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POPULATION AND DECAY OF HIGH-SPIN STATES IN $^{157-161}\text{Yb}$:
EVOLUTION OF NUCLEAR SHAPES AS A FUNCTION SPIN AND NEUTRON NUMBER.

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Abstract

The population and decay of the entry states in $^{157-161}\text{Yb}$ and $^{155-158}\text{Er}$ from the reactions of 136- and 149-MeV ^{20}Ne with ^{144}Nd and ^{146}Nd have been investigated with the Spin Spectrometer gated with a Ge detector. Statistical-model calculations reproduce the main features of the entry state populations. The entry lines, $\langle E^* \rangle$ as a function of multiplicity, M_Y , show changes in slope at high M_Y which are due to changes in the decay mode as a result of changes in nuclear structure. Energy spectra of the continuum γ -rays and angular distributions as a function of M_Y show the onset of a dipole component localized at 650 ± 100 keV accompanied by an equally intense quadrupole component at twice the energy that continues to evolve to higher energies with increasing multiplicity. For $^{157,158,159,160,161}\text{Yb}$ the dipole component appears at $M_Y = 21, 22, 23, 25$, and 27 (at spin $I \approx 38, 40, 42, 45$, and 50), respectively. At precisely these multiplicities the entry lines show a decrease in slope. In ^{158}Yb the dipole component disappears at $M_Y = 28$ and the entry line resumes its original slope. The results are consistent with the following picture. At low spins for $^{157,158}\text{Yb}$ the nuclear shapes evolve from prolate to slightly oblate particle-aligned structures. At $I \approx 38, 40, 42, 45$, and 50 the $^{157,158,159,160,161}\text{Yb}$ nuclei, respectively, develop high-K rotational bands which may be built on oblate structures with large deformation ($\epsilon \approx 0.3$). At $I = 49$ a transition to triaxial shape appears to occur in ^{158}Yb .

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The excitation energy and angular momentum dependence of fusion reactions and the behavior of nuclei at high spin has been an important theme of experimental heavy-ion physics during the past two decades¹⁾. The evolution of nuclear structure as a function of angular momentum and proton or neutron number is of fundamental importance in understanding the interplay of the collective and single particle degrees of freedom which determines nuclear behavior away from closed shells²⁾.

Earlier attempts to determine the entry state distributions by means of γ -ray multiplicity measurements have produced significant results only on the first two moments of the M_γ distribution^{3,4)}. Excitation energy distributions of the entry states have been obtained from measurements of particle spectra^{5,6)}. These earlier experiments gave information on the projections on either the spin or the excitation energy axes. More recently the entry line was deduced using a γ -ray sum spectrometer^{5,6)}. With the availability of the Spin Spectrometer⁷⁻⁹⁾ the difficulties associated with the inability of earlier techniques to measure simultaneously E^* and M_γ have been eliminated and accurate entry state populations in E^* and M_γ space have been measured¹⁰⁾.

The properties of nuclei near $A = 160$ have been the subject of many theoretical and experimental investigations. The rotating liquid drop model (RLDM) predicts the evolution of nuclear shapes with increasing spin to proceed from spherical, at $I = 0$, to increasingly more deformed oblate structures up to $I \approx 70$ (for $A = 160$) and then through rapidly increasing tri-axial deformations to fission¹¹⁾. In nuclei this behavior is strongly modified by the underlying shell structure. At low spins ($I < 20$) pairing effects are responsible for the significant prolate deformations ($\epsilon = 0.1-0.3$) observed in the $N = 88-94$ rare earth nuclei. In this spin range excitation energy and angular momentum are generated by collective rotation perpendicular to the symmetry axis. As the rotational frequency is increased, the Coriolis force aligns the spins of a few particles along the rotational angular momentum. These effects cause the backbending phenomenon¹⁾ and can break the axial symmetry, but the nuclei retain a basically prolate shape ($\gamma \approx 0^\circ$)¹²⁾. On the other hand, nuclei with $N = 82 - 86$ are spherical or slightly oblate¹³⁾ and generate angular momentum, at least up to $I \approx 38$, by aligning quasiparticle spins. The magnitude of the oblate deformation is generally expected to increase with I . Collective rotational bands can, in principle, be built on these oblate aligned-quasiparticle states. The properties of

such collective states in oblate nuclei have recently been discussed theoretically^{15,16)}. The shell effects that persist at high spins are expected to break the oblate axial symmetry at significantly lower spins than predicted by the RLDM, and lead possibly to super-deformed triaxial shapes with $\epsilon \approx 0.6$ ¹⁷⁾.

