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EVOLUTION OF NUCLEAR SHAPES AT HIGH SPINS

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I. Introduction

Outstanding progress has been made during the past ten years on an understanding of the properties of nuclei excited into states of high angular momentum. Much of the experimental progress has resulted from γ-γ coincidence measurements utilizing complex detector arrays. Many of the properties of the yrast and near-yrast bands in nuclei revealed in these measurements have become reasonably well explained by current theory. Both cranked shell model (CSM) and cranked Hartree-Fock Bogoliubov (CHFB) calculations have enjoyed considerable success in accounting for many aspects of high spin behavior. However, for a detailed understanding of the structure of these high spin states and for a stringent test of these models, it is necessary to resort to measurements of their static and dynamic electromagnetic multipole moments. During the past few years we at Oak Ridge have concentrated on studies of the latter quantity, the dynamic electric quadrupole (E2) moments which are a direct reflection of the collective aspects of the nuclear wave functions. For this, we have carried out Doppler-shift lifetime measurements utilizing primarily the recoil-distance technique.

The nuclei with neutron number N ≈ 90 possess many interesting properties. These nuclei have very shallow minima in their potential energy surfaces, and thus, are very susceptible to deformation driving influences. It is the evolution of nuclear shapes as a function of spin or rotational frequency for these nuclei that has commanded much of our interest in the lifetime measurements to be discussed here. There is growing evidence that many deformed nuclei which have prolate shapes in their ground states conform to triaxial or oblate shapes at higher spins. Since the E2 matrix elements along the yrast line are sensitive indicators of deformation changes, measurements of lifetimes of these states to provide the matrix elements has become the major avenue for tracing the evolving shape of a nucleus at high spin. Of the several nuclei we have studied with N ≈ 90, those to be discussed here are ^{160,161}Yb [FEW82], [JOH82], [FEW82], [FEW85] and ^{158}Er [OSH84a], [OSH84b]. In addition, we will discuss briefly the preliminary, but interesting and surprising results from our recent investigation of the N = 98 nucleus, ^{172}W [RAO85].

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II. Experimental Aspects and Data Analyses

Both ^{160}Yb and ^{161}Yb were produced by the reactions ^{116}Cd(^{48}Ti,xn) and its inverse ^{48}Ti(^{116}Cd,xn), at a center-of-mass energy of 145 MeV in each case. The recoil-distance device used in the measurements is discussed in [JOH81]. It was designed to fit inside the annular opening of a 25-cm x 25-cm NaI crystal which acts as a total-energy filter. In this way it was possible to gate on given regions of the total γ-ray energy spectrum and get enhancement of the desired reaction channel. Spectra were obtained for a total of 17 different flight times.

Lifetimes were extracted from the resulting decay curves by the computer program, LIFETIME [WEL85] which includes all of the usual corrections [STU76] to the data. Knowing the general features of the level scheme, one usually models a two-step cascade side feeding to each level to account for population from undefined transitions. The program then solves the Bateman equations while adjusting the lifetimes and initial populations of the levels to obtain the best fits to the decay curves. Both the shifted and unshifted γ-ray intensities are used in the fitting procedure. Uncertainties in the lifetimes were determined by the method of the subroutine MINOS, described in [JAM75].

Excited ^{158}Er nuclei for these studies were produced via the reaction ^{128}Te(^{34}S,4n) at a bombarding energy of 155 MeV. In these experiments the large NaI detector was removed in order to place an array of five Ge detectors at 90° with respect to the beam direction and at close geometry (6 cm) to the target. This was done in order to test if a high-efficiency coincidence measurement could offer simplifications in the analysis and interpretation of the experimental data, especially with respect to simplifying the analyses problems associated with side feeding. Direct side feeding makes no contribution to a γ-ray transition if the spectrum is gated by band members higher than the transition of interest.

Measurements were taken on ^{158}Er at a total of 14 target-stopper distances. A portion of the total-projected spectra taken at four of the target-stopper separations is shown in Fig. 1. These spectra are of excellent statistical quality and reveal a favorable peak-to-background ratio in the 0° detector as a result of using the Compton suppression shield.

