CONF-830469--8

BNL--33219

DE83 014396

CHAPTER 1

NEW REGIONS OF NUCLEAR DEFORMATION *

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It has long been expected from general theoretical considerations that nuclei with Z and N far removed from major shell closures should exhibit considerable collectivity and may be deformed in their groundstates. A number of calculations have recently attempted to quantify these expectations through detailed predictions of nuclear shapes across the periodic table. In this contribution we review predictions and experimental data for the regions with Z,N=(40,40), (40,64) and (64,64) which are all off the valley of stability. Emphasis is placed on the experimental techniques and data obtained from the first of these regions where the prediction of extremely large prolate deformation has been experimentally verified.

1. INTRODUCTION

We begin with an arbitrary distinction between what we will term "old" and "new" regions of deformation. The "old" regions are considered to be those which lie along the

*Research carried out in part under the auspices of the U.S.Department of Energy under Contract No.DE-AC02-76CH00016.

valley of stability, namely some light s-d shell nuclei, the rare earth region, and the actinides. Many of these nuclei have been studied in great detail, especially using the techniques of γ-ray spectroscopy which allow precise nuclear structure information to be extracted.

We categorize the "new" regions of deformation simply to be those which lie away from the valley of stability. Until recently, these regions were not accessible to experiment and data are still very limited. Despite their inaccessibility, the presence of these "new" regions has been predicted for many years. Figure 1 was published[1] in 1963 and shows both old and new regions of deformation, including the intermediate mass areas around Z,N=(40,40), (40,64) and (64,64). It was expected that if both proton and neutron numbers were away from major shell closures the large number of valence nucleons should lead to polarization of the nuclear core and would result in permanent groundstate deformation.

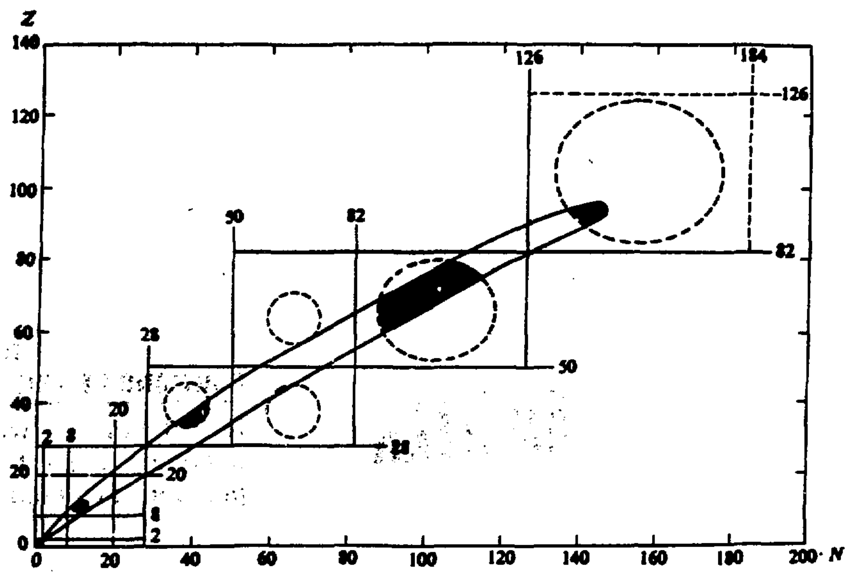


FIGURE 1 A schematic view of "old" and "new" regions of deformed nuclei.

NEW REGIONS OF NUCLEAR DEFORMATION

Several groups[2-7] have recently made more quantitative estimates of nuclear shapes and binding energies in these regions. The general method is to calculate a nuclear potential by combining the liquid drop energy with a correction for shell structure in a potential of that shape. Figures 2 and 3 show some results from this type of calculation, as taken from ref. 4. In Fig. 2 the potential energy surfaces for spherical (^{84}Sr) and deformed (^{76}Sr) nuclei are shown as a function of quadrupole (ε_2) and hexadecapole (ε_4) deformation. Figure 3 shows the quadrupole deformation at the minimum of the potential energy surface for more than 4000 isotopes. All the features anticipated in Fig. 1 are reproduced, but now on a quantitative basis.

