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Evolution of Nuclear Shapes at High Spins
as Determined by Lifetime Measurements

Noah Johnson

Oak Ridge National Laboratory
Oak Ridge, TN 37831

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To increase both our understanding of the structure of high-spin states and of the evolution of nuclear shapes as a function of spin and to provide a stringent test of the nuclear theories relevant to these topics, we have resorted to lifetime measurements of these states, primarily by the Doppler-shift recoil-distance technique. The dynamic electromagnetic multipole moments extracted from these measurements are a direct reflection of the collective aspects of the nuclear wave functions. We have concentrated on nuclei near $N = 90$, where the potential energy surfaces are often shallow in the γ degree of freedom and thus, are rather susceptible to the deformation driving influences of the quasiparticles involved in the rotation-alignment process.

In a series of earlier measurements on $^{159,160,161,162,163}\text{Yb}$ we¹ placed the recoil-distance device (plunger) inside a large NaI crystal which acted as a total decay energy filter and provided some reaction-channel selection in the heavy-ion induced fusion process. Transition quadrupole moments (Q_t) were extracted from these data by use of the equation:

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

The Q_t values reveal a significant reduction in the collectivity for the higher spins. A plot of these data for $^{160,161}\text{Yb}$ is shown in Fig. 1. At least qualitatively, the loss of collectivity at the higher rotational frequencies is accounted for by the self-consistent calculations of Bengtsson, Chen, Zhang, and Åberg² as well as by the cranked shell model approach of Frauendorf, Leander,

and May³. An inspection of the routhian for the $i_{13/2} (+, +1/2)$ neutron orbital reveals rather clearly its strong driving character to $\gamma > 0^\circ$, resulting in the movement toward triaxial shapes for these nuclei.

Lifetime measurements have also been carried out⁴ on another $N = 90$ nucleus, ^{158}Er . In order to simplify the spectra and to test for improvements in fits to the data when sidefeeding to the state of interest is eliminated, these measurements were made in the γ - γ coincidence mode. The experimental arrangement was similar to that shown in Fig. 2 where a ring of gating Ge detectors was placed at 90° to the beam and a Compton-suppressed Ge detector was located at 0° to record the shifted and unshifted peaks in the spectra. (In this figure the detector arrangement has not been moved forward about the plunger). Lifetimes of the 2^+ through 22^+ members of the yrast sequence were extracted from data involving both gating above and gating below the transition of interest and from the total projected spectrum. Good agreement was achieved between these various approaches and a plot of average Q_t values is shown in Fig. 3. The trend in the ground band shows evidence of centrifugal stretching while the s band shows a reduction in collective strength when compared with the ground band. In Fig. 4 the Q_t values for the s, 8^- and 9^- bands of ^{158}Er are plotted and the reducing trend at higher rotational frequencies is rather pronounced.

R. Bengtsson and T. Bengtsson⁵ have carried out self-consistent calculations for the yrast band of ^{158}Er and find stretching in the ground band comparable to experiment. In the s band, however, their calculations lead to Q_t values comparable to that of the 2^+ state. An interesting observation is that should one make the assumption that all of the loss of collectivity for the

20^+ state in ^{160}Yb and ^{158}Er results from triaxiality, γ deformations of 27° and 22° , respectively, would be required.

The calculated systematics of triaxial shape driving⁶ orbitals suggest that the collectivity should not drop at higher neutron number around $N = 98$, where the aligned $i_{13/2}$ orbits are different because the Fermi level lies higher in the shell. Here it is expected that $i_{13/2}$ quasiparticles will drive γ into the collective sector ($\gamma < 0$). To provide a test of this idea we⁷ have carried out lifetime measurements on $^{172}_{74}\text{W}_{98}$. This nucleus is a slow upbender as shown in Fig. 5. The experimental arrangement of Fig. 2 was used in the measurements. The data taken at 19 target-stopper distances were also analyzed in several modes involving gating above (GA) the transition of interest, sums of gates below (SGB) a transition, and from the total projected (TP) coincidence spectra.

As before, lifetimes were extracted by use of the computer program LIFETIME⁸ which applies all the usual corrections to the data and handles the problems of feeding by direct solution of the Bateman equations. Program fits to the shifted and unshifted intensities for some ^{172}W transitions are shown in Fig. 6. The Q_t values for the ^{172}W yrast sequence are plotted in Fig. 7. This, at first surprising, result shows about a 15% reduction in the Q_t values for $I > 12$.

