NUCLEAR MASS SPECTROSCOPY WITH
INTENSE PROTON BEAMS -- PROPERTIES OF FAR-UNSTABLE NUCLEI

P.G. Hansen ^{*)}
CERN, Geneva, Switzerland
and
The ISOLDE Collaboration

Presented at the
6th International Conference on
High-Energy Physics and Nuclear Structure
Santa Fe, New Mexico, USA
9-14 June 1975

Geneva - 10 June 1975

*) On leave from the Institute of Physics, University of Aarhus, Denmark.

THE
FEDERAL
BUREAU OF
INVESTIGATION
UNITED STATES DEPARTMENT OF JUSTICE
WASHINGTON, D. C. 20535

TO : DIRECTOR, FBI
FROM : SAC, NEW YORK
SUBJECT: [Illegible]

RE: [Illegible]

NUCLEAR MASS SPECTROSCOPY WITH INTENSE PROTON BEAMS -- PROPERTIES OF FAR-UNSTABLE NUCLEI

P.G. Hansen^{*}
CERN, Geneva, Switzerland
and
The ISOLDE Collaboration

ABSTRACT

Progress in accelerator and target-ion-source techniques now permits a large number of experiments that would have been very difficult or impossible a few years ago. Intensities of the secondary, radioactive beams at the reconstructed ISOLDE at the CERN Synchrocyclotron are expected in favourable cases to reach 10^{10} - 10^{11} atoms per second of one mass number. As examples of recent experiments at CERN and elsewhere, nuclear ground-state properties and delayed-particle spectra are discussed.

INTRODUCTION

During the last few years there has been considerable progress in the study of nuclei far away from the line of beta stability. The use of high-energy and medium-energy proton accelerators have contributed in an essential way to these studies. Within the limits of the present paper it is not possible to give a general review of this work (see, for example, the more extensive papers¹⁻³), and in the following only selected examples will be given.

The first part of the paper contains a brief outline of the experimental problem and of some of the new experimental techniques that are being developed. After this follows a discussion of some new results on nuclear ground-state properties and on beta decay with high Q-values.

EXPERIMENTAL TECHNIQUES

The use of high-energy projectiles permits the production of far-unstable nuclei through very complex spallation reactions. As an example one can quote a recent experiment⁴ in which ^{188}Pb was studied from the (stoichiometric) reaction $^{232}\text{Th} (p, 9p36n)$ produced by 600 MeV protons. The detection of individual reaction products following spallation can best be carried out after the products have been sorted with respect to both Z and A. Such a sorting is provided by an on-line electromagnetic isotope separator (Fig. 1).

The heart of such a system is clearly the target and the ion source, which together determine the chemical selectivity of the separation, its yield, and its speed. New experimental techniques that may make as many as 27 elements available for this purpose have been developed by Ravn et al.⁵, who use 8-20 cm thick molden-metal targets

^{*}On leave from the Institute of Physics, University of Aarhus, Denmark.

Fig. 1. Schematic diagram of the ISOLDE-2 on line isotope separator at CERN. (1) Target and ion source, the arrow symbolizes the 600 MeV proton beam. (2) Acceleration stage. (3) Analyzing magnet. (4 and 5) Collector chamber and switchyard. (6) Electrostatic quadrupole lenses for beam formation.

at temperatures up to 1400°C . The chemical selectivity for the reaction products is enhanced through the use of different types of ion sources; thus certain rare earths (ytterbium, thulium, europium, and samarium) may be obtained from an ultra-high temperature ($\sim 3000^{\circ}\text{C}$) rhenium-tipped surface ionization source. In the most favourable cases, the intensities of the secondary beams of mass-separated radioactive products at ISOLDE-2 are foreseen to reach 10^{10} - 10^{11} atoms/sec for one mass number at the peak of the yield curve. The detection limit with such a system is in favourable cases extremely low: an event rate of 1 h^{-1} will correspond approximately to a cross-section of 10^{-39} cm^2 .

An interesting hybrid spectrometer has recently been used for a high-resolution study of the optical spectra of radioactive sodium atoms. In this experiment Huber et al.⁶ used a target of molten aluminium placed in the 150 MeV beam of the Orsay Synchro-cyclotron. An atomic beam of sodium emerging from the oven was pumped optically with a laser and subsequently analysed in a six-pole magnet. The outgoing atoms were finally stopped on the ion-source of a small mass spectrometer. This experiment has served to determine isotope shifts and moments of the isotopes $^{21,22,24,25}\text{Na}$; many interesting applications of this technique seem possible.

On the whole it is probably fair to say that the study of nuclei away from stability is progressing at a rate determined by the need for developing new experimental techniques. This field can be expected to represent a challenge to experimentalists for some time to come.