Transitions from one type of behavior to another may be observable in a single nucleus as a function of spin. For states near the yrast line, these effects are expected to vary in a systematic way with neutron and proton number. We present here evidence in support of such an evolution of nuclear shapes in the $^{157-161}\text{Yb}$ ($N = 87 - 91$) isotopes.

Metallic targets of ^{144}Nd and ^{146}Nd were bombarded with 136- and 149-MeV ^{20}Ne beams from ORIC. A Ge detector at 117° to the beam was used to trigger the Spin Spectrometer and to select the exit channel by gating on known low-lying transitions in individual reaction products. In these experiments 69 of the 72 detectors in the spectrometer were used, covering 92.3% of 4π . For every event all nonzero pulse heights and the associated times relative to the Ge pulse were recorded on magnetic tape. The event tapes were processed to (1) correct for nonlinearities in the NaI pulse heights, (2) match the gains of the NaI elements, (3) derive an accurate reference time for each event by averaging the times of the NaI pulse, and separate neutron and γ -ray pulses by time of flight. The processed events were sorted to create a Ge spectrum for each fold k and each 1-MeV interval in the total pulse height H . The peak areas of a few low-lying transitions in the xn and αxn products were determined by least-squares fits with Gaussian shapes to provide the populations, $Q_x(H,k)$, for each exit channel x . Alternately, gates on the lower transitions from each product corresponding to the peaks and the nearby background were placed on the Ge counter. The events were then scanned to produce the $Q_x(H,k)$ distributions directly. Both methods gave the same results. The populations $R_x(E^*, M_Y)$ were obtained by an iterative least-squares unfolding procedure^{9,10)}.

Some of the results are illustrated in fig. 1a which shows the experimental $Q_{6n}(H,k)$ distribution from the $^{146}\text{Nd} (^{20}\text{Ne}, 6n)$ reaction at 136 MeV. Contour maps of the entry-state distributions $R_x(E^*, M_Y)$ from the xn channels are shown in fig. 1b.

Fig. 1. Entry-State distributions for xn products from 136-MeV ^{20}Ne on ^{146}Nd . (a) Experimental map in (H, k) space for the 6n channel. (b) Contour maps of experimental results in (E^*, M_γ) space for the xn channels. (c) Contour maps of the calculated distributions in (E^*, I) space. (d) Contour maps in (E^*, M_γ) space from the same calculation as in (c). The cross-section contours decrease going outward by the factors of 1.4, 2.0, 4.0 and 8.0 relative to the peak value of the 6n channel and are given by the dotted, full, dashed and dash-dotted curves, respectively. The heavy dots locate the maximum intensity for each channel. The ^{160}Yb yrast line used in the calculations is shown by the curve below the contours.

Statistical model calculations were carried out using the Monte Carlo code JULIAN-PACE¹⁸⁾ modified to include a more realistic treatment of γ -ray strengths¹⁰⁾. The E1 γ -ray emission strength function included the giant dipole resonance with shape parameters taken from experimental systematics and strength determined by the energy-weighted sum rule¹⁰⁾. Statistical E2 and M1 transitions were included with $B(E2) = 1.0$ W.u. and $B(M1) =$

0.005 W.u., together with collective stretched E2 transitions with $B(E2) = 100$ W.u. for $E_\gamma < 2.0$ MeV. The Monte Carlo cascades proceeded to the vicinity of the yrast line with these parameters and then were assumed to reach the ground state or anyrast state with $I < 2$ by stretched E2 transitions. The yrast lines were taken from the RLDM for $I > 22$. Below spin 22 the moment of inertia was assumed to decrease linearly with decreasing I to simulate the behavior typical of rotational nuclei.

