Quasivibrational Bands at High Spins in ^{158}Yb

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High-spin states in the transitional nucleus ^{158}Yb were populated via several (HI,4n) reactions. Two yrast bands were established up to $I^\pi = (40^+)$ and (31^-). In contrast to the negative-parity band up to $I = 31$ and the positive-parity states up to $I = 24$ which show collective rotational patterns, states with $I^\pi = 26^+$–36^+ exhibit a nearly vibrational excitation mode. Such a quasivibrational pattern suggests a gradual transition toward oblate shapes and is the first evidence for a "band termination" in a heavy nucleus.

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Rare-earth nuclei with neutron numbers $82 \lesssim N \lesssim 90$ offer a unique opportunity to study spin-induced nuclear shape transitions. Being situated between the nearly doubly magic ^{146}Gd "core" at one end, and the well-deformed nuclei at the other, they span a variety of shapes which range from moderately oblate to prolate. In particular, the transitional nuclei ($N \simeq 88$) which have soft potential-energy surfaces are predicted to experience large changes in their shape parameters as the angular momentum is increased and/or high-j quasiparticles are excited.[1] Study of these shape changes and the associated excitation modes provides valuable insight into the question of the interplay between collective and single-particle degrees of freedom in nuclear systems. Recently, transitions from collective to noncollective structures have been reported in several $N = 87$ nuclei[2,3] as well as in the $N = 88$ nucleus ^{154}Dy.[4] In this Letter we report on the high-spin behavior of ^{158}Yb ($N = 88$) which is markedly different from that observed in neighboring nuclei.

The high-spin states in ^{158}Yb were populated via (HI,4n) reactions using a 100-MeV ^{18}O beam from the double tandem facility at Brookhaven National Laboratory, a 115-MeV ^{20}Ne beam from the Oak Ridge Isochronous Cyclotron, and a 285-MeV ^{64}Ni beam from the Holifield Heavy Ion Research Facility tandem at Oak Ridge National Laboratory. The ^{20}Ne run utilized an array of six Ge counters along with two 25×25-cm^2 NaI crystals which served as a total-energy spectrometer. More than 100 million events, defined by coincidence firing of both NaI detectors and a minimum of two Ge counters, were collected in this mode. Analysis of these data resulted in the identification of the yrast sequence up to spin 32.

The ^{64}Ni run was carried out in the spin spectrometer,[5] with six Ge counters replacing four NaI elements at 24°, one at 92°, and one at 64°. By the demand of a coincidence of two or more Ge detectors and at least 22 NaI detectors in the spin spectrometer, events of high multiplicity were emphasized. As a result, γ rays from radioactivity and Coulomb excitation were strongly suppressed and those from the 5n channel and fission products were significantly reduced. In the first phase of this run, the recoiling residual nuclei were allowed to decay in flight. Subsequently, to reduce the severe Doppler broadening, a 1-mg/cm^2-thick ^{98}Mo target backed with $\simeq 15$ mg/cm^2 of natural lead was used. No effects of Doppler broadening were observed in this mode which indicates that feeding times are long even for the highest-spin states populated with this reaction. In the off-line analysis of these data the gains of all Ge and of all NaI detectors were separately matched, and pulses due to the neutrons were removed by their time of flight. The corrected data were then scanned to generate several E_γ-E_γ matrices that were gated with various two-dimensional cuts in the total map of pulse height versus fold to enhance the 4n channel. A recently developed background-subtraction technique[6] was used to remove nearly 90% of the Compton events present in these matrices before the generation of gated coincidence spectra. An example of these gated spectra is shown in Fig. 1.

On the basis of the γ-γ coincidence data from these runs we established the even- and odd-spin yrast states up to spins 40 and 31, respectively (Fig.2). The presence of four doublets within the positive-parity yrast cascade makes determination of their intensities difficult, so that ordering of some transitions within this cascade remains uncertain. This is indicated by dashed horizontal lines in Fig. 2. Multipolarities of the γ rays deexciting low- and medium-spin states were deduced from angular-distribution data, namely, ^{18}O-induced γ-ray yields at eight angles. Angular-correlation data from the ^{64}Ni-induced reaction provided additional information on the multipolarities of γ rays deexciting the high-spin states. The parity of the odd-spin band is assumed to be negative on the basis of the systematics. In addition to the odd- and even-spin bands shown in Fig. 2, a third and weaker cascade of γ rays (350, 484, 564, 614, 685, 705, 708, 725, 797, and 839 keV) was found to feed the $I^\pi = 10^+$ state. This cascade has not yet been placed in the decay scheme.

