CURRENT EVIDENCE FOR THE ONSET OF A NEW DEFORMATION REGION NEAR Z = 11, N = 20

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Abstract

The possibility that a new deformation region far from stability starts near Z = 11, N = 2C 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 1. High separation efficiencies and short diffusion times, comparable to the shortest $\beta$-decay half lives, have been accomplished for alkali elements, although some other elements have also been separated2. Several contributions to this conference present the results obtained by our group for Li and Na neutron-rich isotopes. They deal with the $\beta$-delayed $\gamma$, n, $\alpha$ and even $^6$He emission3,4).

These spectroscopic results shed a new light on the question of a possible region of deformation appearing far from the valley of $\beta$ stability in the vicinity of $Z \sim 11, N \sim 20$. Such a possibility was clearly indicated by mass measurements of the neutron-rich Na isotopes5 and subsequent Hartree-Fock calculations6 which accounted for the masses measured and found that Na isotopes experienced a sudden increase of their prolate deformation at $N \sim 20$. 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 un-applicable.

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 $Z \sim 38, N \sim 60$ illustrates the consistency of these three criteria: i) binding energy: a direct mass measurement of Rb isotopes shows a marked increase of $S_{2n}$ binding energy against two-neutron emission for $N \gtrsim 60$ over the smooth decrease of $S_{2n}$ with increasing $N$ extrapolated from less exotic isotopes7). This extra binding energy is interpreted, as for Na isotopes5,6), as due to a shape transition.

ii) location of the first 2+ level of an even-even isotope: the $^{98,100}$Sr daughters of $\beta$-active $^{98,100}$Rb have extremely low first 2+ states8). The empirical formula $E(2^+) = 3\hbar^3/2\hbar = 1224 (\epsilon/(A^{1/3})^{-1}$) associates a large deformation to a low value of $E(2^+)$. iii) isotope shift: the values of $\Delta \langle r^2 \rangle$, the variation of the mean square charge radius among the Rb isotopes, measured by atomic beam laser spectroscopy9,10,11), 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 calculations12) successfully account for experimental results i) and iii) simultaneously, and associate them with an increase of the $B_2$ quadrupole deformation parameter.

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

3. SYSTEMATICS OF TWO-NEUTRON BINDING ENERGIES

The earlier results5) on $S_{2n}$ have been confirmed with smaller uncertainties1) 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 $N \sim 20$. For that purpose, $Q(\alpha)$ measurements were undertaken. Our improved knowledge4) of $\beta$-decay schemes makes this a reasonable approach in spite of the possible systematic errors which sometimes affect this method. A very preliminary run with poor geometry and low statistics has been performed at the CERN SYM...
chrotron in our continuing investigation of the $\beta$-decay of neutron-rich Na isotopes. The method, which consists in fitting the stretched E spectrum to a spectrum of reference with a known value of $E_B$(max) was used to determine the Q($\beta$) value of $^{32}$Mg. From the known $^{32}$Na mass(1), the $^{32}$Mg mass, hence the value of $S_{2n}(^{32}$Mg), 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 $\beta$ transition. An experiment is planned for later this year with a better geometry for the plastic detector.

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

We report elsewhere at this conference the $\gamma$ activities from the $\beta$ decay of $^{30}$Mg and $^{32}$Mg.

For the latter, the values of the $\gamma$-intensities are now accurate enough to definitely confirm earlier results(14) which indicated that the 885 keV $\gamma$-ray is by far the most intense. It can then be assigned to a transition to the $^{32}$Mg ground state. This implies that the lowest excited state of $^{32}$Mg lies at 885 keV. As for nearly all even-even nuclei this level should have $J^\pi = 2^+$, as should the lowest level of $^{30}$Mg, at 1483 keV, now well established from the detailed level scheme reported in ref. 4.

Whether the 885 keV level of $^{32}$Mg is fed directly by a $\beta$-branch from $^{32}$Na remains an open question since the sum of all the other $\gamma$-activities from $^{32}$Na approximates to the intensity of the 885 keV $\gamma$-ray. Hence the latter might only result from cascade feeding from higher-lying $^{32}$Mg levels. However if it were not so, i.e. if the other $\gamma$-activities would not all feed the 885 keV level, hence that level was directly fed by a $\beta$-branch from $^{32}$Na, it would not preclude a $2^+$ assignment. The reason is that a negative parity for the $Z = 11$, $N = 21$ $^{32}$Na 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 $^{32}$Mg at an energy as low as 885 keV, much lower than the 1483 keV excitation energy measured in $^{30}$Mg. 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(15). The isotope shifts of the Na isotopes were measured recently(10,11). They show a fast and continuous increase of $\delta R(2)$ 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(6) 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 $\delta R(2)$. First the shape transition might take place at $A = 32$ rather than 31. Second it might set in less abruptly than the calculations suggest(6), 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 $\tilde{\delta} < r^2 >$ 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 $\tilde{\delta}(r^2)$ 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 $2 < 11$, $N \approx 20$. 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$^6$ reproduced the dependence of $S_{2n}$ with $A$, and found large prolate deformations. For such deformations, Nilsson's level diagram$^16$ shows that the $1/2^+$ and $3/2^+$ states associated with the $1f 7/2$ shell actually cross the $1d 3/2$ level. In that sense, the failure$^17$ 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$^18$ with an extended basis which find a large number of particles occupying the $1f 7/2$ 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$^19$ 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 Nilx$^{21}$ using a Yukawa-plus-exponential macroscopic model with microscopic corrections again observe large quadrupole deformations for $A \approx 31$ in Na and $A \approx 32$ 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 $\alpha$-stability.

Références

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DISCUSSION

H. Boarm: 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. Détat: 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. Détat: First, the occurrence of large static deformations at a so-called magic number helps to understand the relativity 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. Kluge: 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 $P_{9/2}$ for $^{21,23,27}$Na. The measured values are all small. $Q_{E}(^{23}$Na) is slightly positive. $Q_{E}(^{25,27}$Na) are slightly negative. Others $^{27}$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 $^{23,25,27}$Na except that they support the assumption that they could be vibrational since the radii are large and the $\alpha^2$ value in $^{19}$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.