Lifetime Measurements of High-Spin States in ^{166}Yb

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The Doppler-shift attenuation method was used to measure lifetimes of yrast states in ^{166}Yb. Values of τ range from 0.16(2) ps at 24^+ to 0.05(1) ps at 34^+. The $B(E2)$ values decrease from 240 to 120 single-particle units in this spin range, indicating a loss of collectivity which likely reflects a change of the nucleus towards triaxial shape. The side-feeding times are consistent with rotational cascades having moments of inertia 25% larger than the yrast sequence or $B(E2)$ values around 60 single-particle units.

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With the present high-resolution and highly efficient germanium detector arrays, discrete nuclear states have been observed typically above spin $30\hbar$.[1-4] In the region of well-deformed nuclei the γ-ray energies indicate that rotational bands exist up to these high spins, since they follow the rotational relationship $E_\gamma = (4I-2)\hbar^2/2\mathcal{J}$, with reasonably constant values of $\mathcal{J}$. However, a direct way to determine whether collectivity has survived the large Coriolis and centrifugal effects at these high angular velocities is to measure the transition quadrupole moments of the states, e.g., through their lifetimes. The present Letter describes results for the nucleus ^{166}Yb obtained with use of HERA,[5] an array of 21 Compton-suppressed germanium detectors. For the first time it was possible to make line-shape analysis of transitions in coincidence with high-spin discrete-line gates. This reduces the background and extraneous lines in the resulting spectra, extending considerably the range of spins at which lifetimes can be measured. We have determined the lifetimes in ^{166}Yb up to $I=34$ and find that the yrast states in ^{166}Yb start losing collectivity above spin $26\hbar$. This is interpreted as a movement towards triaxial deformation of the equilibrium nuclear shape, and may be caused by the alignment of the available valence nucleons; such is the case in lighter rare-earth nuclei where it is observed to occur at lower spins.[6,7]

The reaction used was 180 MeV ^{40}Ar+^{130}Te. The ^{40}Ar beam was provided by the Lawrence Berkeley Laboratory 88-in. cyclotron. For one experiment two thin Te targets (360 and 200 μg/cm^2) were stacked together and 90 million triple or higher gamma coincidence events were recorded on tape. In the other experiment a 1-mg/cm^2 Te target on a 13-mg/cm^2 Au foil was used, and 210 million triple or higher coincidence events were recorded. From the unbacked data the yrast sequence was extended from the previously published[8] data (24^+) up to the 38^+ level.[9] The 21 detectors subtended eight different angles to the beam direction ranging from 0° to 154°.

The sum of four yrast discrete-line gates (494 +509+588+667-keV peaks), from the 16^+ through 22^+ states, was used to produce the three background-subtracted spectra shown in Fig. 1. Figure 1(a) shows the unbacked data and Figs. 1(b) and 1(c) show the coincident γ rays in the backed-target experiment, detected in counters positioned at forward and backward angles, respectively. The line shapes of the peaks above the 667-keV line show clearly the shoulders created by lifetimes plus feeding times which are in the range of the mean slowing-down time in gold (0.6 psec).[10] A simple estimate can be made by inspection of the line shapes of the top transitions. The transitions above spin 30 seem to have sharp and nearly symmetrical line shapes with a centroid between the stopped and fully shifted channels. For the 32→30 transition (Fig. 2) the centroid of its line shape shows a Doppler shift of only 10.5 keV (corre-

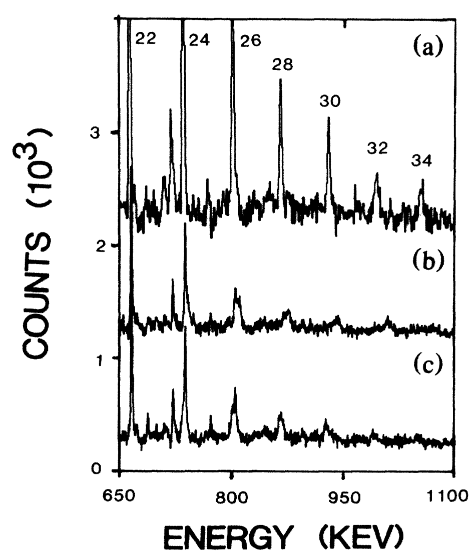

FIG. 1. Spectra gated by yrast states 16^+, 18^+, 20^+, and 22^+: (a) Unbacked-target data (1000 counts offset); Au-backed data detected at (b) 45° (1000 counts offset), and (c) 121° to the beam direction.

