COLLECTIVE PROPERTIES AND SHAPES OF NUCLEI AT VERY HIGH SPINS

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INTRODUCTION

A topic which has been of major interest to us for some years now involves the evolution of nuclear collectivity at high rotational frequencies and the accompanying changes in the shapes of nuclei in these extreme conditions. We carry out these studies by determining the dynamic electromagnetic multipole moments which are a reflection of the collective aspects of the nuclear wave functions. The most direct way to get these multipole moments is by measurements of excited-state lifetimes which provide the transition matrix elements in a fairly straightforward fashion.

Although the primary emphasis of this paper is on the collectivity of the very high-spin states in ^{160}Yb and ^{164}Yb, it is important to review briefly some work we began about ten years ago on lifetime studies of moderately high spins in nuclei near N = 90 using the recoil-distance (RD) method. These nuclei are just at the onset of permanent deformation and are known to be very soft with respect to deformation changes. This softness is clearly illustrated in contour diagrams of their potential-energy surfaces. For example, the potential energy surface of ^{160}Yb reveals that the minimum in the potential occurs around $\varepsilon \sim 0.2$ and that it is very shallow in the γ degree of freedom. Because of their γ softness, we (Johnson, 1982; Fewell *et al.*, 1985; Fewell *et al.*, 1988; McGowan et al., 1991; Oshima *et al.*, 1986) have studied several nuclei near N = 90 (^{159,160,161,162}Yb, ^{158}Er) to assess to what extent the polarization effects induced by rotation alignment of high-j quasiparticles affect their collectivity.

Our RD results for ^{160}Yb and ^{161}Yb revealed a marked loss of collectivity in the spin range of 12-22 $\hbar$ and although we were able to analyze the RD data for only a limited number of states in ^{162}Yb, it too shows some indications of a similar dropoff in collectivity. For these nuclei, where the Fermi surface lies near the bottom of the $i_{13/2}$ shell, we were able to understand our lifetime results – at least qualitatively – in terms of cranked shell model (CSM) calculations (Bengtsson *et al.*, 1983). After the backbend, these nuclei undergo a shape change (driven by the aligned $i_{13/2}$ quasineutrons) to a triaxial shape that is oriented so as to reduce the collectivity of the rotation, i.e., to positive values of the asymmetry shape parameter γ.

From the calculated systematics of triaxial shape-driving orbitals, it is expected that if one moves to where the Fermi surface is near the middle of the $i_{13/2}$ neutron shell, the minimum in the quasiparticle energy becomes shallower and moves to negative γ, reaching $\gamma = -120°$ (noncollective rotations of a prolate ellipsoid) when the whole shell is below the Fermi surface. Since negative values of γ correspond to enhanced collectivity, the nuclei near N = 98 will not be expected to show a reduction in collectivity in their *s* bands. A few years ago, we turned to studies of the light-mass tungsten and osmium nuclei to verify this idea. Here we carried out RD measurements on ^{170}W (McGowan *et al.*,

1988), ^{172}W (McGowan *et al.*, 1991) and ^{172}Os (Virtanen *et al.*, 1988). The data revealed that up to moderately high rotational frequencies ($\hbar\omega$ = 0.25 MeV) the transition quadrupole moments (Q_t) of these three mid-shell ($\nu i_{13/2}$) nuclei remain fairly constant.

More recently we have returned to those nuclei near N = 90 to address the question of what happens to the collectivity at yet higher rotational frequencies. Specifically, we have measured lifetimes of states in ^{160}Yb (Johnson *et al.*, 1991) and ^{164}Yb (Xie, 1990; Xie *et al.*, 1990; Xie *et al.*, 1990) in the spin range of 22-36. In these measurements we utilized the Doppler Broadened Line Shape (DBLS) Method because the very small values of the lifetimes prohibit use of the RD method.

EXPERIMENTS AND RESULTS

For the DBLS studies of ^{164}Yb, high-spin states were populated via the ^{124}Sn(^{44}Ca, 4n) reaction at a beam energy of 189 MeV. The beam was provided by the 25-MV Tandem Accelerator at Oak Ridge. This beam energy was chosen to maximize the yield of the 4n channel. The main competing reaction channels were 5n (^{163}Yb), 6n (^{162}Yb) and 3n (^{165}Yb). In this experiment, a 1.03 mg/cm^2 ^{124}Sn target, evaporated onto a 10 mg/cm^2 gold backing, was used to measure the lifetimes of the high-spin states of ^{164}Yb. A total of 170 million triple or higher-fold γ-ray coincidence events were accumulated. The Compton Suppression Spectrometer System used to collect these data consisted of 20 suppressed Ge detectors and it is shown in Fig. 1.