The main features of the measured populations such as the positions of the entry lines $\langle E^* \rangle$ vs. M_γ , and the cross sections for individual exit channels are reproduced well by the calculations. Figs. 1c and 1d show the calculated populations for the $(^{20}\text{Ne}, xn)$ channels in (E^*, I) and (E^*, M_γ) space, respectively. (The mapping of M_γ to I used below for low spins was derived from the calculated entry lines as functions of M_γ and of I .) The measured and calculated entry lines from the data of fig. 1 are compared in fig. 2a. Good agreement is observed for the positions and the slopes of the main part of the entry lines. At the higher multiplicities the data show a decrease in the slope of the entry lines for ^{161}Yb and ^{160}Yb at $M_\gamma = 28$ and 25, respectively. This effect cannot be reproduced by the statistical model calculations with any reasonable variation of the parameters that does not involve onset of a different decay mode or a rapid increase in the effective moment of inertia Q_{eff} of the product nuclei. We can distinguish between these possibilities by examining the associated γ -ray spectra.

Pulse-height spectra from all the NaI detectors in the spectrometer were constructed for each coincidence fold k , and from five groups of detectors at 24.4° , 45.6° , 65.7° , 77.5° , and 87.3° (and their supplements) with respect to the beam. These were coincident with known low-lying transitions in the various Yb products observed in the Ge counter. The contribution of the Compton background in the Ge gate was subtracted. The measured angular distributions were used to determine the multipolarities with the assumption that only stretched dipole and stretched quadrupole radiations contribute. The γ -ray energy spectra were derived from the NaI pulse-height spectra by an iterative unfolding procedure taking into account the detector response functions. The latter were obtained from measurements with radioactive sources for γ -ray energies between 136 and 4439 keV, and by extrapolation for higher energies. These response functions include the effect of coincidence summing appropriate for each pulse-height spectrum⁹⁾.

The associated multiplicities for each spectrum were determined from the spectrometer response functions^{7,8)} and the deduced entry state populations $R_x(E^*, M_Y)$ as described in detail in ref. 9).

Fig. 2. Entry lines and γ -ray spectra for the Yb isotopes. (a) Experimental entry lines $\langle E^* \rangle$ vs. M_Y (points) and calculated entry lines (solid curves) from 136-MeV ^{20}Ne on ^{146}Nd for the $^{161}, ^{160}, ^{159}\text{Yb}$ products. (b) and (c) Experimental (points) and calculated (solid lines) entry lines $\langle E^* \rangle$ vs. M_Y from 149-MeV ^{20}Ne on ^{146}Nd for ^{160}Yb and ^{159}Yb , respectively. (d) Experimental entry line (points) from 149-MeV ^{20}Ne on ^{144}Nd for ^{158}Yb . (e) - (h) Continuum γ -ray spectra of 161 - ^{158}Yb for each M_Y indicated from the reactions in (a) - (d), respectively. (i) γ -ray spectra of ^{157}Yb for each M_Y indicated, from the reaction of 149-MeV ^{20}Ne on ^{144}Nd . The dashed lines in (b) and (c) were drawn parallel to the calculated entry lines. The dashed line in (d) was obtained as described in the text.

Selected γ -ray energy spectra from all the detectors in the spectrometer normalized to their respective multiplicities are shown in figs. 2e to 2i. The spectra from ^{161}Yb (fig. 2e) show a rather simple behavior. A bump is seen with an upper edge which moves to higher energies with increasing M_γ up to ≈ 27 . The angular distribution data are consistent with a stretched quadrupole character for this bump. The spike at ≈ 700 keV in the $M_\gamma = 29$ spectrum in fig. 2e shows a stretched dipole character. Despite the localized dipole transitions, the upper edge continues to move to higher E_γ for the highest multiplicities. The appearance of this dipole component explains the decrease in the slope of the entry line seen at $M_\gamma = 28$ in fig. 2a. Interestingly, the dipole component is located at about half the energy of the quadrupole component (≈ 1.4 MeV).

