Intrinsic Quadrupole Moment of the Superdeformed Band in ^{152}Dy

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(Received 9 February 1987; revised manuscript received 3 June 1987)

The attenuation of the Doppler shift has been measured for γ rays emitted from the superdeformed states in the nucleus ^{152}Dy, recoiling in a ^{108}Pd target and its gold backing. The transitions from the high-spin members of the superdeformed band are fully shifted, indicating feeding times of not more than a few femtoseconds. The partially shifted low-spin transitions yield a quadrupole moment of 19 ± 3 $e \cdot$b, in excellent agreement with the value expected for a superdeformed shape.

PACS numbers: 23.20.Ck, 21.10.Ft, 21.10.Re, 27.70.+q

The recent observation[1] of nineteen γ rays in a rotational cascade in ^{152}Dy has for the first time enabled discrete energy levels to be identified in a nucleus up to an excitation energy of 30 MeV and spin of $60\hbar$. This represents a major extension of the detailed experimental knowledge of the near-yrast behavior of a nucleus. The measured dynamic moment of inertia $\mathcal{J}^{(2)}_{\rm band}$ is in good agreement with the value expected[2] for a superdeformed prolate rotor with a major-to-minor axis ratio of 2:1. However, it is known[3] that particle alignment coupled with a strong interaction can cause a large apparent increase in the moment of inertia, even though the deformation remains constant. Thus it is important to have a more direct experimental measurement of the shape, which can be obtained from the collectivity of the nucleus. The superdeformed band is calculated[2] to have an extremely large intrinsic quadrupole moment of 18 $e \cdot$b [corresponding to a collective in-band $B(E2)$ of 2390 Weisskopf units (W.u.)] compared with 5 $e \cdot$b or less for the smaller deformations common in rare-earth nuclei. In this paper we report on the measurement of the lifetimes within the superdeformed band in ^{152}Dy by the Doppler-shift-attenuation method. These data give an upper limit of not more than a few femtoseconds on the feeding time for the superdeformed structure, and yield a value of 19 ± 3 $e \cdot$b for the intrinsic quadrupole moment. This direct measurement of enhanced collectivity is thus conclusive evidence that the band is associated with the superdeformed shape.

The experiment was carried out at the Daresbury Laboratory with the use of the 20-MV tandem accelerator to populate the high angular momentum states of ^{152}Dy by the reaction ^{108}Pd(^{48}Ca,$4n$)^{152}Dy at 205 MeV. The subsequent γ-ray events were observed with the TESSA3 multidetector array consisting of twelve escape-suppressed germanium detectors[4] and a fifty-element bismuth-germanate (BGO) ball.[5] The target consisted of 1.3 mg cm^{-2} of ^{108}Pd on a 15-mg-cm^{-2} gold foil, so that the recoiling nuclei slowed up in the target and backing before finally stopping. A total of 2×10^8 γ-γ suppressed coincidence events were recorded together with the BGO-ball data[5] of sum energy and fold. A time interval was recorded between the BGO-ball signal and the second germanium event. A 10-ns window placed on this interval was sufficient to reject many of the neutron-induced events in the germanium detectors and also to reject coincidence events involving delayed γ rays from below the 10- and 60-ns isomers in ^{152}Dy. A second time difference was measured between the γ-γ event and a subsequent BGO-ball event which recorded at least three additional ball elements firing within 200 ns. This provided an efficient method of identifying whether an event was associated with the subsequent decay of the 60-ns isomer in ^{152}Dy. Further conditions were imposed on the sum energy and fold data to reject other reaction channels and finally resulted in an overall efficiency of 56% in the selection of ^{152}Dy events.