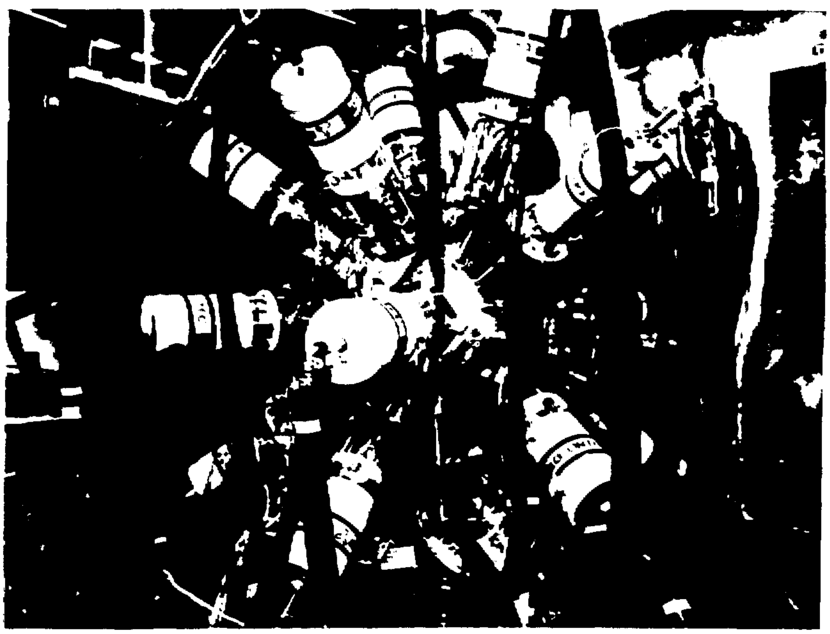

Fig. 1. Oak Ridge Compton Suppression Spectrometer System consisting of 20 Ge Detectors, each surrounded by a scintillator shield to detect and reject any events involving Compton-scattered photons.

Recently we also carried out similar experiments on ^{160}Yb produced in the reaction ^{120}Sn(^{44}Ca, 4n) ^{160}Yb at a beam energy of 200 MeV. Measurements were made on two different targets. In one case a 1.05-mg/cm^2 target of ^{120}Sn evaporated onto a 10 mg/cm^2 Au backing was employed, and in the other the same thickness of ^{120}Sn was used, but the backing was 28 mg/cm^2 Pb. With the Au-backed target we had a total of 394 x 10^6 γ-γ coincidence events involving a 45° or a 135° detector with any other detector. For the Pb-backed target 90 x 10^6 such events were accumulated. Data analysis for 160Yb was carried out in a fashion similar to that for ^{164}Yb, except that we had two sets of data for ^{160}Yb.

Analysis of the DBLS data was accomplished with the computer program *LINESHAPE* (Wells and Johnson, 1991). This program incorporates most of the subroutines in the lineshape analysis program *DSAMFT* written and supplied to us by J. Gascon (Gascon, 1989; Gascon *et al.*, 1990). The program includes the routine *DECHIST* written by Bacelar (Bacelar, 1989) to simulate the velocity history, including direction, of a series of recoiling nuclei using Monte Carlo techniques. In *LINESHAPE* we have added numerous new features to facilitate the analysis of DBLS data. For example, we have added the least-squares minimization routine *MINUIT* (James and Roos, 1975) and the stopping power routine *STOPO* (Milner, 1989) which provides the option of three prescriptions to generate a set of stopping powers for the recoiling nuclei.

With this program one calculates the line shapes for a transition at a series of 200 time steps over the range during which the nucleus comes to rest in the backing medium. First, the Monte Carlo technique is used to trace both the scattering directions and the velocities of the recoiling ions with the program *DECHIST*. This accounts primarily for the nuclear stopping power where large-angle scattering and large energy losses occur. For electronic stopping powers we used the tabulations of Northcliffe and Schilling, 1970). For each γ-ray transition energy, the apparent velocity distributions seen by 4 detectors at each, 45° and 135° in our experimental setup were then projected out of the file created by *DECHIST* via the program *HISTAVER*. These results were stored in "shape vs. time" matrices. Each matrix, with its 200 time steps, provides a complete set of shapes ranging from the fully-shifted (t = 0) to the "stopped" peaks. To illustrate, the variations in the energy distributions for the $32^+ \rightarrow 30^+$ transition in ^{160}Yb at six time intervals are shown in Fig. 2.