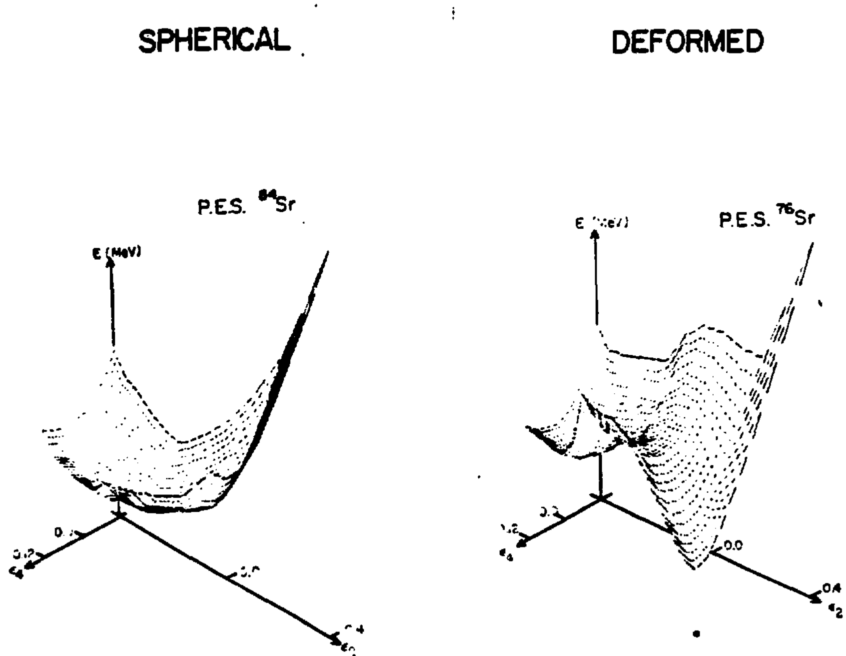


FIGURE 2 Potential energy surface for spherical and deformed nuclei. The data are from ref. 4.

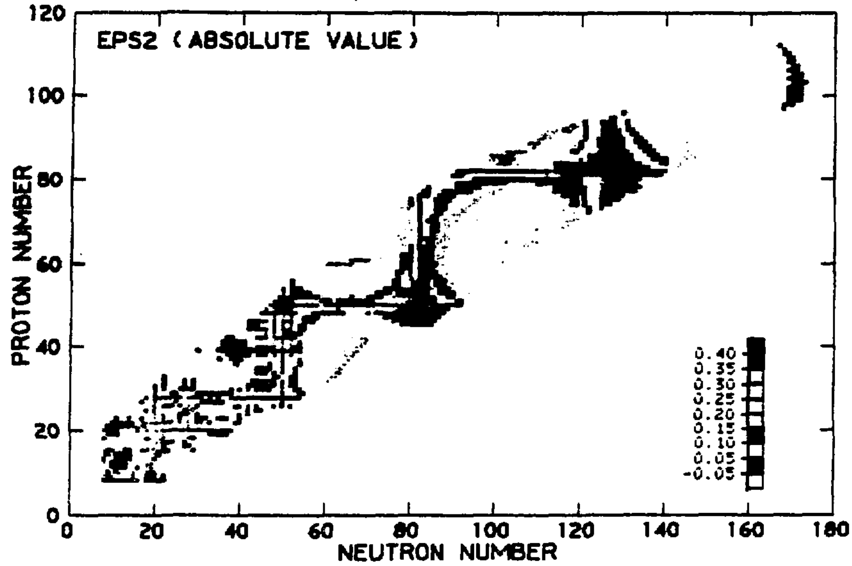


FIGURE 3 The quadrupole deformation of the minimum of the nuclear potential energy surface calculated (ref. 4) for more than 4000 isotopes.

The parameterization of deformation and the nuclear potentials used in the microscopic part of the calculations vary between models. The results agree near stability (where parameters are fitted to data on known nuclei), but discrepancies appear for predictions of nuclear properties far from stability. In particular, the shape of nuclei in the intermediate mass deformed regions is controlled by the microscopic or shell structure correction and shows large differences between models. Consequently, the predictions as to which isotopes are most deformed, the size of that deformation and whether oblate, prolate or triaxial shapes are most stable, vary from model to model. An experimental determination of nuclear shapes in these new regions, and its evolution with mass and spin, can provide diverse and discriminating tests of the calculations.

