Observation of a Discrete-Line Superdeformed Band up to 60ℏ in ^{152}Dy

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A rotational band of nineteen transitions with a moment of inertia $\mathcal{J}^{(2)}_{\rm band}$ of $84\hbar^2$ MeV^{-1} has been observed in ^{152}Dy. The band feeds into the oblate yrast states between 19^- and 25^- and it is proposed that the lowest member of the band has a spin of 22^+ and thus the band extends up to 60ℏ. It is identified as the yrast superdeformed band and its intensity accounts for the whole of the ridge structure seen previously in continuum E_γ-E_γ correlations.

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The nucleus ^{152}Dy has been extensively studied and three different structures have been identified. The low-spin yrast levels have a pseudovibrational structure[1] which develops into a low-deformation ($\beta \approx 0.15$) prolate rotational band[2] extending up to 40ℏ. This band, in the spin region between 8ℏ and 38ℏ, lies between 0.5 and 1.5 MeV above the yrast states which have a weak oblate structure formed by particles in equatorial orbits.[3-5] At higher spins the γ-ray continuum is dominated by a collective $E2$ bump.[6] Part of this bump has been shown to arise from superdeformed ($\beta \approx 0.6$) bands from the existence of ridges with a moment of inertia $\mathcal{J}^{(2)} = (85 \pm 2)\hbar^2$ MeV^{-1} in E_γ-E_γ correlation spectra.[7,8] In this Letter we present data showing a discrete-line rotational band extending over nineteen transitions from 602 to 1449 keV with an almost constant energy separation of 47 keV which corresponds to the superdeformed moment of inertia. The major γ-ray decay deexciting the band feeds into the yrast oblate structure between the 19^- and 25^- states and then proceeds via the 60-ns 17^+ isomer. Additionally 25% of the decay intensity bypasses this isomer. We propose that the decay process from the bottom of the band is essentially statistical, involving several transitions, and we assign the spin at the bottom of the band to be 22ℏ, thus establishing the spin at the top of the band to be 60ℏ. This is the first observation of a discrete-line superdeformed band and it extends the spin at which discrete states have been seen from about 46ℏ (e.g., ^{158}Er, Tjøm *et al.*[9]) to 60ℏ.

The experiment was carried out on the tandem accelerator at the Daresbury Laboratory using the TESSA3 spectrometer, which consists of a 50-element bismuth germanate (BGO) crystal ball similar to that used in TESSA2[10] with twelve escape-suppressed germanium detectors.[11] The states in ^{152}Dy were populated by the reaction ^{108}Pd(^{48}Ca, $4n$) at 205 MeV with a target consisting of two 500-μg-cm^{-2} self-supporting foils isotopically enriched at 95% in ^{108}Pd. A 15-mg-cm^{-2} gold catcher foil was positioned 5 cm downstream of the targets such that it was outside the focus of the germanium detectors but within the full detection efficiency of the BGO ball. A total of over 150 million double (Ge-Ge) coincidences were recorded together with the sum energy and number of hits (fold) in the BGO ball. The time difference between the BGO ball and the second-coincidence germanium detector was recorded and enabled most of the neutron-induced events in the germanium detector to be rejected as they are delayed. The time interval was also measured between the Ge-Ge event and any subsequent BGO-ball event which occurred within 200 ns. The resulting time spectrum had an exponential decay shape caused by events originating from isomers decaying at the catcher foil, thus allowing positive identification, with 25% efficiency, of Ge-Ge coincidences preceding the 60-ns isomer in ^{152}Dy. Two matrices of Ge-Ge coincidences were constructed. The "isomer" matrix was selected by the demand that an isomer decay was recorded in the BGO ball within 150 ns, and by the requirement of a high fold and sum-energy condition which halved the ^{152}Dy events and rejected virtually all events associated with the 13-ns ^{151}Dy isomer. The "prompt" matrix was selected by the requirement that no isomer decay was recorded in the BGO ball, thus reducing by 25% the intensity of the ^{152}Dy decay proceeding via the 60-ns isomer, and by a fold and sum-energy condition which maximized the