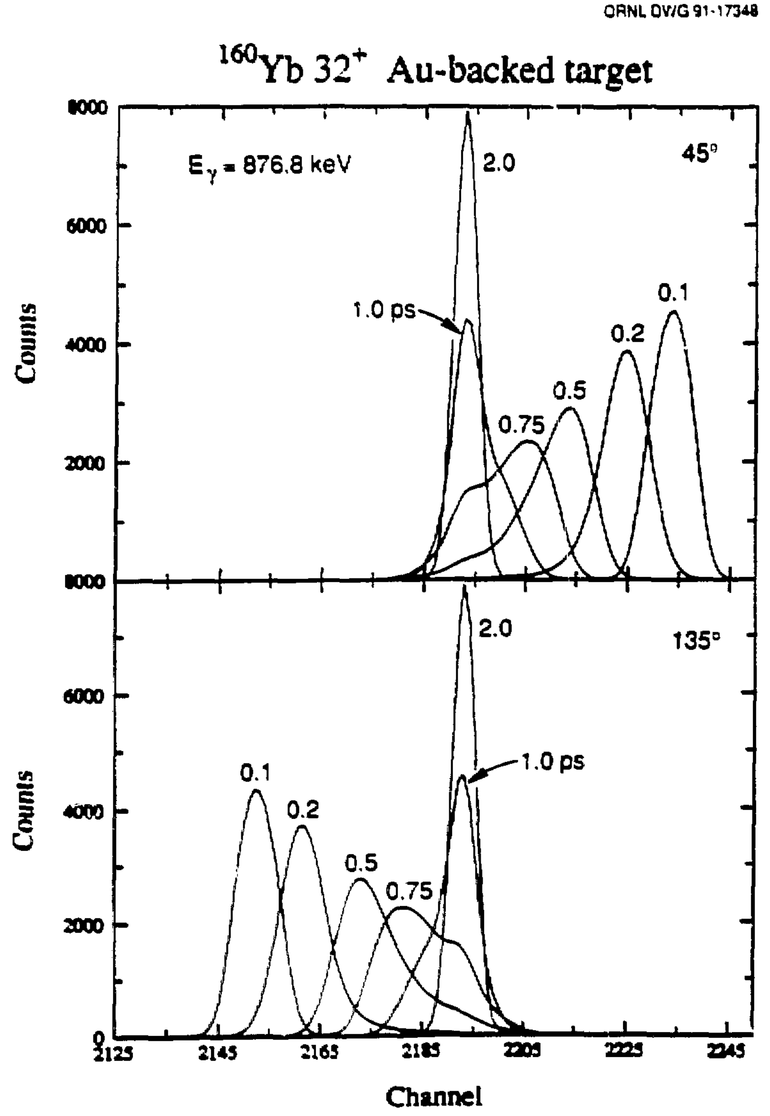

Fig. 2. Calculated energy distributions for the 876.8-keV, $32^+ \rightarrow 30^+$ transition in ^{160}Yb at six time intervals from the matrix of 200 such intervals generated by the computer program.

The time-dependent decay yield for a level is determined by both its lifetime and the lifetimes of levels that feed into it. The decay information from the known precursors cascading into the level of interest is handled in a straightforward manner by the analytical solutions of the Bateman equations. However, it is necessary to set up a model for the side feeding from the γ-ray continuum. We have tried both two-step cascade side feeding and five-state rotational-band side feeding where a moment of inertia of 65 MeV^{-1} was used. The results from both types of modeling were used in the final averaging process.

In the fitting program *LINESHAPE*, the output files of *HISTAVER* are used to calculate the energy distribution that best matches the experimental line shape. The program carries out a χ^2 minimization of the fit for (1) Q_t, the transition quadrupole moment; (2) Q_S, the transition quadrupole moment for a modeled side-feeding transition; (3) a normalizing factor [N] to normalize the intensity of the fitted transition at each angle; (4) the intercept [A] and slope [B] of a linear background; and (5) the intensities of any stopped background peaks one designates. For illustrative purposes, the data for the $26^+ \rightarrow 24^+$ transition in ^{164}Yb and the program fit to these data (the smooth solid line) are shown in Fig. 3. The dashed line shows the background and interfering peaks which are subtracted in the region of the lineshape under consideration.