In ^{160}Yb a more pronounced change in decay mode is observed. For M_γ up to 25 ($I \approx 45$) the spectra show an evolving bump (fig. 2f) which is completely consistent with stretched E2 transitions at all E_γ , as may be seen from the anisotropies shown in fig. 3a ($M_\gamma = 16 - 19$). Above $M_\gamma = 25$

Fig. 3. Anisotropies of the γ -ray continuum in $^{160}, ^{159}, ^{158}\text{Yb}$. The M_γ values give the half maximum limits corresponding to the k gates.

($I \approx 45$) the γ -ray spectra show that the additional transitions are localized at $E_\gamma = 650$ keV, and that the edge of the quadrupole bump moves upward somewhat less rapidly as M_γ is further increased. The transitions localized at 650 keV clearly arise from dipole radiation (see fig. 3a, $M_\gamma > 26$). An analysis of the difference of spectra for successively higher multiplicities, coupled with the anisotropy information, indicates a dipole to quadrupole ratio of $(0.9 \pm 0.2) : 1.0$. The presence of dipoles accounts for the decrease in slope of the entry line in fig. 2b. These additional $\Delta I = 1$ transitions must be taken into account in deriving the mapping of M_γ to I above $M_\gamma = 25$. The constant slope of the entry line above $M_\gamma \approx 27$ further suggests that the ratio of the dipole to quadrupole transitions remains essentially constant up to $I = 54$.

The presence of the dipole component is also responsible for the apparently slower evolution of the quadrupole edge with M_γ , simply because now $\Delta I / \Delta M_\gamma = 1.5$. This leads to the smooth dependence of Q_{eff} on I shown in fig. 4a. Here we have assumed rotational behavior and have derived Q_{eff} from the midpoint of the upper edge of the quadrupole bump. Fig. 4a shows that the edge of the quadrupole bump continues to evolve in the range $I = 45$ –54 precisely as expected for collective rotational motion, provided that the effect of the dipole transitions on the mapping of M_γ to I is taken into account. Erroneously high values of Q_{eff} result if the presence of the dipoles is not taken into account in the mapping $M_\gamma \rightarrow I$, or if the convolution of the populations $R_x(E^*, M_\gamma)$ with the reverse responses⁹⁾ is not used in obtaining the values for M_γ corresponding to each gating bin in (H, k) space.

The trend for the appearance of the dipole component at progressively lower spins as N is decreased continues in the lighter Yb isotopes, as shown by the data in figs. 2 and 3. An additional interesting phenomenon is observed in ^{158}Yb . The entry line for the population of ^{158}Yb in the 149-MeV reaction of ^{20}Ne with ^{144}Nd (fig. 2d) shows the expected slope for $M_\gamma < 22$. At $M_\gamma = 22$ the slope of the entry line decreases and then for $M_\gamma = 28$ it increases, taking on a value close to its previous one. Selected spectra from the $^{144}\text{Ne} (^{20}\text{Ne}, 6n)$ reaction at 149 MeV normalized to their multiplicity are shown in fig. 2h. Two prominent features are apparent in these spectra. The first is a bump at $E_\gamma \approx 600$ to 800 keV which evolves smoothly up to $M_\gamma \approx 20$. The other is the appearance above $M_\gamma \approx 22$ of a second bump at higher energy with its upper edge reaching ~ 1.4 MeV at $M_\gamma \approx 28$. The behavior

Fig. 4. Effective moments of inertia Q_{eff} as a function of spin I in ^{160}Yb (a), ^{159}Yb (b), and ^{158}Yb (c). The solid lines give Q_{eff} from known yrast levels.

of these bumps with increasing M_γ , when correlated with the angular distribution data (fig. 3c) and the shape of the entry line (fig. 2d), provides a consistent picture of the de-excitation of ^{158}Yb . The yrast decay scheme for ^{158}Yb is known up to $I^\pi = 12^+$ and includes a cascade of stretched E2 transitions with energies from 358 to 683 keV¹⁹). The motion of the upper edge of the lower bump is consistent with the continuation of a predominantly

quadrupole cascade up to $M_Y \approx 20$ ($I \approx 36$). However, the angular distributions of the γ rays from 500 to 800 keV for M_Y between 12 and 20 are less anisotropic than would be expected for pure stretched quadrupole radiation (fig. 3c, $M_Y = 14-19$), indicating the presence of some dipoles. Furthermore, below $M_Y \approx 20$ the difference of spectra for successive M_Y bins show that the additional γ rays contribute not only to the upper edge of the bump as generally observed in the yrast cascade of a good rotor¹⁾, but also to the region of the peak (see fig. 2h). These features suggest a tendency toward an aligned-quasiparticle structure, characteristic of nuclei with small oblate deformations²⁾.