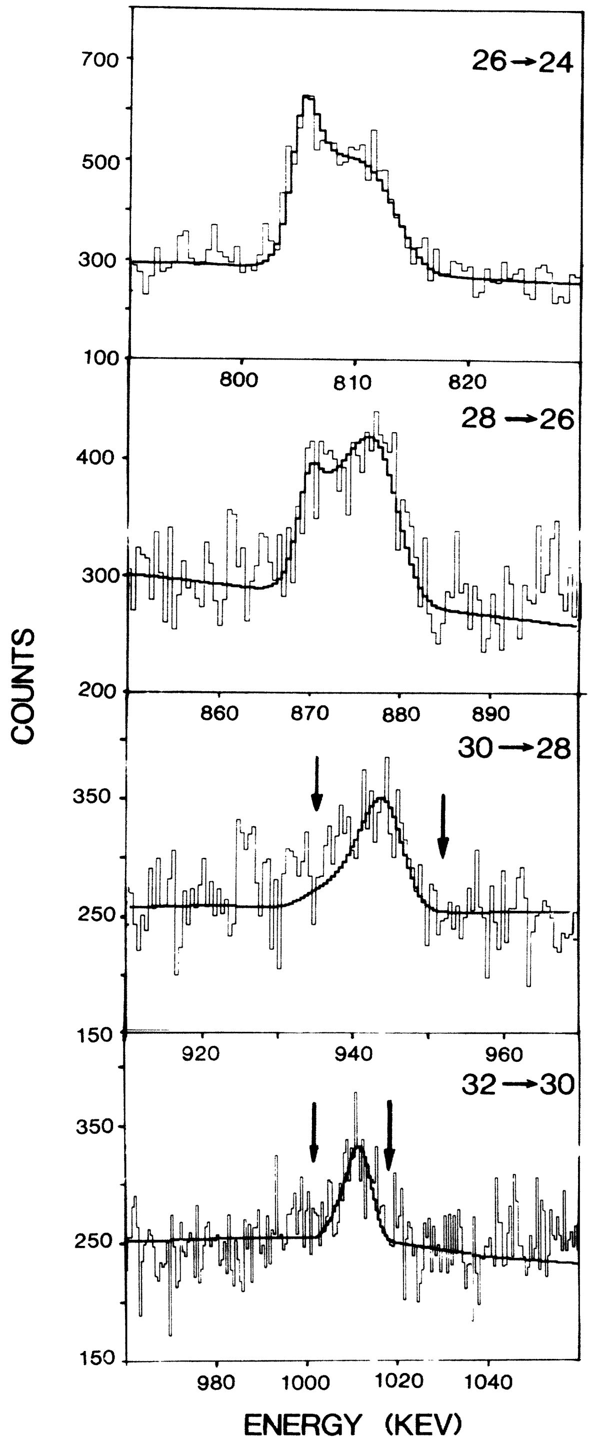

FIG. 2. Fits (thick line) to peaks shown in Fig. 1(b). The stopped (left arrow) and fully shifted (right arrow) positions are shown for the lowest two peaks. The bump observed at the indicated stopped peak of the 32→ 30 line shape at this angle is a statistical fluctuation.

sponding to a feeding time of 0.3 psec), less than the full Doppler shift which would be 17 keV. Such line shapes are obtained if several transitions of roughly similar lifetime precede (feed) the observed transition (but not a single long-lived isomer at higher spin, since this would create a largely asymmetric peak). The effect of several exponential decays in sequence is to create a "step delay" in the population; i.e., the average γ-ray emission time of the nth decay in the sequence is of order $n\tau$, where τ is the typical lifetime of the preceding transitions. From this delay, one can estimate the $B(E2)$ of the rotational cascades feeding the 32^+ level to be ~ 130 single-particle units (s.p.u.), since in a pure rotational band the total feeding time is about five times the lifetime of the last state for this γ-ray energy range.

