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The structure and spectroscopy of neutron-rich nuclei

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Abstract. Our knowledge of the structure and spectroscopy of neutron-rich nuclei has greatly increased due to two important developments in nuclear physics: the construction of large γ-ray arrays to investigate prompt γ-rays from fission and deep-inelastic reactions; and the availability of radioactive nuclei from fragmentation and spallation reactions. In this review examples will be given of the advances that have been made in our understanding of the properties of neutron-rich nuclei. The examples are necessarily selective, given the limitations of space and time.

PACS. 23.20.Lv Gamma transitions and level energies

1 Introduction

The structure of nuclei on the proton-rich side of the stability line, over a wide range of atomic numbers, has been extensively investigated due to the characteristics of fusion-evaporation reactions. It has not been so easy to study neutron-rich nuclei. A great number of such nuclei can be produced in fission and deep-inelastic reactions. The problem arises from the fact that so many nuclei (some of which may have unknown levels) are produced simultaneously. The advent of large γ-ray arrays led to new initiatives in the investigation of neutron-rich nuclei because the arrays have sufficient sensitivity and resolving power to disentangle the very many prompt γ-rays from the broad range of reaction products. More "focussed" studies can be carried out using fragmentation or spallation since reaction products of interest can be selected either by electromagnetic devices or by ion sources and mass separators. As yet, the intensity of these secondary beams tends to be low, but specific measurements, such as Coulomb excitation or β-decay, can provide important information.

The science case for the investigation of neutron-rich nuclei has been made many times. The interest focusses on the role of the excess of neutrons in modifying the mean-field potential, and the consequential effect on the spin-orbit potential and pairing. In the lightest of neutron-rich nuclei, the discovery of neutron haloes has shown the need to include three-body effects; data are accumulating that demonstrate the modification of magic numbers because of the more diffuse surface; and some evidence for a weakening of pairing has been presented.

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This review can concentrate only on a couple of aspects of the structure of neutron-rich nuclei. The first section will discuss some results on nuclei in the $A = 30$–40 region. In this section we shall try to illustrate how experiments using fragmentation, spallation and deep-inelastic production mechanisms can provide complementary data that build up a picture of nuclear structure. The second section will present some new results from prompt γ-ray spectroscopy of fission fragments produced in spontaneous fission. New information on the evolution of collectivity with (N, Z) and angular momentum will be discussed.

2 The A = 30–40 region

The neutron-rich $A = 30$–40 region (and, in particular, the $N = 20$ isotones) has been of interest since the masses of the sodium isotopes [1] were found to be in disagreement with the expectations of shell model calculations based on *sd* configurations. The anomaly was explained [2] by the proposal that intruder configurations, leading to deformed states, lay lower in energy than the spherical, "shell model" states. Confirmation of this idea came two decades later when the $B(E2)$ transition rate between the ground and 2^+ states in ^{32}Mg was found to be consistent with a highly deformed structure [3]. This breakthrough came about by the use of the technique of secondary beam excitation, following the production of ^{32}Mg by fragmentation. Further studies of this island of deformation have been and are being carried out.

The nucleus ^{34}Si lies at the border of this island, and exhibits characteristics of a doubly magic nucleus. The first-excited 2^+ state lies at an energy of 3.326 MeV. Recently the $B(E2)$ transition rate from the ground state

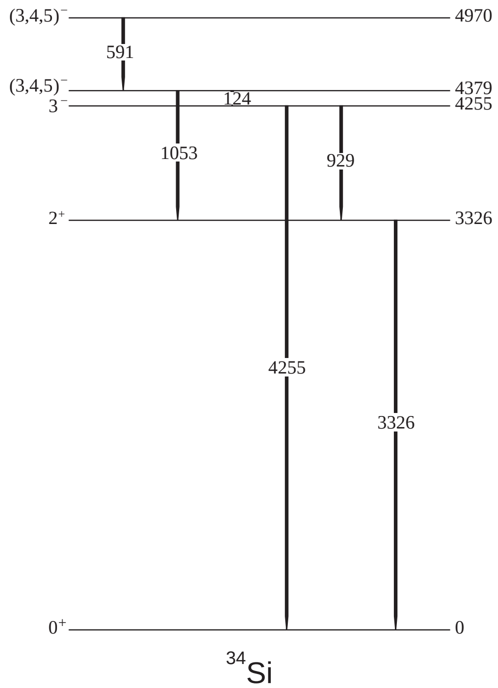

Fig. 1. Level scheme of ^{34}Si seen [5] in the β-decay of ^{34}Al. Level and γ-ray energies are in keV.

to the 2^+ state has been determined [4]. The transition rate is somewhat less than would be expected from a shell model calculation based purely on the *sd* shell. This suggests that the wave function of the 3.326 MeV state consists mainly of the *intruder* configuration. If this is indeed so, one might expect a rotational band to exist, of which the 3.326 MeV state is a member.

