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Line shapes and lifetimes in the ^{135}Nd superdeformed band

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Lifetimes of members of the superdeformed band in ^{135}Nd have been determined by a Doppler-shift attenuation method. In this case, where side feeding occurs along the entire length of the cascade, centroid analysis does not give a unique answer and line-shape analysis is necessary. We find a transition quadrupole moment of 7.4 ± 1.0 b, corresponding to an axis ratio of 1.42. The side feeding is ~4 times slower than the main cascade.

A nucleus may show bands with quite different moments of inertia, suggesting a variety of different shapes. Of great interest recently has been the discovery[1] of bands at high spin in the mass-150 region that have moments of inertia indicative of strongly prolate shapes with a 2:1 axis ratio. Consideration of the potential-energy calculations that could explain this behavior suggested[2] that nuclei with other numbers of protons and neutrons might also show strongly deformed shapes, thus superdeformed (SD) in a generalized sense of being part of a chain of nuclei whose deformations vary systematically depending upon the neutron and proton numbers, but are larger than near-ground-state yrast values. (The axis ratios range downwards from 2:1, but also possibly up to the not yet observed 3:1 cases.) Such bands are now well known in the mass-130 region, and in fact, observation[3] of the first example, ^{132}Ce, came even before the high-spin 2:1 shapes were found in the mass-150 region.

In all of these cases, the initial indication of the magnitude of the deformation in the band was obtained from values of the moments of inertia,

$$J^{(1)}/\hbar^2 = I/\hbar\omega(I)\,, \tag{1}$$

$$J^{(2)}/\hbar^2 = dI/\hbar d\omega(I)\,, \tag{2}$$

where $2\hbar\omega(I) = E_\gamma(I+1 \rightarrow I-1)$ and $2\hbar\, d\omega(I) = E_\gamma(I+2 \rightarrow I) - E_\gamma(I \rightarrow I-2)$. Values of $J^{(2)}$, the dynamic moment of inertia, are readily determined from the differences in the (electric quadrupole) transition energies, but the less sensitively fluctuating values of $J^{(1)}$ require knowing the spins of the states. In none of these cases in the mass-130 and mass-150 regions are these spins actually determined, but estimates (probably good to $\pm 2\hbar$) give values of $J^{(1)}$ that can be used to yield approximate (major to minor) axis ratios c/a, from the expression for a rigid, axially symmetric rotor,

$$J^{(1)}/J_0 = [1 + (c/a)^2]/2(c/a)^{2/3} \tag{3}$$

where J_0 is the rigid-sphere value, $0.00976AR^2$ (in $\hbar^2$ MeV^{-1}), with $R = 1.2A^{1/3}$ (in fm).

But since moments of inertia depend not only upon the nuclear deformation, but also upon the pairing correlations and the particle alignments, they are not a reliable measure of deformation. Better are the reduced quadrupole transition probabilities $B(E2)$, or the derived transition quadrupole moments Q_t, since they depend primarily on the shape and deformation. For a prolate, axially symmetric rotor (which is the shape corresponding to the strongly deformed prolate minimum in most calculations of potential-energy surfaces), expressions for the $B(E2)$ and Q_t are

$$B(E2) = (5e^2/16\pi) Q_t^2 \langle I_i 2K0 \,|\, I_i 2 I_f K\rangle^2\,, \tag{4}$$

$$Q_t = 0.4ZR^2[(c/a)^2 - 1]/(c/a)^{2/3}\,. \tag{5}$$

Measurement of large Q_t's are best made using Doppler-shift methods, and where the transitions of interest are expected to be very fast, Doppler-shift attenuation methods (DSAM) provide a general method for going to lifetimes of less than a picosecond. Indeed, the first two SD examples observed, the band in ^{132}Ce and the 2:1 band in ^{152}Dy, have had the average values of their band Q_t's so determined by DSAM centroid-shift experiments, Refs. 4 and 5, respectively, as well as the more recently discovered ones in ^{149}Gd (Ref. 6), ^{150}Gd (Ref. 7), ^{131}Ce, ^{133,137}Nd (Ref. 8), and ^{191}Hg (Ref. 9). With the exception of ^{133}Nd, these measurements essentially confirmed the large deformations indicated by the moments of inertia. Two assumptions were made in these centroid measurements. One is that the band can be represented by a single, average value of Q_t. The second is that any side feeding into the band has the same time distribution as the main band and can be ignored.

The second example of a SD band in the mass-130 region was found[10] in ^{135}Nd. Because it has moments of inertia comparable to those of ^{132}Ce, we assumed it also had a comparable deformation. But to confirm this supposition, we have carried out the Doppler-shift measurement described in this paper.