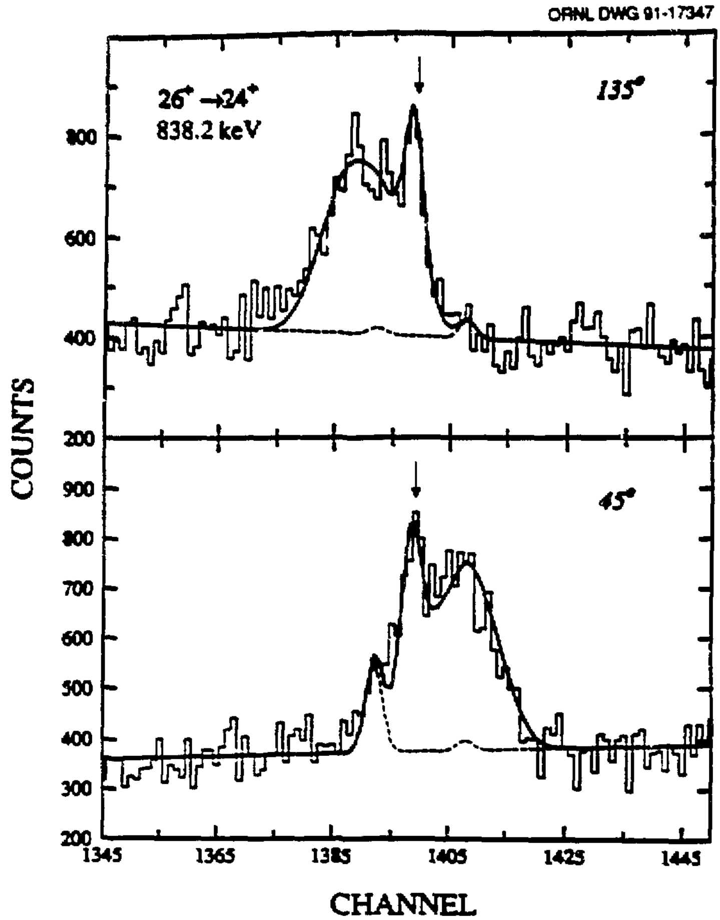

Fig. 3. Least squares fits for the 838.2-keV, $26^+ \rightarrow 24^+$ transition in ^{164}Yb. The data in the top frame result from a coincidence between any one of the four Ge detectors at 135° (backward) and any other Ge detector while that from the bottom frame is generated in a similar fashion for the four 45° (forward) Ge detectors.

In our current version of the program the uncertainties in the lifetimes are determined by the method of the subroutine *MINOS*. In this procedure, it is assumed that the point in the parameter space where χ^2 takes on its lowest value χ^2_{min} determines the most likely or best-fit parameter values, and that the region over which χ^2 takes on values smaller than χ^2_{min} + 1 corresponds to the "one-standard-deviation" confidence interval of 68%. The uncertainty for a given parameter was found by varying that parameter in steps above (below) its best value. At each step, this parameter was fixed and χ^2 was reminimized by varying all the other parameters. The step at which the reminimized χ^2 equaled χ^2_{min} +1 was used for the positive (negative) uncertainty for this parameter. This procedure can lead to rather asymmetric error limits on some of the lifetimes and transition quadrupole moments.

Once the decay curves have been fitted and the lifetimes determined, it is a simple matter to extract reduced electric quadrupole transition probabilities, B(E2). From these, the transition quadrupole moments, Q_t, are computed according to the expression

$$B(E2; I \rightarrow I-2) = \frac{5}{16\pi} < I\,2\,0\,0 \big| I-2\,0 >^2 Q_t^{\;2}, \qquad (1)$$

where the term in brackets is a Clebsch-Gordan coefficient.

