for the doubly magic nucleus \textsuperscript{296}114\textsuperscript{184}. However, other decay modes have also to be considered. Figure 1 gives two examples for sets of overall half lives calculated for superheavy nuclei. In Fig. 1a, α-decay dominates at Z=114 and higher atomic numbers so that the maximum half life is expected\textsuperscript{10} for \textsuperscript{296}114\textsuperscript{184}. Note the broad shore to the west from where the island is approached in heavy-ion reactions. This shape of the island is reproduced in more recent calculations\textsuperscript{11} although the half lives decrease by several orders of magnitude with a maximum value of 10\textsuperscript{7} yr for \textsuperscript{286}114\textsuperscript{184}. A quite different and more unfavourable shape of the island was obtained in the calculations\textsuperscript{12} summarized in Fig. 1b showing a steep decrease of the half lives at the west side due to the considerably lower fission barriers obtained. In any discussion of extrapolated half lives one should keep in mind their uncertainties of many orders of magnitudes.

Fig. 1 Calculated half lives of superheavy nuclei shown as contours of constant overall half life plotted versus proton and neutron number; after refs. 10 (a) and 12 (b).

When superheavy elements are formed in nuclear reactions they carry excitation energy and angular momentum. Both these properties decrease the effective fission barrier. As theoretical calculations\textsuperscript{13,14} indicate, the barrier should disappear at about 50 MeV excitation energy and 30 units of angular momentum.

In spontaneous fission of superheavy nuclei, the fission fragments should carry an unusually high kinetic energy, 200-230 MeV, and evaporate an unusually large
number of neutrons, about ten\(^{15}\). More recent experimental data on fission properties of heavy nuclei indicate\(^{16}\) that the kinetic energy may be even higher, about 270 MeV, but the neutron multiplicity may be lower, about five. Hence, the observation of high total kinetic energy and neutron multiplicity should constitute a characteristic fingerprint for superheavy nuclei. For short-lived superheavy nuclei, detection of energetic \(\alpha\)-particles may be a characteristic and sensitive method\(^{17,12}\).

Concerning the chemistry of superheavy elements I should restrict myself to the remark that their position in the periodic table has been predicted by quantum-mechanical calculations of their ground state electronic structure\(^{17}\). Accordingly, element 110 should be a homologue of platinum, element 112 a homologue of mercury, and element 114 a homologue of lead. Details of their chemical behaviour have been discussed\(^{14}\) which form the basis of chemical separation procedures that will be mentioned below.

3. Searches at accelerators

Heavy-ion reactions seem to be the only practical way of producing superheavy elements in the laboratory: one tries to jump from the peninsula of known nuclei in one step over the sea of instability to the superheavy island. Two different approaches can be used as is outlined in Fig. 2. The upper branch illustrates complete fusion of the interacting nuclei. The compound nucleus is excited since, in general, more kinetic energy is required to overcome the Coulomb barrier than energy is consumed in the fusion process. Part of the excitation energy is carried away by particle evaporation, mostly of neutrons. For very heavy compound nuclei, fission into two fragments of comparable size dominates; however.

In the second process illustrated by the lower branch in Fig. 2, the two interacting nuclei stick together for a very short time, about \(10^{-21}\) s, forming a composite system and separate again. During the short contact, the kinetic energy of the projectile can be partially or completely transformed into internal excitation and rotation. Although the atomic and mass number of the reaction products are in general close to those of the interacting nuclei, a substantial number of protons and neutrons can be transferred between the interacting nuclei. Hence, a characteristic feature of these damped collisions is the broad distribution of excitation energy, angular momentum, atomic and mass number of the outgoing products. The reaction products deexcite by particle evaporation and, in heavy systems, by fission.

3.1 Fusion reactions

Since complete fusion was a successful way for the synthesis of the heaviest elements, it was quite natural to use this type of reaction in the first attempts to produce superheavy elements in the laboratory. The problem lies in the extreme neutron excess of the nuclei located in the centre of the island. This is illustrated by Table 1 which contains the fusion reactions tried together with the upper limit for the production cross section and with the range of half lives covered. As one can see from the compound nuclei listed in the Table, the vicinity of element 114 can only be reached in combinations which mean the numbers far below 184 whereas this magic neutron number can only be produced with atomic numbers as high as 122. Neutron evaporation from the compound nuclei will further increase this dilemma. A more detailed discussion of these reactions can be found in a recent review article\(^{18}\).

Among the systems listed in Table 1 the reaction

\[
^{248}\text{Cm}^{152} + ^{48}\text{Ca} \rightarrow ^{296}\text{X}^{180}
\]

has been studied most extensively since it provides the closest approach to the island if both the proton and neutron numbers are considered. Let me illustrate this point by Fig. 3a which is identical with Fig. 1a but shows in addition the landing place after the \(^{48}\text{Ca}+^{248}\text{Cm}\) reaction. We overshoot the centre of the island and lose, with the \(^{48}\text{Ca}\) projectile energies applied in the experiments, four neutrons. Then, a short lived \(\alpha\)-emitter is produced followed by two electron capture transitions which lead towards the region of relatively long half lives. The final nucleus, \(^{292}\text{X}\), should decay by fission with a half life of about 1 h. This sequence is shown in more detail in Fig. 4. Experiments with this reaction are difficult, however, since neither the very neutron rich actinide isotope \(^{292}\text{Cm}\) with 3.6\(\times\)10\(^{10}\) yr half life nor the very neutron rich projectile \(^{48}\text{Ca}\) with 1.1% natural abundance are generally available.


<table>
<thead>
<tr>
<th>System</th>
<th>Compound</th>
<th>Cross-section (cm$^2$)</th>
<th>Half life range</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th + $^{48}$Ca</td>
<td>$^{280}$Hg$^{170}$</td>
<td>$3 \times 10^{-35}$</td>
<td>$\geq 3 \times 10^{-3}$</td>
<td>21</td>
</tr>
<tr>
<td>$^{232}$Pa + $^{48}$Ca</td>
<td>$^{279}$Hg$^{168}$</td>
<td>$4 \times 10^{-35}$</td>
<td>$\geq 3 \times 10^{-3}$</td>
<td>21</td>
</tr>
<tr>
<td>$^{232}$U + $^{48}$Ca</td>
<td>$^{281}$Hg$^{169}$</td>
<td>$7 \times 10^{-35}$</td>
<td>$\geq 2$ h</td>
<td>21</td>
</tr>
<tr>
<td>$^{248}$Cm + $^{40}$Ar</td>
<td>$^{288}$Hg$^{174}$</td>
<td>$2 \times 10^{-32}$</td>
<td>$10^{-3}$ s - 1 d</td>
<td>22</td>
</tr>
<tr>
<td>$^{242}$Pu + $^{48}$Ca</td>
<td>$^{290}$Hg$^{176}$</td>
<td>$1 \times 10^{-35}$</td>
<td>2 h - 1 yr</td>
<td>23</td>
</tr>
<tr>
<td>$^{243}$Am + $^{48}$Ca</td>
<td>$^{291}$Hg$^{176}$</td>
<td>$2 \times 10^{-35}$</td>
<td>2 h - 1 yr</td>
<td>23</td>
</tr>
<tr>
<td>$^{246}$Cm + $^{48}$Ca</td>
<td>$^{296}$Hg$^{178}$</td>
<td>$2 \times 10^{-35}$</td>
<td>2 h - 1 yr</td>
<td>23</td>
</tr>
<tr>
<td>$^{248}$Cm + $^{48}$Ca</td>
<td>$^{296}$Hg$^{180}$</td>
<td></td>
<td>See Fig. 5</td>
<td></td>
</tr>
<tr>
<td>$^{208}$Pb + $^{84}$Kr</td>
<td>$^{292}$Hg$^{174}$</td>
<td>$1 \times 10^{-30}$</td>
<td>$\geq 6 \times 10^{-7}$ s</td>
<td>24</td>
</tr>
<tr>
<td>$^{208}$Pb + $^{86}$Kr</td>
<td>$^{294}$Hg$^{176}$</td>
<td>$5 \times 10^{-35}$</td>
<td>$3 \times 10^{-3}$ s - 100 d</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1.5 \times 10^{-30}$</td>
<td>26</td>
</tr>
<tr>
<td>$^{238}$U + $^{59}$Co</td>
<td>$^{297}$Hg$^{178}$</td>
<td>$4 \times 10^{-33}$</td>
<td>1 s - 30 h</td>
<td>27</td>
</tr>
<tr>
<td>$^{238}$U + $^{60}$Ni</td>
<td>$^{298}$Hg$^{178}$</td>
<td>$2 \times 10^{-33}$</td>
<td>1 s - 30 h</td>
<td>27</td>
</tr>
<tr>
<td>$^{238}$U + $^{65}$Cu</td>
<td>$^{303}$Hg$^{182}$</td>
<td>$8 \times 10^{-33}$</td>
<td>1 s - 30 h</td>
<td>27</td>
</tr>
<tr>
<td>$^{238}$U + $^{65}$Cu</td>
<td>$^{303}$Hg$^{182}$</td>
<td></td>
<td>2 h - 1 yr</td>
<td>28</td>
</tr>
<tr>
<td>$^{232}$Th + $^{76}$Ge</td>
<td>$^{308}$Hg$^{186}$</td>
<td>$1 \times 10^{-34}$</td>
<td>$2 \times 10^{-6}$ s - 1C h</td>
<td>29</td>
</tr>
<tr>
<td>$^{136}$Xe + $^{170}$Er</td>
<td>$^{306}$Hg$^{184}$</td>
<td>$1.5 \times 10^{-33}$</td>
<td>$2 \times 10^{-6}$ s - 1C h</td>
<td>29</td>
</tr>
<tr>
<td>$^{238}$U + $^{76}$Ge</td>
<td>$^{314}$Hg$^{190}$</td>
<td>$1 \times 10^{-34}$</td>
<td>$5 \times 10^{-3}$ s - 1 yr</td>
<td>30</td>
</tr>
<tr>
<td>$^{243}$Am + $^{68}$Zn</td>
<td>$^{311}$Hg$^{186}$</td>
<td>$5 \times 10^{-32}$</td>
<td>$10^{-9}$ s - 5 d</td>
<td>31</td>
</tr>
<tr>
<td>$^{232}$Th + $^{84}$Kr</td>
<td>$^{316}$Hg$^{190}$</td>
<td>$5 \times 10^{-30}$</td>
<td>$\geq 6 \times 10^{-7}$ s</td>
<td>24</td>
</tr>
<tr>
<td>$^{238}$U + $^{84}$Kr</td>
<td>$^{322}$Hg$^{194}$</td>
<td>$8 \times 10^{-29}$</td>
<td>$\geq 6 \times 10^{-7}$ s</td>
<td>26</td>
</tr>
</tbody>
</table>

All the experiments with the $^{48}$Ca-on-$^{248}$Cm reaction reported so far remained negative. The results are summarized in Fig. 5 giving the upper limits for production cross sections plotted against the assumed half life of the superheavy nuclei. A variety of techniques has been applied in these experiments. The Dubna group (D in Fig. 5) used two different chemical separation procedures and inspected the samples by spontaneous fission (SF) and $\alpha$-particle counting (a$\alpha$). The Berkeley-Livermore collaboration applied two different chemical procedures (chem) and performed an experiment to detect extremely volatile elements during and after bombardment. Attempts were also made to detect short lived species by counting catcher foils in which the reaction products recoiling out of the target were collected (foils). Further, the recoil atoms were stopped in a gas and transported with a gas jet to a rotating-wheel counting system (VM). Finally, spontaneous fission decay in flight was searched for (dif). As Fig. 5 demonstrates, radiochemical techniques are most sensitive among the methods applied so far but are limited to half lives exceeding several seconds. There is a strong demand for techniques giving access to shorter half lives with sensitivities comparable to those of the radiochemical approaches.

