A SUPERDEFORMED BAND IN ^{151}Dy☆

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A rotational band of 19 (possibly 20) transitions extending to spin $\sim 131/2\ \hbar$ has been observed in ^{151}Dy with an average dynamic moment of inertia $\mathscr{I}^{(2)} = 79\ \hbar^2$ MeV^{-1}. This band is identified as a superdeformed band in ^{151}Dy. The value of $\mathscr{I}^{(2)}$ agrees with cranked Strutinsky calculations. Similarities as well as striking differences with the superdeformed bands of neighboring nuclei are observed.

With the discovery of a band of 19 discrete transitions in ^{152}Dy [1] corresponding to the rotation of a superdeformed nucleus ($\beta \sim 0.6$) it became clear that detailed gamma-ray spectroscopy can be performed up to very high spin in weakly populated potential energy minima of very large deformations. This fascinating result provides incentive to map regions of the nuclear chart where superdeformation occurs for an understanding of the underlying microscopic structure. While rotational bands with $\beta \sim 0.45$ have been found in several nuclei with mass around $A = 130$ [2,3], very few cases are known so far in the $A = 150$ region. In fact, discrete bands have been reported only in ^{152}Dy, ^{149}Gd [4], and ^{148}Gd [5]. Additional, but weaker, evidence for superdeformation has come from studies of energy correlations in the quasicontinuum in light Dy, Er [6] and Gd [7] nuclei. In contrast, theoretical studies [8–10] predict many nuclei in the $A = 150$ region to be superdeformed at high spin and these calculations require further experimental verification. In this letter we present evidence for superdeformation in ^{151}Dy based on a rotational band extending over 19 (possibly 20) transitions with an essentially constant energy difference of 51 keV and an average dynamic moment of inertia of 79 $\hbar^2$ MeV^{-1}.

The experiment was carried out at the ATLAS accelerator with the Argonne–Notre Dame gamma-ray facility which consists of an inner array of 50 hexagonal BGO elements surrounded by 12 Compton suppressed germanium spectrometers (CSG) arranged in two rings. The array covers ~ 80% of 4π around the target. It is used as a gamma-ray calorimeter and provides a measure of the gamma-ray multiplicity. The sensitivity of the CSGs was necessary for detection of very weak gamma-rays. The states in ^{151}Dy were populated with the ^{122}Sn(^{34}S, 5n) reaction at 174.5 MeV. With this choice of beam energy and projectile–target combination, the ^{151}Dy final nucleus is populated with a maximum angular momentum in excess of 65 $\hbar$ and an excitation energy of 33 MeV, assuming a kinetic energy of 2 MeV per neutron. These conditions are similar to those used in refs. [1,4,5] where

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discrete superdeformed bands have been observed. The target consisted of four stacked ^{122}Sn self-supporting foils (three 200 μg/cm^2 and one 300 μg/cm^2 thick). With a threshold of 5 on the number of array elements firing in coincidence with 2 CSGs or more, a total of 3.2×10^8 events were recorded. In addition to the energy and time information measured in the CSGs, the gamma-ray sum-energy, the prompt and delayed multiplicities and the hit pattern of the array were stored on magnetic tape.

In the analysis, at least 18 detectors of the BGO array were required to fire in coincidence with the CSGs. This procedure enhances the relative yield of the high spin states in ^{151}Dy by selecting events with high gamma-ray multiplicity and also reduces the contribution of some of the other evaporation channels. (The coincidence matrix still contains contributions from the 4n (^{152}Dy) and 6n (^{150}Dy) channels with 14 and 28% intensities, respectively.) The number of events in the final gamma–gamma-coincidence matrix was 1.5×10^8.