Results from cranked self-consistent calculations are shown as a dashed line in Fig. 7 and as expected when the mid-shell $i_{13/2}$ neutron orbitals provide the driving force, it does not show a reduction in Q_t at the higher spins. What is needed is a high-j low- Ω orbit near the Fermi surface which can drive the shape toward positive γ deformation. As shown in the tabulation of Fig. 8, the

proton $h_{9/2}$ [541]1/2 orbital is a possible candidate. Although the band structures are not so well known around ^{172}W , there seems to be evidence for proton $h_{9/2}$ alignment in odd Z neighbors, e.g., ^{171}Ta (Ref. 9). Figure 9 shows alignment (i_x) plots for bands built on the $\pi h_{9/2}$ [541]1/2 and $\pi h_{11/2}$ [541]9/2 states. The former shows an alignment gain of $\sim 6 \hbar$, but when the odd proton is in the [541]9/2 orbit, $i_x > 7 \hbar$. Thus, it appears that the [541]1/2 protons are contributing to the alignment along with the $i_{13/2}$ neutrons as substantiated by the fact that they are blocked and, thus, contribute less to the alignment of the [541]1/2 band. Blocking and alignment gain arguments for several nearby nuclei attest to the prominence of the [541]1/2 orbital in this region.

A 3-band mixing calculation was carried out for the ground band, the $\pi(h_{9/2})^2$ band, and a $\pi(h_{9/2})^2 - \nu(i_{13/2})^2$ band. As seen in the solid line of Fig. 7, the results are in good agreement with experiment. This calculation shows that the $h_{9/2}$ protons most likely are involved in the ^{172}W upbend and offer an explanation for the reduced Q_t values at high spin.

Further evidence for a 3-band crossing comes from the measured dynamical moment of inertia, $\mathcal{J}^{(2)}$, defined as

$$\mathcal{J}^{(2)} = 4 / \{E_Y(I+2 \rightarrow I) - E_Y(I \rightarrow I-2)\}.$$

The plot of $\mathcal{J}^{(2)}$ for ^{172}W (Fig. 10) has only one peak, but there is also a shoulder just below the peak. This shoulder was reproduced by the 3-band mixing calculation corresponding to the solid curve in Fig. 7, but it cannot be obtained from a 2 band model and it does not occur, for example, in the $N = 98$ isotone ^{168}Yb (see Fig. 10). Examination of Fig. 10 shows that in the odd-Z

neighbor ^{171}Ta , the shoulder is present in the positive parity band, but it is blocked out by a proton in the $[541]1/2$ orbital.

Additional empirical evidence linking the third band to proton $h_{9/2}$ alignment is the systematic observation of a shoulder or two peaks in the $\mathcal{J}^{(2)}$ plot for doubly even nuclei throughout the region where $\pi [541]1/2$ comes low in energy. The crosses in Fig. 8 indicate such cases. On the outskirts of the region of crosses in Fig. 8 there are some other nuclei, indicated by crosses in parentheses, for which evidence for a third band has been found at spins just above the first upbend or backbend.

To summarize the results for ^{172}W , a measurement of transition quadrupole moments for the yrast states in this nucleus has revealed an unexpected drop at high spin which could be explained by the simultaneous alignment of $h_{9/2}$ protons and $i_{13/2}$ neutrons. The role of the $h_{9/2}$ protons is supported by energy-level systematics which show that a crossing of three interacting bands does indeed occur precisely in the region of nuclei where the odd-Z ground state is $h_{9/2}$, and in odd-Z nuclei the "extra" band is blocked out by an $h_{9/2}$ proton quasiparticle.

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Fig. 1

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Table II. Experimental $[541]^{1/2}$ excitation energies in keV for odd-Z nuclei, from Refs. 15-17. Crosses (bars) mark doubly even nuclei where evidence for a third band is (not) found in the yrast levels at $I < 22$.

Z	N	96	98	100	102	104	106	108	110
79						0	0	121	325
78							X		
77							0	0	186
76		X	X	X	X	X	(X)		
75		0 ^a			0	65	357	599	917
74		—	X	X	X	—	—		
73			0	0	51	186	628		
72		—	(X)	—	(X)				
71		107	29	71	124	354	762		
70		—	—	—	—				
69		182	172	342	751				

^a From in-beam studies only.

Fig. 8

Fig. 9

Fig. 10

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