Why have these experiments failed? Either the fusion cross section must be extremely low or a dramatic loss by fission competition must occur during the neutron
Fig. 3  Landing places achieved in the complete fusion of $^{48}$Ca with $^{248}$Cm (dots) and in damped collisions between two $^{235}$U nuclei (squares) in the contour maps of Figs. 1a,b.

Fig. 4  Neutron evaporation and radioactive decay chain after complete fusion of $^{48}$Ca with $^{248}$Cm using the half lives of ref. 10. At the top excitation energies and two sets of fission barriers$^{10,12}$ for the intermediate nuclei formed in the neutron evaporation process are given.

Evaporation chain. It is well known that very fissile isotopes of the elements 105 to 107 can be produced by (HI,2n) reactions\textsuperscript{34} or even by (HI,n) reactions\textsuperscript{34}. The (HI,2n) reaction cross sections show an empirical systematics if plotted versus the Coulomb energy between projectile and target nucleus\textsuperscript{34}. The Coulomb energy between $^{48}$Ca and $^{248}$Cm is lower than that for similar systems successfully applied for the synthesis of isotopes of the elements 105 to 107; from the empirical systematics one reads a cross section of $10^{-3}$ barn for the ($^{48}$Ca,2n) reaction on $^{248}$Cm. However, the experiments were carried out at higher energies corresponding to a ($^{48}$Ca,4n) channel. In this case, a fission catastrophe could occur during the neutron evaporation chain as is indicated at the top of Fig. 4: One ends in the evaporation chain with an excitation energy of 8 MeV being too low for evaporation of an additional neutron but exceeding the fission barrier of 2.9 MeV calculated with the parameters leading to the steep west shore in Fig. 1b. The super-heavy nuclei will completely vanish by fission.

The higher bombarding energies were chosen since theoretical treatments of heavy-ion fusion reactions predicted that an extra push of kinetic energy above the barrier is required to fuse very heavy nuclei. For the system $^{48}$Ca + $^{248}$Cm, it was estimated that the bombarding energy was still too low by 10 to 30 MeV to provide for this extra push\textsuperscript{34}. Here we touch one of the conceptual problems\textsuperscript{34} associated with the question how to make superheavy elements. The problem of an extra push of kinetic energy has recently been studied\textsuperscript{40} with a two-dimensional model allowing for dynamical deformations of projectile and target nuclei in the entrance channel. Recent experimental data\textsuperscript{41,42} indicate that an extra push is indeed required when the entrance channel model parameter exceeds $(Z/A)_{\text{eff}} = 33$. For the $^{48}$Ca + $^{248}$Cm system one obtains a value of 33.9 for this parameter corresponding to an extra push of a few MeV. On the other hand, it has been observed\textsuperscript{43} that fusion can occur with sizeable cross sections at projectile energies below the classical interaction barrier. This means that fusion through barrier penetration can occur with compound nucleus excitation energies considerably lower than those
obtained at or above the barrier. Of course, this can only occur at the cost of up to several orders of magnitude in the total fusion cross section. The problem of optimisation then, is to find a bombarding energy where the loss in the fusion cross section is overcompensated by the largely increased survivability of the compound nucleus resulting from an evaporation chain considerably shorter than the one indicated in Fig. 3.

3.2 Damped collisions

An alternative pathway to the superheavy elements was opened by the first studies\(^{44,45}\) of the interaction of two colliding uranium nuclei at the Unilac accelerator. These studies demonstrated that the superheavy island can be reached by nucleon transfer during the short contact time of the composite system. If the doubly magic nucleus \(^{256}\text{U}\)\(^{184}\) would be formed in a binary reaction the complementary fragment would be an ytterbium isotope:

\[
238\text{U} + 238\text{U} + \rightarrow 258\text{U} + 114 + 174\text{Yb} + \text{X}.
\]

Fig. 6 shows the element distribution in the reaction between two \(^{238}\text{U}\) nuclei as obtained in radiochemical studies\(^{45}\). The element yields peak at uranium in a narrow distribution due to quasi-elastic transfer of a few nucleons. The underlying, broader distribution results from nucleon transfer in damped collisions. Reaction products from quasi-elastic and damped collisions undergo fission as is evident from the broad fission-product distribution between atomic numbers 30 and 70 and the steep decrease of the cross sections for elements beyond uranium which could be followed\(^{45}\) over eight orders of magnitude up to fermium (Z=100). Before fission the element distribution in the damped collision should be symmetric around uranium. This primary distribution can easily be reconstructed\(^{45}\). The resulting distribution is reproduced by calculations in which the nucleon transfer in damped collisions is treated as a diffusion process\(^{46}\), as can be seen in Fig. 6. Extrapolation to the light complementary fragment with Z\(_2\)=70 leads to a cross section of about 1 \(\times\) 10\(^{-26}\) cm\(^2\) at 8.3 MeV/u bombarding energy in cross sections of about 10\(^{-34}\) cm\(^2\) for element 114 nuclei with less than 30 MeV excitation energy\(^{46}\), an energy range for which the survival probability against fission should be larger than 50\% for the first neutron-evaporation step provided the neutron number is close to 184. Neutron numbers close to this magic number are estimated for element 114 fragments originating from uranium-on-uranium collisions if one applies the rules observed\(^{45}\) for the distribution of neutrons and protons between fragment pairs in very heavy systems. This leads to a much closer access to the centre of the island than in fusion reactions, as is demonstrated by Fig. 3. Taking all estimates together, one may expect a cross section of about 10\(^{-25}\) cm\(^2\) for element 114. This corresponds, with the accessible beam intensities, to production rates of a few atoms per week, a rate just exceeding the detection limit of the most sensitive methods available at present.

The results of direct searches for superheavy elements in the uranium-on-uranium reaction are depicted in Fig. 7. As in Fig. 5, upper limits for the production cross sections are plotted versus the assumed half life. In the experiments of a Darmstadt-Mainz collaboration, two different chemical separation procedures were applied (chem), and recoil atoms were transported with a wheel system during bombardment to plastic foil fission track detectors (wheel). In the latter experiments a background due to known spontaneously fissioning actinide nuclei was observed which sets the limits for the detection sensitivity. A Marburg-Gießen collaboration\(^{49}\) and a München group\(^{47}\) applied a gas jet for rapid transport of the recoil atoms to the detector system (jet). In the experiments of a Darmstadt-Heidelberg collaboration\(^{44}\) the recoil atoms were implanted into a surface barrier detector (Sec) for detection. All these experiments remained negative. As in the case of the \(^{44}\text{Ca} + \text{Cm}\) reaction, one notes a lack of sensitive measurements for short lived nuclei which would require, as the wheel experiments show, a separation from actinide nuclei also produced in the damped collision process.
Fig. 7 Upper limits for the production cross section of superheavy elements in collisions of two uranium nuclei plotted versus half life. Data from refs. 27, 44, 48, 49; see text.

These searches have recently been extended into two directions: According to theoretical estimates with the diffusion model, the cross section should increase by two orders of magnitude if $^{238}$U instead of $^{235}$U is bombarded with $^{238}$U ions. Experiments with the $^{238}$U + $^{248}$Cm reaction were begun by a Berkeley-Darmstadt-Livermore-Mainz-Oak Ridge collaboration. Preliminary data of these experiments which again showed no evidence for superheavy elements are displayed in Fig. 8. Three different chemical procedures were used: collection of gases volatile at room temperature (noble gases), evaporation of volatile species at higher temperatures (gas phase chemistry), and aqueous solution chemistry. The experiments were hampered by the limited stability of the curium metal targets in the uranium beam. Therefore, the sensitivity that could be reached with present time beam intensities has not yet been achieved. Further experiments will be carried out soon.

In the other series of experiments a theoretical suggestion was followed that when fissile nuclei are chosen as target or projectile they may undergo fission during close contact with a reaction partner, and one of the fission fragments may fuse with the projectile to form a superheavy nucleus. This suggestion has been shown by a Münchener group to produce negative results in the reaction of $^{208}$Pb with $^{138}$Xe where an upper cross-section limit of $1.2 \times 10^{-12}$ cm$^2$ was obtained for half lives between $10^{-12}$ and $10^4$ s, and in the reaction of $^{208}$Pb with $^{238}$U carried out by a Marburg-Gießen-Darmstadt collaboration using a rotating wheel system (wheel), the gas jet method (gas jet), and chemical procedures (chemistry) with results shown in Fig. 9.

Fig. 8 Upper limits for the production cross section of superheavy elements in the $^{238}$U + $^{248}$Cm reaction plotted versus half life.