Lifetimes for the yrast sequence of ^{158}Er were determined from four different sets of coincidence data: 1) that from gating on the first

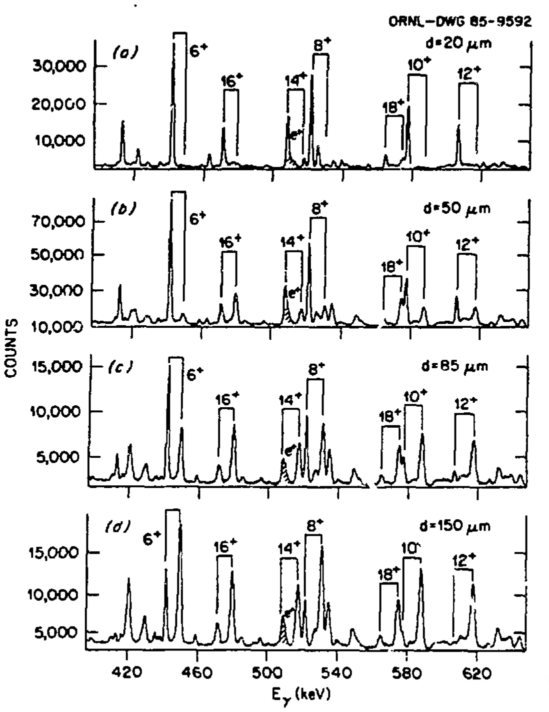

Fig. 1. Illustrative "total-projected" coincidence spectra of ^{158}Er covering the 400-650 keV region for four of the fourteen distances measured.

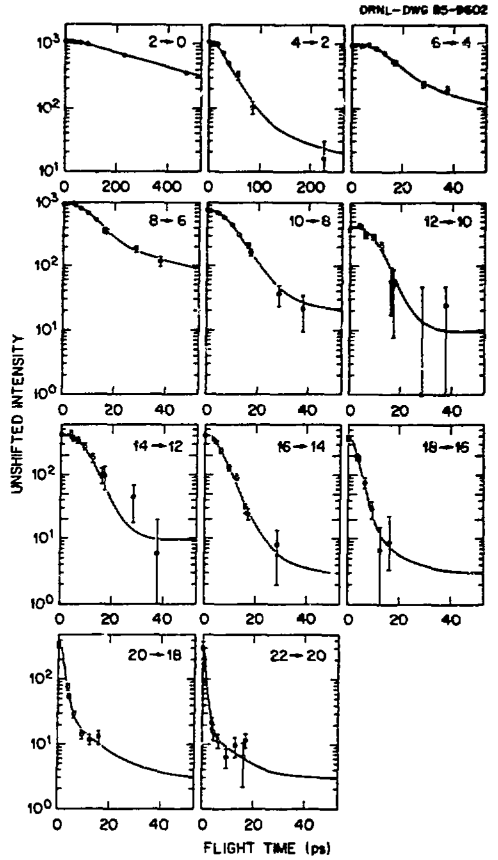

Fig. 2. Decay curves for members of the yrast sequence in ^{158}Er. The points represent the experimental data with the appropriate corrections. The solid curves are the fitted time distributions determined by the program LIFETIME.

transition above the one of interest; 2) that from gating on the second transition above the one of interest; 3) that from the sum of all gates below the transition of interest; and 4) that from the total-projected coincidences. Although side feeding to the state of interest is not eliminated in the last two types of data, they have an advantage in being of excellent statistical quality. In fact, we found that the program LIFETIME handled their more complex side feeding conditions quite well, based on comparisons of lifetimes from all four sets of data. In Fig. 2 are shown experimental data for each state and the program fits to these data.

For the ^{172}W studies, the ^{124}Sn (^{52}Cr, 4n) reaction was utilized at a beam energy of E_{Lab} = 230 MeV. The experimental arrangement was similar to that for ^{158}Er measurements, except here we used six large volume Ge detectors at 90° for coincidence gating. Data were collected for 18 recoil flight distances ranging from 16 μm to 7mm. To this point, the preliminary lifetime analyses are available only for the total projected coincidence spectra and the sums of gates below the transition of interest.

III. Discussion

Experimental transition quadrupole moments, Q_t, were obtained from the reduced electric quadrupole transition probabilities, B(E2), according to the expression

$$B(E2:I\rightarrow I-2) = \frac{5}{16\pi} \langle I\ 2\ 0\ 0 | I-2\ 0\rangle^2 Q_t^2,$$

where the term in brackets is a Clebsch-Gordon coefficient. In Fig. 3, these Q_t values are plotted as a function of the rotational frequency for some yrast and near-yrast states in ^{160}Yb and ^{161}Yb. Figure 4 shows a plot of Q_t values for the yrast sequence of ^{158}Er. The latter data show clear evidence of centrifugal stretching in the ground band as expected for an N = 90 nucleus. The data for the ground band of ^{160}Yb are, unfortunately, too limited to indicate whether this effect is present there.