To study in detail the lifetimes involved in the transitions from the 34^+ through 24^+ states a Doppler-shift attenuation program was developed.[11] The magnitude and direction of the velocity for the recoiling ions in the target and backing materials was calculated in a Monte Carlo fashion. In the slowing-down process both electronic and nuclear stopping were considered. For the electronic stopping power the tabulated values of Ref. 10 were used corrected for the atomic shell structure of the stopping material.[12] For the nuclear stopping power, a multiple Coulomb scattering formalism was used.[13] The decay model used has a rotational band with the known yrast discrete-line energies and a set of rotational transitions with the same moment of inertia preceding the highest known transition. Lifetimes above spin 36 were chosen to give the best fit to the line shape of this transition ($36^+ \rightarrow 34^+$). The subsequent decay was then allowed to proceed with individual lifetimes as free parameters. The side-feeding intensities to these states (obtained experimentally from the unbacked data) were considered to come from rotational bands with the same transition energies as the yrast sequence. These bands were controlled by a single Q_0 moment which was a parameter in the fit, and for each state a new side band with its own Q_0 was allowed. In this way the yrast-band lifetimes and the side-band feeding times were fitted at each spin. The data were then fitted for the forward, backward, and near 90° detector groups in the experimental setup. These three groups involved fourteen independent angles. The fits obtained at forward angles for some transitions can be observed in Fig. 2. Table I contains a summary of the fitting parameters. The relative errors in the lifetime and feeding times obtained in such a fit are small since the number of data points exceeds the number of free parameters, particularly since three different groups of detectors are fitted simultaneously. Therefore we believe that the largest source of uncertainty (not reflected in the error bars of Fig. 3 and Table I) comes from systematic errors in the treatment of the slowing-down process, which could be as large as $\pm 20\%$ for the absolute numbers quoted.

Both lifetimes and derived $B(E2)$ values are given in Table I. There is a loss of collectivity towards higher spins but, nevertheless, even at 34^+ the nucleus remains very collective (123 s.p.u.). The decrease in $B(E2)$

TABLE I. $B(E2)$ values of the high-spin transitions.

I_i	Int.[a]	E_γ (keV)	τ (ps)	$B(E2)$ ($e^2 \cdot b^2$)	$B_w(E2)$[b] (s.p.u.)	β ($\gamma=0$)	γ ($\beta=0.3$)	$B_{SB}(E2)$[c] (s.p.u.)
24	16.2	738.9	0.16(2)	2.19(24)	238(30)	0.32(2)	-14^{+6}_{-5}	44
26	12.0	806.0	0.10(1)	2.20(22)	245(24)	0.33(2)	-22^{+4}_{-5}	50
28	7.8	870.2	0.10(1)	1.54(17)	166(18)	0.27(2)	8^{+4}_{-4}	75
30	6.4	935.0	0.08(1)	1.34(22)	144(24)	0.25(2)	16^{+5}_{-7}	70
32	3.7	1000.5	0.06(1)	1.28(24)	138(26)	0.25(2)	14^{+5}_{-6}	80
34	2.9	1060.0	0.05(1)	1.15(27)	123(29)	0.23(3)	17^{+5}_{-8}	80

[a]Intensities of the transitions in percent relative to the 4^+ decay.

[b]$B_w(E2)^{-1} = \frac{1}{3}\langle I_i \mid I_f \rangle^2 \tau E_\gamma^5$; E_γ (MeV), τ (ps), and the Clebsch-Gordan coefficient $\langle I_i \mid I_f \rangle^2 \sim 0.36$ for this region of spin.

