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Dominance of the $i_{13/2}$ Neutron in Yb Backbending

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Two decoupled rotational bands in ^{165}Yb are observed in (heavy ion, xn) experiments. The $i_{13/2}$ band does not backbend, whereas the $h_{9/2}$ band does. This provides strong evidence that only $i_{13/2}$ neutrons contribute to backbending in this region.

In the last few years, experimentalists have identified thirteen different Dy, Er, and Yb nuclei exhibiting rotational bands that suffer discontinuities at large angular momentum values. It is generally agreed that the cause of the discontinuities in these backbending bands is a crossing with another band. The two most popular theories explain this second band as one with less pairing than in the ground state. The Coriolis antipairing models of Kumar,[1] Krumlinde,[2] and Faessler *et al.*[3] propose a reduction in the pairing strength between many or all neutrons because of the Coriolis interaction, while the rotation-alignment model of Stephens and Simon[4] requires pairing collapse between only one pair of the highest-angular-momentum neutrons ($i_{13/2}$ in this region). We present the observation of two decoupled bands in ^{165}Yb, one which backbends and one which does not. This provides strong experimental evidence that only the $i_{13/2}$ neutrons are important in the backbending process in light Yb nuclei.

The experiments described here are a part of our studies of rotational bands in ^{163,164,165}Yb populated by (heavy ion, xn) reactions using beams of ^{12}C, ^{20}Ne, ^{22}Ne, and ^{40}Ar ions from the Oak Ridge isochronous cyclotron. Excitation function, γ-γ coincidence, and γ-ray angular distribution measurements have been performed. The band structure in ^{165}Yb was deduced primarily from a coin-

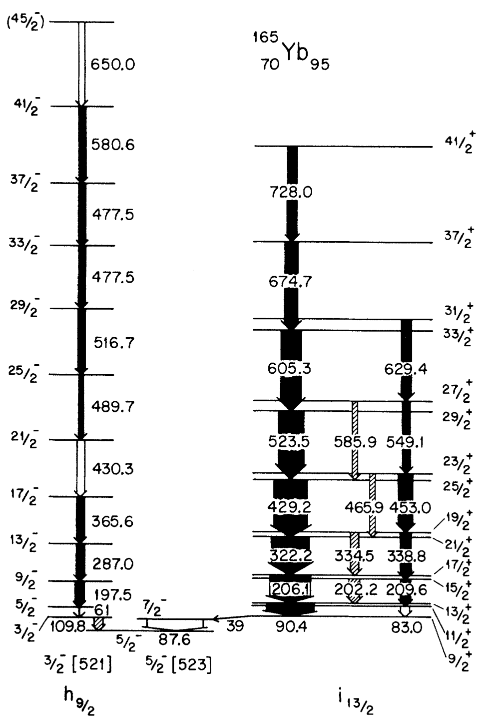

FIG. 1. Level scheme of ^{165}Yb. The widths of the arrows are proportional to the transition intensities (corrected for internal conversion) observed at 90° in the (^{22}Ne, 5n) reaction at 109 MeV. The energies and intensities of the 39-, 61-, 430-, and 490-keV transitions could not be measured accurately because of the presence of x rays or other γ rays at these energies in the spectra. All γ rays, except those at 110 keV, are placed with the aid of coincidence data. The transition arrows are darkened in those cases where the A_2 and A_4 values are consistent with a pure quadrupole assignment; cross-hatched arrows indicate predominately dipole transitions. The multipolarities could not be obtained for the remaining ones.

cidence experiment employing two large-volume Ge(Li) detectors and the reaction ^{148}Nd(^{22}Ne, 5n) with an incident beam energy of 109 MeV. The angular distribution data were acquired at angles of 0°, 45°, and 90° via the reaction ^{156}Gd(^{12}C, 3n) at 58 MeV.