A new band of 19 transitions extending from 577 to 1490 keV was observed in spectra generated from the matrix. The band was seen in individual spectra gated on each transition. The spectrum shown in fig. 1 was obtained by summing the spectra in coincidence with the cleanest coincidence gates (577, 682, 734, 940 and 1194 keV). All the transitions belonging to the band are visible with, perhaps, the exception of the two highest transitions for which firm assignments were made on the basis of the inspection of the individual coincidence spectra. All other transitions appearing in fig. 1 and in the individual coincidence spectra could be assigned to known transitions in ^{151}Dy [11] or to contaminants in ^{152,150}Dy. The coincidence data also revealed the presence of a weak line at 522 keV which may be the lowest transition in the band. However, strong contaminant peaks in ^{152}Dy and in ^{151}Dy at the same energy preclude a definitive assignment. With the exception of the weakest lines, the stretched-E2 character of the transitions was established from the angular distribution measured at 34.5°, 90° and 145.5° with respect to the beam.

The average moment of inertia of the new band is consistent with a superdeformed shape. In addition,

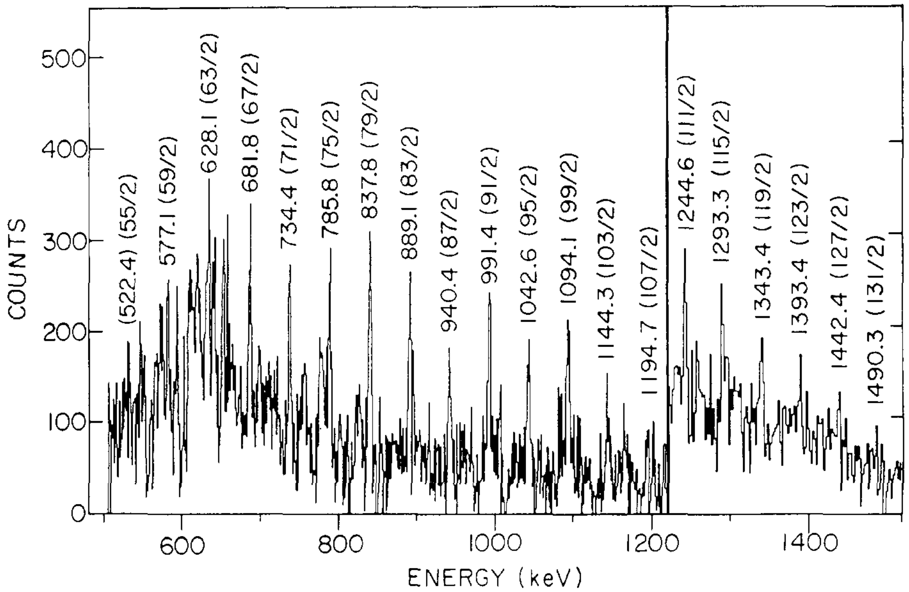

Fig. 1. Gamma-ray spectrum in ^{151}Dy obtained by summing coincidence gates on the selected transitions (577, 682, 734, 940, and 1194 keV) in the superdeformed band. Note that the higher part of the spectrum was compressed by a factor of 2. The Doppler correction is different for the upper part of the spectrum because of the shorter emission times of the high energy transitions (see text for details). The transition energies and the proposed spin assignments are included. The placement of the lowest transition is tentative. All the transitions belonging to the band are visible with, perhaps, the exception of the two highest transitions for which firm assignments were made on the basis of the inspection of the individual coincidence spectra.

it has many properties similar to those observed in the superdeformed bands in the neighboring ^{152}Dy and ^{149}Gd [1,4] nuclei. Therefore, this band is henceforth referred to as the superdeformed (SD) band and it is assumed to correspond to the rotation of the ^{151}Dy nucleus with a very large prolate deformation (axis ratio of 2:1).

From several coincidence spectra gated on gamma-rays in the SD band and in the yrast band it was possible to derive an intensity of 1.8% for the total flow through the SD band under the multiplicity condition mentioned above. This number corresponds to an absolute intensity of 1.3% of all ^{151}Dy decays (i.e. when the multiplicity condition is removed), and to about 0.6% of the estimated total evaporation residue yield.