Figure 3 compares the kinematical moments of inertia $\mathscr{I}^{(1)}$ of the yrast bands in ^{158}Yb (filled circles) with similar bands in ^{160}Yb (open circles).[7] A noteworthy feature is the contrasting behavior of the two bands in ^{158}Yb. In the case of the supposed negative-parity band [(Fig. 3(b)], which would consist of $i_{13/2}h_{9/2}$ neutron orbitals, we observe its first band crossing ($AE \rightarrow AEBC$) at an angular frequency of $\hbar\omega \simeq 0.36$ MeV, close to that of ^{160}Yb. (A, B, C and D designate the $i_{13/2}$ neutron orbitals nearest to the Fermi surface. E and F represent the $h_{9/2}$ neutron orbital.) Furthermore, both nuclei exhibit an upbending in the frequency range of $\hbar\omega \simeq 0.44$ MeV, which has been shown[8] to be due to the Coriolis alignment of an $h_{11/2}$-proton pair in the $N = 90$ isotopes. The overall behavior of this band is not very different from other odd-spin odd-parity bands in the more collective nuclei in this region.

The low- and medium-spin states in the positive-parity band [Fig. 3(a)] show a similar collective behavior up to spin 24. At higher spins, however, this band shows an excitation pattern which is quite different from that of the odd-spin band or the yrast even-spin bands in neighboring nuclei (e.g., ^{160}Yb shown in Fig. 3, or the $N = 88$ isotones[4,9]). In particu-

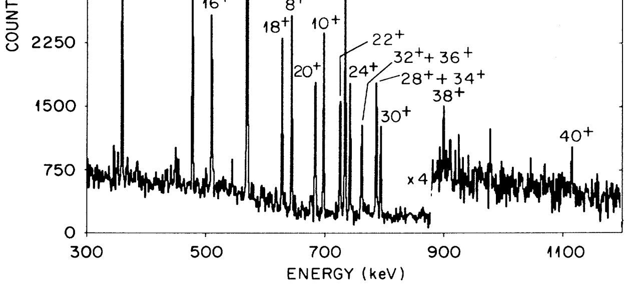

FIG. 1. Gamma-gamma coincidence spectra obtained from the ^{98}Mo + 285 MeV ^{64}Ni reaction. Summed gates include deexcitation γ rays from 16$^+$ to 36$^+$ states.

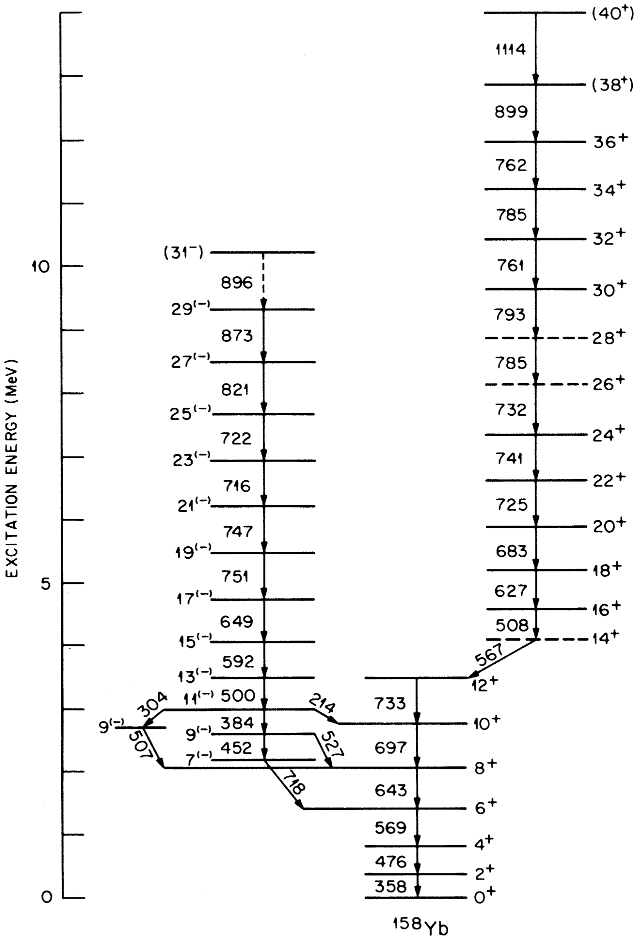

FIG. 2. Partial decay scheme for ^{158}Yb. Gamma-ray energies are given in kiloelectronvolts. Dashed horizontal lines indicate uncertain ordering of the transition γ rays. Parentheses indicate uncertain spin-parity assignment.