NUCLEAR GROUND-STATE PROPERTIES

Two recent experiments have dealt with the ground-state masses of far-unstable nuclei. In the work by Aleklett et al.⁷, masses of light Kr and Rb isotopes were determined via the beta-decay energies. The data, of which an example is shown in Fig. 2, underline the importance of including a Wigner symmetry-energy term $\beta T/A$, (T is the isospin) in addition to the usual liquid-drop symmetry energy $\alpha T^2/A$. The measurements are consistent with $\beta/\alpha \approx 1$. It is also interesting to note that the odd-odd nuclei $^{76,78}\text{Rb}$ (Fig. 2) are much more strongly bound than one would expect; the reason for this is not clear.

Fig. 2. Experimental (black dots) and theoretical masses of light rubidium isotopes, after subtraction of a smooth liquid-drop value including a pairing term. The broken and full lines represent respectively an older mass formula and the new Seeger-Howard formula, of which only the latter includes a Wigner term. This term is expected to be the main cause of the increased binding towards the $N = Z$ line.

In an experiment by Thibault et al.⁸, the masses of extremely neutron-rich sodium isotopes were determined by direct mass spectroscopy. The isotopes $^{26-32}\text{Na}$ were produced in fragmentation reactions with 24 GeV protons from the CERN Proton Synchrotron (PS) and detected on-line with a spectrometer with a resolution $M/\Delta M = 650$. The results, illustrated in Fig. 3, show that $^{31,32}\text{Na}$ are surprisingly strongly bound and also that $N = 20$ no longer remains a magic number in this region of the nuclear chart.

The discovery made a few years ago by Bonn et al.⁹ that the optical isotope shifts of the light mercury atoms indicate a sharp increase in the size of the mercury nucleus below $N = 106$, continues

to attract considerable experimental and theoretical attention. Interpreted as the onset of a new region of strong quadrupole deformations, the shape transition differs from previously known cases, because the lowest excited levels in $^{184,186}\text{Hg}$ do not show rotational character. It will be extremely interesting to see the behaviour of the isotope shifts of the even isotopes -- whenever such measurements became possible.

Fig. 3. Two-neutron separation energies for sodium isotopes compared with those for the elements P-Ca, and with theoretical estimates. Note that a Hartree-Fock calculation (the curve HF), seems to explain the surprisingly strong binding of the heaviest sodium isotopes (from Ref. 8).

DELAYED-PARTICLE SPECTRA

An early result to come out of the study of far-unstable nuclei has been a better understanding of nuclear beta-decay to very highly excited levels of heavy nuclei. Experiments with total absorption gamma-ray spectrometers have shown^{10,11} that the beta strength as a function of excitation energy behaves in a very different way for β^- and for β^+ decay. This apparent asymmetry is linked to the existence of collective states which govern the transition rates; the corresponding situation in muon capture will be familiar to many participants

at this conference. Theoretical models of the gross beta transition rates have been developed; they are of special importance for the theoretical understanding¹² of the r-process for nucleosynthesis in the stars.

For very neutron-deficient nuclei the decay is expected to be systematically accompanied by the emission of charged particles, protons and alphas, from highly excited levels populated by the beta transitions. The reason for this is that the high proton excess of these nuclei leads to very favourable separation energies for protons and alphas, while neutron emission is energetically forbidden. The study of delayed-particle spectra provides information about the strength functions for beta decay and particle emission, and about level densities.

For neutron-deficient nuclei with $A > 50$, 14 delayed-proton emitters are known¹, the heaviest being the mercury isotopes ^{179,181,183}Hg. In a number of these cases detailed information on spectral shapes, fine structure, absolute intensities, Q-values, and p-γ coincidences are available, and theoretical analyses have been carried out on the basis of the statistical model. It is, however, only very recently that the competing process of beta-delayed alpha emission has been observed^{13,14} in a few cases, listed in Table 1.

Table I Beta-delayed alpha emission from neutron-deficient nuclei^{a)}

Isotope	$T_{1/2}$ (sec)	Delayed-particle intensity p/dis	
		protons	alphas
¹¹⁸ Cs	16.4 ± 1.2	$(4.4 \pm 0.6) \times 10^{-4}$	$(2.4 \pm 0.4) \times 10^{-5}$
¹²⁰ Cs	58.3 ± 1.8	$(7 \pm 3) \times 10^{-8}$	$(2.0 \pm 0.4) \times 10^{-7}$
¹⁸¹ Hg	3.6 ± 0.3	$(1.3 \pm 0.4) \times 10^{-4}$	$(9 \pm 3) \times 10^{-8}$

a) Data from Refs. 13 and 14.

The data rate in the ¹⁸¹Hg experiment¹³ was extremely low: a total of 10 alpha particles were observed in the energy region 10-12 MeV. These events are assumed to represent beta-delayed alphas from states at 4-6 MeV excitation in the daughter ¹⁸¹Au. One may use the intensity of $(9 \pm 3) \times 10^{-8}$ to estimate a strength function for alpha decay, which in absolute units for the reduced transition probability is 0.02 MeV^{-1} , in rough agreement with a cluster estimate based on the shell model. It is striking that the alpha strength in a 1 MeV interval actually exceeds the reduced transition probability of 0.006 of the favoured ground-state alpha decay.