The ^{152}Dy spectrum is dominated by the discrete transitions between the oblate states below $40\hbar$. These states have lifetimes[6] greater than a few picoseconds, and therefore the γ rays are not Doppler shifted. However, the decays from the higher-spin superdeformed states are known to have lifetimes[7] less than 100 fs and will thus be Doppler shifted. The gains of the germanium detectors were matched so that all the stopped transitions had the same energy calibration. The fast superdeformed γ rays should then be Doppler shifted to higher energies in the four forward detectors ($\theta=35°$, $\cos\theta=0.82$) and to lower energies in the four backward detectors ($\theta=145°$, $\cos\theta=-0.82$). The spectra, shown

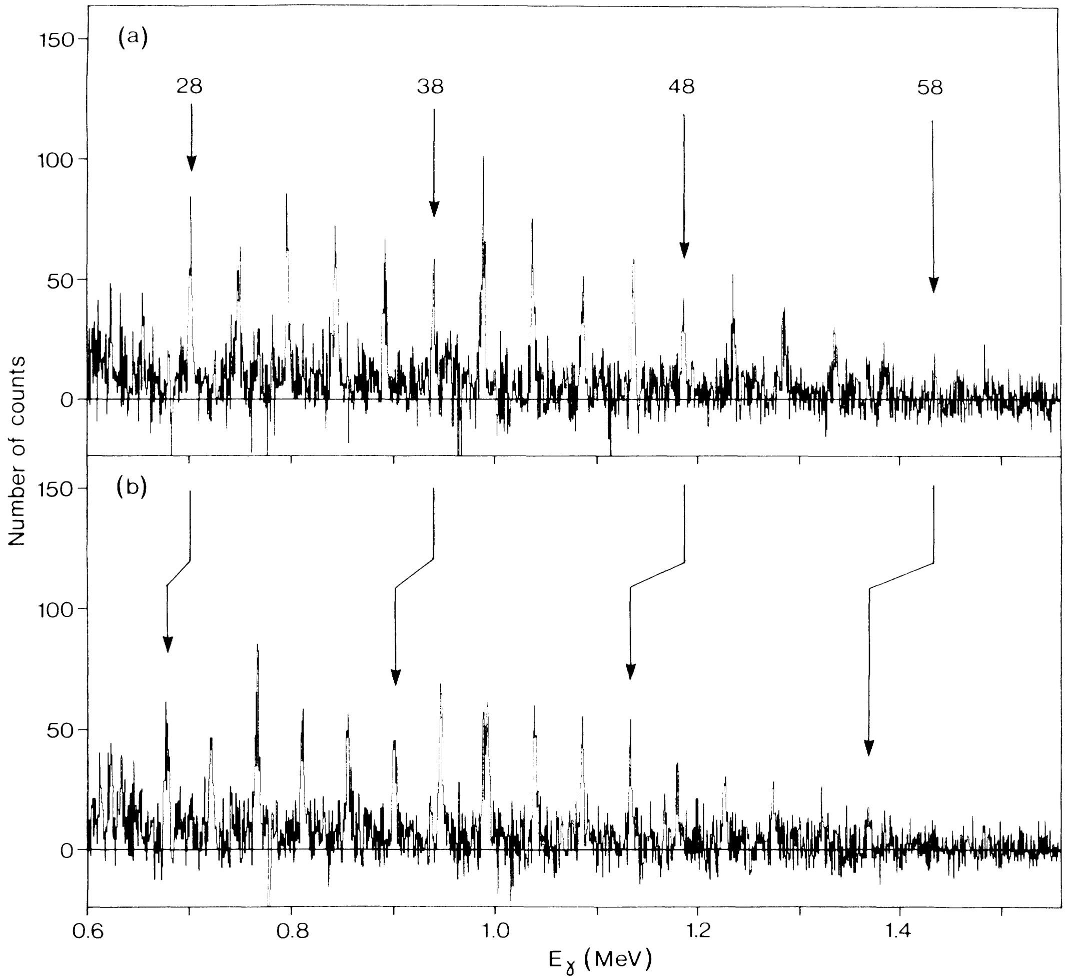

FIG. 1. γ-ray spectra in ^{152}Dy obtained by the summation of spectra gated by members of the superdeformed band. The numbers above the γ rays indicate the spin values of the emitting states. (a) Spectrum derived from the forward ($\theta=35°$) detectors showing the γ rays Doppler shifted to higher energies. (b) Spectrum derived from the backward ($\theta=145°$) detectors.