A different behavior is seen in the decay of ^{158}Yb above $M_Y = 22$. The upper edge of the low energy bump stops moving to higher energies as M_Y increases. At the same M_Y the entry line shows the decrease in slope (fig. 2d) and the lower half of the intense bump ($E_Y < 700$ keV) exhibits an angular distribution characteristic of stretched dipole radiation (fig. 3c). These three observations indicate the onset at $M_Y = 22$ of a strong dipole component which is well localized in energy. From difference spectra, from the angular distributions (fig. 3c) and the shape of the entry line, we estimate that the dipoles are confined to a narrow region of 650 ± 100 keV. Assuming that the dipoles are 650 keV each, we estimate from the shape of the entry line that 3 to 4 out of the 6 transitions between $M_Y = 22$ and 28 are dipole. In this way we obtain the dashed line in fig. 1d for the corrected entry line. The mapping of M_Y to I is based on this dashed line.

For $M_Y > 22$ the high energy bump in the ^{158}Yb spectra becomes increasingly prominent, and evolves with increasing M_Y in the way expected for a rotational quadrupole cascade with approximately constant moment of inertia. The angular distributions for all $M_Y > 22$ show clearly that the transitions in this energy region are indeed stretched E2.

Another change in the decay mode is seen at high M_Y from the spectra in fig. 2h and other spectra for $M_Y = 26$ and 27 (not shown). The dipole component at 650 keV stops increasing at $M_Y = 27$ whereas the high energy quadrupole component continues to evolve to the highest multiplicities studied. This is consistent with the increase in slope of the entry line at $M_Y = 27$ and with the fact that the entry line has resumed the slope characteristic of quadrupole radiation above $M_Y = 28$.

The decay features of ^{158}Yb are illustrated in fig. 5 by the differences between spectra with successively increasing multiplicities. These spectra show an increase in energy with increasing M_Y of the upper quadrupole bump which appears first as a shoulder in the $M_Y = 21.7 - 16.8$ difference (bin 3 - bin 2 of fig. 5). In the $M_Y = 25.1 - 21.7$ difference (4 - 3), two separate bumps are now seen. These bumps move apart as M_Y increases. Angular distributions for these difference spectra show that the lower of these two bumps is not purely dipole. In fact, in both the (3 - 2) and (4 - 3) differences, the lower bump is almost pure quadrupole above $E_Y > 700$ keV. In the $M_Y = 26.6 - 25.1$ (5 - 4) difference this low energy quadrupole component has disappeared but a remnant of the 650-keV dipole peak is still present. (The intriguing behavior for $E_Y < 400$ keV is probably not significant because the unfolding procedure introduces large uncertainties at such low E_Y). From an analysis of these difference spectra using angular distributions to isolate the dipole component, we estimate the ~ 3.5 stretched dipole transitions, all at $E_Y = 650 \pm 100$ keV, occur in the highest multiplicity cascades, in good agreement with the inferences from the shape of the entry line.

Fig. 5. Difference spectra from the decay of ^{158}Yb (see text).

The behavior of ^{157}Yb was investigated by the $^{144}\text{Nd}(^{20}\text{Ne}, 7n)$ reaction at 149 MeV for the multiplicity range between 8 and 23. For this limited range of M_Y the spectra in fig. 21 show a behavior identical to that of

¹⁵⁸Yb. The appearance of a dipole component and of a high energy quadrupole bump occurs at $M_Y \approx 21$ ($I \approx 38$).

We have observed a systematic variation of the decay mode in the ¹⁵⁷⁻¹⁶¹Yb isotopes that correlates with neutron number and nuclear spin. The variations in the decay mode are reflected in the onset of a strong dipole component localized at half the energy of a second quadrupole component. This quadrupole component continues to evolve in energy as expected for collectively rotating nuclei. The dipole component appears at $I \approx 38, 40, 42, 45$, and 50 in the ^{157, 158, 159, 160, 161}Yb isotopes, respectively. The spectra for ^{157, 158}Yb suggest a behavior similar to that of lighter $N = 87, 88$ nuclei such as ¹⁵²Dy¹³⁾ which is characteristic of particle-aligned states found in slightly oblate nuclei.

