Multiple Superdeformed Bands in ^{153}Dy

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Multiple superdeformed rotational bands have been identified in a nucleus for the first time. Cascades of 14, 13, and 11 transitions have been assigned to three bands in ^{153}Dy. Despite the small intensities, it has been possible to follow the decay of these bands from an angular frequency of 0.7 down to 0.4 MeV/$\hbar$. In all three cases, the dynamic moment of inertia $\mathcal{J}^{(2)}$ is nearly constant. Assignments to high-N intruder orbitals are suggested through comparison of these values of $\mathcal{J}^{(2)}$ with theoretical calculations based on the cranked shell model.

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The discovery of a single rotational band built on a superdeformed (SD) nuclear state (axis ratio 2:1) in ^{152}Dy (Ref. 1) confirmed long-standing theoretical predictions[2-4] that such shapes should exist in the $A=150$ region at high spin. The discovery has stimulated a flurry of experimental activity which has led to the subsequent location of a SD band in each of a number of nuclei near $A=150$.[5-9] These bands are very weakly populated, intensities of 1%–2% of the reaction channel being typical.

It is understood that the unusual shape is stabilized by high-N orbitals, which are normally occupied in nuclei beyond the ^{208}Pb double-shell closure but are depressed to near the Fermi level in mass $A=150$ at an axis ratio of 2:1. From a study of the variations of the $\mathcal{J}^{(2)}$ moments of inertia of SD bands from one nucleus to the next, it has been possible to suggest the individual orbits responsible for these bands.[10-13] In this work we were motivated to find a nucleus exhibiting more than one SD band, since a comparison among bands within one nucleus rather than among bands in several neighboring nuclei constitutes a much stronger test of the orbital assignments. Furthermore, from a study of the relative populations of the multiple bands it should be possible to infer their relative excitation energies in the feeding region, and hence the ordering of the observed configurations within the second potential well.

The sizable energy gaps at large deformations for $N=86$ and $Z=66$ (Refs. 10 and 11) are critical to the stable formation of the ^{152}Dy SD potential well. Since there are a number of orbitals available for the 87th neutron and the 67th proton, the neighboring $A=153$ nuclei should be well suited to a search for multiple SD bands. We have chosen to study ^{153}Dy.

High-spin states in ^{153}Dy were populated by the ^{124}Sn(^{34}S,5n) reaction with the beam produced by the MP tandem Van de Graaff accelerator at the Chalk River Tandem Accelerator Superconducting Cyclotron facility. In each of two separate experiments γ rays were detected by the 8π spectrometer which consists of a ball of 71 bismuth germanate (BGO) crystals covering approximately 95% of the solid angle and an array of twenty high-resolution Compton-suppressed Ge detectors. Events were recorded when more than ten BGO detectors fired (i.e., fold $K \geq 10$). The first experiment, at a beam energy of 165 MeV, used two stacked self-supporting 0.4-mg cm^{-2} targets, and 2×10^8 γ-γ Ge coincidences were obtained. In a second experiment at 167 MeV, only γ-γ-γ Ge coincidences were recorded. Three stacked 0.4-mg cm^{-2} targets were used and a total of 1.4×10^8 triple coincidences were obtained.

A higher-fold requirement, $15 \leq K \leq 24$, was imposed during the off-line analysis of the data with a correspondingly higher γ-ray sum energy. This resulted in a set of data relatively free of the competing 4n (^{154}Dy) and 6n (^{152}Dy) channels. After this cut in the data, 1.26×10^8 events remained in the γ-γ experiment and 7×10^7 triple coincidences from the second experiment were sorted into a cube. No strong SD band was found with conventional techniques. A search for a weaker band was difficult because most individual γ-γ coincidences were not statistically significant. A new technique was developed[14] to examine the data for the long chains of coincident γ rays with nearly constant energy spacing (i.e., nearly constant $\mathcal{J}^{(2)}$) which characterize the decay of an SD nucleus. A two-dimensional periodic correlation technique was used to search the matrix for regular coincidence patterns, including the possibility of small departures from constant $\mathcal{J}^{(2)}$. Since only very weak peaks are expected, the maximum peak size was limited to a value that is only a few percent of the strongest yrast transition, ensuring that a few very strong peaks do not dominate the correlation. If there are m γ

rays in a cascade, there should be $m(m-1)$ peaks in the γ-γ matrix and a strong signal could be obtained even for very weak bands. A similar technique was used on the triples data by summing over all $m(m-1)(m-2)$ possible coincidences. The longer the cascade of transitions, the stronger the signal is relative to the noise. Conventional coincidence techniques were then used to test the bands that were suggested by the correlation method.