These questions about nuclear shapes can be answered using the well established γ-ray techniques developed in the "old" deformed regions if the isotopes in question can be produced. The curvature of the valley of stability permits experimental access to the neutron deficient regions through the use of heavy ion induced compound nuclear reactions. Some techniques developed for these studies are discussed in section 2, together with a comparison of data with calculations. The evolution of shape with spin in the transitional nuclei near Z,N=(40,40) has been studied and is discussed in section 3. The neutron rich area around Z,N=(40,64) has only been probed using fission fragment spectroscopy, and is reviewed briefly in section 4, while predictions for heavier deformed regions are examined in section 5.

2. Spectroscopy of the (Z,N)=(40,40) region

There are several beam and target combinations which can lead to the formation of compound nuclei in the N~Z~40 region. However, in the compound system the proton separation energy is low (<5 MeV) and the neutron separation energy high (>12 MeV) so the de-excitation of the compound nucleus is dominated by charged particle evaporation leading back toward stability. If the compound nucleus is formed at low excitation energy, the number of evaporated particles can be kept to a minimum, but even so a method of channel selection is needed if studies of the structure of isotopes produced in the weak neutron emitting channels are to be made.

Two alternatives are available. Either one can detect the residual nuclei directly, or one must measure the multiplicity of all particles involved in the de-excitation of the compound system to the final residual nucleus. The first of these choices involves the use of a recoil mass spectrometer, of which several exist[8] or are under construction. They offer the advantage of excellent channel selection for mass and reasonable Z-identification if the recoil products are not too low in energy. The alternative method, measuring the light evaporated particles, is the technique that we have used. The method demands highly enriched targets and very low levels of contamination to ensure that only one species of compound nucleus is formed. It can have high efficiency, especially for inverse reactions, and works well in some reaction channels not suited to recoil separators (e.g., α-evaporation channels). The method is versatile and inexpensive.

A schematic diagram of the experimental arrangement required for this type of study is shown in Fig. 4. This apparatus was used at BNL during 1982 to investigate the N~Z~40 region. Several reactions were studied, including ^{24}Mg, $^{28,29}Si$, ^{32}S on ^{58}Ni and ^{39}K, and ^{40}Ca on ^{40}Ca.

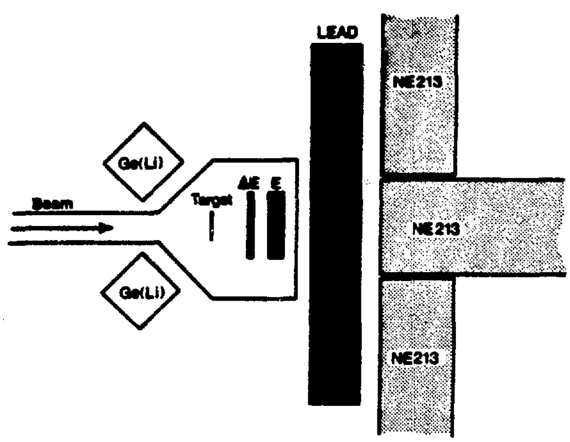
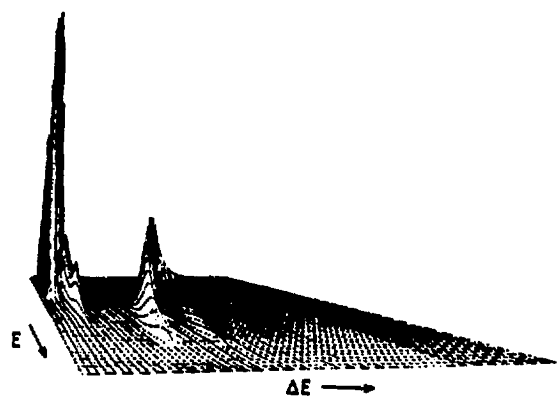


FIGURE 4 Apparatus for studying very neutron deficient nuclei.

A Si-surface barrier telescope subtending 0.85 str and consisting of 150μ and 1000μ elements was used. Figure 5 shows a typical E-ΔE map where proton, deuteron and alpha peaks can be seen, together with peaks from coincident charged particles (2p, 3p, αp, etc.).