A most interesting feature of the data in Fig. 3 is that the quasiparticle bands in both ^{160}Yb and ^{161}Yb show an overall trend of loss of collectivity with increasing ω. For ^{160}Yb there are three different two-quasiparticle bands, with each showing Q_t values behaving somewhat similarly as a function of the rotational frequency. Likewise, ^{161}Yb shows one- and three-quasiparticle bands with rather similar behavior. As seen in Fig. 4, the ^{158}Er Q_t values also show a dropoff in the s band. In fact, the Q_t values for the 8$^-$, 9$^-$ and s bands

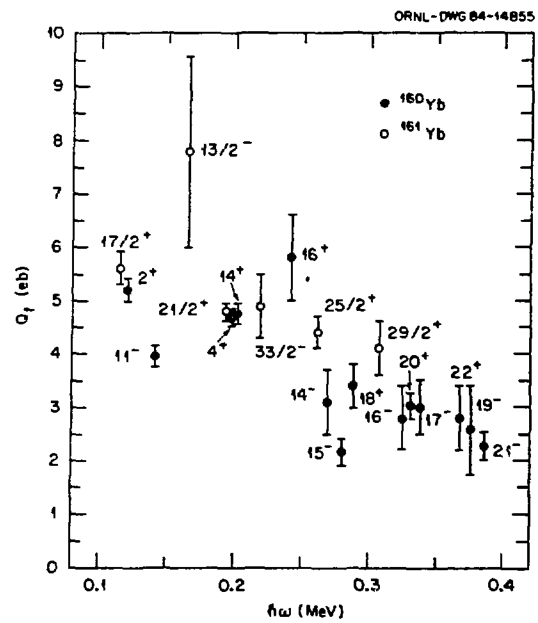

Fig. 3. Transition quadrupole moments of some yrast and near-yrast states of ^{160,161}Yb vs rotational frequency.

of ^{158}Er show a reducing trend when plotted as a function of rotational frequency, although it is less pronounced than is the data of Fig. 3. The common aligned quasiparticle in all of these bands is the lowest energy $i_{13/2}$ orbital with parity and signature $(\pi,\alpha) = (+,+1/2)$. This quasiparticle is coupled to the $(-,+1/2)$ and $(-,-1/2)$ $h_{9/2}$ orbitals to form the 6^- and 9^- side bands in ^{160}Yb and the 8^- and 9^- bands in ^{158}Er. The similarities in the behavior of Q_t with ω for these bands suggest the possibility that the $i_{13/2}$ $(+,+1/2)$ quasineutron has a dominant influence on the core.

Addressing the ideas discussed above, the group at Lund has reported [BEN83] results of self-consistent cranked Hartree-Fock-Bogoliubov (HFB) calculations of the shape of ^{160}Yb as a function of angular momentum. They find that the $i_{13/2}$ alignment produces a quadrupole deformation ε_2 which is near the ground-state value and which remains approximately constant with spin. However, the triaxiality parameter γ shows a steady increase, reaching about 10° by $I = 18^+$, the highest spin they reported. (In the Lund convention, $\gamma = 0°$ corresponds to collective rotations of a prolate ellipsoid and $\gamma = 60°$ corresponds to noncollective rotations of an oblate ellipsoid.)

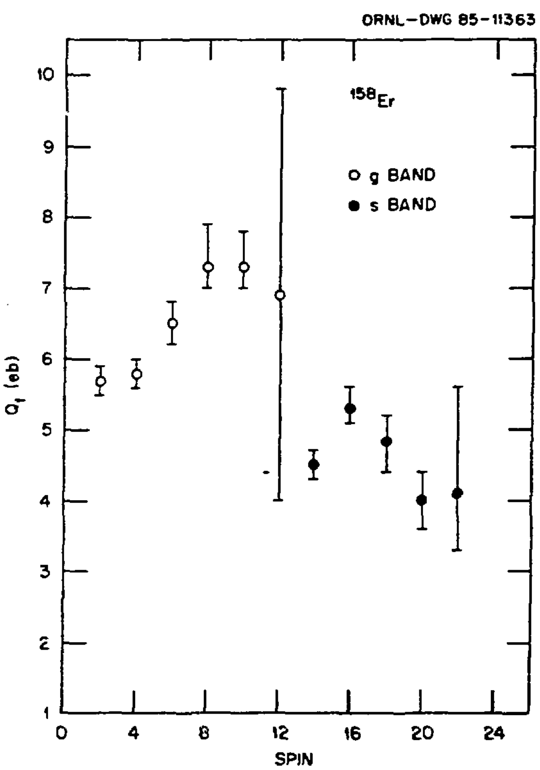

Fig. 4. Transition quadrupole moments of yrast states in ^{158}Er.