Figure 1 illustrates the summed γ-ray spectra obtained for the three bands located by these techniques. All three bands, labeled 1, 2, and 3, are very weak with intensities of only 0.25%, 0.18%, and 0.13% of the reaction channel (with the above fold requirement). Therefore, it was not possible to measure the quadrupole moment that would ensure that these bands are indeed SD. The very weak population of these bands is probably due to two factors: (1) The summed intensity of ~0.6% is split among three bands and (2) the expected decrease in the barrier height for nuclei beyond the shell gap should lead to a smaller trapping probability and hence decreased intensity.[15,16] For band 1, the 900-keV gate is strong enough and free enough of contamination to observe most of the other members of the band. The same is true for the 862- and 909-keV lines in band 2, but there is no uncontaminated line in band 3. In all cases the γ rays assigned to these bands made a significant individual contribution to the correlation signal. This is strong evidence that the lines are in mutual coincidence.

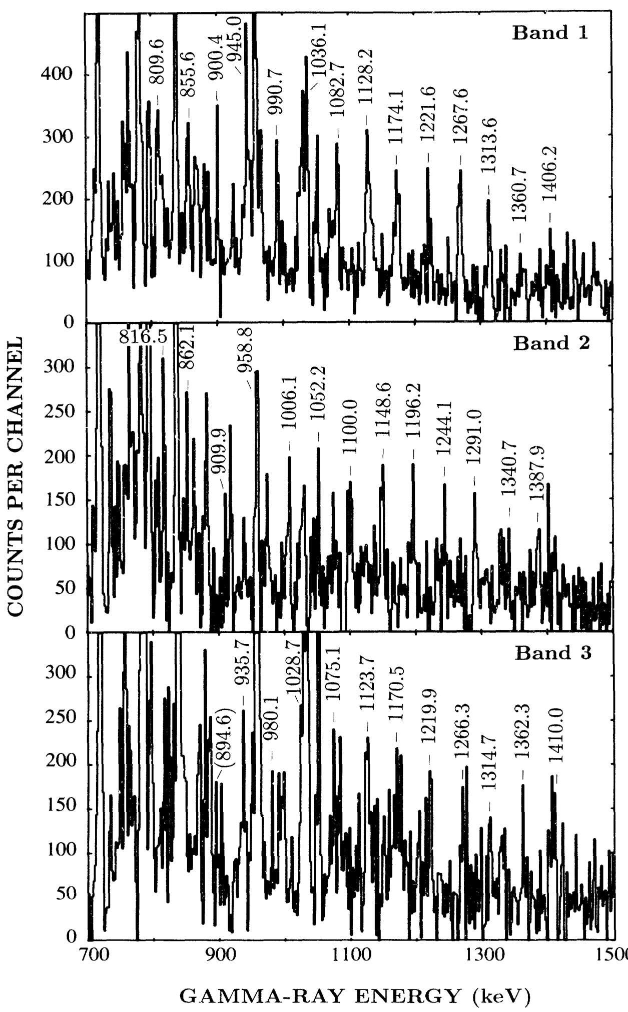

FIG. 1. Efficiency-corrected summed spectra for the three SD bands. Band members are labeled by their energies. All individual coincidence gates were included in the sum except for the 958.8-, 1006.1-, and 1052.2-keV gates of band 2.

The highest-energy transitions in band 3 are very similar to those in band 1. However, it is possible to conclude that there are indeed two separate sets of transitions through summing gates set on the lowest-energy lines (where the bands are distinct) and carefully examining the differences in the resulting spectra.

The known SD band in ^{152}Dy was seen only weakly in the data and examination of a second matrix sorted to accentuate the lines in ^{154}Dy did not show these cascades. Although some lines in ^{150}Gd were observed, the known SD band was not seen. Transitions in ^{153}Tb were present in the matrix at a level of less than 5% of the intensity of ^{153}Dy lines. These observations strongly suggest that all three bands belong to ^{153}Dy.

It has been possible to establish that all three bands feed a number of known high-spin levels[17] in ^{153}Dy. In particular, the 837-keV transition in between states of spin $\frac{55}{2}$ at 6740 keV and $\frac{59}{2}$ at 7577 keV is populated in the decay of all three bands.