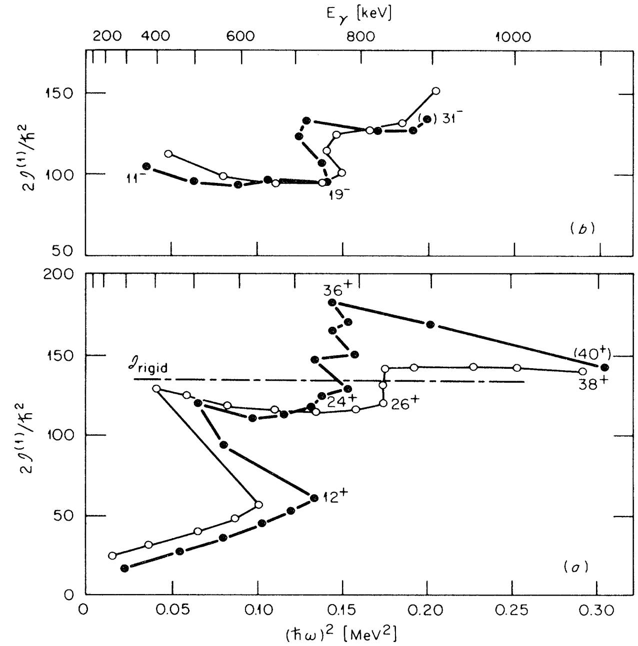

FIG. 3. Plots of moments of inertia, as $2\mathscr{I}^{(1)}/\hbar^2$, vs $(\hbar\omega)^2$ for (a) positive-parity bands and (b) negative-parity bands in ^{158}Yb (filled circles) and ^{160}Yb (open circles).

lar, the rise of $\mathscr{I}^{(1)}$ resumes past spin 20 and takes the extreme form of a vertical ascent after the second discontinuity at spin 24. The resulting moment of inertia exceeds the rigid-rotor value by nearly 40%. Such a large $\mathscr{I}^{(1)}$ has not been observed previously and is a consequence of the quasivibrational excitation mode. (The energies of the γ rays deexciting the states with spin $24 \leqslant I \leqslant 36$ remain within a 730–790-keV interval.)

The second discontinuity, around spin 24, might at first seem to arise from rotational alignment effects ($h_{9/2}$ neutrons, $h_{11/2}$ protons, or both). Since the alignment of the $h_{11/2}$-proton pair occurs at a higher frequency in the sideband, it cannot account for this discontinuity. The $h_{9/2}$ neutron orbital, on the other hand, lies close to the Fermi surface for $N=88$ isotones, and its alignment is in part responsible for the upbending around spin 24 in this nucleus and its isotone ^{156}Er.[9] However, this mechanism alone (i.e., the $AB \rightarrow ABEF$ crossing) cannot account for the nearly $11\hbar$ gain in alignment that is experimentally observed. Neither can it explain the near constancy of the γ-ray energies. Indeed, the experimentally observed pattern of the gamma-ray energies cannot be reconciled with the predictions of models used to describe the high-spin states in stably deformed nuclei. In the case of collective rotation, E_γ increases smoothly with spin, except in narrow band-crossing regions (see, e.g., ^{160}Yb). In the case of the single-particle excitation mode, far from having constant energies, γ rays develop irregular energies and multipolarities (see, e.g., ^{154}Dy at high spins[4]). For both of these extreme modes, the moments of inertia at high spins are close to the rigid-rotor values.

Quasivibrational excitation patterns (i.e., nearly equal E_γ and sharply rising $\mathscr{I}^{(1)}$) also exist at spins below 18 in the $N=86$ nuclei, and at medium spins in the transitional $N=87$ nucleus ^{157}Yb.[10] On the basis of the systematics, it was suggested that they arise from soft-triaxial to oblate shape transitions.[2] The present study extends these patterns to high spins and lends further support to this interpretation. Indeed, on the basis of cranked shell-model calculations, Ragnarsson *et al.*[11] have recently suggested that the states in the 26- to 36-spin range in ^{158}Yb belong to an yrast band which continuously minimizes its energy by adjusting its shape parameters and acquiring larger γ values, where γ is the asymmetry parameter. This band finally "terminates" on the noncollective oblate axis at spin 36, which is obtained by alignment of the angular momenta of its valence particles with respect to the ^{146}Gd core along the oblate symmetry axis. Yrast states with spins greater than 36 would have a different intrinsic configuration and are predicted to decay by higher-energy interband transitions. The observed decay pattern closely resembles this prediction. Interestingly, the same calculations[12] predict coexistence of rotational bands which, similar to the observed negative-parity band, stay within the prolate region and retain their collectivity up to high rotational frequencies.