How may one populate an excited band, if it exists? Other production mechanisms may provide a means. Very recently the β-decay of ^{34}Al has been investigated [5]. The ground-state angular momentum of ^{34}Al is $4\hbar$, and therefore the β-decay selection rules would favour the population of $J = 3$, 4, 5 states. It transpires that such states are indeed seen, but they are 1p-1h, negative-parity excitations of the spherical core. The level scheme reported by Nummela *et al.* is shown in fig. 1. Since in this experiment the β-decay of ^{35}Al was also observed, populating the $N = 21$ single-particle states, we now have more, useful knowledge of the *spherical* configurations in this region.

To populate an excited band, a reaction mechanism that leaves the product with a reasonable excitation energy and angular momentum will be required. A suitable mechanism would be deep-inelastic reactions. In these reactions the rapid N:Z equilibration implies the production of neutron-rich ejectiles if a heavy target is bombarded by a beam with a mass near 40. A series of experiments is underway in Legnaro using the GASP array [6] to investigate neutron-rich ejectiles, starting with a ^{37}Cl beam interacting with a heavy target of ^{160}Gd. Decay γ-rays from levels in phosphorus and chlorine isotopes with $J = 6$ to 8 have already been observed. A new experiment with a ^{36}S beam has just been performed, which will give the possibility of observing higher-spin states in ^{34}Si, and hence the intruder structure.

3 Fission fragment spectroscopy: The A = 100–120 region

Fission fragment spectroscopy was "reborn" [7] in the 1980s when it was realised that the new γ-ray arrays had sufficient selection power to disentangle the multitude of prompt γ-rays emitted from the very many products of fission. Initially yrast sequences were determined [8, 9] and some of the first information about the structure of neutron-rich, intermediate-mass nuclei was obtained. With the development of more efficient arrays, data were obtained on excited, non-yrast bands [10–12], leading to knowledge of double-γ-phonon rotational bands in ^{106}Mo, triaxiality in Ru isotopes, and the strength of pairing in ^{100,102}Zr, respectively. The new data provided evidence of an interesting evolution of nuclear shapes and deformation as a function of (N, Z) and angular momentum: the most neutron-rich isotopes of Sr and Zr seem to be stably, axially-symmetric deformed; those of Mo are soft to γ vibrations; the Ru isotopes had characteristics consistent with stable triaxiality; and the Pd and Cd isotopes, as the $Z = 50$ closed shell was approached, were showing structures based on vibrations about sphericity.

An important issue that needed to be addressed was the nature of the shape transition between $N = 58$ and 60 in the Sr and Zr isotopes. This very sharp transition had already been seen in the excitation energies of the first 2^+ states populated in β-decay. It was likely that the deformed configuration that was the ground state in the $N = 60$ isotopes could exist as excited states in the lower N nuclei. Detailed spectroscopy had identified candidate bands in the $N = 58$ and 59 isotopes of Sr and Zr, but the deformations of these structures were not known.

It was evident that confirmation of the proposed variation of structure with N, Z and angular momentum could only be obtained by determining electromagnetic transition rates in the yrast bands, and in the excited bands observed in the $N = 58$ and 59 isotopes.

A technique (the Doppler profile method) for measuring lifetimes of states produced in spontaneous fission with values in the picosecond region (this implies states with $J = 8$–12 in the nuclei of interest) has been developed [13, 14]. The measurements on Zr isotopes showed that the transition quadrupole moments were the same at $J = 8$–12 as at $J = 2$, consistent with their stable, axially symmetric shape. However, the transition quadrupole moment for Mo isotopes at higher spins was found to be smaller than the value determined at $J = 2$. This was explained as being due to increasing triaxiality as the $h_{11/2}$ neutrons align with increasing angular momentum.