Another theoretical approach has also been taken [LEA83] [FRA83] and it involves a more phenomenological examination of the effects of the γ degree of freedom on the energy of the quasiparticles and the core. The cranked shell model (CSM) is used to calculate the quasiparticle energies which are added to the energy of the rotating core as a function of γ. In the N~90 transition region, the $i_{13/2}$ quasiparticles drive the equilibrium value of γ to around 5°. So, at least qualitatively, both the self-consistent results for ^{160}Yb and the CSM results (calculated for ^{160}Yb, but will be very similar for ^{158}Er) are seen to be in agreement with our experimentally observed loss of collectivity at high rotational frequencies in the quasiparticle bands. However, we point out that should all of the loss of collectivity in these two nuclei be attributed to triaxiality, it is necessary to invoke values of γ in excess of 20° at spin 18^+.

An interesting aspet of the CSM approach above is that the deformation driving tendency is strongly affected by the location of the Fermi surface of a nucleus. If it lies low in the shell, then the high-j quasiparticle has its lowest energy for $\gamma > 0$. When the Fermi surface lies near mid shell, γ tends to move to the negative sector, giving rise to triaxiality conforming to collective rotations of an oblate ellipsoid. Admittedly, a nucleus whose neutron Fermi surface lies near the middle of the $i_{13/2}$ shell should be a well-deformed rotor with a pronounced minimum in its potential energy surface and, therefore, it is expected to be relatively resistant to triaxial deformation driving influences.

In measuring the lifetimes of high-spin states in ^{172}W (N = 98, which is near the middle of the $i_{13/2}$ shell), we did not anticipate a significant difference in the collectivity at spins 18-20 in the yrast sequence from that found low in the ground band. At this point we [RAO85] have only partially completed the data anlayses, but to our surprise, the Q_t values of ^{172}W shown in Fig. 5 display a very similar behavior to the much softer nuclei near N = 90. This result raises some very interesting questions relating to which degrees of freedom are changing to produce this effect. Obviously, additional lifetime measurements of nuclei near N = 96-100 are important; but the search for better theories to account for such phenomena is equally demanded.

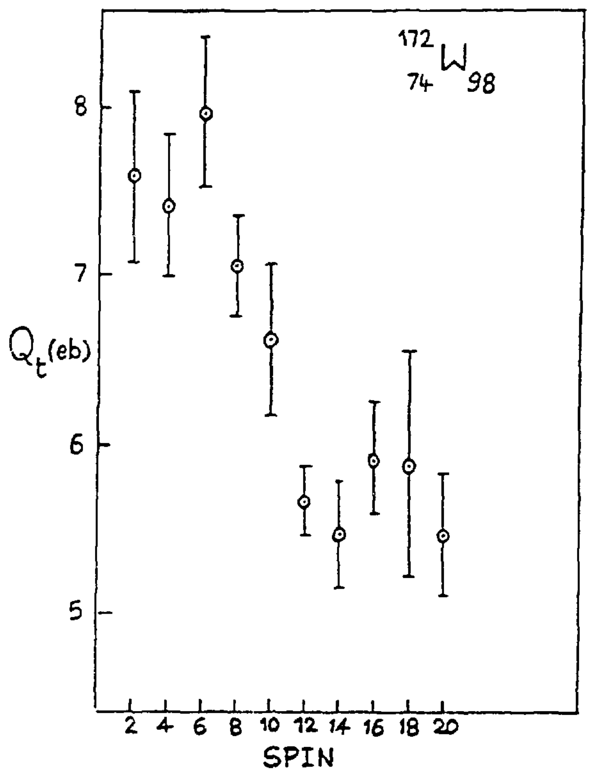

Fig. 5. Transition quadrupole moments of yrast states in ^{172}W.

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