Fig. 9 Upper limits for the production cross section of superheavy elements in the $^{208}$Pb + $^{238}$U reaction plotted versus half life.
One may argue that these experiments have failed because in damped collisions of $^{238}$U with $^{244}$Cm at dissipated energies of 150 MeV it was suggested that the heaviest fragments might be formed with elongations outside their fission saddle point\(^5\). However, as is discussed in more detail in a separate contribution to this conference\(^7\) the production cross sections for actinides up to $Z=101$ in the $^{238}$U + $^{244}$Cm and $^{234}$U + $^{244}$Cm reactions are consistent with the decay by multiple chance fission of fully equilibrated fragments with minimum excitation energies of 30 to 40 MeV corresponding to the evaporation of 3 to 4 neutrons from the primary fragments. This excitation energy is in agreement with an estimate from a one-body dissipation plus particle-hole model\(^8\). The same model predicts minimum excitation energies of 25 MeV for $Z=114$ in the $^{244}$Cm reaction if fragment deformations are absent\(^9\). This should lead to somewhat shorter neutron evaporation chains than indicated in Fig. 3 with final nuclei having half lives long enough for detection even if the pessimistic picture of Fig. 3b holds.

4. Outlook

Faced with so many unsuccessful attempts to make superheavy elements in the laboratory one may feel pessimistic about the possibilities to reach the island or may doubt whether it exists at all. This seems to be premature, however: We have not yet fully explored the potential of heavy-ion reactions; complete fusion at or below the barrier or damped collisions between heavy target nuclei and projectiles distinctly lighter than the very heavy ones applied so far may be considered promising alternative approaches. There is a need for sensitive techniques covering the region of short half lives, and there may be alternative chemical procedures in experiments aimed at reaching the utmost detection sensitivity. Whatever the final outcome, we will learn more about the forces that terminate the periodic table at its upper end.

References

8) Flerov, G. N., these Proceedings.


DISCUSSION

G. Goldhaber: What are the chances that any spectroscopic information on any of the new heavy isotopes may be obtained in the foreseeable future?

G. Herrmann: What one can measure are the alpha energies and fission half life. Even the question of fine structure in the alpha decays is very difficult to investigate at the level of a few atoms per week production rate. I think that one should be quite pessimistic. The limit at the moment is not the beam intensity but is the target problem. We can produce more beam than we can apply to the target. The UNILAC is a very efficient way to bore holes into everything.

D. Hofmann: If we could measure the properties of the spontaneous fission that is taking place, that would certainly be most interesting and most useful.

G. Schult: When you discussed calcium 48 on curium 248 right at the reaction, you are with the energy way above the fission barrier. Now I wonder how well one knows how fast fission occurs on competition with neutron emission. The question is do you get the 4n channel at all?

G. Herrmann: That is the main problem. It has not been observed and according to the cross-section systematics, it should have been found. One answer is that fission barriers are much lower than expected. Unfortunately, the barriers go twice into the whole business, in the reaction and in the half life. The results and the chances to make the superheavies are very sensitive to the fission barrier heights.

P. Armbuster: May I comment on this once more. These results on the heavy elements 100 to 107 gave us some optimism that you can produce these heavy elements in the super heavy region by reactions where you have a small excitation energy. So these 4n de-excitation channels what we always thought we would have in the last five or six years, then I think the chances are much smaller to survive. But now having these chances that there may be the 1n and 2n channels gives us our optimism we have gained in the last year.

J. Jarzabek: You would like to observe a 4n reaction from a compound nucleus. Do you have some experimental evidence that the compound nucleus itself was formed in the reaction you were studying?

G. Herrmann: The heaviest systems in which this has been demonstrated were presented by Gottfried Münzenberg and by the Ar on Pb in the Dubna data. The evaporation residue would be a superheavy element. If we would find it, it would be OK.

D. Hofmann: Some years ago we talked more about making odd Z superheavy elements and now most of the discussions centre on even Z. Do you have a comment on that?

G. Herrmann: I think this has to do with the target and projectiles that are available. 48Ca is an extremely neutron-rich nucleus. 248Cm is the heaviest not too radioactive nucleus you can get in milligram amounts. For the deep inelastic reactions, this does not play a role because you produce a broad distribution in atomic number. So this argument may still hold for the deep inelastic that chances are better for an odd Z element.

D. Hofmann: And the possibility of using an odd Z target such as einsteinium has also been proposed. Again there are grave target problems.

G. Herrmann: The problem is then of course that what one earns in cross-sections one may lose in the target thickness and the number of atoms in the target.
FUSION CROSS-SECTIONS AND THE NEW DYNAMICS
W.J. Swiatecki
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA.

Abstract
The prediction of the need for an extra push over the interaction barrier in order to make the heavier nuclei fuse is based on a simple algebraic theory of the energy-dependence of the fusion cross-section. A comparison with recent experiments promises to provide a quantitative test of the "New Dynamics" (the theory of macroscopic nuclear shape evolutions based on the one-body dissipation concept).

1. Introduction
For relatively light nuclear systems one would expect the interaction-barrier configuration of two tangent nuclei to be driven automatically toward fusion by the cohesive nuclear forces. For sufficiently heavy systems, or for systems with sufficient angular momentum, however, the centrifugal force would be expected to prevent automatic fusion. An extra bombarding energy over the interaction barrier—a "push"—would then be required to overcome the relevant saddle point in configuration space and achieve fusion.

2. Nuclear Fusion according to the New Dynamics
These qualitative expectations were analyzed\(^1\,^2\,^4\) using a schematic model based on the "New Dynamics" obtained by combining the electrostatic and surface tension forces with the "one-body" nuclear dissipation (a type of viscosity appropriate, under certain assumptions, for an assembly of particles whose mean free paths are long, rather than short, compared to the size of the system\(^1\,^2\,^3\)). In the schematic model the nuclear shapes were parameterized as two spheres connected by a portion of a cone.

A result of those studies, which follows largely on dimensional grounds (given the structure of the New Dynamics together with an approximation exploiting the relative smallness of the neck between the two nuclei), is that the kinetic energy in the radial (or approach) degree of freedom, i.e., the radial injection energy \(E_r\), over the interaction barrier, necessary to overcome the saddle point for fusion, should have the following approximate appearance:

\[
E_r = \begin{cases} 
0, & \text{for } (Z^2/A)_{	ext{eff}} + (L/L_{ch})^2 \ll (Z^2/A)_{	ext{thr}} \\
K \left[(Z^2/A)_{	ext{eff}} + (L/L_{ch})^2 - (Z^2/A)_{	ext{thr}}\right]^2 + \\
\text{higher powers of the square bracket,} & \text{for } (Z^2/A)_{	ext{eff}} + (L/L_{ch})^2 > (Z^2/A)_{	ext{thr}}. 
\end{cases}
\]

In the above, \((Z^2/A)_{	ext{eff}}\) is the effective fissionability of the colliding nuclear system, defined by

\[
(Z^2/A)_{	ext{eff}} = 4Z_1^2 Z_2^2 A_1^{1/3} A_2^{1/3} (A_1^{1/3} + A_2^{1/3})
\]

and \((Z^2/A)_{	ext{thr}}\) is a pure number, specifying the threshold value of the effective fissionability, beyond which an extra push is needed. The quantity \((L/L_{ch})\) is the angular momentum of the system, \(L\), in units of a characteristic angular momentum, given by

\[
L_{ch} = \frac{e \sqrt{\mu}}{2 f} \frac{A_1^{2/3} A_2^{2/3} (A_1^{1/3} + A_2^{1/3})}{\sqrt{A_1 + A_2}}.
\]

In the above equations, \(Z_1, Z_2, A_1, A_2\) are the atomic and mass numbers of the two colliding nuclei, \(n\) is the nuclear mass unit (taken as 931 MeV/c\(^2\)), \(r_0\) is the nuclear radius constant (taken as 1.229 fm), \(e\) is the proton charge, and \(f\) is the effective "angular momentum fraction", i.e., the fraction of the total angular momentum which is responsible for the centrifugal force in the separation degree of freedom\(^2\,^4\,^5\). This force, as represented by the term \((L/L_{ch})^2\), along with the electric repulsion, proportional to \((Z^2/A)_{	ext{eff}}\), opposes capture inside the fusion saddle point and calls for an increased injection energy according to eq. (1). (For approaching nuclei \(f = 1\); for two spheres rolling on each other without sliding \(f = 5/7\). The use of a fixed effective value of \(f\) represents a rough attempt to handle the actually intricate problems associated with the presence of angular momentum.)

The constant \(K\), which specifies how rapidly the extra push increases with excess over the threshold condition, follows from the model in 1) as

\[
K = \frac{A_1^{1/3} A_2^{1/3} (A_1^{1/3} + A_2^{1/3})^2}{32 \sqrt{\pi} \frac{e^2}{\hbar c} a^2}
\]

where \(a\) is a pure number (equal to about 5 in the schematic model of 1)). We will refer to \(K\) as the "thud wall stiffness coefficient". The reason for the name is that, because of the large absolute magnitude of the one-body dissipation, most of the extra push is dissipated soon after contact in a "thud" and a "clutch". Hence the fusion of systems with effective fissionabilities exceeding appreciably the threshold value is opposed by a large "thud wall"—see Fig. 13 in 1. The pure number \(a\), independent of \(A_1, A_2\), will be called the "Thud wall slope coefficient".

Even without describing the workings of the schematic model used to derive the above expressions, I hope that the general idea is clear: when the electric and centrifugal forces exceed a certain threshold value, an extra push is obviously necessary for fusion. This simple physical idea was incorporated in a schematic model based on the New Dynamics, and the structure of the extra push expression, derived to lowest order in the excess over the threshold condition, came out as eq. (1). Since the one-body dissipation theory has no
adjustable parameters (there is no adjustable
to the pure numbers $Z^2/A_{eff}$
and $a_0$ do depend on the approximations of the
schematic model, in particular on the parametriza-
tion of the nuclear shapes by spheres connected by
a conical neck. Also, the factor $f$ is an effective
angular momentum fraction, expected to be somewhat
less than unity, but not known precisely. So, in
addition to taking these numbers from some
schematic model, one may also want to treat them
as adjustable parameters when comparing the
general structure of the theory with experiment.

3. The Extra Push Theorem

In a collision between two spheres the
cross-section for just barely making contact (the
reaction cross-section) is given by the standard
formula

$$
\sigma = \frac{2}{\pi} c^2 \left( 1 - \frac{E_B}{E} \right),
$$

which can also be written as

$$
\frac{dE}{\pi r_c^2} = E - E_B,
$$

where $E_B$ is the potential energy at contact (the
"interaction barrier"), and $r_c$ is the center
separation at contact. (For sharp spheres it is
just the sum of the radii.)