Most of the reaction strength to the residual ^{165}Yb nucleus proceeds to the ground state through an intense cascade of eight coincident γ rays with energies of 90.4, . . . , 728.0 keV (see Fig. 1). The A_2 and A_4 values derived from the angular-distribution experiment are consistent with the assignment of a stretched $E2$ cascade. In addition to the yrast sequence, a second cascade of quadrupole transitions (209.6, . . . , 629.4 keV) was observed with mixed $\Delta I = 1$ cross-over transitions to the yrast cascade. This second set of $\Delta I = 2$ levels is shifted up in energy relative to the yrast set. Similar shifts have been observed in the light Er and Dy nuclei,[5-8] and are attributed to the Coriolis mixing of various Ω states of the $i_{13/2}$ neutron configuration (Ω is the projection of j, the individual-particle angular momentum, on the symmetry axis). In the case of ^{163}Er ($N = 95$ as for ^{165}Yb), the lowest member of the mixed band is $\frac{5}{2}^+$, corresponding to the $\frac{5}{2}^+[642]$ Nilsson level.[5] However, judging from the energies of the lowest 2^+ states in the adjacent even-even nuclei, we feel that ^{165}Yb is more similar in deformation to ^{161}Er ($N=93$), and thus more similar in the degree of Coriolis mixing. The bandhead of this mixed sequence of levels in ^{161}Er is $\frac{9}{2}^+$ (Ref. 5), with the $\frac{5}{2}$ and $\frac{7}{2}$ states probably shifted up in energy by the mixing. The energies of the intense transitions seen here in ^{165}Yb are quite similar to those observed in the ^{161}Er yrast cascade, and consequently we assign spin and parity of $\frac{9}{2}^+$ to the lowest-lying member of the band. This assignment is supported also by the nature of the decay of this state. From the work of Tamura *et al.*[9] on the decay of ^{165}Yb, the ground state of ^{165}Yb is thought to be $\frac{5}{2}^-[523]$. We identify an 88-keV γ ray as the $\frac{7}{2}^- \to \frac{5}{2}^-$ transition in this band and also a 39-keV γ ray as the $\frac{9}{2}^+ \to \frac{7}{2}^-$ transition from the $i_{13/2}$ band. We have observed a prompt coincidence between the 88- and 39-keV γ rays, and a delayed coincidence ($T_{1/2} > 50$ nsec) between the 88- and 206-keV γ rays. The $\frac{9}{2}^+$ bandhead in ^{161}Er is also an isomeric state (70 ± 20 nsec), decaying by means of a 45.6-keV transition to a $\frac{7}{2}^-$ state.[5]

The importance of these experimental results lies not so much in the mixed $i_{13/2}$ band, but rather in another stretched $E2$ cascade of ten γ rays (197.5, . . . , 650.0 keV). All placements in this band, including that of the two 477-keV transitions, are based on coincidence data. The transitions are ordered mainly on the basis of the γ-ray intensities observed in various reactions at different energies. The intensities in Fig. 1 were obtained in the (^{22}Ne, 5n) reaction at 109 MeV, where the side feeding into the $h_{9/2}$ band is minimal. A more normal decrease in the intensities was found in the (^{12}C, 3n) reaction at 54 MeV, giving some evidence on the ordering. In addition, the 490-keV transition intensity was easier to extract in the (^{12}C, 3n) reaction, due to less contamination by the $16^+ \to 14^+$ γ ray of ^{164}Yb, and was found to be more characteristic of its placement in the band. However, since the γ rays in this band are rather weak, and thus have somewhat uncertain intensities, it was necessary to use the additional constraint of a smoothly varying moment of inertia to order the transitions in some cases.