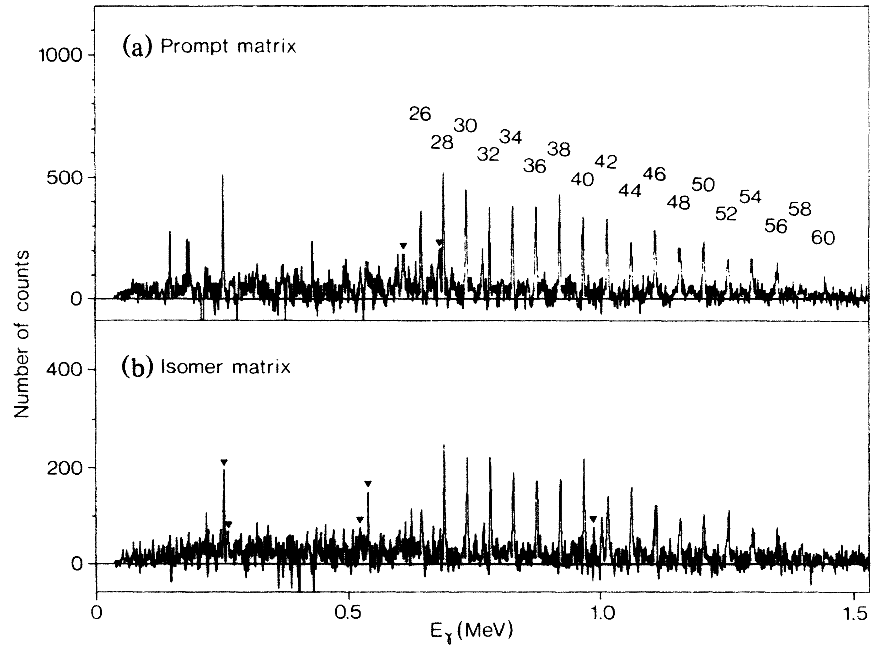

FIG. 1. Gamma-ray spectra in ^{152}Dy obtained by summation of gates set on most members of the superdeformed band. (a) Spectrum generated from the prompt matrix, as described in text, with gates set on all band transitions between 647 and 1256 keV; triangles indicate the 614- ($2^+ \to 0^+$) and 685- keV ($6^+ \to 4^+$) γ rays. (b) Spectrum generated from the isomer matrix with gates set on the 647-, 693-, 738-, 829-, 876-, 923-, 1017-, 1161-, and 1209-keV transitions; triangles indicate the 254-, 262-, 525-, 541-, and 991-keV transitions between the yrast oblate states.

^{152}Dy-channel contribution but still included 25% of the $3n$ (^{153}Dy) and 16% of the $5n$ (^{151}Dy) channels. Both matrices included a narrow window 10 ns wide on the Ge-ball time interval to reject the slower neutron-induced Ge events.

A new band of nineteen transitions extending from 602 to 1449 keV was observed in spectra generated from both matrices. The band was seen in individual spectra gated on each transition. The spectra shown in Fig. 1 were obtained by the summing of gates on many of the γ rays observed in the band which exhibits an almost constant energy separation increasing slightly from 46 to 48 keV. The derived moment of inertia $\mathcal{J}^{(2)}_{\rm band}$ is shown in Fig. 2(a) and it declines from $88\hbar^2$ to $85\hbar^2$ MeV^{-1} over the lowest six transitions, followed by a further slight decrease to $83\hbar^2$ MeV^{-1} over the next twelve transitions. These values are close to that predicted for a superdeformed band, and consistent with the $(85 \pm 2)\hbar^2$ MeV^{-1} extracted from continuum E_γ-E_γ correlation studies.[7,8] The ridge structure in these previous measurements was observed down to around 800 keV, whereas the discrete-line band extends down to 602 keV. The intensity distribution down the band is listed in Table I and shows an initial feeding over the few highest transitions, and an extremely rapid decline with virtually all the intensity feeding out of the band on either side of the 647-keV γ ray. This decay pattern is not due only to the statistical competition between in-band $E2$ and out-of-band $E1$ transitions, as it would occur much more slowly over a number of transitions. It is more likely caused by the disappearance, at a particular spin, of the

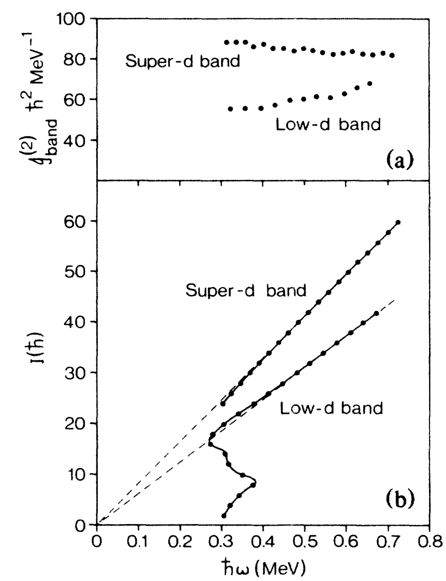

FIG. 2. (a) Plots of moment of inertia $\mathcal{J}^{(2)}$ vs frequency for the superdeformed band and the low-deformation band in ^{152}Dy. (b) Plots of spin against frequency for the superdeformed band and the low-deformation band in ^{152}Dy. The linear part of each graph is extrapolated back towards the origin.