Equations (5,6) follow simply from
conservation of energy (and angular momentum). Thus the right-hand side of eq. (6) is the energy
excess over the interaction barrier, equal, by
conservation of energy, to the tangential (orbital,
or rotational) energy at contact (the left-hand
side). To verify this, write

$$
L^2 = [(\text{mass})(\text{velocity})(\text{moment arm})]^2 = \left[ m \sqrt{2E/M_b} \right]^2
= 2ME_b^2 + 2ME_0/h,
$$

where $M$ is the reduced mass and $b$ the impact
parameter, so that $dE/\pi r_c^2$ equals $L^2/2Mr_c^2$,
the rotational energy at contact.

Now when one asks for making contact not
"just barely", but with a finite radial energy $E_r$--just sufficient to ensure fusion--the
energy-conservation equation (6) is replaced by

$$
\frac{dE}{\pi r_c^2} + E_r = E - E_B.
$$

Using for $E_r$ eq. (1) (together with eq. (7) to
eliminate $L^2$) one readily verifies that eq. (8)
may be rewritten as

$$
\frac{dE}{\pi r_c^2} + \left( c_1 + c_2 \frac{dE}{\pi r_c^2} \right) = E - E_B,
$$

where

$$
c_1 = \sqrt{K} \left[ \left( \frac{Z^2}{A_{eff}} \right)_{\text{thr}} - \left( \frac{Z^2}{A_{eff}} \right)_{\text{eff}} \right],
$$

$$
c_2 = \frac{\sqrt{K}}{\frac{r_0}{A_{1/3}}} \frac{8r_0^2}{a_1 a_2^{1/3}}.
$$

Denoting by $\Gamma$ the energy-weighted reduced
cross-section, i.e., the cross-section in units of
$\pi r_c^2$, multiplied by the energy $E$, and calling
the deviation of $\Gamma E/\pi r_c^2$ from the standard result,
$E - E_b$, the "cross-section defect" $A$, where

$$
A = E - E_B - \frac{\sigma E}{\pi r_c^2},
$$

we may state the content of the (energy-
conservation) equation (9) in the form of the
following compact Extra Push Theorem:

"When an extra radial injection energy is
needed for fusion, the square root of the
cross-section defect should be approximately
linear when plotted against the energy-weighted
reduced cross-section, viz.:

$$
\sqrt{\Gamma} = c_1 + c_2 \Gamma + \ldots
$$

Thus, by plotting the square root of the
experimental values of $E - E_b = \sigma E/\pi r_c^2$ versus
$E_0/\pi r_c^2$, one should find, approximately, a
straight line, with intercept $c_1$ and slope $c_2$.
Plotting the ratios $c_1/c_2$, multiplied by
$8r_0^2/A_{1/3} A_{1/3}$, for a series of systems versus
the systems' effective fistilities ($Z^2/A_{eff}$) should
give, according to eqs. (10,11), a straight line
with slope $1/\Gamma^2$ and intercept $L^2/A_{1/3} \Gamma_{thr}^2$.
Hence

follow the three parameters of the theory: the
thud wall slope coefficient $c_1$, the threshold value
of the effective fistility ($Z^2/A_{eff}$), and the
angular momentum fraction $f$.

4. Comparison with Experiment

The above analysis was applied to the recent
measurements in $^{41}$, where a beam of $^{208}Pb$ was
made to interact with seven targets: $^{26}Mg$, $^{27}Al$,
$^{48}Ca$, $^{50}Ti$, $^{52}Cr$, $^{56}Fe$, and $^{60}Ni$. (Fusion in
this context means reactions resulting in final
fragments with a mass distribution centered around
symmetry.)

Figure 1 shows a comparison of the measured
fusion cross-sections with theory. The solid
curves refer to the standard formula (5) and the
dashed curves to the extra push prediction,
obtained by solving the quadratic eq. (9) for $\sigma$:

$$
\sigma = \frac{2}{\pi} \sqrt{\left( c_1 c_2 + 1/2 \right)^2 - \left( \frac{c_2}{c_2} E - E_B \right)^2 - \left( \frac{c_1 c_2 + 1/2}{c_2} \right)^2}.
$$

In constructing the dashed curves in Fig. 1
we took $r_c$ to be the sum of the central radii of
the two nuclei, augmented by 1.14 fm to take
account of the diffusion of the nuclear
surfaces (this choice reproduces the
initial slopes of the reaction cross-sections for
$^{26}Mg$ and $^{27}Al$ in Fig. 1). Thus:

$$
\sigma = \frac{2}{\pi} \sqrt{\left( c_1 c_2 + 1/2 \right)^2 - \left( \frac{c_2}{c_2} E - E_B \right)^2 - \left( \frac{c_1 c_2 + 1/2}{c_2} \right)^2}.
$$
Fig. 1. Comparison of experimental fusion cross-sections (associated with outgoing fragment masses centered around symmetry) with theory. The solid curves are conventional reaction cross-section predictions, and the dashed curves incorporate the requirement of an extra push in the approach degree of freedom. (I deduced the data points from Ref. (4) and added purely nominal 10% error bars.)

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\[ r_c = C_1 + C_2 + 1.14 \text{ fm}, \]
\[ C = R - 1 \text{ fm}^2/R, \]
\[ R = 1.28 \text{ A}^{1/3} - 0.76 + 0.8 \text{ A}^{1/3} \text{ fm}. \]

For the interaction barrier \( E_B \) we used the barrier following from the proximity interaction in \( \text{eq} \), reduced by \( 4\% \).

The three parameters of the theory were found to have the following approximate values:

\[ \frac{Z^2}{A} \sim 33 \pm 1, \tag{15a} \]
\[ a \approx 12 \pm 2, \tag{15b} \]
\[ f \approx (3/4) \pm 10\%. \tag{15c} \]

The deviation of the \( 33 \pm 1 \) in eq. (15a) from the value 26-27 suggested by the schematic model in \( \text{eq} \) correlates quantitatively with the deviations of the schematic model's saddle-point shapes from the accurately known macroscopic shapes \( \text{eq} \). The same is true qualitatively of the deviation of \( a \approx 12 \pm 2 \) in eq. (15b) from \( a \approx 5 \), suggested in \( \text{eq} \). The value of \( f \) suggested by eq. (15c) is intermediate between the value appropriate to approaching spheres and to spheres rolling on each other without sliding. (The cluturing stage is being investigated within the framework of the one-body dissipation theory by G. Fai, private communication.)

### 5. Conclusions

The degree of correspondence between theory and experiment in Fig. 1 leaves a lot to be desired, and the significance of the correspondence is by no means clear. More work will have to be done on filling in, extending and rechecking the measurements, and on making more nearly quantitative calculations along the lines of \( \text{eq} \). But it seems that, by measuring the fusion cross-sections, one has available another method of testing quantitatively the predictions of the one-body dissipation theory. When combined with other tests (in particular on evaporation-residue cross-sections, where the theory predicts the need of an “extra-extra-push” \( \text{eq} \)) and by extending existing tests in the context of deep-inelastic collisions and fission, a confrontation of theory and experiment may be achieved which will be sufficiently broad to delineate quantitatively the degree of validity of the New Dynamics.

### Acknowledgments

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### References


Post-deadline paper
GROSS PROPERTIES OF NUCLEAR DENSITY DISTRIBUTIONS

E.R. Hilf and R. Wolff
Institut für Kernphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, Germany

Abstract

The gross properties of nuclear density distributions are studied in terms of the Ford and Wills moments, their first and second differences which are related to the radii, diffusenesses and surface-fall off asymmetries ("flairs"). The latter property seems to be relevant only for some close-to-magic nuclei and for extremely n-rich nuclei.

1. Introduction

The equilibrium properties of nuclei, such as the mass, neutron- and proton-density distributions have been studied in the past by the Hartree Fock energy density method [1-3].

In order to exhibit the gross trends of the $N$,Z-dependence of the equilibrium properties it has been useful in the past to set up macroscopic models in which the nuclear binding energy is described as a balance of driving and restoring forces such as nuclear matter saturation, neutron excess, Coulomb-energy and nuclear surface properties. These quantities are expressed then in terms of properties of the neutron- and proton density distributions, such as the radius, the diffuseness and may be the deviation from a symmetric (with regard to the half-density radius) density fall off, sometimes named 4) "flair". In the Droplet-model of Myers and Swiatecki only the radii are varied to find the equilibrium.

In order to set up a respective model including eventually the variation of the diffusenesses and "flairs", we give here some definitions of density-moments, comment on shell-effects, and study the dependence of the nuclear mass on these next higher order density quantities.

2. Geometrical properties of the nuclear surface

Each of the density distributions for neutrons and protons may be described by a series of quantities, here called the surface moments, which are to be defined independent of assumptions on the type of function (elsewhere called "model-independent"). They should be chosen so that they carry the bulk of dependence of the masses on the density distribution.

In this section we give the definitions for one of the nucleon-distributions and drop the index n or p.