To interpret the second band, we depend upon the observation of two other transitions in this sequence and upon the systematics of Nilsson levels in this region. Although x rays dominate the 60-keV portion of the spectrum, there is some evidence for a 61-keV γ ray in coincidence with the 198-keV transition in an experiment involving a low-energy photon detector. The presence of such a low-energy transition in this cascade would be suggestive of the $\frac{3}{2}^-[521]$ band seen in this region. This Nilsson level, the $\Omega=\frac{3}{2}$ projection of the $h_{9/2}$ neutron configuration, is the ground state of Er and Dy nuclei with $N=91$ and 93 and a low-lying state in ^{163}Er with $N=95$[5] and ^{167}Yb with $N=97$.[10] The 110-keV γ ray is assigned as the crossover from this band to the ground state in ^{165}Yb, based on its largely dipole multipolarity and its intensity, although we have no proof that it is in coincidence with the 198-keV transition. A possible peak at 110 keV could not be observed in our long γ-γ experiment, since a discriminator level was set too high. Subsequent experiments of much shorter durations produced no evidence of a 110–198-keV coincidence relationship, but in these cases the data were not of sufficient statistical accuracy to eliminate such a possibility. We feel that the presence of the 61- and 110-keV transitions and the systematics of band structure in neighboring nuclei argue for the placement of the sequence of ten γ rays, beginning with that of 198 keV, in the $\frac{3}{2}^-[521]$ band, rather than in the ground band with a 198-keV $\frac{9}{2}^- \to \frac{5}{2}^-$ transition.

The significance of these two bands in ^{165}Yb can best be demonstrated by discussing them in the framework of the rotation-alignment model of Stephens and co-workers.[4,11] In this model, the effect of the Coriolis force on a high-j particle in a low-Ω state is to align j with the rotational angular momentum, R, of the even-even core. For the aligned $i_{13/2}$ band, the $\frac{17}{2}\to\frac{13}{2}$ spacing would, in the limit, be equal to the average $2\to 0$ spacing of the adjacent even-even nuclei. For ^{165}Yb and ^{163}Yb, $E(\frac{17}{2}\to\frac{13}{2})/E(2\to 0)$ is 1.83 and 1.40, respectively, suggesting that the limit is being approached as one considers more neutron-deficient nuclei which have smaller deformations and lower Fermi surfaces.

The importance of the decoupled or aligned odd-

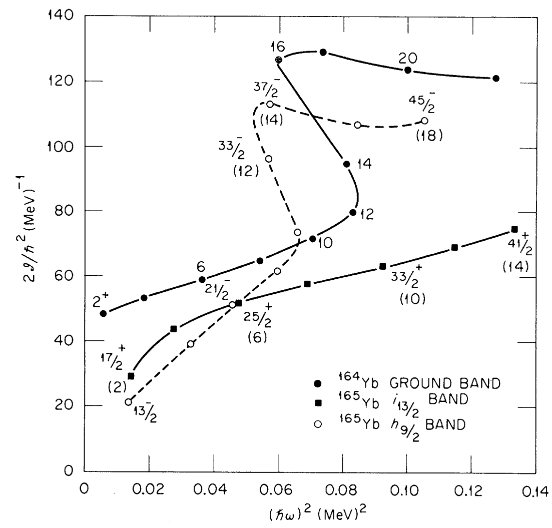

FIG. 2. Graph of $2\mathcal{J}/\hbar^2$ versus $(\hbar\omega)^2$ for the ground-state band of ^{164}Yb and the two decoupled bands in ^{165}Yb. The variables plotted are obtained from the transition energies in a way described in Ref. 13; for the odd-A bands, $j=\frac{9}{2}$ or $\frac{13}{2}$ is subtracted from the spin of the level before the calculation.