As theoretical estimates indicated that the observation of beta-delayed alphas should be easier in lighter nuclei, a search was carried out for the isotopes of caesium with results as illustrated in Fig. 4 and Table 1.

Fig. 4. Beta-delayed alpha spectrum from ^{118}Cs detected with a counter telescope with an energy resolution of 55 keV FWHM. The inset shows a schematic representation of the ^{118}Cs decay.

There is not yet sufficient information available to permit an analysis of the $^{118,120}\text{Xe}$ alpha strength functions; it may, however, be of interest here to briefly point out that fluctuation phenomena are expected to influence the observed alpha intensities in an important way, and that this effect is probably part of the explanation for the very strong alpha branch of ^{118}Cs .

It has previously been shown^{1,10} how the fine structure in delayed-proton spectra arises from (Porter-Thomas) fluctuations in the individual transition probabilities. It is, however, important to note that the fluctuation phenomena also must be taken into account when calculating certain average quantities; thus in neutron physics the statistical correction factors known as fluctuation functions¹⁵ in some cases amount to a factor of 2. Even more dramatic effects may, however, be expected in an experiment where average branching ratios between a small number of exit channels are observed.

A simple example will suffice to make the point. Consider the decay of an unresolved group of levels of the same spin and parity. Assume that one has only two decay channels, protons and alphas, each to a single final level, and that the *average* widths are Γ_p and Γ_α . (The gamma widths should be negligible for ^{118}Xe , but not for ^{181}Au .) With the fluctuation contribution taken into account, the observed

alpha branch will be $\Gamma_\alpha / [\Gamma_\alpha + (\Gamma_\alpha \Gamma_p)^{1/2}]$, which implies a sizeable enhancement of a weak alpha branch. A further investigation of this effect, which also plays a role in other experiments, and of its relation to fine structure is in progress.

CONCLUDING REMARKS

In this short survey I have left out a number of interesting experiments, for example those dealing with ground-state alpha decay of very neutron-deficient nuclei and those dealing with nuclear level schemes. Let me in conclusion mention that several new experiments are now starting at CERN, such as atomic-beam magnetic resonance, new applications of optical pumping, direct mass spectroscopy, high-resolution X-ray spectroscopy, and the production of radioactive targets for use in in-beam spectroscopic studies.

The field of far-unstable nuclei is a young and vigorous one; the progress is limited not so much by data rates and the need for fancy data handling as by the need for developing a new approach and new experimental techniques. The relatively few groups that are working in this field look towards the future with considerable optimism and enthusiasm.

REFERENCES

1. P.G. Hansen *in* Proc. Internat. Conf. on Nuclear Structure and Spectroscopy, Amsterdam, 1974 (eds. H.P. Blok and A.E.L. Dieperink), (Scholar's Press, Amsterdam, 1974), Vol. 2, pp. 662-695.
2. P.G. Hansen, R.A. Naumann and R.A. Sorensen, contributions *in* Proc. Heavy-Ion Summer Study, Oak Ridge National Laboratory (ed. S.T. Thornton), CONF-720669 (National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia, USA, 1972).
3. R. Klapisch *in* Nuclear Spectroscopy (ed. J. Cerny), (Academic Press, N.Y., 1974), Vols. I-III (1974).
4. P. Hornshøj, P.G. Hansen, B. Jonson, H.L. Ravn, L. Westgaard and O.B. Nielsen, Nuclear Phys. A230, 365 (1974).
5. H.L. Ravn, S. Sundell and L. Westgaard, Nuclear Instrum. Methods 123, 131 (1975).
6. G. Huber, C. Thibault, R. Klapisch, H.T. Duong, J.L. Vialle, J. Pinard, P. Juncar and P. Jacquinot, Phys. Rev. Letters 34, 1209 (1975).
7. K. Aleklett, G. Nyman, E. Roeckl and L. Westgaard, paper presented at the AMCO-5 Conference, Paris, 2-6 June 1975 (in press).
8. C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard and W. Reisdorf, Phys. Rev. C (in press).
9. J. Bonn, G. Huber, H.-J. Kluge, L. Kluger and E.W. Otten, Phys. Letters 38B, 308 (1972).
10. P.G. Hansen, Advances in Nuclear Physics 7, 159 (1973).
11. P. Hornshøj, B.R. Erdal, P.G. Hansen, B. Jonson, K. Aleklett and G. Nyman, Nuclear Phys. A239, 15 (1975),
12. T. Kodama and K. Takahashi, Nuclear Phys. A239, 489 (1975).
13. P. Hornshøj, K. Wilsky, P.G. Hansen and B. Jonson, Phys. Letters 55B, 53 (1975).
14. P. Hornshøj, P. Tidemand-Petersson, R. Bethoux, A.A. Caretto, J.W. Grüter, P.G. Hansen, B. Jonson, E. Hagberg and S. Mattsson, Phys. Letters (in press).
15. J.E. Lynn, The theory of neutron resonance reactions (Clarendon Press, Oxford, 1968), p. 226.