The band in ^{135}Nd was produced in a $5n$ reaction by the irradiation of a 1.06 mg/cm^2 target of ^{100}Mo on a 11 mg/cm^2 gold backing with a 175-MeV beam of ^{40}Ar from the LBL 88-Inch Cyclotron. Twenty Compton-suppressed Ge detectors of the HERA array viewed the target, and 280×10^6 triple- and higher-coincidence events were stored on magnetic tapes. These results were sorted into four two-dimensional arrays in which one axis consisted of a special group of detectors, the four forward (42°), or four backward (two at 154° and two at 146°), or two near-forward (51°), or four near-backward (121°) detectors, and the other axis was any coincident detector. Two clean, essentially stopped (546 and 677 keV) gates at the bottom of the band were set on the latter axis to provide forward- or backward-shifted spectra of this band. Examples are shown in Fig. 1. The centroid shifts of the transitions from their stopped positions were determined, and knowing the average value of the cosine of the angles for that group of detectors, the average value of v/c at which each transition was emitted could be calculated. These results are plotted in Fig. 2 with error bars that indicate the range of results obtained by different ways of determining the experimental centroids. The average recoil velocities range from near that of the initial recoil velocity, 0.0272c, at the top of the band, to fully stopped, for the 546-keV transition at the bottom.

The computer program of Ref. 11, slightly modified, provided histories (collision paths) for the slowing down of the recoiling ^{135}Nd nuclei in the target and gold backing, and an associated program calculated the multiple-step-cascade decay for a chosen value of Q_t for the band. In the slowing-down calculation, the production of ^{135}Nd nuclei was considered to be uniform throughout the target, with the initial recoil velocity depending upon the position in the target. For the electronic stopping power the program IRMA was used[12] (which includes consideration

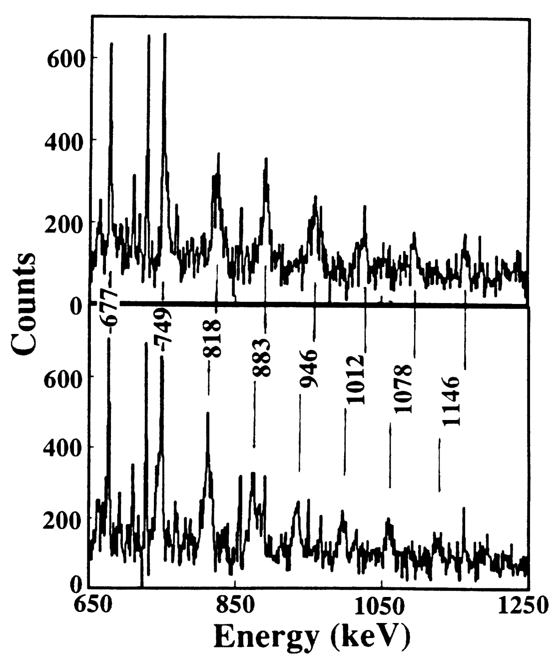

FIG. 1. Superdeformed band spectra in ^{135}Nd from the sum of coincidence gates on the 546- and 677-keV transitions in four forward (top) and four backward (bottom) detectors.

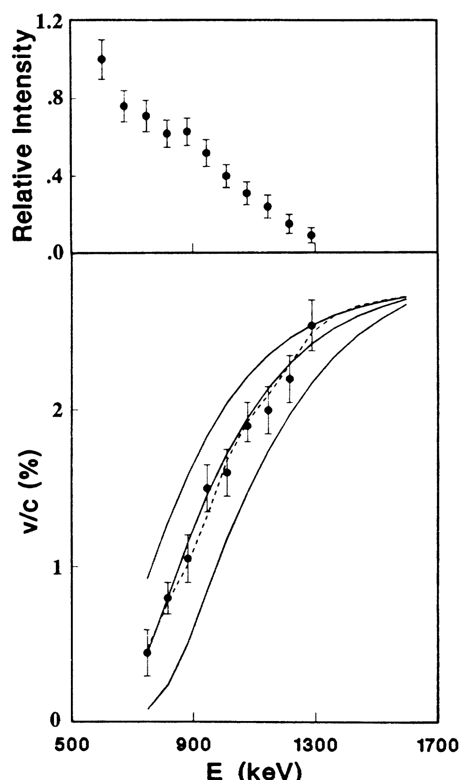

FIG. 2. Bottom: Average value of v/c for recoiling nuclei when emitting SD band transition of energy E_γ. Experimental points are shown, as well as calculations for band Q_t =4.0, 5.4, and 7.0 b with no side feeding (solid lines), and a calculated curve for band Q_t =7.4 b but with side feeding of experimentally observed intensity which is approximately four times slower than the main cascade (dashed line). Top: Relative intensity of SD transitions vs E_γ.

of the atomic shell structure of the target and backing material). For the nuclear slowing, the formalism[13] of Lindhard, Scharff, and Schiøtt was employed, with the magnitude and direction of the recoil velocity after a collision calculated by Monte Carlo methods. Five thousand histories of the slowing-down process were run, and the resulting velocity profiles projected toward each group of detectors (for up to 600 time steps of ~4 fs) were stored.