neutron band comes at high spin, where the even-even core should backbend. It is known that ^{164}Yb and ^{166}Yb begin to backbend at $I=14$. We show our data[12] on ^{164}Yb in a standard plot of essentially the moment of inertia versus the square of the rotational frequency in Fig. 2 (the points up to 16^+ were previously established by Lieder *et al.*[13]). The favored sequence of levels in the $i_{13/2}$ band of ^{165}Yb is also plotted. The $\frac{41}{2}^+$ level is equivalent to $R=14$ of the core, but yet shows no departure from the regular spacings established lower in the band. This indicates, as in the cases of the light Dy and Er nuclei,[6-8] that the aligned $i_{13/2}$ neutron is blocking further decoupling of similar neutrons from the core, thus identifying the $i_{13/2}$ neutron as the main cause of backbending in this region. This technique of using blocking in odd-A rotational bands to investigate the particles contributing to backbending was shown to be valid by Grosse, Stephens, and Diamond,[6,14] who compared the regularly spaced $i_{13/2}$ bands in odd-N Er nuclei to the backbending $h_{11/2}$ bands in odd-Z Ho nuclei.

There is still room for controversy, however, since even those advocating general pairing collapse agree that the $i_{13/2}$ neutron should play the largest role in this region. The question is whether there are other neutrons which also contribute to backbending. A possible answer to this question can be obtained by considering the second band found in our experiments. Before arriving at this answer, we must first recall that the Coriolis matrix element is given by $\frac{1}{2}[j(j+1) - \Omega(\Omega\pm1)]^{1/2}$. Thus for ^{165}Yb, the $\frac{5}{2}^+[642]$ neutron ($j=\frac{13}{2}$, $\Omega=\frac{5}{2}$) certainly experiences the largest Coriolis-mixing effects, while the next most important case should be $\frac{3}{2}^-[521]$, $j=\frac{9}{2}$ and $\Omega=\frac{3}{2}$. This second band is plotted in Fig. 2, assuming that the $\frac{13}{2}^- \to \frac{9}{2}^-$ transition is equivalent to $2\to0$ of the even-even core. Below $I=\frac{29}{2}$, the slope of this curve is greater than for the ground-state band of ^{164}Yb or the $i_{13/2}$ band of ^{165}Yb. This is reasonable since the Coriolis mixing is less and the alignment occurs more slowly. However, at $I=\frac{33}{2}$ ($R=12$), severe backbending takes place in a way similar to ^{164}Yb. It is true that the change occurs at $R=12$, sooner than for ^{164}Yb or ^{166}Yb. A similar behavior was reported by Grosse, Stephens, and Diamond[14] in comparing the odd-proton bands of Ho nuclei to the ground bands in the even-even Er cases.

The difference in behavior of the decoupled $h_{9/2}$ and $i_{13/2}$ bands is quite striking. When the $i_{13/2}$ neutrons in the even-even core are blocked in the aligned $i_{13/2}$ band of ^{165}Yb, this band does not backbend. In contrast, when the $h_{9/2}$ core neutrons are blocked in the aligned $h_{9/2}$ band, backbending does occur. This strongly suggests that the $i_{13/2}$ neutrons are crucial in the backbending process, whereas the $h_{9/2}$ neutrons are not. In the Coriolis antipairing model, the Coriolis force weakens most easily the pairing between the high angular-momentum neutrons in Nilsson levels near the Fermi surface. Thus Faessler *et al.*[3] explained that in ^{166}Yb both the $\frac{5}{2}^+[642]$ level ($i_{13/2}$) and the $\frac{5}{2}^-[523]$ state (an $f_{7/2}$ level nearer to the Fermi surface than the former one) should contribute to backbending. The Fermi surface for ^{164}Yb is found between the close-lying $h_{9/2}$ and $i_{13/2}$ levels discussed extensively in this paper. One would expect, therefore, that Coriolis antipairing should have an effect on neutrons in both levels in the even-even core of ^{165}Yb. The backbending of the decoupled $h_{9/2}$ band seems to indicate that the rotation alignment of $i_{13/2}$ particles occurs at a lower rotational frequency than general Coriolis pairing loss for the light-Yb nuclei. However, this may not be the case in regions where the Fermi surface is, for example, near the higher-Ω $i_{13/2}$ levels. In addition, our experiments demonstrate the investigative strength of using the selective blocking in different bands in the same odd-A nucleus to isolate the cause of backbending.

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