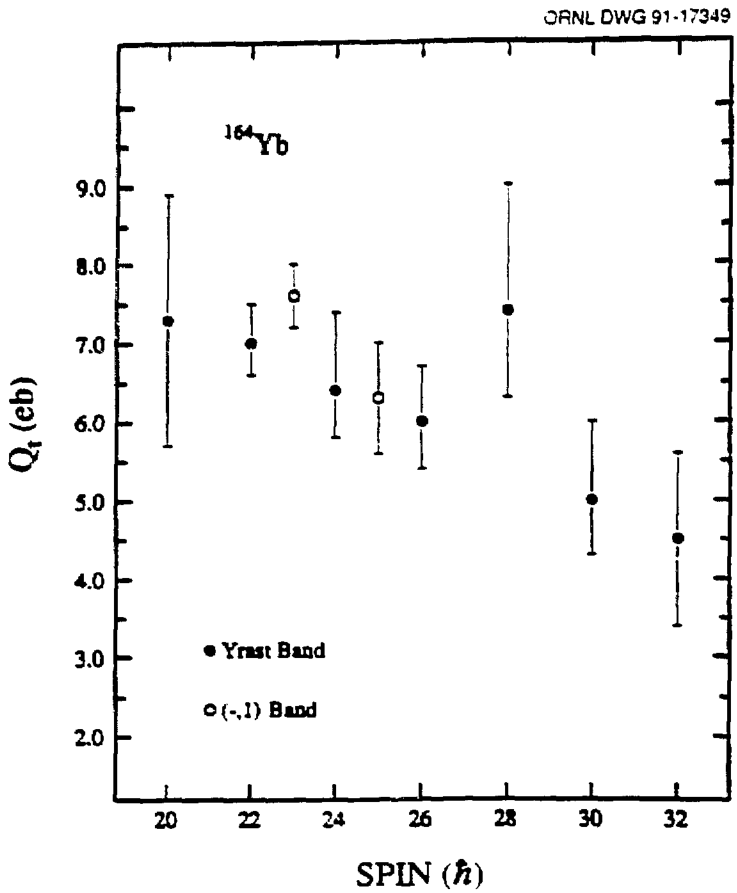

Fig. 4. Transition quadrupole moments (Q_t) versus spin for some members of the yrast sequence and the (-,1) band in ^{164}Yb.

In Fig. 4, the Q_t values determined for the 20^+ through 32^+ yrast transitions in ^{164}Yb are shown, along with values for two states in the (-,1) band. Figure 5 shows our Q_t values for 22^+ through 36^+ yrast transitions in ^{160}Yb. Also shown in Fig. 5 are the values for the lower members of the yrast and ground bands from our earlier RD measurements on this nucleus (Johnson, 1982; Fewell *et al.*, 1985; Fewell *et al.*, 1988). These ^{160}Yb Q_t values from the DBLS measurements are averages of the results for the Pb-backed and Au-backed ^{120}Sn targets. The errors are the largest Minos values determined in any of the fits. It is important to stress that data analyses are still not finalized and, thus, the picture for ^{160}Yb could eventually vary somewhat from that shown in Fig. 5.