TABLE I. Gamma rays observed in the isomer spectra of Fig. 1(b). The intensities are given relative to the average intensity of the 693- to 1064-keV γ rays in the superdeformed band.

E_γ (keV)	Relative intensity	E_γ (keV)	Relative intensity
602	0.10 ± 0.03	541	0.18 ± 0.04
647	0.40 ± 0.04	991	0.23 ± 0.05
693	1.00 ± 0.04	262	0.10 ± 0.02
738	0.97 ± 0.04	525	0.27 ± 0.04
784	0.99 ± 0.05	254	0.24 ± 0.05
829	1.00 ± 0.04		
876	0.97 ± 0.05	571	0.15 ± 0.04
923	1.04 ± 0.05	627	0.19 ± 0.04
970	0.99 ± 0.07	770	0.26 ± 0.04
1017	1.06 ± 0.05	1005	0.56 ± 0.08
1064	1.01 ± 0.06		
1112	0.94 ± 0.07		
1161	0.90 ± 0.06		
1209	0.86 ± 0.07		
1256	0.93 ± 0.07		
1305	0.78 ± 0.07		
1353	0.60 ± 0.07		
1401	0.40 ± 0.07		
1449	0.28 ± 0.07		

potential-energy barrier between the superdeformed minimum and the deeper minima closer to spherical shapes. We note that Åberg[12] predicts that one superdeformed band lies 1 MeV lower in energy than other bands of the same deformation, and we propose that this is the band which we have observed.

The next step is to establish the spin at the bottom of the yrast superdeformed band. The spectrum in Fig. 1(a) clearly shows the 614- (2^+-0^+), and 685-keV (6^+-4^+) transitions together with a stronger 647-keV γ ray which must contain some 4^+-2^+ intensity. There are many other weaker γ rays including indications of transitions in the low-deformation prolate band, but the presence of ^{151}Dy and ^{153}Dy decays in the prompt matrix makes the background subtraction difficult and we cannot fix the spins of the superdeformed band from this spectrum. However, the major (75%) deexcitation path of the band is via the 60-ns isomer in ^{152}Dy and the isomer matrix has no contribution from ^{151}Dy and ^{153}Dy and therefore the background subtraction is much more reliable. This was carried out by normalization on the 148- and 220-keV transitions (see inset in Fig. 3 for the decay scheme above the 60-ns isomer) and resulted in the observation of yrast γ rays between 17^+ and 25^- with the intensities listed in Table I. There is a further isomer of 10 ns in this decay path at 21^- and because of the recoils moving out of view of the germanium detectors our detection efficiency for the 262-keV (21^--19^-)

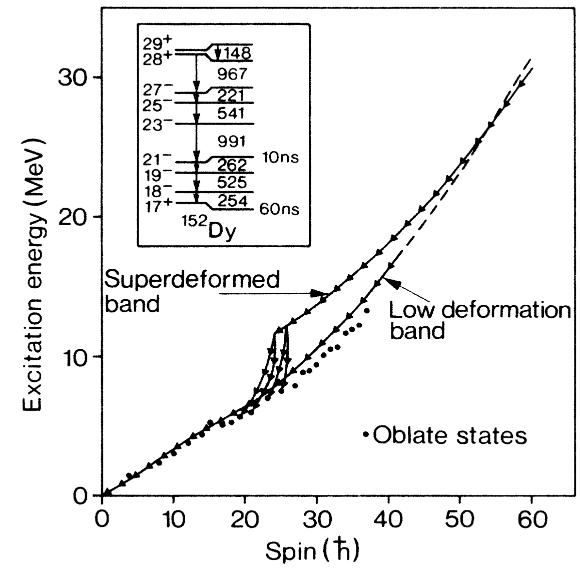

FIG. 3. The decay paths of the prolate collective bands in ^{152}Dy. Some typical decay paths deexciting the superdeformed band to the oblate states are illustrated. Inset: the oblate states in ^{152}Dy just above the 17^+ isomer.

and subsequent transitions is only 14%. However, the 525-keV (19^--18^-) γ ray can be fed directly, and this clearly happens. The intensities listed in Table I establish the following feeding pattern: $(19 \pm 4)\%$ to the 25^- level, $(6 \pm 5)\%$ to the 23^- level, $(56 \pm 14)\%$ to the 21^- level, and $(19 \pm 4)\%$ to the 19^- level. Therefore the average spin on entry to the yrast oblate states is $21.5\hbar$.