Differences in the $\mathcal{J}^{(2)}$ moments of inertia have been used by several authors[6,8–11] to determine the occupation of particular high-N orbitals. The values of $\mathcal{J}^{(2)}$ are plotted versus rotational frequency in Fig. 2. It is clear

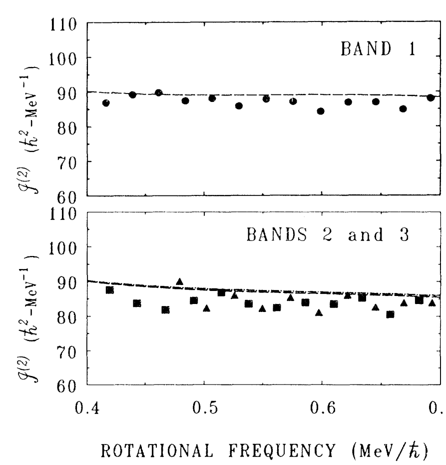

FIG. 2. The moments of inertia $\mathcal{J}^{(2)}$ for the three SD bands in ^{153}Dy [band 1 (●), band 2 (■), and band 3 (▲)]. The lines are the theoretical predictions for the $\pi 6^4 \nu 7^3$ and the $\pi 6^4 \nu 7^2$ configurations.

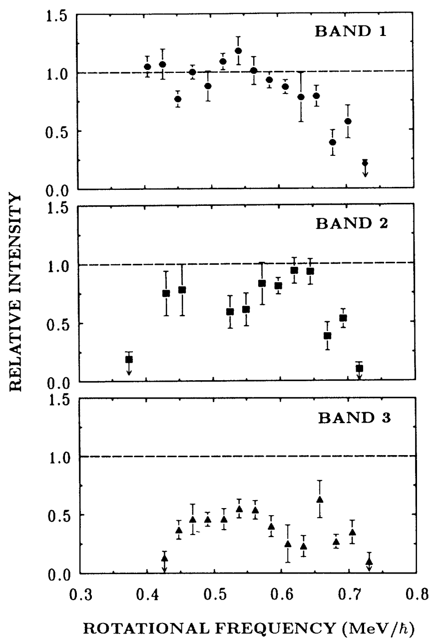

FIG. 3. Intensities of band members for the three SD bands relative to the intensity of the 945.0-keV transition.

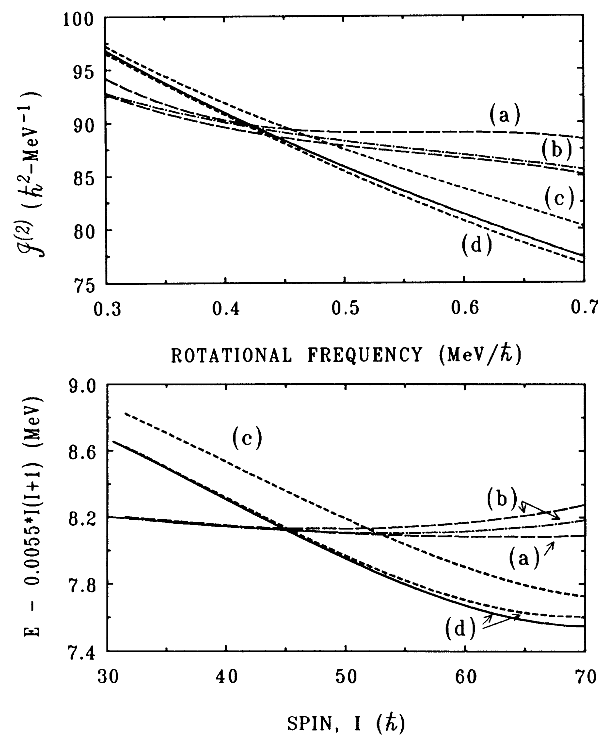

FIG. 4. Theoretical predictions for the $\mathcal{J}^{(2)}$ moments of inertia and the energies relative to a reference for SD bands in ^{153}Dy. The parity and signature (π,α) following the convention of Ref. 18 are the following: curve *a*, $\pi 6^4 \nu 7^3$ $(-,-\frac{1}{2})$; curve *b*, $\pi 6^4 \nu 7^2$ $(-,\pm\frac{1}{2})$ $(\alpha=+\frac{1}{2}$ denoted by the dot-dashed line); curve *c*, $\pi 6^3 \nu 7^3$ $(+,-\frac{1}{2})$; and curve *d*, $\pi 6^3 \nu 7^2$ $(+,\pm\frac{1}{2})$.

that all three bands have a nearly constant $\mathcal{J}^{(2)}$. The average value of $\mathcal{J}^{(2)}$ for band 1 is 87 $\hbar^2\mathrm{MeV}^{-1}$ and the values for bands 2 and 3 are very similar at 84 $\hbar^2\mathrm{MeV}^{-1}$. The similarity of the $\mathcal{J}^{(2)}$'s for bands 2 and 3 suggests that they may be signature partners. Indeed, a comparison of these two bands shows that the combined series of transition energies forms a very regular sequence. The average energy of a pair of adjacent transitions in one signature differs from the transition energy in the other sequence by ~1 keV.