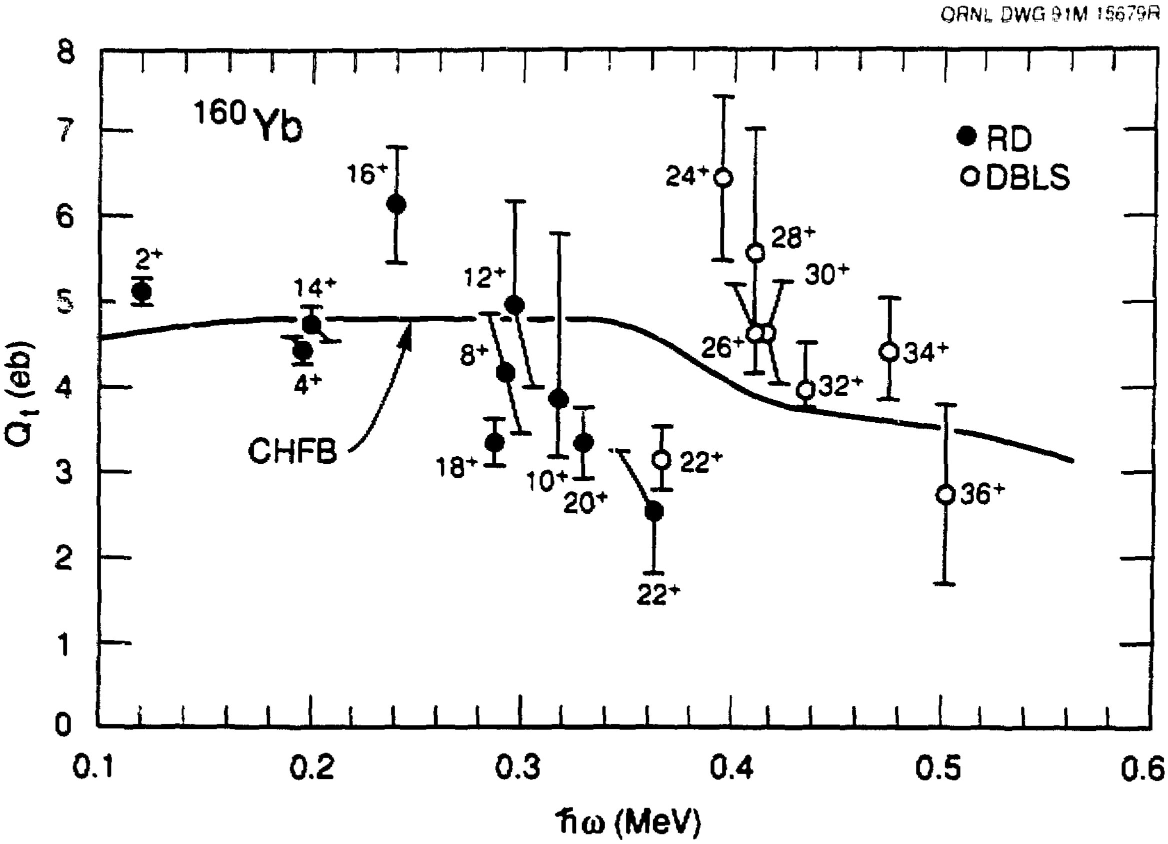

Fig. 5. Transition quadrupole moments (Q_t) for members of the yrast sequence in ^{160}Yb. The solid points are from earlier recoil-distance measurements (Fewell *et al.*, 1988) and the open circles are from the current DBLS experiments.

DISCUSSION

After our earlier RD measurements on ^{160}Yb there was much discussion about the rather significant dropoff in collectivity at I = 18-22. As already pointed out, this behavior is accounted for in a qualitative way in CSM calculations. One of the interesting questions that remained, however, concerned the issue of whether the Q_t values in the spin range of 20-40$\hbar$ would remain at about 3, if they would decrease yet further, or if there would be a return to collectivity similar to that in the ground band. Inspection of Fig. 5 indicates that the latter is probably the correct answer. Unfortunately, the $20^+ \rightarrow 18^+$ transition showed very little indication of a lineshape. Had we been able to get a lifetime for this transition from our DBLS data, we would have a better check on the indicated drop in collectivity reported in our earlier RD measurements.

This observed loss of collectivity in the rotational frequency range of $\hbar\omega = 0.29$-0.36 MeV and the recovery to about that of the ground band in the range of $\hbar\omega = 0.38$-0.48 MeV is difficult to understand within the framework of the cranking theories. It is especially puzzling that this recovery sets in at I = 24$^+$ because an examination of a plot of aligned angular momentum vs $\hbar\omega$ for the ^{160}Yb yrast sequence shows that following the rotation alignment of a pair of $i_{13/2}$ quasineutrons, there is only a smooth, gradual gain in alignment up to $\hbar\omega = 0.42$ MeV (at I = 26$^+$), at which point alignment of $h_{11/2}$ quasiprotons sets in. Thus, it is not at all clear why a sudden increase in collectivity at I = 24$^+$ should occur since this state is still predominately of an $i_{13/2}$ quasineutron character.

Strutinsky-type calculations of the expected shape evolution scheme for ^{160}Yb lend to predictions of possible band termination at a spin of 36$^+$ (Byrski *et al.*, 1987). They found two configurations which could exhaust the angular momentum by alignment of all valence particles along the rotation axis, arriving at $\gamma = 60°$ for $I = 36^+$. Such a band termination should produce a significant reduction in the collectivity in this process. Examination of Fig. 5 shows that, indeed, there is a sizable drop in Q_t at $I = 36^+$. However, because of the large error limits on this Q_t value, we cannot say with certainty that we have a signature for band termination.