The experimental information on density distributions is usually presented in terms of their density-moments6).

$$<r^k> := \int dr \cdot r^k \rho(r).$$

(2)

The surface-moments are now defined by

$$S_k := \frac{(3k)!}{2} R_k.$$

(3)

For convenience we introduce the relative surface-moments

$$s_0 = S_0, \quad s_1 := \frac{6}{\pi^2} \frac{s_1}{S_0}, \quad s_2 := -\frac{1}{2} \frac{s_2}{S_0}.$$

(4)

In order to ease the comparison to experimental data on density-distributions, given by the $R_k$ for various $k$, one may approximate the differentials (3) by differences, we use

$$S_1(k) = S_0(k+1)-S_0(k); \quad S_2(k) := S_1(k)-S_1(k-1).$$

(5)

3. Application to analytic density-functions

To exhibit what informations the surface-moments give on a density-distribution let us calculate then for the model-function

$$\rho(r) = \rho_0 \left(F(r) + aF'(r)\right)$$

(6)

where

$$F(r) = (1+exp((r-c)/a))^{-1}.$$  Then with

$$\left(\frac{a}{c}\right)^3 << 1, \quad \left(\frac{a^2}{c^2}\right)^2 << 1, \quad \left(\frac{a^4}{c^4}\right)^2 << 1,$$

(7)

and with the linear moments for the Fermi-distribution

$$<r^k> = 4\pi \rho_0 \cdot \frac{k+1}{k+1} \frac{\pi^2}{6} \left(\frac{a}{c}\right)^2 \cdot (k+1) + O\left(\frac{a^3}{c^3}\right)^4 \right)$$

(8)

after integration by parts and expansion we get for the distribution (6) the surface-moments in the approximation (7),

$$S_0 = C \cdot \left(1 - \frac{3}{2} \cdot \left(k+3\right) \cdot \left(\frac{a}{c}\right)^2 \right),$$

(9a)

$$S_1 = C \cdot \left(-1 + \frac{3}{2} \cdot \left(\frac{a}{c}\right)^2 \cdot \left(1 - \frac{3}{2} \cdot (k+2) \cdot (2k+3)\right)\right),$$

(9b)

$$S_2 = C \cdot \left(-\frac{\pi^2}{3} + \frac{\pi^2}{3} \cdot \left(\frac{a}{c}\right)^2 \cdot \left(\frac{a}{c}\right)^2 \right).$$

(9c)

For nuclear density-distributions $a/c \sim 10^{-2}$, while $(a/c)^4 \sim 10^{11}$, thus to first order the relative surface-moments

$$s_0 = C, \quad s_1 = \left(\frac{a}{c}\right)^2, \quad s_2 = \frac{a}{c}$$

(10)

measure the size, the diffuseness and the flair of the surface respectively and thus represent the model-independent generalization of the quantities $c$, $(a/c)^2$, $a/c$.

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Since for the distribution (6) the central density $\rho_0$ is assumed to be known, one can calculate the surface shape moments defined by S"u\ssmann$^4$.

\[ \gamma_3 = \gamma_1 / \Gamma_3^{3/2}, \quad \Gamma_3 = \int dr (r-R)^3 \rho'(r)/\rho_0 \]  

where $R$ is defined, so that $\Gamma_1 = 0$.

Although this definition is normalized in that $\Gamma_0 = 1$ and the $\gamma_i$ being dimensionless, the disadvantage is that the "central density" $\rho_0$ has to be known. Thus they cannot be evaluated from experimental scattering data, as has been pointed out by Barrett.$^7$

With regard to our model-independent surface-moments we can, however, give an expression, which for functions with known $\rho_0$ coincides to first order with S"u\ssmann's flair,

\[ \gamma_3 = -3\sqrt{2} \frac{s_2}{s_1 s_0} \]  

4. Methods of calculation

The ground state properties of nucleis are normally calculated in minimizing the total energy by varying the density distributions of neutrons and protons. The equilibrium then serves the nuclear mass and nucleon-densities. Comparing to experimental masses one may then repeat the minimization for all known nuclei by adjusting some force-parameters or related quantities to get an optimal prediction power.

The simplest strategies of this kind are

1. The Droplet-model of Myers and Swiatecki$^5$. Here just the radii of the neutron- and proton density-distributions are varied whereas the diffusenesses are kept fixed. 11 "force"-parameters are used. The overall trend of the nuclear radii are beautifully reproduced. However, despite the many more force-parameters compared to the Bethe$^8$-Weizs"acker$^9$ liquid-drop formula with no variation of the radius, the fit to masses is not much improved. This confirms that the unexplained mass-differences are to a large extent not smooth functions of $N$ and $Z$ but reflect the extra binding of near magic $N$ or $Z$ nuclei. The relative successes of the macroscopic mass-formulae$^{10-12}$ thus is due to their addition of shell-correction terms.

2. With regard to the droplet-model the next step would be to allow for the variation of the diffusenesses and the flairs. It is here that we may expect the importance of the inclusion and the study of possible shell-effects of surface-moments,

\[ S_1 = \frac{S_1}{S_1} (1 + \sigma_i) \]  

where $S_1$ is assumed to be the result of a pure "droplet-model and $\sigma_i$ a possible shell-effect to be calculated microscopically.

More microscopically we performed Hartree-Fock type calculations, i.e. we minimized the nuclear energy with respect to the single-particle wave-functions and solved the resulting Euler-equations of Motion. Within the framework of Hartree-Fock calculations with Skyrme-forces Vautherin et al.$^11$ have shown, that the nuclear energy is given as an integral of a nuclear energy-density of the nuclear volume.

In our calculations we adopted the energy-density proposed by Tondeur$^3$. The functional is given in terms of the density, the kinetic-energy density and the spin-orbit density. All these quantities are defined in terms of single particle wave-functions.

Once the self-consistent density is known, the gross properties of the nuclear density distributions are obtained by evaluating their respective surface-moments (3). We will study, to what extent the moments are affected by the shell-structure the $\rho$-similarities of the single particle wave-functions at the Fermi-energy.

To study the gross properties of the $(N,Z)$-dependence and the stability of the surface moments without shell-effects we have to express the nuclear energy-density in terms of the density alone. One way to obtain this relation is given by the semi-classic approximation$^{13}$, which allows for a gradient expansion of certain quantum-mechanical density quantities$^{14}$ or the spin-orbit density Brack et al.$^14$ obtained to lowest order:

\[ \mathcal{L} = \hat{\mathcal{L}} - \frac{2m}{\hbar^2} \rho \hat{\rho} \quad \text{etc.} \]  

For the kinetic-energy density the lowest order term in the semi-classic approximation is the well known $\tau=\rho^{3/2}$ Fermi-gas relation. Since we are studying surface properties of nuclear density-distributions it is necessary to include some gradient term. To lowest order in the gradient, the semi-classic approximation yields

\[ \tau = \frac{3}{5} \frac{\hbar^2}{2m} (3\rho^2)^{2/3} \rho^{2/3} 5/3 + \frac{1}{36} \frac{\hbar^2}{2m} (-1)(\nabla \rho)^2. \]  

As a test we compared the total kinetic energies from (15) with and without the gradient term to the exact value of the kinetic energy. The result for particles bound by a Woods-Saxon potential-well are given in table 1. The gradient term clearly improves the Fermigas value.

However, it has still to be investigated to what extent the approximations (14) and (15) affect the resulting equilibrium density-distributions to deviate from the original Hartree-Fock results. To avoid possible unrealistic excursions in the course of the minimization we restricted the allowed density-functions to the set (6). Thus the gross properties of the surface-moments calculated with the method of this section may be affected by this restriction.
Table 1:

<table>
<thead>
<tr>
<th></th>
<th>56(\text{Ni})</th>
<th>208(\text{Pb})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Protons</td>
<td>Neutrons</td>
</tr>
<tr>
<td>(T_{\text{ex}})</td>
<td>480.05 MeV</td>
<td>504.46</td>
</tr>
<tr>
<td>(T_{5/3})</td>
<td>448.23</td>
<td>471.31</td>
</tr>
<tr>
<td>(T_{\text{S.C.}})</td>
<td>461.61</td>
<td>485.30</td>
</tr>
</tbody>
</table>

Total kinetic energy of nucleons in a spherical Woods-Saxon wall. \(T_{\text{ex}}\) gives the exact kinetic energy, \(T_{5/3}\) is the Fermi-gas value (semi-classical kinetic energy density without gradient terms) and \(T_{\text{S.C.}}\) the result of eq. (15).

5. Shell effects of the surface-moments

1. Size

To get an upper limit within the non-equilibrium Droplet-model\(^9\) for the shell effects \(\sigma_0\) of nuclei let us assume that the gain in binding due to shell effects \(\Delta W\) acts as a driving force to compress the nucleus against the restoring incompressibility of the nucleus; then the loss of binding due to the squeezing is

\[
M_k = \frac{1}{18} \int dV k \cdot \rho \cdot (\rho - \rho_0)^2 / \rho_0.
\]

(16)

For spherical nuclei and approximating \(\rho \approx 3\rho (4\pi R^3)\) and because of \(|R| < M_k\) and solving for the relative radius-change \(\sigma_0 = (R/R_0 - 1)\) we get

\[
\sigma_0 < 2 - \sqrt{|M|} / R_0.
\]

(17)

With \(K = 280\) and \(M\) of the order or less than 10 MeV this results to \(|\sigma_0| < 4\%\) for light nuclei \((A < 40)\) decreasing to \(|\sigma_0| < 2\%\) for the heavy nuclei.

Beiner et al.\(^2\) and Tondeur\(^3\) extracted nuclear radii from Hartree-Fock calculations. Inspecting their figures we read off \(\sigma_0\) to be of the order of 2\% for light nuclei, decreasing to \(-4\%\) for heavy nuclei.

For the lead isotopes we calculated microscopically the surface-moments both in the Hartree-Fock energy density formalism and the semiclassical approximation. The results for neutrons are given in table 2. Clearly the shell-effects of the neutron radii is of the order of or less than \(0.4\%\).

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>The neutron surface-moments (S_4(k=2)) of lead isotopes in Hartree-Fock, and the semiclassical approximation</td>
</tr>
<tr>
<td>Hartree-Fock</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>122</td>
</tr>
<tr>
<td>124</td>
</tr>
<tr>
<td>126</td>
</tr>
<tr>
<td>130</td>
</tr>
<tr>
<td>132</td>
</tr>
</tbody>
</table>

The restoring forces due to the incompressibility and symmetry energies cannot be inferred from Hartree-Fock because the absolute value of the nuclear energy does not enter the minimisation but may be inferred by calculating in the semiclassical approximation the total binding for slight deviations of the radii from their equilibrium values. In fig. 1 we have displayed one contour line encircling nicely the minimum and exhibiting both restoring forces.

Accurate experimental data have been given by Fricke et al.\(^5\) and analyzed by Friedrich et al.\(^6\) and Rychel\(^7\). These data were analyzed for shell effects, subtracting, the Droplet-model radii, by Salles de Aranjio\(^8\) and, taking out the deformation, by Myers\(^9\). Inspecting his figure 1 yields as an experimental estimate \(\sigma_0\) to be less than 1\% for light and even smaller for heavy nuclei. Thus the shell effects of radii are small percentage wise.

2. Diffuseness

For the neutrons of the lead isotopes we do not find more than a few percent for \(\sigma_1\) (see table 2).

The restoring forces in the semiclassical approximation have been studied. As an example we display in fig. 2 an energy contour line for distorting the proton-diffuseness and the neutron-radius from their equilibrium values. The restoring forces are strong and establish a nice stable minimum.