The two assumptions mentioned earlier were made, as has been done in all previous SD transition moment measurements: a single value of Q_t was used for the whole band (so the changes in the transition lifetimes were due entirely to the fifth-power dependence on the transition energy), and no side feeding was considered. Calculations were done with three, two, and one additional transitions placed above the known transitions of the band to take into account the effect of unobserved, higher-lying transitions. These had the same moment of inertia and Q_t values as those of the latter. Since these first transitions are very fast (large transition energies), there will not be very much difference in the results, but the scheme with only one additional gamma ray gives a lower limit on the value of Q_t for the band members, and most of the calculations used this assumption. Figure 2 shows the experimental centroids and three curves calculated with $Q_t = 4.0$, 5.4, and 7.0 b. Thus the value of Q_t indicated for this band was 5.4 b. It was a surprise, then, that this was so small compared to the value found for ^{132}Ce, 8.8 b, since their moments of inertia are similar.

But the measurements have been done by two different groups under different conditions. Perhaps most importantly, different computer programs, with different treatments of the slowing of the recoil nuclei, were used in obtaining the calculated curves to compare with the data. With this latter point in mind, we have calculated stopping histories with our program from the information given in Ref. 4 for the ^{132}Ce study, and then compared these calculated curves with those given there. There is rather good agreement, although our curves are slightly higher, giving a best fit to the data for $Q_t = 8.0$ b rather than the 8.8 b published in Ref. 4. Such a difference of 10% could well be in different treatment of the slowing of the recoiling nuclei in the programs, but it cannot explain the much smaller Q_t found for ^{135}Nd.

There is reason to suspect that the second assumption, not considering the side feeding, may not be good in this case. In ^{135}Nd the band continues to pick up side feeding, though in decreasing amounts, all the way to the lowest transitions,[10] as shown in Fig. 2. If this feeding has a significantly different time distribution than the main band, it must be included in the calculation. Comparison of the experimental line shapes of the moderately slow (946, 883, and 818 keV) transitions with the calculated ones, Fig. 3, shows a poor fit; there is not enough stopped peak present in the calculated shapes, particularly for the 883-keV transition, although the centroids appear adequately matched. This is actually what could happen if the side feeding is slower and the main band is faster than the values corresponding to the centroids, and so compensate to give the observed centroids. Since the band is, in fact, continuously fed from the side, we attempted to fit the line shapes by allowing each state in the main cascade to be additionally fed (with the experimentally determined side-feeding intensity) by a side band. Each such band is assumed to have as many transitions and the same energies as the main-band cascade to that state, and each has a single (not necessarily the same) quadrupole moment. Relatively good agreement of the calculated and experimental line shapes were obtained using Q_t values of 7.4 and 3.5 b for the main and side-feeding bands, respectively. Slightly better fits were obtained by gradually decreasing the values of the side-band $B(E2)$'s from $\frac{1}{3}$ to $\frac{1}{5}$ of the main cascade values. However, these decreases are near the limit of sensitivity of the calculations, and so may not be significant.

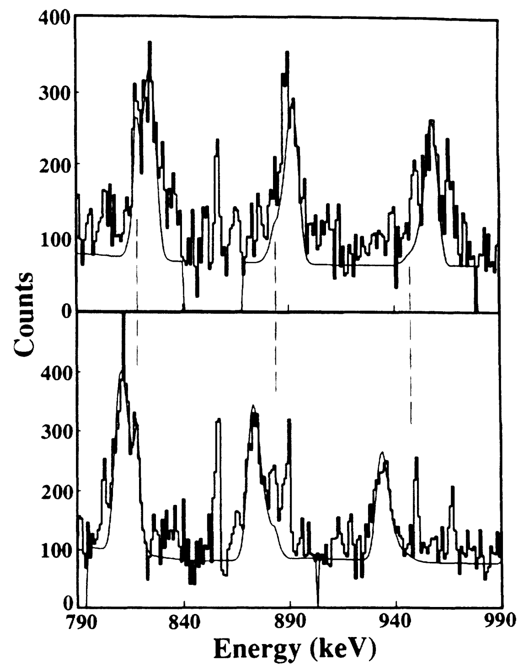

FIG. 3. Line shapes of 818-, 883-, and 946-keV transitions for forward (top) and backward (bottom) detectors; Experimental, in coincidence with the sum of 546- and 677-keV gates (heavy histogram), and calculated, with $Q_t = 5.4$ b and no side feeding. Dashed lines indicate positions of stopped peaks.