Figure 3 shows a comparison of the in-band γ-ray intensities as a function of rotational frequency. The feeding pattern of all three bands is very similar with one-half of the feeding being accomplished by $\hbar\omega \approx 0.67$ MeV. This is remarkably similar to the pattern observed[8] in ^{150}Gd and ^{151}Tb and indeed all cases of superdeformation in the mass region have been found to be fed primarily above $\hbar\omega \approx 0.6$ MeV. Since band 1 is stronger than the other two bands, it is reasonable to assume that it is yrast at the excitation energy where these bands are being fed. Intensity differences should result from energy differences at the feeding point.

The deexcitation from the bands in ^{153}Dy occurs within one or two transitions. The presence of strong transitions among normal deformation states has prevented a precise determination of the frequency at which the deexcitation takes place.

Calculations of the structure of possible SD configurations were made with the same methods that were used in Refs. 10 and 11. A cranked Nilsson-Strutinsky calculation was performed. Equilibrium deformations were determined and the energy for each possible configuration was calculated as a function of spin. The principal effect may be seen in Figs. 8 and 9 of Ref. 11 where the deformation parameters $\epsilon_2=0.58$ and $\epsilon_4=0.03$ are appropriate. The single-particle states below the $N=86$ gap at $\omega=0$ are filled in ^{152}Dy. Two signature-degenerate SD bands may be formed by placing the 87th neutron in the negative-parity $N_i=5_8$ orbital. Another negative-parity band is obtained by filling the third $N=7$ $(j_{15/2})$ orbital (i.e., a $\nu 7^3$ configuration). Since the $Z=66$ gap is not very large in the parametrization used for the Nilsson model,[11] the $\pi 6^4$ $(i_{13/2})$ configurations come lowest at low spin and the $\pi 6^3$ positive-parity configurations lower at high spin. Figure 4 shows the results of these calculations for the lowest-energy SD configurations. Similar results have been obtained by Shimizu, Vigezzi, and Broglia[12] and Nazarewicz, Wyss, and Johnson[13] who have included pairing. Since at large deformation ^{152}Dy is doubly magic, pairing is expected to play a minor role in ^{153}Dy, particularly in determining the position of energy levels and for the $\mathcal{J}^{(2)}$ moment of inertia.

The variation of $\mathcal{J}^{(2)}$ for all observed SD bands has been understood[10,11] in terms of occupations of the high-N orbits $\pi 6$ ($i_{13/2}$) and $\nu 7$ ($j_{15/2}$). It is therefore reasonable to attempt a configuration assignment based on $\mathcal{J}^{(2)}$ moments of inertia. The three negative-parity bands are predicted to have a nearly constant $\mathcal{J}^{(2)}$ over the frequency range that is observed experimentally. The $\pi 6^3$ configurations are expected to have a decreasing $\mathcal{J}^{(2)}$ over this range. With this in mind, it is reasonable to assign the three bands as follows (see Fig. 4): band 1, $\pi 6^4 \nu 7^3$ with negative parity and signature, $(-,-\frac{1}{2})$; bands 2 and 3 $(-,\pm\frac{1}{2})$ $\pi 6^4 \nu 7^2$. The predictions for $\mathcal{J}^{(2)}$ have been shown along with the experimental data in Fig. 2. One can see that the general trend has been calculated correctly, although the theory overestimates the values for $\mathcal{J}^{(2)}$ slightly. The predicted signature splitting at $\hbar\omega \approx 0.7$ MeV would suggest that the $\pi 6^4 \nu 7^2$ $(-,+\frac{1}{2})$ band should be populated more strongly than its signature partner and therefore has been assigned to band 2. The $Z=66$ gap must be somewhat larger than that obtained in the present calculations. Otherwise the $\pi 6^3$ configuration would have been yrast in the feeding region and would therefore have been populated. Similar conclusions can be drawn from the assignments[10,11] of the SD bands in ^{151,152}Dy and, in fact, the $Z=66$ gap is larger in the Woods-Saxon model calculations of Ref. 13. No $M1$ transitions between these bands are expected to be strong enough to be observed and none were detected.

In conclusion, the observation of three discrete-line SD bands has allowed the most complete test yet of the calculations of these configurations. More detailed information that will become available from the next generation of detector arrays should allow further tests of the effects of these different configurations on the deexcitation process.

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