The intensity distribution along the SD band, derived from the coincidence spectra, is shown in fig. 2. The decreasing intensity seen at the highest spins presumably reflects the initial feeding population. At lower spin, the intensity remains essentially constant over a total of 8 transitions. Decay out of the SD band towards the yrast line occurs rather abruptly over a range of 2 or 3 transitions. Transitions which link the SD band to the known yrast states could not be identified and it is likely that many different decay paths share the intensity. This is corroborated by the feeding pattern into the yrast line which was found to be spread over 4 states (the relevant yrast level structure is given as an insert in fig. 2) in the following way: (36±8)% to the 57/2 level, (16±9)% to the 53/2 level, (20±12)% to the 51/2 level and (28±11)% to the 49/2 isomer. Therefore, the average spin on entry into the yrast states is 53/2 $\hbar$.

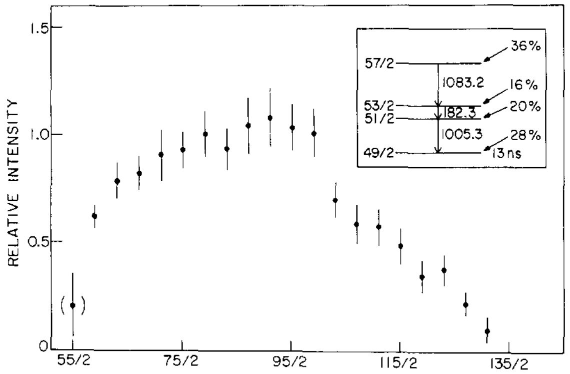

Fig. 2. Relative intensity of the gamma-rays in the superdeformed band of ^{151}Dy as deduced from the coincidence spectra. The inset presents the feeding from the superdeformed band into the yrast levels.

The spin of the lowest level in the SD band is estimated to be 51/2 $\hbar$. This value follows from the deexcitation pattern out of the SD band (fig. 2), the average spin of entry into the yrast line (53/2 $\hbar$) and the assumption of a $\Delta I = 1.5\ \hbar$ angular momentum removal by the transitions linking the SD states and the yrast line. This value of ΔI is plausible since the deexciting transitions are most likely statistical [1,4] and the SD band will be about 3 MeV above the yrast line at the point of deexcitation, if one assumes that it becomes yrast at $I = 115/2\ \hbar$ as predicted [8,9]. The highest spin reported here is 131/2 $\hbar$.

The data also contain information on the lifetimes in the SD band. Under the experimental conditions, the average time the ^{151}Dy recoils take to escape the target is 43 fs. Gamma-rays from the highest spin states can be emitted before the nuclei leave the target. By comparing the gamma-ray energies in the forward and backward CSGs it was found that the Doppler shifts for the 9 highest transitions decrease with spin and are different from the average shift for the strongest yrast transitions (which are emitted outside the target because of their ps lifetimes). Thus, deexcitation between the 131/2 and 99/2 levels proceeds in less than 43 fs, a time scale comparable to the one reported by Bentley et al. [1] for ^{152}Dy. This indicates that the transitions reported here are highly collective as expected for a SD band. A preliminary analysis of the E_γ–E_γ correlation matrix indicates that the discrete band accounts for at least 75% of the intensity in the superdeformed ridge. Any underlying correlated continuum radiation is very weak.