FIGURE 5 A telescope map showing loci from protons, alphas, deuterons, double-protons and alpha plus protons. Smaller peaks due to triple events are also present.



By measuring the ratio of γ-ray intensities in spectra gated by 1- and 2-protons the proton multiplicity can be extracted, as is shown in Fig. 6.

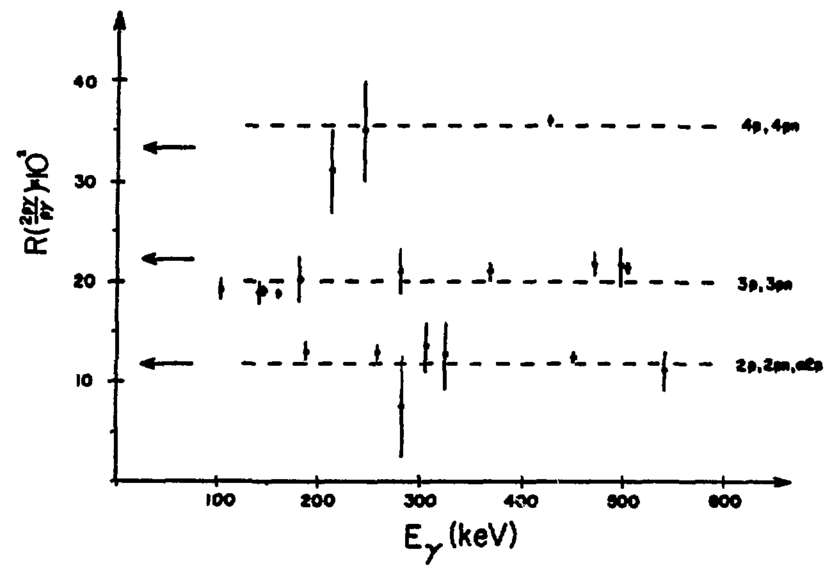


FIGURE 6 Photopeak intensity ratios from spectra gated by 1 and 2 protons. Data are from the $^{40}Ca + ^{40}Ca$ reaction at 117 MeV.

This method is only valid if the charged particle evaporation spectrum (and hence angular distribution) is the same for all reaction channels. The arrows on the left of Fig. 6 are the 2-, 3- and 4-proton ratios calculated using this assumption; it can be seen to be approximately correct.

Neutrons were simultaneously detected in an array of 5 NE213 liquid scintillator detectors. One may naively expect that the ratio method should be valid for extracting the neutron multiplicity as well. However, this is not the case; the shapes of the neutron evaporation spectra are very channel dependent, as predicted by evaporation calculations, and the ratios deduced are sensitive to both the reaction used and the detector size and position. Consequently this method has been found to be unreliable for deducing neutron multiplicities.

Using the arrangement shown in Fig. 4, states in many previously unstudied isotopes were observed, both in this region and near $^{100}_{50}Sn_{50}$. Figure 7 shows these new isotopes marked by an "*". We have reported results for $^{77-80}Sr$ (10) and ^{77}Rb.(11) These nuclei have been found to be some of the most deformed known with quadrupole deformation, $\varepsilon_2 \sim 0.4$, which corresponds to an ellipsoid with an axis ratio near 3:2. These observations agree with the predictions of Möller and Nix,[4] and also recent calculations by Nazarewicz and Aberg[6] and Dudek[7], but not with several other calculations.[2,3,5]

These nuclei are not good classical rotors, as the E_{4^+}/E_{2^+} ratio is only 2.8, and they may be triaxial or γ-soft in shape. To clarify this, one needs to observe more than the first few members of the groundstate band, and hence greater experimental sensitivity is required.