Detailed systematic calculations of nuclear structure effects as a function of spin in these Yb isotopes, have been performed by Andersson et al.¹⁶⁾. We use the general features of their results as a guide to possible interpretation of the changes in the decay mode that we observed. Their results for ¹⁵⁸Yb and ¹⁶⁰Yb are reproduced in fig. 6. The predictions for the odd isotopes ^{157, 159, 161}Yb were obtained by interpolation. Near the ground state all the Yb isotopes should be prolate due to the effects of pairing. As the spin is increased the calculations predict a systematic decrease in deformation along the prolate axis ($\gamma \approx 0^\circ$). At higher spins a sudden change to oblate shape is predicted for the lighter Yb isotopes, which occurs at progressively higher spins with increasing neutron number. As the spin is further increased the nuclear shape evolves back toward prolate via intermediate triaxial configurations. ¹⁶²Yb is predicted to be oblate only for I near 60. ¹⁶⁰Yb is predicted to become oblate at $I \approx 50$, and to remain oblate for I between 50 and 70 before it becomes triaxial. ¹⁵⁸Yb is predicted to become oblate at low spin and to evolve to triaxial above $I \approx 50$.

In ^{157, 158}Yb we have found evidence in the continuum spectra for aligned single-particle states for I values from about 20 to 35. This is just the behavior which should be expected if these nuclei have the weakly deformed ($\epsilon \sim 0.1$) oblate shapes predicted by the calculations. These calculations also lead us to expect the strongly localized stretched dipole radiation to be associated with an oblate shape since all the relevant nuclei are predicted to be oblate in the spin region for which the dipoles are observed. However, it seems clear from the localization of the dipoles very near half the energy

Fig. 6. Trajectories in the (ϵ, γ) plane of the equilibrium shapes for the Yb isotopes calculated in ref. 16 (solid lines). The solid lines for the odd A isotopes were obtained by interpolation. The dashed lines represent pictorially the shape changes according to our interpretation of the data. The dots and open circles give the spin values demarking the trajectories

of the coincident quadrupole radiation (observed at the same multiplicities), that transitions in collective bands are responsible for these γ rays. The yrast states of an oblated nucleus, whatever its deformation, are most likely to be aligned quasiparticle states with spins along the symmetry axis. These are therefore $K \approx I$ states upon which collective states could

be built. Theoretical investigations suggest that appreciable collectivity should not be expected for $|\epsilon| < 0.25$, but could be important for larger deformations²⁰⁾. The excited states of these bands will not be yrast, but could conceivably lie close to the yrast line. M1 radiation should in fact be favored within these high-K bands since the rotational model predicts $B(M1) \propto K^2$ while $B(E2) \propto 1/K$. For example, using the rotational model formulae with $E_\gamma(M1) = 0.65$ MeV, $E_\gamma(E2) = 1.3$ MeV, and $Q_0 = 7.55$ eb, the equal E2 and M1 widths observed experimentally at $I = 45$ in ^{160}Yb would be consistent with a $(g_K - g_R)$ value of 0.1, which corresponds to a g_K of ~ 0.5 assuming $g_R \sim Z/A$.