It is interesting to compare the data for ^{151}Dy with the results reported for the SD bands observed in ^{152}Dy [1] and ^{149}Gd [4]. (Equivalent information on ^{148}Gd is not available.) The gamma-ray intensity flowing through the SD band is comparable in ^{152,151}Dy and ^{149}Gd. The three experiments report numbers of the order of 1% of the ground state population and the number of transitions reported is the same as well. The intensity pattern as a function of spin is remarkably similar: in the two Dy nuclei 80% of the feeding has occurred at spin 50 (99/2) $\hbar$ and 50% population is achieved at spin 56 (115/2) $\hbar$. The corresponding numbers are not that different for ^{149}Gd where 80 (50)% population is in the SD band at spin 103/2 (115/2) $\hbar$. This pattern is in contrast with the one observed in rotational bands with smaller deformations in the rare earth nuclei: the side feeding into discrete states extends to very low spin, even when states with $I \sim 50\,\hbar$ are seen. In the three cases the decay out of the band is presumed to occur via statistical transitions and, again, occurs within the same spin range: the average deexcitation spin is 27 $\hbar$ in ^{152}Dy and 28 $\hbar$ in ^{151} Dy and ^{149}Gd. Finally, the mean entry spin into the yrast line is identical in the two odd-even nuclei (26.5 $\hbar$) and smaller in ^{152}Dy (21.5 $\hbar$).

Since these three experiments have been performed at similar excitation energies and angular momenta, these comparisons suggest that the feeding mechanisms in and out of the SD bands are similar in the three nuclei. Even at the highest spins, a single band carries all the intensity. For ^{152}Dy it has been suggested [8] and calculated [9] that this is due to a large gap in the single-particle spectrum at $Z=66$ and $N=86$. A similar gap would have to be present for $Z=64$ and $N=85$ and could become smaller for $Z=64$, $N=84$ (in order to account for the weaker population in ^{148}Gd [5]). Assuming that the deexcitation towards the yrast line occurs when the potential energy barrier between the SD states and yrast states can be penetrated effectively so that statistical decay out of the band competes with collective in-band transitions [8], the comparison suggests that the SD minima have similar properties in the three nuclei.

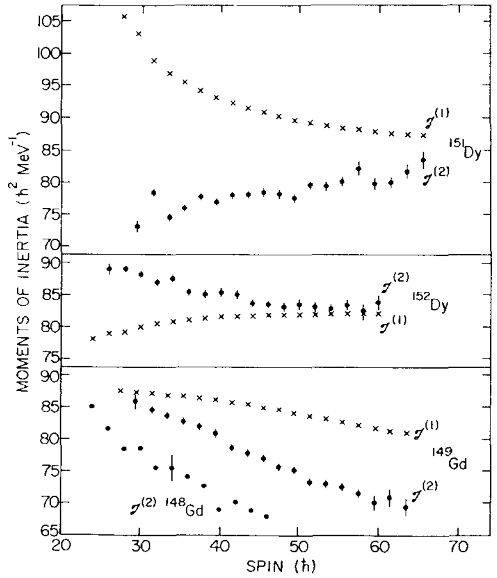

Fig. 3. Static ($\mathscr{J}^{(1)}=(2I-1)\hbar^2/E_\gamma$) and dynamic ($\mathscr{J}^{(2)}=4\hbar^2/\Delta E_\gamma$) moments of inertia for the nuclei ^{151}Dy (top), ^{152}Dy (middle) and ^{149}Gd (bottom) as a function of spin. The $\mathscr{J}^{(2)}$ moment of inertia for ^{148}Gd has been added for comparison, assuming that the spin of the lowest member of the band is $I=24\,\hbar$.