A technique was required so that a wider range of lifetimes could be measured, in order to determine the transition quadrupole moments of all observed members of the ground-state band. This would provide confirmation of the trend in quadrupole moments suggested by

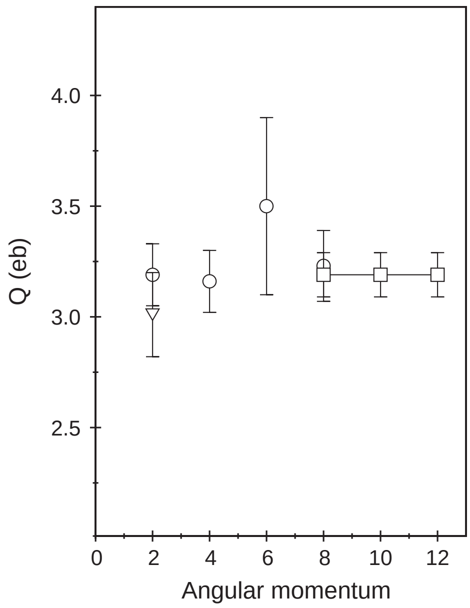

Fig. 2. The measured transition quadrupole moments of the ground-state band of ^{100}Zr. See text for the explanation of the symbols.

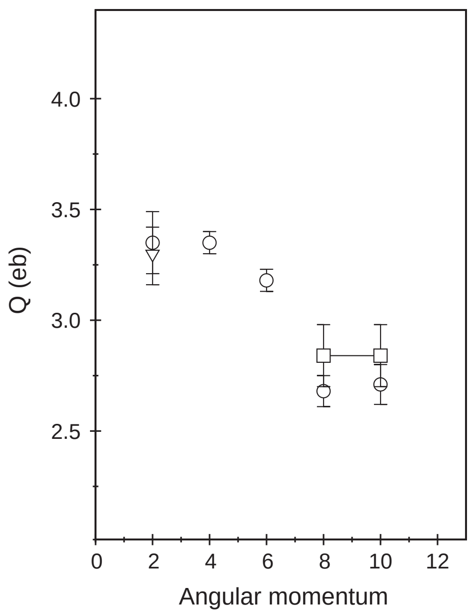

Fig. 3. The measured transition quadrupole moments of the ground-state band of ^{104}Mo. See text for the explanation of the symbols.

the Doppler profile method. An experiment has now been performed [15] allying EUROBALL with the SAPHIR array of solar cells. This experiment uses the differential plunger technique, specially adapted for use with spontaneous fission.

Complete results are now available for the transition quadrupole moments of ^{100}Zr and ^{104}Mo. These results are shown in fig. 2 and fig. 3. The Q_0 for the 2^+ to 0^+ transitions (open triangles) is taken from ref. [16]; the open squares, joined by the solid line, are the values determined by the Doppler profile method (DPM), assuming a constant Q_0 for the series of transitions; and the open circles represent the values determined from the lifetimes of the individual states measured with the differential plunger technique. It can now be seen clearly that the ground-state rotational band of ^{100}Zr has a constant Q_0 as a function of angular momentum, consistent with a stable axial symmetry. On the other hand, the differential plunger measurements confirm the suggestion of the DPM that the Q_0 of ^{104}Mo reduces with angular momentum. This implies that the soft nucleus ^{104}Mo is changing its shape as it gains rotational frequency.