Examples of the line shapes of the same three transitions as shown in Fig. 3 but calculated with slow side feeding are given in Fig. 4, as well as the experimental shapes (again). These figures also illustrate an unfortunate complication in the analysis of the line shapes: the interference of other lines. In this particular cascade, the 946- and 883-keV transitions are the most sensitive to the effects of the slow side feeding, and only in the backward and near-backward spectra are their line shapes clear of another (stopped) line, the 949- and 888-keV transitions, respectively. The 949-keV line is one of the four or five connecting transitions that carry about half of the intensity at the bottom of the band into the ground band. So far, these connecting transitions are the only ones that have been seen in the SD bands in the mass-130 and mass-150 regions.

Figure 2 also shows the centroid curve calculated with

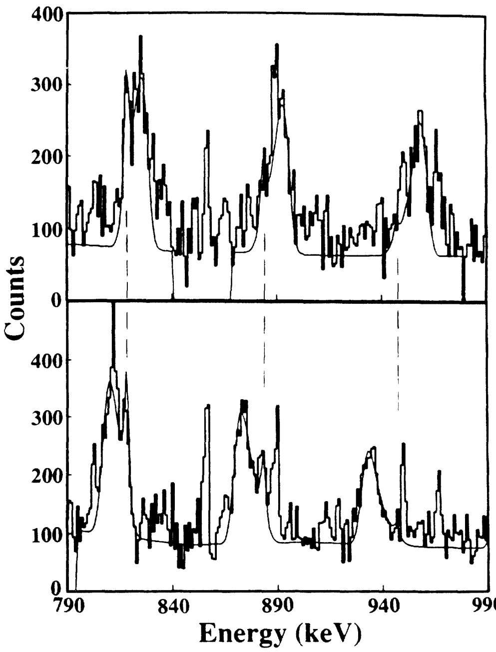

FIG. 4. Same as Fig. 3 but calculated curves are with $Q_t = 7.4$ b and with side-feeding cascades whose transition quadrupole moments decrease from 4.0 to 3.3 b as one goes down in spin in the main band. Dashed lines indicate positions of stopped peaks.

the (optimum) side feeding used in obtaining Fig. 4. It can be seen that the agreement is even slightly better than with no side feeding (the kinks in the curve are due mainly to the side feeding), and the feeding is required to fit the line shapes in Fig. 4. However, with this additional parameter (quadrupole moment for slow side feeding), a number of values of Q_t in the range of 7.4 ± 0.5 b, with a concomitant change in the side-feeding moment, give line shapes that cannot easily be distinguished by eye, or even by a χ^2 plot. In addition, uncertainties in the electronic stopping data used, and possibly still larger uncertainties in the accuracy of the Lindhard, Scharff, and Schiøtt nuclear stopping theory require a further increase in the range of error to at least $Q_t = 7.4 \pm 1.0$ b. This value is probably not significantly smaller than that given for ^{132}Ce, 8.8 b (remembering that there is a 10% difference in the two calculations, giving 8.0 b with our stopping program), and corresponds, through Eq. (5), to an axis ratio (c/a) of 1.42. We believe this is a better measure of the nuclear shape than the ratio given by Eq. (3), which yields an axis ratio of 1.29 for the measured $J^{(1)}$ value of $55\hbar^2$ MeV^{-1} near the top of the band.

All that can be said about the side feeding is that it appears to be about 4 times slower than the main-band cascade, if treated as a single additional parameter. Actually, the $B(E2)$ values for the side-band transitions are probably even less than one-fourth those of the main band, as their energies are likely to be larger than, rather than equal to, those of the latter. Such values, however, are comparable to those from the sparse data available[14,15] for normal states in ^{134,135,136}Nd nuclei.

We have several conclusions. (1) Our best estimate is that the SD band in ^{135}Nd has a transition quadrupole moment $Q_t = 7.4 \pm 1.0$ b, with appreciable side feeding (though decreasing in intensity) all the way down the cascade that is of order 4 times slower than the transitions in the main band. (2) Our value of this moment is about 10% less than that of the band in ^{132}Ce (using the same DSAM program) but this is inside the uncertainties. For the ^{135}Nd band, this suggests an axis ratio of $c/a = 1.42$. (3) In determining lifetimes in a band by Doppler-shift techniques, one may use the simple centroid-shift method if there is no side feeding into the band, or if it occurs well above the transitions being measured. (4) Where possible, line-shape analysis should be applied, and in the present case this gives a different result; a more accurate one, we believe.

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