The static and dynamic moments of inertia $\mathscr{J}^{(1)}$ and $\mathscr{J}^{(2)}$ for all the SD bands under discussion are presented in fig. 3. Similarities as well as striking differences can be seen. In the Dy isotopes the values of $\mathscr{J}^{(1)}$ and $\mathscr{J}^{(2)}$ become essentially constant at the highest spins ($I>44\,\hbar$) and have values very close to each other, the difference being somewhat larger in ^{151}Dy. This indicates that both nuclei rotate like rigid bodies. The value measured for $\mathscr{J}^{(2)}$ is somewhat smaller in ^{151}Dy (81 $\hbar^2$ MeV^{-1} versus 83 $\hbar^2$ MeV^{-1}) and is in good agreement with calculations by Chasman (ref. [9] and table 1 in ref. [7]) where the drop in the value of $\mathscr{J}^{(2)}$ is due to a smaller deformation. The striking difference in the general behavior of $\mathscr{J}^{(1)}$ and $\mathscr{J}^{(2)}$ should, however, also be pointed out. We note that for ^{151}Dy the value of $\mathscr{J}^{(1)}$ exceeds that of $\mathscr{J}^{(2)}$. In contrast, $\mathscr{J}^{(2)} > \mathscr{J}^{(1)}$ in ^{152}Dy, a fact for which there is, to our knowledge, no explanation. Furthermore, while $\mathscr{J}^{(1)}$ is seen to decrease and $\mathscr{J}^{(2)}$ to increase with spin in ^{151}Dy, the opposite happens in ^{152}Dy. While the changes in the value of $\mathscr{J}^{(2)}$ are only of the order of 4% in the two Dy nuclei, much larger variations are seen in the Gd isotopes: the decrease of $\mathscr{J}^{(2)}$ persists over the entire spin range and the absolute value is smaller as well. These results can again be accounted for in the calculations by Chasman [9]. The Gd isotopes are calculated to be less deformed and the changes in $\mathscr{J}^{(2)}$ are attributed to the spin dependence of the shell corrections. In the case of the Dy isotopes, the shell corrections as a function of spin remain essentially unchanged. An alternative explanation for the decrease invokes residual pairing [4,8].

In conclusion, a band of 19 (possibly 20) transitions corresponding to rotation of a superdeformed ^{151}Dy nucleus has been observed. The properties of the band resemble closely those reported for the superdeformed band in ^{152}Dy. This indicates that the mean field properties are not modified greatly by the removal of a single neutron.

This experiment is the first one performed with the full Argonne–Notre Dame gamma-ray facility. The authors express their gratitude to V. Kubilius for his design work, to J. Ray, J. Timm, J. Joswick, and A. Horvath for their technical assistance, to P. Wilt for help with the electronics, and to T. Moog for the data acquisition software. One of the authors (G.-E.R.) would like to thank the Alexander-von-Humboldt-Stiftung for granting a Feodor-Lynen-Stipendium.

Note added. After this letter was submitted for publication, we learned about the results of recent work by Bengtsson, Ragnarsson and Åberg [12] where the influence of particles excited into high *N*-shells on the dynamic moment of inertia $\mathscr{I}^{(2)}$ is calculated. The difference in the values of $\mathscr{I}^{(2)}$ for ^{152}Dy and ^{151}Dy can be explained, at least qualitatively, by the difference in the respective contributions of $i_{13/2}$ protons and $j_{15/2}$ neutrons for the two nuclei. In particular, the rise seen in ^{151}Dy is calculated to originate mainly from the contribution of the four $i_{13/2}$ protons.

References

[1] P.J. Twin et al., Phys. Rev. Lett. 57 (1986) 811;
M.A. Bentley et al., Phys. Rev. Lett. 59 (1987) 2141.
[2] E.M. Beck et al., Phys. Lett. B 195 (1987) 531, and references therein.
[3] R. Wadsworth et al., J. Phys. G 13 (1987) L207, and references therein.
[4] B. Haas et al., Phys. Rev. Lett. 60 (1988) 503.
[5] M.A. Deleplanque et al., preprint;
P. Taras et al., private communication.
[6] M.J.A. de Voigt et al., Phys. Rev. Lett. 59 (1987) 270.
[7] M.W. Drigert et al., Phys. Lett. B 201 (1988) 223;
G. Hebbinghaus et al., Phys. Rev. Lett. 59 (1987) 2024.
[8] I. Ragnarsson and S. Åberg, Phys. Lett. B 180 (1986) 191.
[9] R.R. Chasman, Phys. Lett. B 187 (1987) 219.
[10] J. Dudek et al., Phys. Rev. Lett. 59 (1987) 1405.
[11] B. Haas et al., Nucl. Phys. A 362 (1981) 254.
[12] R. Bengtsson, I. Ragnarsson and S. Åberg, Lund preprint MPh-88/01.