If we accept, for now, these arguments a parallel between the data and the calculations is found. The evidence for a transition to aligned-particle behavior at low spin in $^{157,158}\text{Yb}$ has been mentioned. We identify this behavior with small deformations. The localized M1 radiation, which we tentatively identify with oblate deformations $|\epsilon| > 0.3$, sets in at $I \approx 38, 40, 42, 45$, and 50 in $^{157,158,159,160,161}\text{Yb}$ respectively. This suggests an evolution along the $\gamma = 60^\circ$ axis (see fig. 6) for $^{157,158}\text{Yb}$ in the direction of increasing $|\epsilon|$ between $I \approx 20$ and $I \approx 40$. The isotopes with $A \geq 159$ appear to undergo a transition to the $\gamma = 60^\circ$ (oblate) axis with $|\epsilon|$ already large enough to allow collective motion. The spins at which this transition occurs as a function of $|\epsilon|$ agree with theory (fig. 6) not only in qualitative trend with A but also quantitatively. All the Yb isotopes are predicted to become unstable with respect to triaxial shapes at sufficiently high spin. Only in the case of ^{158}Yb is this change (or at least its first stage) predicted to occur at spins which are observed in the present experiments. Interestingly, ^{158}Yb is the only nucleus in which we observe the disappearance of the stretched dipole radiation (at spin $I \approx 49$). If we interpret this as evidence that the nucleus is evolving away from the oblate axis, we have further correspondence between theory and experiment.

In fig. 6 we have summarized a plausible path of the evolution of the Yb nuclei as a function of spin using the calculations of Andersson *et al.* (shown on the plots as solid lines) as a guide. The smooth dashed curves represent pictorially the transitions from prolate to oblate and then to triaxial shapes using the ϵ values which we have discussed. The qualitative relationship between experiment and theory as a function of spin is remarkable, except for two points. (1) The data, in the context of our speculative

interpretation, suggest an increase in $|\epsilon|$ for $I \approx 20$ to 40 along the $\gamma = 60^\circ$ axis for $^{157,158}\text{Yb}$. The calculation for ^{158}Yb predicts constant $|\epsilon|$ in this spin range. (2) in all the isotopes we find it necessary to invoke larger $|\epsilon|$ values for the oblate shapes than the calculations predict.

Effective moments of inertia, Q_{eff} , were obtained from the upper edge (half height) of the quadrupole bump, under the assumption of a rotational spectrum. The resulting Q_{eff} values for $^{158,159,160}\text{Yb}$ are shown in fig. 4. In all three cases the Q_{eff} is calculated from two regions in the γ -ray spectrum. In the lower energy bump we can obtain Q_{eff} as long as we stay below the M_γ values where the dipoles are observed. These results are a natural extension of the Q_{eff} values from the known discrete lines at lower spins (solid lines in fig. 4). After the dipoles appear the Q_{eff} values extracted from the upper edge of the accompanying quadrupole bump form groups at high spin, which show an obvious downward discontinuity at I values that are near the onset of the dipole transitions. This result is not inconsistent with the known decrease from $Q_0 (1 + 0.3 \beta)$ and $Q_0 (1 - 0.3 \beta)$ for prolate and oblate rotations perpendicular to the symmetry axes with $\beta = 0.1 - 0.2$ and $0.3 - 0.4$, respectively¹⁾. One simple picture for the mode of de-excitation which is consistent with our data involves 3 to 4 consecutive M1 transitions in competition with about 2 quadrupole transitions extending no more than 4 $\hbar$ and 2.6 MeV above the yrast $K \approx I$ bandheads. This picture is reasonable if the associated bands are not too steep compared to the yrast line.

One of the most speculative aspects of the comparison of our data with the calculation is the association of the localized dipole radiation with collective bands built on high- K oblate states. Other mechanisms can produce localized M1 transitions from high spin states. One of these involves cooling of wobbling modes in triaxial nuclei¹⁶⁾. The only calculation available¹⁶⁾ suggests that such a decay mode leads to small M1/E2 branching ratios and M1 transition energies that are higher than half the associated quadrupole transition energies. Another possibility is collective bands built on high- K states with prolate shapes. Such bands are known to exist²¹⁾ but only occur on or near the yrast line if very specific shell effects are present, since they are unfavored by macroscopic effects.

In the present analysis of our data we have not selected excitation

energy, only γ -ray multiplicity. Consequently, at each M_γ we are averaging mainly over decay paths which begin almost ten MeV above the yrast line. One might thus expect structure effects sensitive to the addition of single neutrons to be washed out. Yet we observe a strong correlation of decay mode with neutron number. This may be interpreted as an indication that structural effects persist at high excitations above the yrast line, a rather unlikely prospect, or as an indication that the nuclear de-excitation approaches the yrast line rapidly, so that the bulk of the collective transitions which we observe occur quite close to the yrast line.

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