in Fig. 1, were generated by summation of gates on the known superdeformed γ rays. They clearly illustrate that the energies of the transitions are shifted and accurate measurements could be made of the average fractional shift $\Delta E_\gamma/E_\gamma=\langle(v/c)\cos\theta\rangle$, where v is the recoil velocity of the nucleus. The fractional shift is plotted in Fig. 2 as a function of the spin of the emitting state. The full Doppler shift of the recoils, $\langle(v/c)\cos\theta\rangle$, is calculated to vary across the target from 2.43% to 2.33%, as illustrated in Fig. 2. These values are consistent with the measured Doppler shift of γ rays from states with lifetimes greater than a few picoseconds when a single thin target of 0.6 mg cm^{-2} was used in a previous experiment. The full-shift line has been placed at a velocity corresponding to the center of the target. As the spin of the band decreases, the data show, there is a gradual decrease in the fractional shift. However, the observed line shapes remain sharp, which is characteristic[8] of cascade feeding down a rotational band.

A knowledge of the feeding intensities of the superdeformed band is required to obtain lifetime values for individual states from the measured Doppler shifts. These intensities were obtained from a further analysis of the thin-target data at the same bombarding energy[1] with the same sum energy and fold conditions used in the present analysis. Gates were set only on the lower-spin members of the band from 647 to 923 keV (excluding 784 keV) and produced the intensity pattern shown in Fig. 3(a). This figure shows that the band has 50% of its final intensity by spin 56$\hbar$ and 80% by spin 50$\hbar$. Consequently below around spin 50$\hbar$ the change in Doppler shift of successive γ rays will depend on the intrinsic lifetimes of the states whereas above this spin it will depend also on the feeding times and intensities into the band.

The average time taken for the recoiling ions to traverse the target is 60 fs and therefore the γ rays from

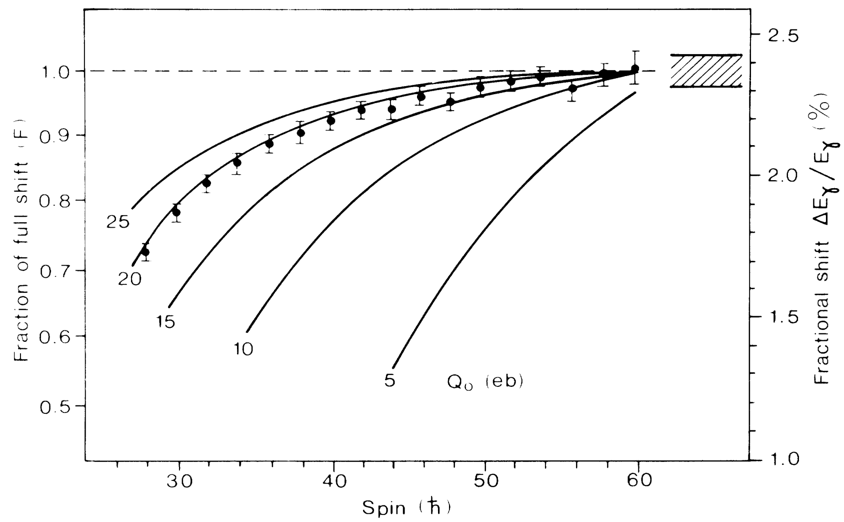

FIG. 2. Measured fraction of the full Doppler shift of γ rays in the superdeformed band. Calculated values of the shift are illustrated for various quadrupole moments with the assumption of a constant deformation and the assumption that feeding transitions have lifetimes of 1 fs. The best fit is for $Q_0 = 19 \pm 1$ $e\cdot$b. The shaded area shows the calculated change in the full shift across the 1.3-mg cm^{-2} target due to the slowing down of the beam.

the highest-spin states are emitted before the recoils leave the target. Consequently, in this case, the slowing-down process in the target plays a very important role, and over the time range of interest, the dominant process in both target and backing is electronic stopping. In order to calculate these processes, the stopping powers calculated by Northcliffe and Schilling[9] were used after normalization to the α stopping powers of Ziegler and Chu.[10] The nuclear stopping was also included following Lindhard, Scharff, and Schiøtt[11] with scattering corrections from Blaugrund.[12] With use of these data, the effective lifetime for each state was determined from the measured Doppler shifts and these are listed in Table I. The measured effective lifetimes of the states above $50\hbar$ are, on average, less than 10 fs, and so the feeding times are very fast and not more than a few femtoseconds. The effective lifetimes of subsequent transitions are dominated by the cumulative feeding down the band, and this produces an effective lifetime of each state which is approximately five times larger than the intrinsic lifetime.