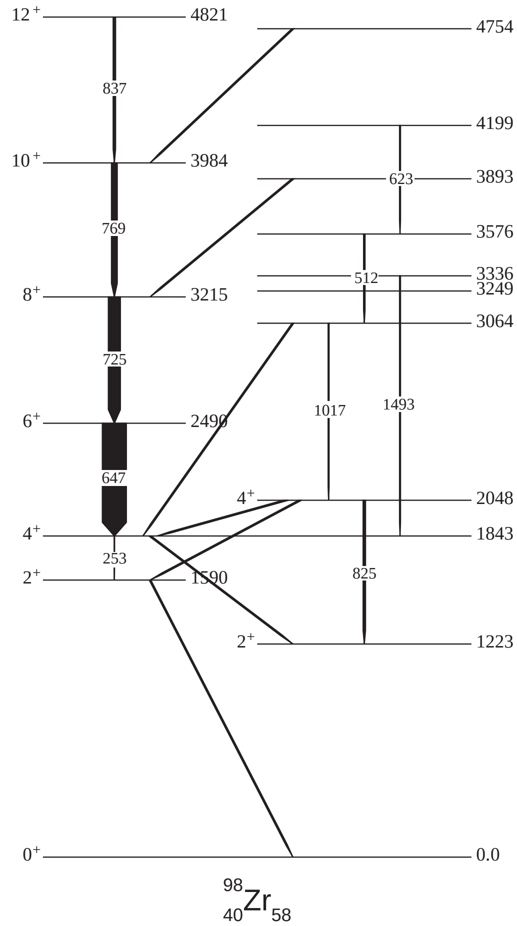

Fig. 4. The partial level scheme of ^{98}Zr, showing the excited band at around 1 MeV above the spherical ground state. See ref. [17] for the full level scheme.

The DPM has also given an answer to the questions concerning the $N = 58$, 59 transition region. In a recent publication [17] new level schemes for and lifetimes in ^{96,97}Sr and ^{98,99}Zr have been presented. Figure 4 shows a partial decay scheme for ^{98}Zr, emphasising the excited band that has been observed. The transition quadrupole moment of this band has been determined by simultaneously fitting the Doppler lineshapes of the transitions from the 8^+, 10^+ and 12^+ states, assuming a constant

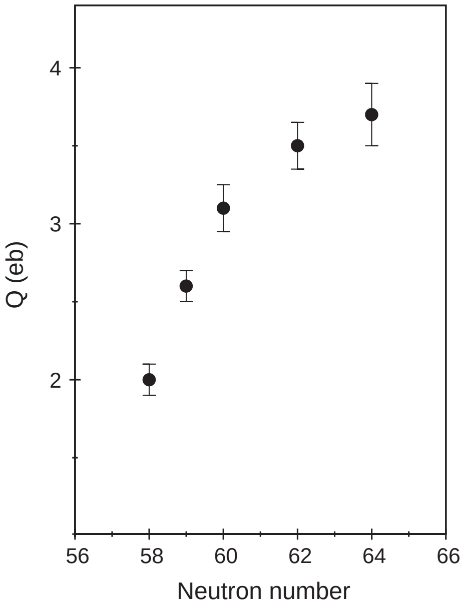

Fig. 5. The variation of transition quadrupole moment of the deformed structures in the Zr isotopes, as measured by the DPM.

quadrupole moment within the band. The value of Q_0 is found to be 2.00(10) eb. This data point is included in fig. 5 along with the Q_0-values for the deformed structures in $^{99\text{-}104}$Zr. The bands in ^{98,99}Zr are excited configurations, whereas those in the heavier Zr isotopes are ground states. Now that the deformed stuctures in ^{98,99}Zr have been identified, it can be seen that the deformation varies smoothly with neutron number. The sharp transition that occurs in the excitation energy of the 2^+ states between $N = 58$ and 60 is a consequence of the crossing in energy of the deformed and spherical configurations. These new data give a full picture [17] of the evolution of deformation change in both the deformed and near-spherical configurations in the neutron-rich isotopes of Sr and Zr.

4 Discussion

In this very selective presentation we have discussed two regions of neutron-rich nuclei currently of some interest. In the first example it was shown how complementary production mechanisms can be used to elucidate the structure of neutron-rich nuclei around $A = 30$–40. In the second example it was shown that it is now possible to apply the full range of spectroscopic techniques to the highly complex problem of investigating neutron-rich nuclei produced as fission fragments. The development of methods to measure lifetimes of states has been crucial in giving a complete picture of the variations in shape as a function of N, Z and angular momentum.

The accessibility of the neutron-rich nuclei produced in fission and deep-inelastic reactions will be greatly enhanced by the availability of radioactive nuclear beams. New reaction mechanisms such as transfer reactions will be used to study their properties. The difficulty in studying these nuclei will change from one of the selection of one single isotope amongst many, to one of the efficient measurement of nuclear parameters under the constraint of low yields. As the example of fission fragment spectroscopy shows, nuclear physicists have the ingenuity to find answers to the problems that face them.

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