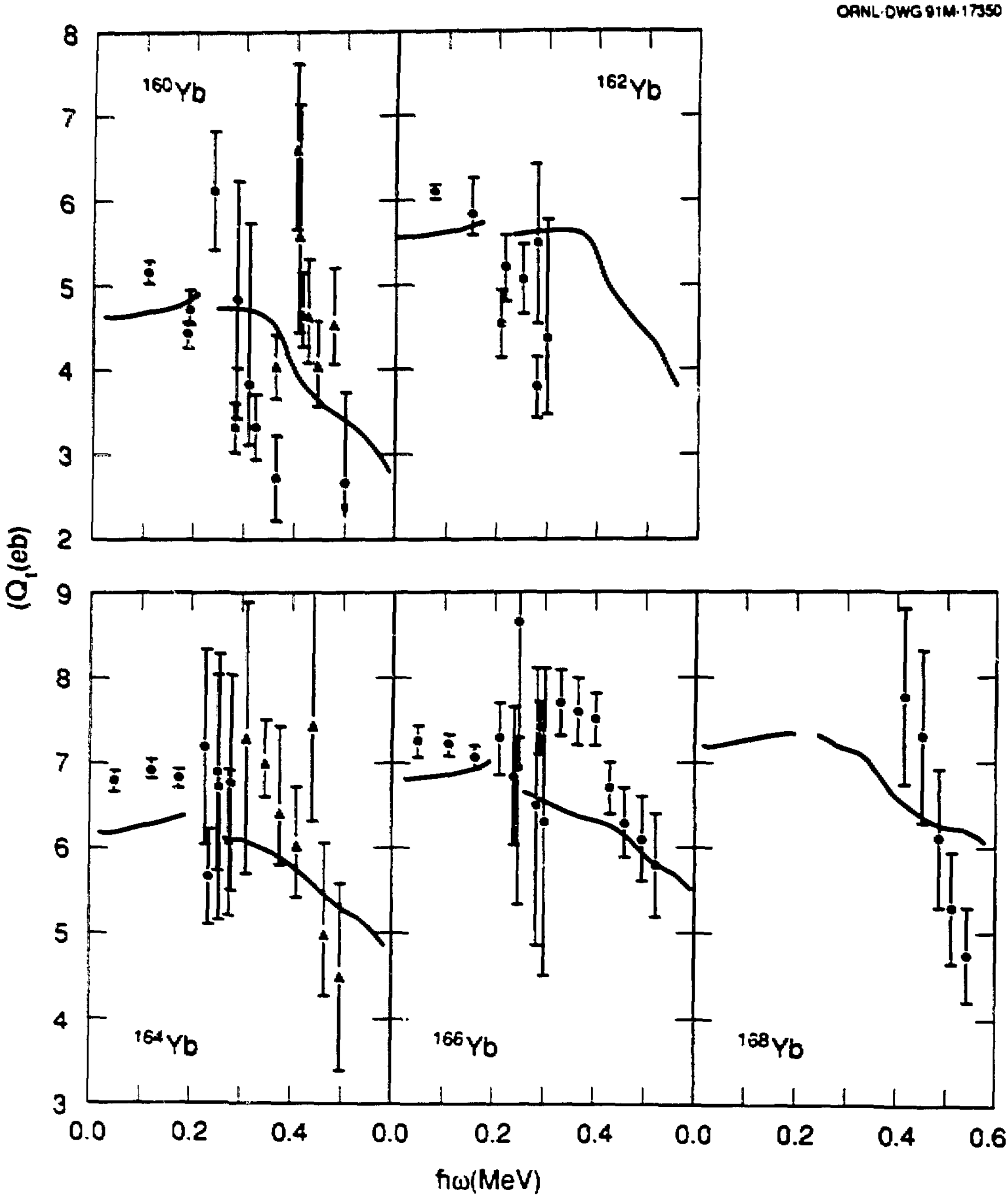

Fig. 6. Systematics of transition quadrupole moments (Q_t) for even-mass ytterbium nuclei plotted as a function of the rotational frequency ($\hbar\omega$). The solid points for ^{160}Yb are from the earlier RD work (Fewell *et al.*, 1988) and the triangles are from the current measurements (Johnson *et al.*, 1991) as are the trangles for ^{164}Yb (Xie *et al.*, 1990). References for the other data are: ^{162}Yb (McGowan *et al.*, 1991); ^{164}Yb closed points (Bochev *et al.*, 1976); ^{166}Yb (Bacelar *et al.*, 1986); and ^{168}Yb (Lisle *et al.*, 1990). The theoretical curves are based on deformation parameters from TRS calculations (Wyss *et al.*, 1990).

Let us now compare these lifetime results for ^{160}Yb and ^{164}Yb with the results for other even-mass Yb nuclei. This is done in Fig. 6 where plots of Q_t vs $\hbar\omega$ are shown. What we see is that in the spin-30 region ^{164}Yb, ^{166}Yb and ^{168}Yb show appreciable loss of collectivity. Within error limits, both ^{164}Yb and ^{166}Yb remain rather constant below spin 26. Unfortunately, the corresponding data is not available for ^{168}Yb, but it is a well-deformed rotor and is expected to display similar behavior. However, both ^{160}Yb and ^{162}Yb show evidence for loss of collectivity in the $I = 12^+ - 20^+$ region.