It is not possible to obtain accurate intrinsic lifetimes (and, hence, a quadrupole moment) for each level because of the small changes in the fractional Doppler shift from state to state. However, if the deformation remains constant within the superdeformed band, the data can be fitted by the assumption of a constant quadrupole moment (Q_0). Calculated fractional Doppler shifts are shown in Fig. 2 for quadrupole moments of 5, 10, 15, 20, and 25 $e\cdot$b, with the assumption that the feeding times into the band are 1 fs.

The data are fitted by a Q_0 of $(19 \pm 1) e\cdot$b which is equivalent to a $B(E2)$ strength of 2660 W.u. When we take into account an additional error, estimated at 15%, due to uncertainties in the slowing-down process, the value of Q_0 becomes (19 ± 3) $e\cdot$b. This is very much larger than the measured values[13] for Q_0 of approximately 5 $e\cdot$b in rotational bands of normal deformation ($\epsilon_2 = 0.2$) in rare-earth nuclei. It is in excellent agreement with the theoretical value[2] of 18 $e\cdot$b for the quadrupole moment of superdeformed levels in ^{152}Dy. Table I lists the intrinsic level lifetimes calculated with the assumption that $Q_0 = 19$ $e\cdot$b. The data in Fig. 2 show that the values of Q_0 are restricted even if the deformation is not constant. At low spins, Q_0 must be around 19 $e\cdot$b, and at higher spins it cannot be less than 15 $e\cdot$b, corresponding to a reduction of 20% in the deformation ϵ_2.

Information on the deformation can also be obtained from the moments of inertia. The static moment $\mathcal{J}^{(1)}_{\text{band}}$ is evaluated from the γ-ray energies and the dynamic moment $\mathcal{J}^{(2)}_{\text{band}}$ from the differences in γ-ray energies. In the previous experiment, using a thin target, some of the γ-ray energies could not be accurately measured because of the presence of high-intensity background γ rays with similar energies associated with the oblate states in ^{152}Dy. However, in the present thick-target data, these superdeformed transitions were Doppler shifted to regions of low-intensity background, enabling their energies to be accurately determined. The mean transition energies, calculated by averaging of data from both experiments, are listed in Table I, and the resultant moments of inertia are shown in Fig. 3(b). This illustrates that above spin $44\hbar$, both $\mathcal{J}^{(1)}_{\text{band}}$ and $\mathcal{J}^{(2)}_{\text{band}}$ become constant at almost the same value indicating that the nucleus behaves like a rigid rotor. The $\mathcal{J}^{(2)}_{\text{band}}$ value of $83\hbar^2$ Mev^{-1} is in excellent agreement with the moment calcu-