The analysis of the experimental data as given by Fricke\(^5\) seem to indicate that there are no appreciable shell-effects of the diffusenesses, even for light nuclei.

3. Flair

With regard to the flair surface-moment the existence of restoring forces is much less obvious and has not been studied so far. Using again the semiclassical approximation for density functions (6) with parameters close to the equilibrium ones, we realise that there is not a well defined deep minimum. As an example an energy-contour line is given in fig. 3 for the \(\sigma_{p,R}\)-correlations. Thus we expect the flair-Degree of freedom, in varying the total energy with respect to the density-distributions, to be the first soft mode. This may allow for more pronounced shell effects. The softness of the flair degree of freedom is also supported by the fact that the minimum value of the energy changes only by around 1 MeV whether one allows for free variation of the "flair"-parameter \(a\) during the minimization or whether one keeps \(a = 0\) fixed while searching for the minimum.

As a first example, the lead isotopes as calculated in Hartree-Fock, however, do not show a strong shell-effect but just a smooth trend with the flair being small. The reason may be that the closed shell which constitutes the magic number 126 is composed of \(3_f/2\) states with wave-functions which contribute equivalently or more to the surface-density-fall off than the \(2g/2\)
states which are filled next. It is left to study the extent to which the calculated relatively small surface moments are a pecu-
liarity of the adopted energy density. A finite range nucleon-nucleon force could have a considerable influece on the wave functions close to the fermi-surface and thus cause a change in the shape of the density distribution, possibly increasing the flair.

As a second example we calculated the flair for some lighter nuclei (see table 5) for single particle states of a spherical Woods-Saxon potential, the parameters of which were generated by the Droplet-model. This should be an underestimate, because the resulting density will create a flair for the potential as well. Clearly, shell effects can be read off from table 3 for the n-flair $\rho_n$ when crossing a neutron magic number, while the influence of the proton number on $\rho_p$ is small. Similar holds for the pro-
ton flairs. Thus we conclude that the shell-effects of the second surface-moments do depend critically on the difference in quantum numbers of the single-particle states bordering the gap in the s,p spectrum at the Fermi-surface of close to magic nuclei.

Table 3:

<table>
<thead>
<tr>
<th>N</th>
<th>76</th>
<th>78</th>
<th>80</th>
<th>82</th>
<th>84</th>
<th>86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flair $S_{2}$ (2) of protons (upper number) and neutrons (lower number) in $\hbar$ for a Woods-Saxon potential.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental data for the Ford-Wills moments (1) have been presented for many nuclei by Wohlfahrt et al (2). The surface moments calculated from his data are given in table 6 for $k = 2$.

Table 4:

<table>
<thead>
<tr>
<th>N</th>
<th>28</th>
<th>30</th>
<th>32</th>
<th>34</th>
<th>36</th>
<th>38</th>
<th>40</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flair $S_{2}$ (2) of proton distribution in $\hbar$; experimental results evaluated from H.D. Wohlfahrt et al (2). Experimental uncertainties as given there are of the order of 15 $\hbar$.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clearly both, an average trend and shell effects of the proton-flair do show up, being considerably strong. However, it should be noted that the - may be pessimistic - experimental uncertainties as quoted in (1) are of the same order. Thus this calls for further even more precise measurements especially for the higher moments.

6. Macroscopic model of nucleus

The inclusion of the surface-degrees of freedom in addition to the neutron-skin into a self-consistent macroscopic model can be set up in using the results of the last section. The total binding is set up as usual as a sum of a smoothly $N,Z$-depend-
ed Droplet-like part $\tilde{M}$ and shell-correction term $\Delta$.

$$M = \tilde{M} + \Delta.$$

But in contrast to the gross theories of the radius up to now, the dependence on the surface moments are

$$M = \tilde{M} \left( \frac{S_0}{n_0}, \frac{p_0}{n_1}, \frac{S_1}{n_2}, \frac{p_1}{n_2} \right) + \Delta \left( \frac{S_0}{n_0}, \frac{p_0}{n_1}, \frac{S_1}{n_2}, \frac{p_1}{n_2} \right).$$

We skipped the dependence on the shell-effects of radii and diffuseness, Be-
cause of the proton-particle being most independent of the neutron excess, we left it out.

The shell-effects of the flair are probably the first shell-dependent quantity which constitutes a coupling between $\tilde{M}$ and $\Delta$ in that the variation of $M$ with respect to the density degrees of freedom can in this order not be replaced by just minimizing $\tilde{M}$ and then calculating $\Delta$ using just the $\tilde{S}_2$. Although the effect on the mass by the flair may be small it does affect the re-
sulting densities.

7. Surface moments for very neutron-rich nuclei

As an example we calculated the surface moments for some lead isotopes, see table 5.

Table 5: Surface moments of lead isotopes

<table>
<thead>
<tr>
<th>N</th>
<th>n_0</th>
<th>n_1</th>
<th>n_2</th>
<th>p_0</th>
<th>p_1</th>
<th>p_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>132</td>
<td>7.43</td>
<td>0.079</td>
<td>-0.0025</td>
<td>7.14</td>
<td>0.054</td>
<td>-0.0021</td>
</tr>
<tr>
<td>140</td>
<td>7.55</td>
<td>0.074</td>
<td>-0.0007</td>
<td>7.20</td>
<td>0.053</td>
<td>-0.0021</td>
</tr>
<tr>
<td>180</td>
<td>8.21</td>
<td>0.115</td>
<td>-0.0952</td>
<td>7.52</td>
<td>0.047</td>
<td>-0.0021</td>
</tr>
</tbody>
</table>

The proton-distribution surface, which is inside the neutron-distribution is not affected at all by the increasing neutron-excess. The neutron-diffuseness for N=180 has a large value in accordance with the finding of Tondeur (22) that the n-diffuse-
ness should for large n-excess rise as (N-N_e)^2. The neutron flair for the most n-rich isotope seems to reflect the shell-
structure; the soft flair degree of freedom.
can probably be better exploited by the loosely bound neutrons at the Fermi-surface.

The inclusion of the neutron-diffuseness and flair degree of freedom might be important to understand the static properties of close to neutron-dripline nuclei.

Acknowledgements

We wish to thank K. Takahashi for helpful and critical discussions at any stage of the work. The computations have been performed at the GSI-computing center.

References
8. H.A.Bethe, R.F.Bacher, Rev. Mod. Phys. 8 (1937) 82
10. W.D.Myers, ADNDT 17 (1975) 411 and ref. therein
11. H.v.Groote et al. ADNDT 17 (1975) 418
15. G.Fricke, this volume
19. W.D.Myers, this volume
22. F.Tondeur, this volume

Fig. 1: Energy-contour line $E=E_{\text{min}}+0.7\text{ MeV}$ for non-equilibrium neutron and proton-radii. $E_{\text{min}}=1622.1\text{ MeV}$. Kinetic energy without gradient term.

Fig. 2: As Fig. 1 for variation of the neutron diffuseness and neutron radius.

Fig. 3: As Fig. 1 variations of proton-flair and neutron-radius.
Appendices
PROGRAMME OF ORAL PRESENTATIONS

Monday 8 June

Morning 9.00-13.00

NUCLEAR RADII, MOMENTS, SPINS

Chairman: G. Schatz

Welcome and opening remarks

E.W. Otten, Colinear-beam laser spectroscopy
C. Ekström, Single-particle structure derived from spins and moments of long isotopic chains
L. Vanneste, Nuclear orientation study of on-line separated In isotopes
G. Fricke, Systematics of radii and nuclear charge distributions deduced from elastic electron scattering, muonic X-ray and optical isotope-shift measurements
C.N. Davids, On-line laser spectroscopy at the Argonne Superconducting Linac
C. Thibault, Masses and radii of alkali nuclei

Afternoon 14.15-17.45

NUCLEAR RADII AND MASSES

Chairman: J. Rayford Nix

M. Brack, Nuclear bulk properties from effective interactions
E. Hilf, Gross properties of nuclei
F. Tondeur, Self-consistent study of nuclei far from stability with the energy-density method
E.R. Flynn, Spectroscopy and mass measurements of neutron-rich isotopes by the \((t,a)\) reaction
U. Keyser, Critical survey of beta-decay energies and nuclear masses for the neutron-rich Rb and Cs isotopes
J. Cerny, A study of the beta-decay energies of highly neutron-deficient indium isotopes
W.-D. Schmidt-Ott, Atomic masses of \(^{147}\)Gd, \(^{147}\)Eu, \(^{147}\)Gd, \(^{148}\)Tb (2.2 min), \(^{148}\)Pr and \(^{150}\)Pr

Evening

Concert at Frederiksborg Castle

Tuesday 9 June

Morning 9.00-13.00

NUCLEAR MASSES AND ALPHA DECAY

Chairman: W.D. Myers

E. Roeckl, Alpha and proton experiments in the tin region
C.R. Bingham, Alpha-decay rates of even-even lead isotopes
E. Hagberg, First observation of \(^{162}\)Hf decay: completion of an alpha-decay chain
D.J. Decman, Time-differential observation of alpha-particle perturbed angular distribution; g-factor measurements for $^{217}$Ac and $^{217}$Ac

S. Hofmann, Decay studies of new neutron-deficient isotopes in the range of elements between gadolinium and lead

N. Zeldes, Nuclear masses and nuclear structure

Evening 17.00-19.45

STRENGTH-FUNCTION PHENOMENA, DELAYED PROTONS AND FISSION

Chairman: G. Rudstam

J.C. Hardy, Complete measurements of beta strength functions

M. Arnould, Nuclear level densities with pairing and self-consistent shell effects

G.D. Alkhazov, The beta strength function in $\beta^+$ decay of Lu, Tm and Ce isotopes

K. Eskola, A new beta-delayed proton emitter $^{93m}$Ru

E. Nolte, Nuclear spectroscopy via ($\alpha$,T$_n$) reactions: The high-spin isomer in $^{95}$Pd

J. Krumlinde, Investigation of beta-delayed fission based on microscopic calculations of the beta strength function

Evening

Lecture by Professor Olaf Pedersen, History of Science Department, University of Aarhus

Wednesday 10 June

Morning 9.00-13.00

DELAYED PARTICLES, MAINLY NEUTRONS

Chairman: O.W.B. Schult

B. Jonson, Beta-delayed emission of two and three neutrons

P.L. Reeder, Beta-delayed two-neutron decay studies for $^{96-99}$Rb

C. Gaarde, Collective spin excitations

E.H.T. Clifford, Kinematic shifts of beta-delayed particles as a probe of $\beta$-$\gamma$ angular correlations