[c]These values have at least 20% uncertainties and are model dependent, as given in the text.

values can result from a decreasing quadrupole deformation or an increasing triaxiality ($\gamma \neq 0$), as can be seen from the relation[14] $B(E2) \approx \beta^2 \cos^2(30° + \gamma)$. Some limits were calculated and tabulated in Table I. For variations in β, γ was kept at 0°, and for γ variations, β was kept at 0.3 (the ground-state value). These variations are only limits for the shape parameters, since a combination of changes in the quadrupole deformation and γ is possible. However, for a well-deformed nucleus like ^{166}Yb, the potential is calculated[15] to be rather stiff for changes on β and it is expected that the major change would be towards positive γ, i.e., a triaxial shape tending toward an oblate nucleus rotating about its symmetry axis.

A change in shape, similar to that suggested here around spin $30\hbar$, has been seen in somewhat lighter nuclei (around $N=88$ or 90) at spins just below $20\hbar$.[6,7] The general reason for this difference seems clear; the lighter nuclei have potential energy surfaces much softer toward shape changes and thus are affected at lower spins. This argument can be carried somewhat further. Shape changes in this region are generally thought to be induced by the population or depopulation of specific orbitals—in this case associated with angular momentum alignments of particular valence nucleons.[16] For the lighter rare-earth nuclei, the first pair of nucleons that align ($i_{13/2}$ neutrons) induce shape changes which create the decreasing $B(E2)$ values. However, in the well-deformed region around ^{166}Yb, the alignment of the $i_{13/2}$ neutrons does not affect the shape appreciably as a result of the stiffness of the potential and the higher position of the Fermi level. It is not until higher rotational frequencies, where other alignments may occur, that the triaxial shapes preferred by those single-particle orbitals influence the equilibrium deformation of the mean field.

However, a second alignment in ^{166}Yb is not apparent in the γ-ray energies of the spin region where the $B(E2)$ values decrease (if present it should cause an increase in $\mathcal{J}$, whereas $\mathcal{J}$ is rather constant in Fig. 3). But $\mathcal{J}$ is also sensitive to properties other than alignments, particularly to the shape and the pairing correlations, whereas the $B(E2)$ values are sensitive essentially only to the shape and deformation. The shape changes suggested by the decrease in $B(E2)$ values will decrease $\mathcal{J}$, and tend to cancel any increase due to alignment. It is, however, a puzzle that such a constant value of $\mathcal{J}$ is obtained over a large range of rotational angular momentum as a result of apparently accidental cancellations. Furthermore this constancy seems to be a feature of middle-shell nuclei at high spins.[4] While it would not be surprising to find alignments, shape changes, and pairing changes systematically interrelated in this region, still no mechanism has been suggested that would lead to such constant values of $\mathcal{J}$.

The side bands which feed the yrast states have longer feeding times, showing either less collectivity [$B(E2)$ ~ 60 s.p.u.] or larger moments of inertia ($\sim 25\%$

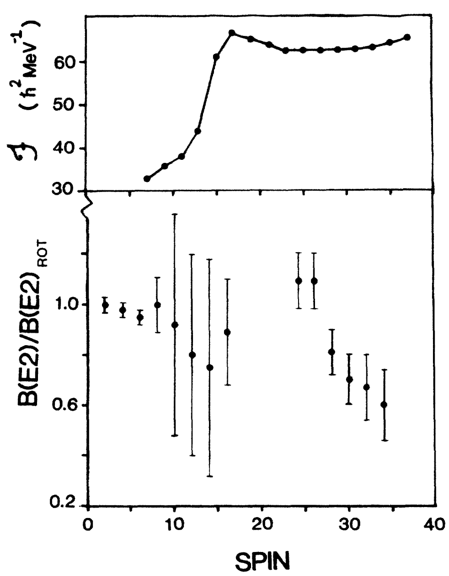

FIG. 3. Variations of $B(E2)/B(E2)_{\text{rotor}}$ and moment of inertia ($\mathcal{J}$) vs spin for ^{166}Yb yrast states. The low-spin ($<20^+$) data for $B(E2)/B(E2)_{\text{rotor}}$ are from Ref. 17. The moment of inertia, extracted from measured transition energies, is from Ref. 9. The $B(E2)/B(E2)_{\text{rotor}}$ values were normalized to 1.0 for the $2^+ \rightarrow 0^+$ transition.