Since discrete γ-ray spectroscopy reveals the structures of only the yrast and near yrast states, we have examined the continuum γ-ray data to ascertain which band structure dominates above the yrast line and beyond spin 40.[13] For this purpose, the γ-ray decay of the entry states was studied by use of the NaI detectors of the spin spectrometer. The NaI spectra were generated by gating on the γ-ray transitions from $I^\pi = 2^+$ to 12^+ states observed in the Ge detectors, and sorted according to the total coincidence γ-ray multiplicity and pulse height. They were subsequently unfolded and decomposed to yield dipole and quadrupole energy-multipolarity spectra. There are several important features. First, a strong and narrow peak, centered around 750 keV, is observed at all multiplicities. The quadrupole component of this peak is nearly three times stronger than the dipole component and is mostly due to the discrete γ rays from the high-spin states. (This peak was erroneously characterized as dipole by Jääskeläinen.[14]) The high-energy edge of this peak falls rapidly and does not move noticeably with increases in the multiplicity (see also Ref. 14). Instead, a second and much broader quadrupole structure gradually develops above 1 MeV. However, the peak of this structure, centered around 1.2 MeV, is associated with entry states which lie several megaelectronvolts above the yrast line for spin values $I \leq 50$. Secondly, the E_γ-E_γ correlation matrices also show an *abrupt* cutoff of the ridge structure above $E_\gamma \simeq 850$ keV, which again indicates the absence of collective rotational bands beyond an angular frequency of $\hbar\omega \simeq 0.45$ MeV. This should be contrasted with the ridge-valley structure of well-deformed nuclei, where it extends well beyond the energies of the last observed discrete γ rays. These features in the continuum data indicate that the near-yrast states are dominated by weakly collective, or noncollective, structures in the spin range of 30 to 50.

Interestingly, the dipole spectra show a strong low-energy component ($300 \leq E_\gamma \leq 750$ keV) which originates from the *near-yrast* states in the spin range of $I \simeq 30$–50. (Excitation energies were deduced from the total pulse-height information.) This component accounts for more than half of the dipole transitions. Recently, Bengtsson and Ragnarsson[12] have pointed out that $M1$ transitions compete strongly with $E2$ transitions close to the "band termination." Should the observed low-energy dipole component prove to be of magnetic character, it would lend further support for occurrence of "band termination" near the yrast line at spins 30 to 50. Although "band termination" has been previously identified in the spectra of some s-d nuclei,[15,16] the present data constitute the first evidence for its existence in a heavy nucleus.

In summary, the yrast positive- and negative-parity bands of ^{158}Yb have been established to high spins. The excitation energies of the negative-parity band up to its maximum observed spin of 31 and of the positive-parity states up to $I = 24$ show a collective rotational pattern. Above spin 24, however, the positive-parity band shows a quasivibrational character. This may indicate a "terminating band" wherein the nucleus continuously adjusts its shape parameters while *gradually* evolving toward an oblate shape. Although both collective and "terminating" bands coexist up to spin $\simeq 30$, evidence from the quasicontinuum γ rays indicates that the latter structure predominates the near-yrast states at spins $I = 30$–50. These data constitute the first evidence for the existence of high-spin "terminating bands" in a heavy nucleus.

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[1] C. G. Andersson *et al.*, Phys. Scr. **24**, 266 (1981).

[2] C. Baktash, in *High Angular Momentum Properties of Nuclei*, edited by N. R. Johnson (Harwood-Academic Press, New York, 1983), p. 207.

[3] T. L. Khoo *et al.*, in *High Angular Momentum Properties of Nuclei*, edited by N. R. Johnson (Harwood-Academic Press, New York, 1983), p. 179.

[4] A. Pakkanen *et al.*, Phys. Rev. Lett. **48**, 1530 (1982).

[5] M. Jääskeläinen *et al.*, Nucl. Instrum. Methods **204**, 385 (1983).

[6] Y. Schutz, to be published.

[7] L. L. Riedinger *et al.*, Nucl. Phys. **A347**, 141 (1980); L. H. Courtney *et al.*, Bull. Am. Phys. Soc. **28**, 982 (1983).

[8] R. Holtzmann *et al.*, Phys. Rev. Lett. **50**, 1834 (1983).

[9] T. Byrski *et al.*, Phys. Lett. **102B**, 235 (1981).

[10] D. Horn *et al.*, Bull. Am. Phys. Soc. **29**, 694 (1979).

[11] I. Ragnarsson, T. Bengtsson, W. Nazarewicz, J. Dudek, and G. A. Leander, following Letter [Phys. Rev. Lett. **54**, 982 (1985)].

[12] T. Bengtsson and I. Ragnarsson, Phys. Scr. **T5**, 165 (1983).

[13] Y. Schutz *et al.*, Bull. Am. Phys. Soc. **29**, 1043 (1984), and to be published.

[14] M. Jääskeläinen *et al.*, Nucl. Phys. **A396**, 319c (1983).

[15] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2, p. 98.

[16] I. Ragnarsson, S. Åberg, and R. K. Sheline, Phys. Scr. **24**, 215 (1981).