K.-L. Kratz, The beta-minus strength function of nuclei far from stability in the A = 90 mass region

B. Fogelberg, Neutron resonance study of a delayed neutron emitter, $^{87}$Kr

E.A. Henry, Investigation of the beta strength function at high energy: Gamma spectroscopy of the decay of 5.8-8 $^{84}$As to $^{84}$Se

Afternoon

Excursion to the island of Hven
Thursday 11 June

Morning 9.00-13.00

LIGHT NUCLEI, NUCLEOSYNTHESIS

Chairman: J. Żylicz

C. Détraz, The neutron-rich sodium isotopes

J.C. Hill, First observation of the decay of the neutron-rich nucleus $^{36}$p

M. Bernas, Study of light neutron-rich nuclei by nuclear reactions

A. Knipper, Study of light nuclei with neutron excess in s-d or f-p shells: Decay of $^{61-65}$Cl, $^{61-65}$K, $^{41,45}$Ca and $^{55}$Sc

H.A. Bethe, Theory of supernova collapse and explosion

F.-K. Thielemann, Thermonuclear reaction rates far from stability and their astrophysical implication

K. Takahashi, Exotic nuclear beta-transitions

Afternoon 14.15-17.45

NUCLEAR STRUCTURE I

Chairman: G.T. Ewan

V. Paar, Collective states and nuclear symmetries

B. Pfeiffer, The level schemes of Sr and Y isotopes in the mass chains $A = 95, 97$ and 99

S. Mattsson, The strongly deformed nucleus $^{109}$Sr

J. Stachel, The nuclear shape in the $A = 100$ region

J. Blomqvist, Doubly-magic systems, in particular $^{132}$Sn

P. Kleinheinz, New results on $^{144}$Cd and its neighbours

K. Cornelis, $0^+$ states in $^{102}$Pd and $^{108}$Cd

Friday 12 June

Morning 9.00-13.00

NEW EXPERIMENTAL DEVELOPMENTS

Chairman: I. Bergström

K.K. Seth, Pionic probes for exotic nuclei

T.J.M. Symons, Fragmentation of relativistic heavy ions

P. Armbruster, Cold fragmentation in thermal nuclear fission

J. Eberth and J.H. Hamilton, In-beam gamma spectroscopy on neutron-deficient nuclei with a neutron-multiplicity technique: Application to the light Kr isotopes

J.B. Wilhelmy, Nuclei far from stability using exotic targets

A. Gizon, The decays of neutron-deficient $^{113}$In and $^{115}$In

- 789 -
Evening 17.00-19.45

NUCLEAR STRUCTURE II

Chairman: J.H. Hamilton

R.A. Sorensen, Shifts of the spherical single-particle levels
D.S. Brenner, The mass 142-148 region
N.I. Pyatov, Strength functions for charge exchange nuclear excitations
J.L. Wood, The ground states of 174-186Pt: An example of a shell model intruder state configuration
J. Sauvage-Letessier, The 185Au region
E.F. Zganjar, The structure of 187Au

Saturday 13 June

Morning 9.00-13.00

HEAVY AND VERY HEAVY ELEMENTS

Chairman: D.C. Hoffman

A. Sobczewski, On the nature of the lowest K∞ = 0- states in the Ra-Th region
G. Münnernberg, Investigations on isotopes of Z ≥ 100
G. Hermann, Attempts to synthesise superheavy elements - a status report
G.N. Flerov, Recent results from Dubna
W.J. Swiatecki, Concluding remarks
LIST OF PARTICIPANTS

Helmut Ahrens
GSI, Postfach 110541
D-6100 Darmstadt 11, BRD

Kjell Aleklett
Studevik Science Research Lab.
S-611 82 Nyköbing, Sweden

G. Alkhazov
Leningrad Inst. of Nuclear Physics, Gatchina
Leningrad, USSR

W. Andrejtscheff
Rutgers University, Department of Physics
Piscataway, N.J. 08854, USA
Permanent address:
Institute of Nuclear Research and
Nuclear Energy,
1113 Sofia, Bulgaria

Peter Armbruster
GSI, Postfach 110541
D-6100 Darmstadt 11, BRD

Marcel Arnould
Institut d'Astronomie et D'Astrophysique
Université Libre de Bruxelles
Av. F.D. Roosevelt, B-1050 Bruxelles
Belgium

Georges Audi
Laboratoire René Bernas Batiment 108
B.P. no. 1, 91406 Orsay, France

Juha H. Äystö
Department of Physics/Univ.cf Jyväskylä
Nisulankatu 78, SF-40720 Jyväskylä
Finland

R. E. Azuma
Dept. of Physics, University of Toronto
Toronto, Ontario, Canada M5S 1A7

Robert C. Barber
Department of Physics, Univ. of Manitoba
Winnipeg, Manitoba, Canada R3T 2N2

Walter Benenson
Cyclotron Laboratory, Michigan State Univ.
E. Lansing, Michigan 48824, USA

Ragnar Bengtsson
Dept. of Mathematical Physics
LTH, Box 725
S-220 07 Lund 7, Sweden

Valter Berg
Institut de Physique Nucléaire
BP no. 1
91406 Orsay Cedex, France

Ingmar Bergström
Forskningsinstituutet för Atomfysik (AFI)
Fäck
S-10405 Stockholm 50, Sweden

Istvan Berkes
Université Lyon-1
43, Bd. 11 Nov. 1918
F-69622 Villeurbanne Cedex
France

Monique Bernas
Institut de Physique Nucléaire d'Orsay
91400 Orsay, France

Hans A. Bethe
Newman Laboratory, Cornell University
Ithaca, N.Y. 14853, USA

Yvon Le Beyec
Institut de Physique Nucléaire
BP no. 1, 91406 Orsay, France

Carrol R. Bingham
Department of Physics, Univ. of Tennessee
Knoxville, Tennessee 37916, USA

Tor Bjørnstad
Nuclear Chemistry Division, Dept. of Chemistry
University of Oslo, Blindern, Oslo 3
Norway

K. Bleuler
Institut für Theoretische Kernphysik
der Universität Bonn, Nussallee 14-16
D-5300 Bonn 1, BRD

J. Blomqvist
Forskningsinstituutet för Atomfysik
S-10405 Stockholm 50, Sweden

H. G. Bohlen
Hahn-Meitner-Institut, Glienicker Str. 100
P. F. 390128, D-1000 Berlin 39, Germany

Jakob Bondorf
Niels Bohr Institutet, Blegdamsvej 17
2100 Copenhagen Ø, Denmark

Jochen Bonn
Johannes-Gutenberg-Universität,
Institut für Physik Jakob-Welder Weg 11
Postfach 3980, D-6500 Mainz, BRD

Catalin Borcea
Joint Institute for Nuclear Research
P.O.Box 79, Head Post Office
19100 Moscow, UUSR

Jørgen Borggreen
Niels Bohr Institutet, Risø
4000 Roskilde, Denmark

Matthias Brack
Institute for Theoretical Physics
Univ. of Regensburg, D-8400 Regensburg, BRD

Clemens Brendel
Institut für Kernphysik, TH Darmstadt
Schloßgartenstrasse 9, D-6100 Darmstadt
BRD

Daeg S. Brenner
Chemistry Department, Clark University
950 Main Street, Worcester, Massachusetts
USA 01610

Merle E. Bunker
Los Alamos National Laboratory
P.O.Box 1663, MS-776, Los Alamos, N.M. 87545
USA
Adrian Gelberg
Institut für Kernphysik der Universität zu Köln
Zülpicher Strasse 77, 5000 Köln 41, BRD

Pieter De Gelder
Nuclear Physics Laboratory
Proeftuinstraat 86, B-9000 Gent
Belgium

William Gelletly
Schuster Laboratory, Univ. of Manchester
Manchester M13 9PL, England

Ronald L. Gill
Brookhaven National Laboratory
Physics Dept. Bldg. 750, Upton,
New York 11973, USA

Andrée Gizon
ISN, 57 Avenue des Martyrs
38026 Grenoble, Cedex, France

Kristoffer Gjøtterud
Fysisk Institutt, P.O.B. 1048
Universitetet i Oslo
Blindern, Oslo 3, Norge

Yasuyuki Gono
Linear Accelerator Laboratory
The Institute of Physical and Chemical
Research, Wako-shi, Saitama, 351 Japan.

Ian S. Grant
The Schuster Laboratory, Manchester Univ.
Manchester M13 9PL, England

G.W. Greenlees
Department of Physics, Univ. of Minnesota
Minneapolis, Minnesota 55455, USA

Reginald C. Greenwood
EG + G Idaho Inc., Idaho Falls, Idaho 83415
USA

Dominique Guillemaud
IPN, B.P. no. 1
F-91406 Orsay, France

Hans-Ake Gustafsson
EP-Division, CERN, CH-1211 Genève 23
Switzerland

Heinz Guggeler
GSI, Postfach 110541, D-6100 Darmstadt
BRD

Erik Hagberg
Atomic Energy of Canada Ltd.
Chalk River Nuclear Laboratories,
Chalk River, Ontario, Canada KOJ 1JO

Joseph H. Hamilton
Physics Department, Vanderbilt University
Nashville, Tennessee 37235, USA

W.D. Hamilton
Physics Division, University of Sussex
Brighton BN1 9QH, England

P.G. Hansen
Institute of Physics, University of Aarhus
DK-8000 Aarhus C, Denmark

J.C. Hardy
Nuclear Physics Branch,
Chalk River Nuclear Lab., Chalk River
Ontario, KOJ 1JO, Canada

Peter E. Haustein
Chemistry Department
Brookhaven National Laboratory, Upton
New York 11973, USA

Eugene A. Henry
Lawrence Livermore National Lab., L-234
P.O.Box 808, Livermore, California 94550
USA

Carl Johan Herrlander
Research Institute of Physics
S-10405 Stockholm, Sweden

Günter Herrmann
Institut für Kernchemie,
Joh.Gutenberg-Universität Mainz
Postfach 3980, D-6500 Mainz, BRD

Eberhard Hilf
Institut für Kernphysik, TH Darmstadt
Schlossgartenstrasse 9, D-6100 Darmstadt
BRD