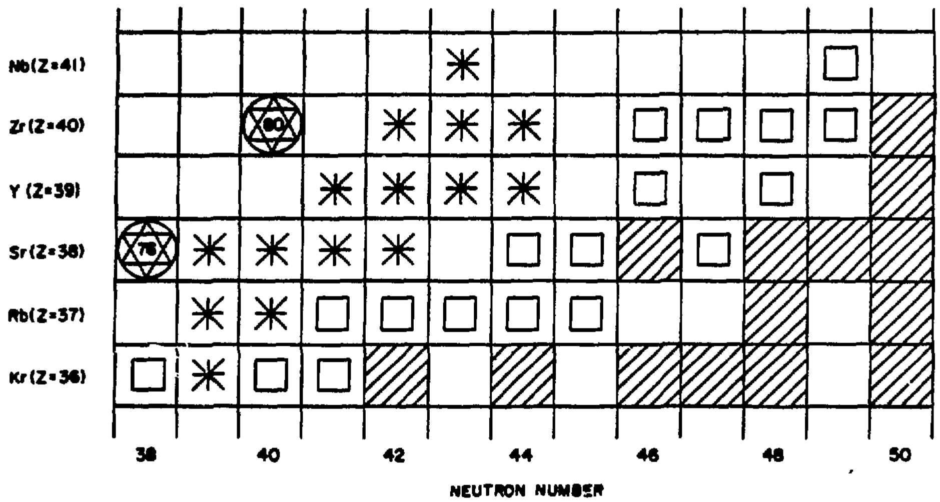


FIGURE 7 A map of the region of deformed nuclei near N=Z=40. Hatched boxes represent stable nuclei; squares, nuclei studied by conventional spectroscopy; stars, new isotopes observed in our studies; and stars and circles the self-conjugate nuclei predicted to be most deformed.

The isotope most weakly produced in Fig. 7 is $^{80}_{39}Y_{41}$ with a production cross section of 3±1 mb, while the states of $^{78}_{38}Sr_{40}$ were studied at ~8±2 mb. In order to improve the experimental efficiency for these measurements, an enlarged array is being assembled at Daresbury. The new detector will contain 33 liquid scintillator detectors with a geometric solid angle of 30% of 4π. In addition, an array of four 20 mm square E-ΔE telescopes will double the charged particle efficiency with better resolution and more explicit multiplicity information. It is expected that the new device will have an order of magnitude greater sensitivity, permitting identifications at ~100 μb and spectroscopy for nuclei produced at about the 1mb level.

3. High spin states in transitional nuclei near (Z,N)=(40,40)

In the region of transition from sphericity to large deformation the nuclei with N=44 are observed to have complex spectra exhibiting both single particle and collective modes of excitation. At $J^{\pi}\sim 8^{+}$ a strong upbend in the groundstate band of ${}^{82}_{38}Sr_{44}$ [12] and a backbend in ${}^{80}_{36}Kr_{44}$ [13] are observed which have been attributed[14] to $(g_{9/2})^2$ proton alignment. Potential energy surface calculations indicate that at relatively low rotational frequency (I~10) these nuclei, which are soft to both β and γ vibration in their groundstates, undergo a shape change and become highly deformed.[7]

In an attempt to differentiate between single particle alignment and shape changing in these nuclei, we have studied high spin bands in ${}^{83}_{39}Y_{44}$, ${}^{84}_{40}Zr_{44}$ and ${}^{80}_{38}Sr_{42}$, using the ${}^{28,29}Si + {}^{58}Ni$ reactions at $E_b \simeq 100$ MeV. The large recoil velocity and the high energy of γ-ray transitions necessitate a careful choice of experimental conditions to minimize Doppler broadening and shifts. In the first experiment at BNL, Compton suppressed γ-ray spectra were collected at 0° in coincidence with an array of Ge(Li) and NaI(Tℓ) detectors placed near the target. ${}^{80}Sr$ and ${}^{84}Zr$ were seen to J~16 and lifetimes were measured to J~10 using RDM and DSAM techniques. Figure 8 shows some bands observed in ${}^{83}Y$, where states up to a possible $J^{\pi}=(45/2^{+})$ were seen. These data appear to support the bandcrossing model of Funke, et al.[14] as the $J^{\pi}=8^{+}$ upbend of ${}^{82}Sr$ and ${}^{80}Kr$ is blocked in the odd proton nucleus.