larger). It is an interesting question why these bands, lying at somewhat higher excitation energies, should differ so much from the yrast band. Furthermore, a Doppler-shift analysis of the bulk of the continuum γ-ray distribution in Er nuclei shows that the $E2$ bump is consistent with rotational cascades having large $B(E2)$ values, around 150 s.p.u.[18] These two results are not necessarily inconsistent since the unresolved cascades leading to the present high-spin yrast states represent only a small part (20%) of all cascades. One possible interpretation of our measurement is that by using high-spin yrast gates we sample continuum cascades that are slower, and cool to the yrast states earlier, than average. Another possibility is that there is a region of slower transitions in all cascades. Since, on average, there are four statistical transitions per cascade, and therefore at least four different rotational bands, it could be that only the last few (4–5) $E2$ transitions are slow, i.e., only the last band. The rotational bands close to the yrast line might be slower because they are more triaxial because of the large role played by a few aligned valence nucleons. The rest of the continuum bands (at higher excitation energies) would have to be faster—more collective. This region of higher collectivity could set in as soon as the core can be substantially broken, producing larger deformations. More experiments are needed to determine which, if either, of these suggestions is correct.

In conclusion, the measurement of transition lifetimes for spins up to 34^+ in rotational nuclei is seen to provide interesting new information on the structure of high-spin states. It is particularly exciting that the method described is capable of measuring lifetimes down to tens of femtoseconds, as fast as any that give rise to resolved lines in these rotational nuclei.

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[1]J. C. Bacelar *et al.*, Nucl. Phys. **A442**, 509 (1985), and references therein.

[2]B. Haas *et al.*, Nucl. Phys. **A362**, 254 (1981).

[3]F. S. Stephens *et al.*, Phys. Rev. Lett. **54**, 25 (1985).

[4]R. Chapman *et al.*, Phys. Rev. Lett. **51**, 2265 (1983).

[5]R. M. Diamond and F. S. Stephens, unpublished; R. M. Diamond, in *Instrumentation for Heavy Ion Nuclear Research*, edited by D. Shapiro (Harwood Academic, New York, 1985), p. 259.

[6]A. Pakkanen *et al.*, Phys. Rev. Lett. **48**, 1530 (1982); H. Emling *et al.*, Phys. Lett. **98B**, 169 (1981).

[7]M. P. Fewell *et al.*, Phys. Rev. C **31**, 1057 (1985).

[8]W. Walus *et al.*, Phys. Scr. **24**, 324 (1981).

[9]E. M. Beck *et al.*, Nucl. Phys. (to be published).

[10]L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables **7**, 233 (1970).

[11]J. C. Bacelar, Nucl. Instrum. Methods Phys. Res. (to be published).

[12]J. F. Ziegler and W. K. Chu, Nucl. Data Tables **13**, 463 (1974).

[13]J. Lindhard, M. Scharff, and H. E. Schiott, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. **33**, 14 (1963).

[14]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, MA, 1975), Vol. 2, p. 164.

[15]J.-Y. Zhang and S. Aberg, Nucl. Phys. **A390**, 314 (1982).

[16]Y. S. Chen, S. Frauendorf, and L. L. Riedinger, Phys. Lett. **171B**, 7 (1986).

[17]B. Bochev *et al.*, Nucl. Phys. **A267**, 344 (1976).

[18]H. Hubel *et al.*, Z. Phys. A **304**, 225 (1982).