John C. Hill
Institut für Kernphysik
Kernforschungsanlage Jülich GmbH
D-5170 Jülich 1, BRD

Dirk Hirdes
Fachbereich Physikalische Chemie
Kernchemie, Philipps-Universität Marburg
D-3550 Marburg, BRD

Per Hoff
EP-Division, CERN, CH-1211 Geneva 23
Switzerland

Darlene C. Hoffman
CNC-DD, MS 760, University of California
Los Alamos National Laboratory, P.O.Box 1663
Los Alamos, New Mexico 87545, USA

Sigurd Hofmann
GSI, Planckstr. 1, D-6100 Darmstadt, BRD

Jorma Honkanen
University of Jyväskylä, Dept. of Physics
Nisulankatu 78, SF-40720 Jyväskylä 72
Finland

Poul Hornshøj
Institute of Physics, University of Aarhus
DK-8000 Aarhus C, Denmark

G. Huber
Johannes-Gutenberg-Universität
Institut für Physik, Jakob-Welder-Weg 11
D-6500 Mainz, BRD

Torben Huus
Niels Bohr Institute
Blegdamsvej 17, 2100 Copenhagen Ø
Denmark

Hans-Bertil Håkansson
Institut für Theoretische Physik
Universität Regensburg, D-8400 Regensburg
BRD
Haruhiko Morinaga  
Fakultät für Physik, TUM  
D-8046 Garching bei München, BRD

Shunpei Morinobu  
Research Center for Nuclear Physics  
Osaka University, Suita, Osaka, 565 Japan

Peter Möller  
Dept. of Mathematical Physics, LTH, Box 725  
S-22007 Lund 7, Sweden

Alex C. Müller  
EP-Division, CERN, CH-1211 Geneva 23  
Switzerland

D.E. Murnick  
Bell Laboratories, IE 430, 600 Mountain Ave  
Murray Hill, New Jersey 07974, USA

Fritz Münich  
Inst. A für Physik, Kernspektroskopie  
Techn. Universität, D-33 Braunschweig  
Mendelssohnstr. 1A, BRD

Gottfried Münzenberg  
GSI, Postfach 110541, D-6100 Darmstadt 11  
BRD

William D. Myers  
Nuclear Science Div. LBL  
Berkeley, Ca 94720, USA

Robert A. Naumann  
Department of Physics, Jadwin Laboratory  
Post Office Box 708, Princeton University  
Princeton, New Jersey, 08544, USA

Rainer Neugart  
EP-Division, CERN, CH-1211 Geneva 23  
Switzerland

Karl Ove Nielsen  
Institute of Physics, University of Aarhus  
DK-8000 Aarhus C, Denmark

Ole Bent Nielsen  
Niels Bohr Institute, Blegdamsvej 17  
2100 Copenhagen Ø, Denmark

J. Rayford Nix  
Max-Planck-Institut für Kernphysik,  
D-6900 Heidelberg 1, BRD

P.J. Nolan  
Oliver Lodge Laboratory, Univ. of Liverpool  
Oxford Street, Liverpool L69 3Bx, England

Eckehart Nolte  
Fachbereich Physik E17, TUM  
D-8046 Garching, BRD

Göran Nyman  
EP-Division, CERN, CH-1211 Geneva 23  
Switzerland

E.W. Otten  
Institut für Physik, Johannes Gutenberg Univ  
Postfach 3980, D-6500 Mainz, BRD

Vladimir Paar  
Prirodoslovno-Matematički Fakultet  
Marulicev trg 19/I  
41000 Zagreb, Yugoslavia

Pierre Paris  
CSNSM, Laboratoire Salomon Rosenblum  
BP. no.1, 91406 Orsay, France

Olaf Pedersen  
History of Science Department  
University of Aarhus, DK-8000 Aarhus, Denmark

L.K. Peker  
Bld.197D, Brookhaven National Laboratory  
Upton, New York 11973, USA

Bernd Pfeiffer  
Institut Laue-Langevin, 156X  
P-38042 Grenoble Cedex, France

René Priëls  
Institut de Physique Corpusculaire  
Chemin du Cyclotron, 2  
B-1348 Louvain-La-Neuve, Belgium

G. zu Putlitz  
GSI, Postfach 110541  
D-6100 Darmstadt 11, BRD

N.I. Pyatov  
Joint Institute for Nuclear Research  
Head Post Office, P.O.Box 79, 101000 Moscow, USSR

Ingemar Ragnarsson  
Dept. of Math. Physics, LTH, Box 725  
S-22007 Lund 7, Sweden

H.L. Ravn  
EP-Division, CERN, CH-1211 Geneva 23  
Switzerland

Paul L. Reeder  
Battelle-Pacific Northwest Laboratory  
P.O.Box 999, Richland, Washington 99352  
USA

Lennart Robertsson  
Chalmers Tekniska Högskola  
Fysiska Institutionen Avd. III,  
S-41296 Göteborg, Sweden

Ernst Roeckl  
GSI Darmstadt, Postfach 110541  
D-6100 Darmstadt 11, BRD

Niels Rud  
Institute of Physics, University of Aarhus  
DK-8000 Aarhus C, Denmark

Jacques Oms  
Institut de Physique Nucléaire, BP no.1  
91406 Orsay, France
Gösta Rudstam
The Studsvik Science Research Laboratory
S-611 82 Nyköbing, Sweden

Mitsuo Sakai
Institute for Nuclear Study, Univ. of Tokio
Midori-cho 3-2-1, Tanashi-Shi, Tokyo 188
Japan

Neil E. Sanderson
Daresbury Laboratory
Science Research Council, Warrington WA4 4AD
Cheshire, England

J. Sauvage-Le tessier
IPN, B.P. no. 1, 91406 Orsay, France

Gertrude Scharff-Goldhaber
Physics Department, Building 510A
Brookhaven National Laboratory
Upton, New York 11973, USA

Dieter Schardt
EP-Isolde, CERN, CH-1211 Geneve 23
Switzerland

Gerd Schatz
Kernforschungszentrum Karlsruhe GmbH
Postfach 3640, D-7500 Karlsruhe 1, BRD

Wolf-D. Schmidt-Ott
II. Phys. Institut der Universität Göttingen
3400 Göttingen, Bunsenstrasse 7-9, BRD

Otto Schult
IKF, KFA Jülich, 517 Jülich, BRD

Kamal K. Seth
Physics Department, Northwestern University
Evanston, Ill. 60201, USA

Raymond K. Sheline
Department of Chemistry, Florida State Univ
Tallahassee, Florida 32306, USA

Kiyoshi Shizuma
IKF, KFA Jülich, D-5170 Jülich 1, BRD

Moshe Shnidman
Brookhaven National Laboratory,
Physics Department, Building 510-A
Upton, New York 11973, USA

Balraj Singh
Physics Department, Kuwait University
P.O. Box 5969, Kuwait, Kuwait

Adam Sobiczewski
Institute for Nuclear Research, Hoza 69
PL-00-681 Warszawa, Poland

Raymond A. Sorensen
Physics Department, Carnegie-Mellon Univ
Pittsburg, PA 15213, USA

Leif Spanier
Dept. of Physics
Lund Institute of Technology
Sölvegatan 14, S-22227 Lund
Sweden

Johanna Stachel
Institut für Kernchemie
Johannes Gutenberg Universität,
D-65 Mainz, BRD

WYadek J. Swiatecki
50A-3122, Lawrence Berkeley Laboratory
University of California, Berkeley
California 94720, USA

T. J. M. Symons
Building 88, Lawrence Berkeley Laboratory
University of California, Berkeley
California 94720, USA

Kohji Takahashi
Institut für Kernphysik der Technischen
Hochschule Darmstadt
Schlossgartenstr. 9, D-6100 Darmstadt, BRD

Jürgen Theobald
Institut für Kernphysik der Technischen
Hochschule Darmstadt,
Schlossgartenstr. 9, D-6100 Darmstadt, BRD

Catherine Thibault
Laboratoire René Bernas, Batiment 108
B.P. no. 1, 91406 Orsay, France

Peer Tidemand-Petersson
II. Physikalisches Institut
Universität Göttingen, Bunsenstrasse 7-9
D-3400 Göttingen, BRD

Friedrich-Karl Tielemann
Max-Planck-Institut für Physik
D-8046 Garching B. München, BRD

Francois Tondeur
Physique Nucléaire Théorique
Université Libre de Bruxelles CP 229
Campus Plaine, B-1050 Bruxelles, Belgium

Francois Touchard
Laboratoire René Bernas, Batiment 108
B.P. no. 2, F-91406 Orsay, France

Norbert Trautmann
Institut für Kernchemie der
Johannes Gutenberg-Universität
Postfach 3980, D-6500 Mainz, BRD

William B. Walters
Dept. of Chemistry, University of Maryland
College Park, MD 20742, USA

Dirk Vandeplassche
Instituut voor Kern- en Stralingsfysica
Celestijnenlaan 200D, B-3030 Leuven
Belgium

Ludo Vanneste
K.U. Leuven, I.K.S., Celestijnenlaan 200D
B-3030 Leuven, Belgium

Geert Wenes
Institute of Nuclear Physics
Proeftuinstraat 86
B-9000 Ghent, Belgium

Jerry B. Wilhelmy
MS 514m CNC-11, Los Alamos National Lab.
Los Alamos, N.M. 87545, USA
J.S. Winfield  
Dept. of Nuclear Physics  
University of Oxford, Keble Road  
Oxford OX1 3RH, England

John L. Wood  
School of Physics  
Georgia Institute of Technology  
Atlanta, GA 30332, USA

Claire L. Woods  
Department of Nuclear Physics  
University of Oxford, Keble Road  
Oxford OX1 3RH, England

Nissan Zeldes  
The Racah Institute of Physics  
The Hebrew University of Jerusalem  
Jerusalem, Israel

Edward Zganjar  
GSI, Postfach 110541  
D-6100 Darmstadt 11, BRD

Jing Ye Zhang  
Niels Bohr Institute, Blegdamsvej 17  
2100 Copenhagen Ø, Denmark

Jan Żylicz  
Institute of Experimental Physics  
ul. Hoza 69, 00-681 Warsaw, Poland

H.L. Yadav  
GSI, Postfach 110541  
D-6100 Darmstadt 11, BRD

Sven Åberg  
NORDITA, Blegdamsvej 17  
DK-2100 Copenhagen Ø, Denmark.
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