In an effort to better understand what is happening at the microscopic level let us turn to some recent Total Routhian Surface (TRS) calculations of these Yb nuclei (Wyss *et al.*, 1990). To determine the TRS, Strutinsky-Bogoliubov cranking calculations were done with a non-axial Woods-Saxon average field. These were done for each nucleus at a fixed multi-quasiparticle configuration and the energy was minimized with respect to β_2, β_4 and γ at various rotational frequencies. Using the deformation parameters extracted from the TRS calculations, we have computed the theoretical Q_t values for these Yb nuclei by use of the expression

$$Q_t = \frac{6}{\sqrt{15\pi}} Zer_0^2 A^{2/3}\beta_2(1+0.36\beta_2)\cos(30°+\gamma) \qquad (2)$$

where Ze is the charge on the nucleus and $r_o = 1.2$ fm. The computed values are shown as solid lines in Fig. 6. It is seen that the loss of collectivity at lower spins in *^{160}Yb is not accounted for.* However, the theoretical Q_t values do show the qualitative trends of the data at high spins. Probably the two main features of agreement for the theoretical curves are: (1) at low $\hbar\omega$ values they show the trend of increasing Q_t values with neutron number as we move up from the N = 90 case; and (2) they show a trend of decreasing Q_t values in each nucleus in the range of $\hbar\omega \approx 0.25–0.50$ MeV.

A recently suggested (Garrett *et al.*, 1988) microscopic explanation for this loss of collectivity at large $\hbar\omega$ was that it could result from the rotationally-induced deoccupation of anti-aligned high-j configurations because of the strong Coriolis effects for the *orbitals with large j and small Ω.* Especially important here are the antialigned orbits, i.e., the orbits in which protons or neutrons are moving in the direction opposite to the rotation. For these, j_x (the angular momentum along the x axis) is negative and the effect of the Coriolis term in the Hamiltonian, $-\omega j_x$, is to produce an increasingly positive contribution to the energy of such a configuration as the rotational frequency increases. At the same time, the aligned orbits will show a decrease in energy. The result is that anti-aligned orbits can rise above the Fermi surface and become deoccupied. Since these two components are in time-reversed orbits near the equator of the elongated ellipsoid, it can be envisioned that this loss of polarization about the core will cause a net reduction in β_2, the nuclear deformation. This is consistent with the lifetime data at large $\hbar\omega$ displayed in Fig. 6.

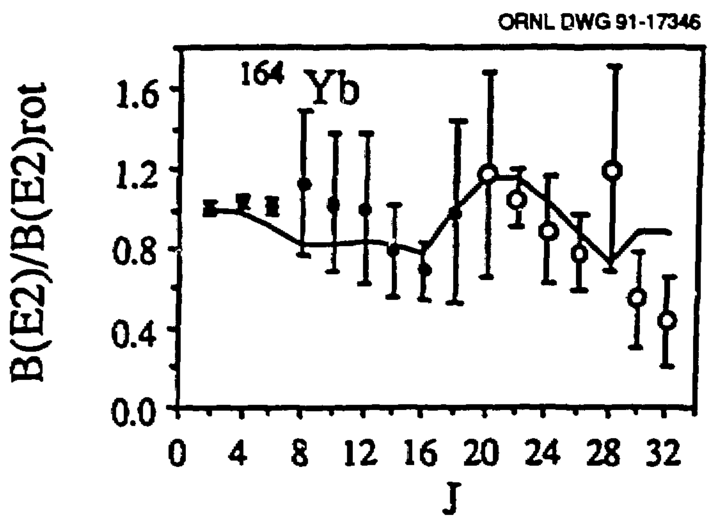

Fig. 7. Comparison of B(E2) values extracted from the ^{164}Yb DBLS results with the predictions of the Fermion Dynamical Symmetry Model (Wu, 1990).

Another approach that has been utilized to account for the effects seen in Fig. 6 is through Fermion Dynamical Symmetry Model (FDSM) calculations (e.g., see Guidry *et al.*, 1986). In this approach the authors start with a truncated shell model space and show that the loss of collectivity is mainly due to a finite particle number effect in the collective subspace, depending on the number of particles in the normal-parity valence levels of the subspace or on mixing SU_3 representations.

The results of recent FDSM calculations for ^{164}Yb (Wu, 1990) are shown in Fig. 7. Displayed here are B(E2) values extracted from our ^{164}Yb DBLS results (compared to rigid-rotor values) and the corresponding FDSM calculated values. As seen, the agreement between experiment and theory is reasonably good.

In conclusion, it is evident that we are making progress at a microscopic level in our understanding of rapidly-rotating nuclei. At the same time, however, it is clear that a fuller understanding of the evolution of collectivity in such systems demands both experimental data of higher quality and more refined theoretical treatments. Vast improvement in the experimental aspects is now on the horizon with the much larger Compton-suppressed arrays currently being constructed.

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