The superdeformed band must be yrast or close to yrast at spins greater than $55\hbar$, and therefore because of its high moment of inertia it will be around 4 MeV above yrast when it deexcites, as illustrated in Fig. 3. We propose that this decay proceeds via statistical-like cascades of several dipole transitions. At the end of these cascades there will be a number of γ rays collecting a considerable fraction of the total intensity and then feeding directly into the yrast oblate states. We suggest that the other γ rays observed in coincidence with the band members (Table I) fulfill this role. If we assume that the superdeformed band has even spins then its average deexcitation spin is $22.8\hbar$, $24.8\hbar$, or $26.8\hbar$ depending on whether the 647-keV γ ray is assigned as a 24^+-22^+, 26^+-24^+, or 28^+-26^+ transition, respectively. These assignments give average spin losses of $1.3\hbar$, $3.3\hbar$ or $5.3\hbar$ for the statistical decays between the superdeformed band and the yrast oblate states. The number of statistical γ rays plus the slope of the yrast line at this point means that the $3.3\hbar$ choice is by far the most likely and thus we assign the 647-keV transition as the 26^+-24^+ decay. Therefore the top transition in the band is the 60^+-58^+ transition at an excitation energy of about 30 MeV in ^{152}Dy.

The fraction of the total γ-ray intensity in ^{152}Dy which flows down the band is estimated to be 2.2% by a direct comparison in the isomer matrix of the intensities of the in-band 693 keV and the γ rays deexciting the yrast oblate states. We note that 693-keV γ rays are in both the superdeformed band and the low-deformation ($\beta \approx 0.15$) band and that the 693-keV coincidence spectrum derived from the prompt matrix shows approximately equal excitation of the two bands, thus placing the intensity of the low-deformation band lower than previously quoted.[2]

We have also examined the E_γ-E_γ correlation matrix using the techniques described in Ref. 7 in which spectra of ΔE_γ were obtained for different regions of $\bar{E}_\gamma$. Peaks were observed at $\Delta E_\gamma = 47$ keV corresponding to the superdeformed ridge in both the prompt and the isomer matrices. However, the intensities in these peaks were similar when the regions of $\bar{E}_\gamma$ were restricted to include only the known discrete-line transitions in the superdeformed band. Therefore we conclude that the discrete-line band accounts for the whole of the ridge structure observed in the γ-ray continuum measurements. Thus there is no evidence below $50\hbar$ for γ rays from other superdeformed bands at higher excitation energies, and any initial population of such bands must have fed into the yrast superdeformed band above this spin.

Plots of spin against frequency are shown in Fig. 2(b) for both the superdeformation and low-deformation prolate bands. We note that the linear part of each band projects very close to the origin. This seems to be a general feature of rotational bands at very high spin[13] and the simplest explanation is that the nucleus is behaving as a classical rotor. The superdeformed band exhibits a slight increase in $\mathcal{J}^{(2)}$ at low spin which is probably due to changes in the superdeformed minimum in the potential-energy surface as the spin decreases and may indicate some triaxiality.

In summary, we have observed a sequence of nineteen γ-ray transitions between 602 and 1449 keV with a constant separation around 47 keV. We propose that they constitute the lowest energy band of the superdeformed prolate shape ($\beta \approx 0.6$) and extend in spin from $22\hbar$ to $60\hbar$. The intensity of this band accounts for the whole of the ridge structure observed in E_γ-E_γ correlations. This is the first observation of a discrete-line superdeformed band and it extends the highest-spin discrete level seen experimentally from $46\hbar$ to $60\hbar$ which is very close to the fission limit for the nucleus. Some properties of the band, such as its length, its rapid feeding, its extremely rapid deexcitation, and its exhausting of the intensity in the superdeformed ridge, are unexpected. They raise many open problems concerning the role of pairing correlations, shell gaps, and giant resonances at high spin and large deformation.

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