A second experiment has been performed using the multiple anti-Compton array TESSA2 at Daresbury Laboratory.[15] This apparatus consists of six Compton

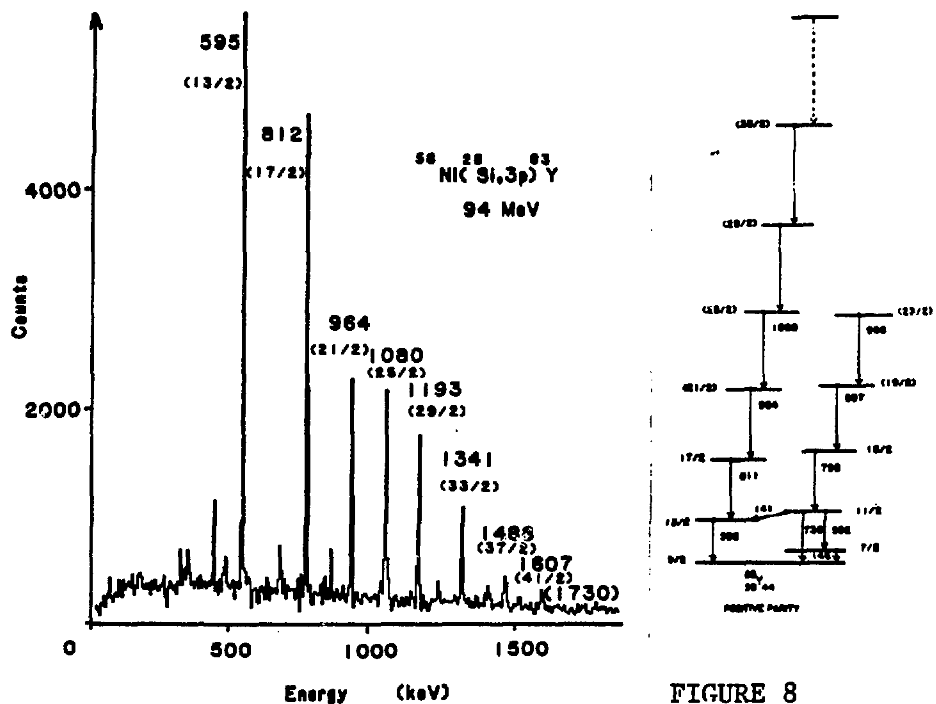


FIGURE 8

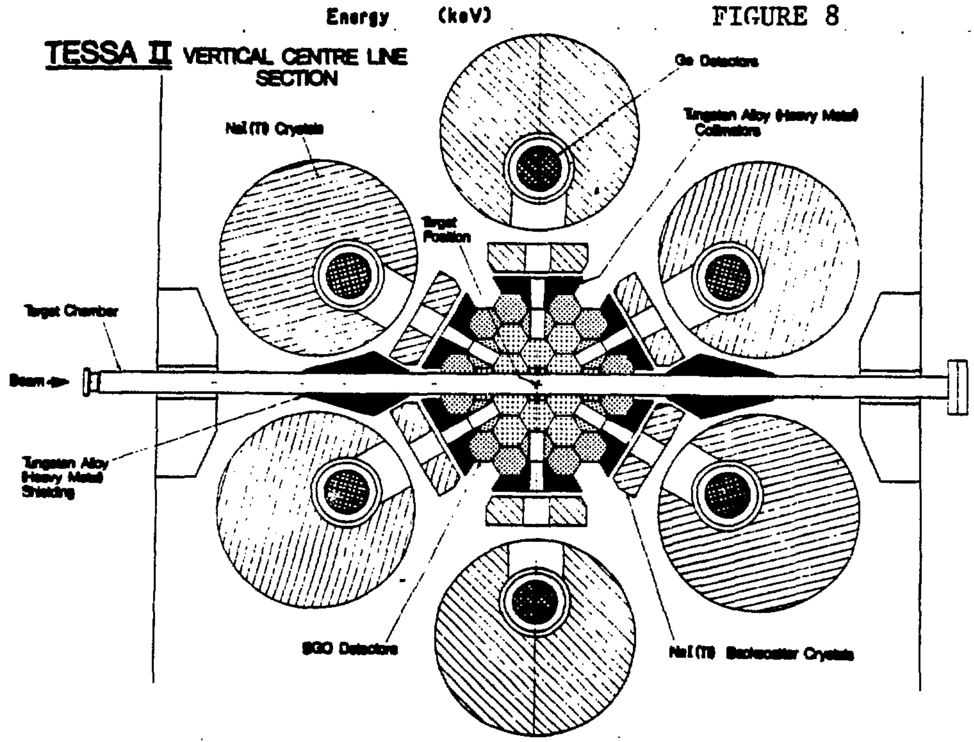


FIGURE 9 Compton suppressed Germanium detectors used at Daresbury to study high spin states in nuclei.