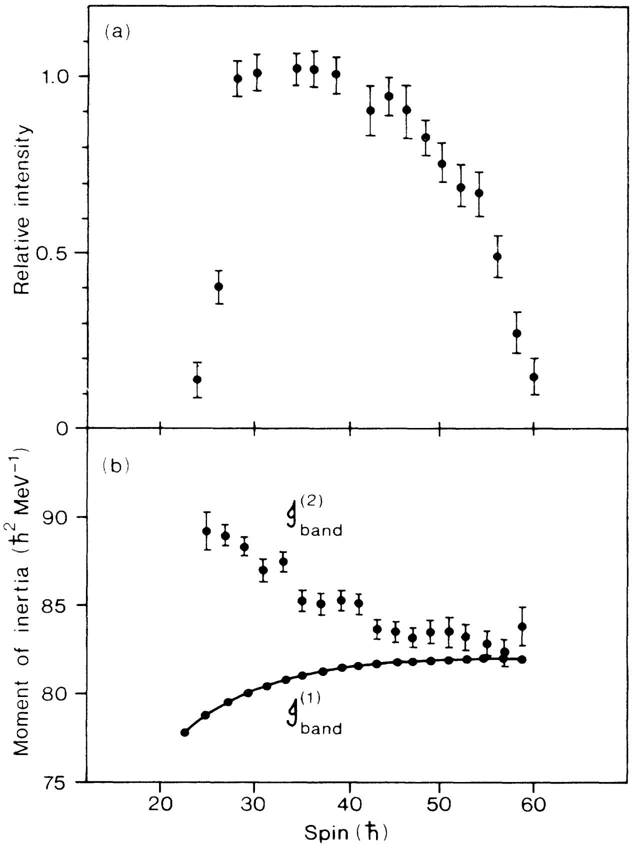

FIG. 3. (a) Relative intensity of the γ rays in the superdeformed band in ^{152}Dy derived from a spectrum produced by gates on the γ rays deexciting the $26\hbar$, $28\hbar$ $30\hbar$, $34\hbar$, $36\hbar$, and $38\hbar$ states. (b) Static moment of inertia $\mathcal{J}^{(1)}_{\rm band}$ and dynamic moment of inertia $\mathcal{J}^{(2)}_{\rm band}$ as functions of spin for the superdeformed band in ^{152}Dy. The values were determined from the γ-ray energies listed in Table I with the spin assignments taken from Twin *et al.* (Ref. 1).

lated[2] for a superdeformed shape. The variations in the moments of inertia at lower spins are not caused by the deformation changing, as the quadrupole-moment data clearly indicate that the shape remains superdeformed. These variations may be due to pairing and alignment effects.

In summary, the fractional Doppler shift has been measured for the discrete-line superdeformed band in ^{152}Dy. The data show that the feeding times of the band are very fast (not more than a few femtoseconds) and that the quadrupole moment of the band is 19 ± 3 $e \cdot$b if we assume a constant deformation. This very large value is conclusive evidence that the band is indeed associated with a superdeformed shape. The accurate measurements of the γ-ray energies indicate that, as the spin increases, the static moment of inertia initially increases, and above $44\hbar$ it is almost constant and equal in magnitude to the dynamic moment of inertia.

TABLE I. The spins (Ref. 1), measured γ ray energies, and effective lifetimes for the superdeformed states in ^{152}Dy. The intrinsic lifetimes listed have been calculated with the assumption that $Q_0 = 19$ $e \cdot$b.

		Lifetime τ_m (fs)	
Spin $\hbar$	E_γ (keV)	Effective (Measured)	Intrinsic (Calculated)
24	602.3 ± 0.3		
26	647.2 ± 0.2		
28	692.2 ± 0.2	190 ± 10	38
30	737.5 ± 0.2	135 ± 10	28
32	783.5 ± 0.3	105 ± 10	20
34	829.2 ± 0.2	82 ± 10	15
36	876.1 ± 0.2	62 ± 8	11
38	923.1 ± 0.2	54 ± 11	9.0
40	970.0 ± 0.2	43 ± 8	6.9
42	1017.0 ± 0.2	33 ± 7	5.5
44	1064.8 ± 0.2	33 ± 7	4.4
46	1112.7 ± 0.3	22 ± 6	3.5
48	1160.8 ± 0.3	26 ± 6	2.8
50	1208.7 ± 0.3	14 ± 7	2.3
52	1256.6 ± 0.3	9 ± 6	1.9
54	1304.7 ± 0.3	5^{+7}_{-5}	1.5
56	1353.0 ± 0.3	16^{+10}_{-8}	1.3
58	1401.7 ± 0.4	3^{+10}_{-3}	1.1
60	1449.4 ± 0.6	< 22	0.9

Grateful thanks are extended to Paul Nolan and his research group for useful discussions and help with the apparatus. This work was supported by grants from the Science and Engineering Research Council (United Kingdom), from whom three of us (M.A.B., H.W.C.G., and J.D.M.) are recipients of postgraduate studentships, with another of us (D.H.) supported by a postdoctoral fellowship.

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