suppressed Ge detectors and a BGO total energy and multiplicity detector, schematically shown in Fig. 9. Analysis of the data has just begun, but in ^{84}Zr the groundstate band has been advanced from J~16 to J~(26)! A tentative decay scheme for ^{84}Zr is shown in Fig. 10. Many other transitions in ^{84}Zr have been found but not yet placed in the decay scheme.

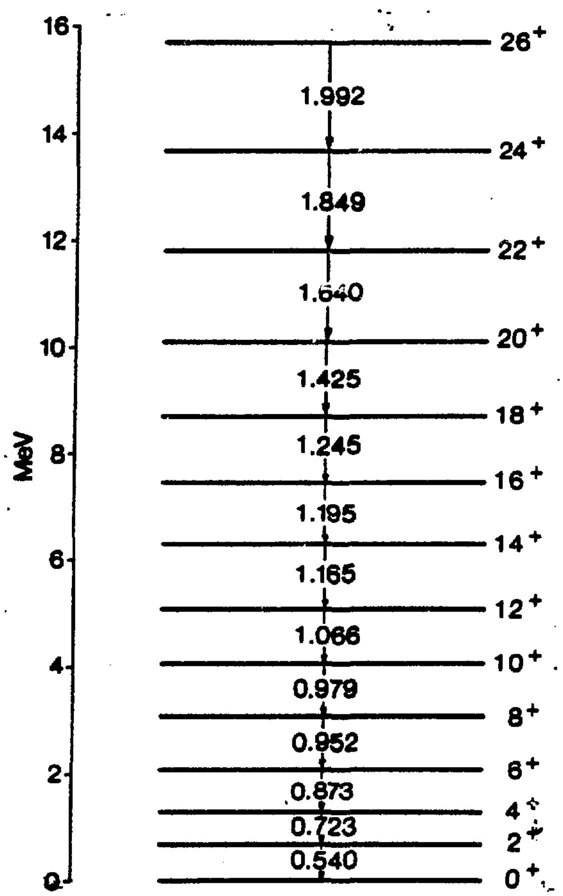


FIGURE 10 The yrast sequence in ^{84}Zr is shown. Several other bands have been observed.

A striking change has been observed in the moment of inertia $\mathcal{J}$ at a rotational frequency $\hbar\omega$=0.6 MeV (Fig. 11).

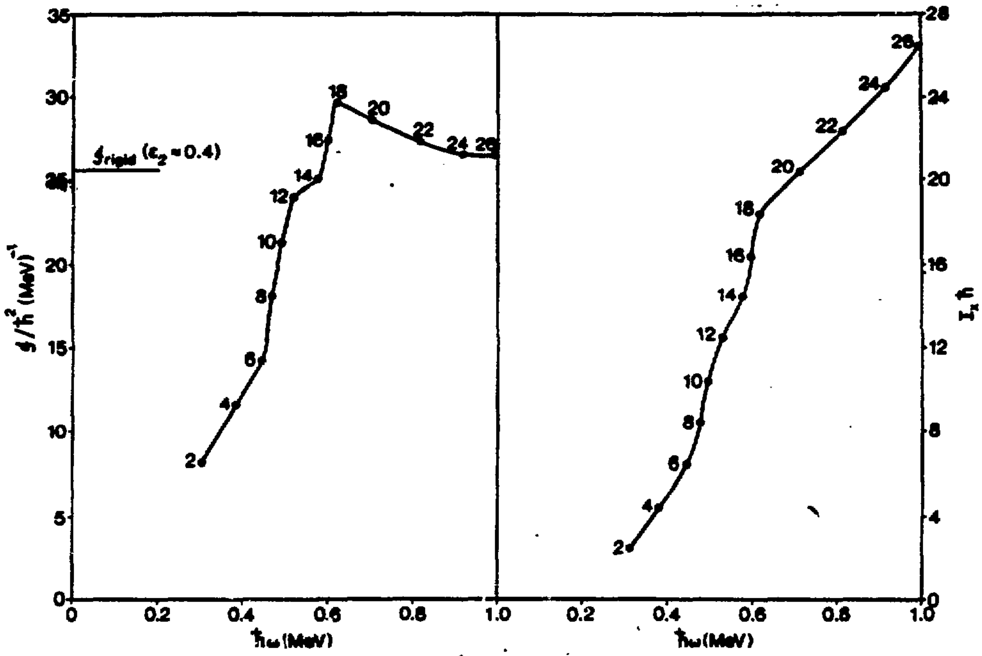


FIGURE 11 For ^{84}Zr: on the right, the increase in spin (I) with rotational frequency, and on the left, the variation of the moment of inertia ($\mathcal{J}$).

After rising rapidly, $\mathcal{J}$ approaches the rigid body value for an ellipsoid with deformation $\varepsilon_2 \sim 0.4$. This may well signal the predicted shape change to yrast states with large deformation. Much work remains to be done on this problem, both in analysis and interpretation of these data.

4. Spectroscopy of the (Z,N)=(40,64) region

The region of deformed rotors with A~100 was first observed by Cheifetz, et al.[16] They examined x- and γ-ray spectra collected in coincidence with fission fragments from the decay of a ^{252}Cf source. Rotational bands were seen in heavy Sr, Zr and Mo isotopes.

More recently, detailed measurements have been made of β^--decay following the mass separation of fission fragments produced in neutron[17,18] and proton[19] induced fission. The lifetimes of the first 2^+ states in $^{98,100}Sr$ have been extracted.[19] The quadrupole moments deduced (Q_o=3.16b for ^{98}Sr; 3.32b for ^{100}Sr) and deformations (ε_2=0.28 and ε_2=0.29, respectively) correspond closely to the predictions of Möller and Nix[4] (ε_2=0.33, ε_4=0.005). These nuclei appear to be extremely good rotors with $E_4{}^+/E_2{}^+$ = 3.00 and 3.23, respectively, which are close to the rigid axially symmetric rotor value of 3.33. The results do not seem to verify the predictions of very γ-soft shapes made by other authors.[5,3,20]

An extended rotational band has been found[21] in the odd-A N=60 nucleus ^{99}Y. A high spin isomer is populated in β^--decay which de-excites into the band at J=19/2.

At present this region has only been studied using fission fragment spectroscopy. Experimental access for "in beam" studies using deep inelastic or massive transfer reactions may be possible and could greatly increase the information available.

5. The $(Z,N)\simeq(64,64)$ region

The heaviest deformed region we shall discuss is, at present, the least studied. Its center, expected to be near mass 130, lies on the wrong side of the proton dripline to be reached in experiment. However, a recent calculation by Leander and Möller[22] predicted that a peninsula of very deformed nuclei (ε_2>0.3) extends well into the region of experimental accessibility. As yet, virtually nothing is known about this region from experiment. Both "in beam" and radioactive decay studies will be needed to clarify the properties of these nuclei, and the complementary nature of prompt and delayed studies must be emphasized. Clearly, this is a promising region for further studies.

Figure 3 indicates that another region of deformed nuclei with Z>86 and N<110 may exist. In principle, compound nuclei in this region may be formed, but the proximity of the proton dripline and competition from fission would make spectroscopic measurements extremely difficult. This region could only be studied using the recoil separator method.

6. Conclusions

The availability of a wide variety of high energy heavy ion beams has opened up new regions of the nuclear table for experimental access, particularly on the neutron deficient side of stability. The development of methods for enhancing the observation of nuclei produced in weak reaction channels, either by multiple coincidence experiments or by recoil separators, should permit spectroscopy of nuclei produced in compound nuclear reactions with cross sections of <1 mb.

With these methods, a few measurements of nuclear properties can be made very far from stability, and detailed spectroscopic studies should be possible on those nuclei which are presently at the limit of our sensitivity. Both deformed regions, as discussed in this paper, and new spherical regions (for example, the nuclei near $^{100}_{50}Sn_{50}$) can be studied.

This type of spectroscopy is in its infancy, but should provide wide ranging and discriminating tests of a variety of nuclear models in the near future.

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