Collectivity of the Superdeformed Bands in ^{152}Dy

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The lifetimes of the γ rays in the collective rotational bands observed in the γ-ray continuum at very high spin in ^{152}Dy are shown to be less than 100 fs for energies above 0.90 ± 0.05 MeV. The corresponding $B(E2)$ values are very enhanced and provide definite evidence that the rotational bands are associated with a superdeformed prolate structure in ^{152}Dy.

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The decay scheme for ^{152}Dy has been established[1,2] up to $40\hbar$ and it exhibits no collective rotational structure. It is interpreted as a sequence of single-particle configurations with spins aligned with an oblate symmetry axis in agreement with a number of calculations.[3,4] These calculations also predict that ^{152}Dy will become prolate with a large deformation of $\beta = 0.6$ before it becomes unstable to fission. The first evidence for this superdeformed shape[5] was obtained at Daresbury in an experiment with the spectrometer[6] TESSA2 in which the E_γ-E_γ correlation technique[7] was applied to the unresolved γ-ray continuum originating from states in ^{152}Dy above $40\hbar$. The essence of the technique is that in the matrix of the energies of two coincident γ rays the signature for rotational bands is the presence of ridges parallel to the $E_{\gamma 1} = E_{\gamma 2}$ diagonal. A narrow ridge was observed which was associated with ^{152}Dy decays and it extended from $E_\gamma = 0.8$ MeV to $E_\gamma = 1.35$ MeV. A dynamic moment of inertia $\mathscr{J}^{(2)} = (85 \pm 2)\hbar^2$ MeV^{-1} was derived from the position of the ridge. This large value of $\mathscr{J}^{(2)}_{\rm band}$ corresponds to that expected for superdeformed collective bands with $\beta = 0.6$. However, anomalously high values of $\mathscr{J}^{(2)}_{\rm band}$ have since been observed[8] in ^{156}Dy for collective bands with a normal deformation of $\beta = 0.2$. These arise because of the strong interaction in the first proton alignment and result in a well-defined ridge in the E_γ-E_γ correlation with a fairly constant $\mathscr{J}^{(2)}_{\rm band}$ close to $85\hbar^2$ MeV^{-1}. The unique signature of the superdeformed collective bands will be their greatly enhanced $B(E2)$ transition strengths and thus the γ rays will exhibit very short lifetimes. This paper reports an experiment to measure these lifetimes and hence establish that the collective ridges observed in ^{152}Dy are of superdeformed origin.

As in the previous experiment[5] the multidetector gamma-ray array[6] TESSA2 was used to detect the γ radiation following the bombardment of a ^{108}Pd target with a 210-MeV ^{48}Ca beam from the 20-MV tandem accelerator at the Daresbury Laboratory. The TESSA2 spectrometer consists of six high-resolution germanium detectors with Compton suppression shields plus a compact fifty-element bismuth-germanate (BGO) ball which provides a measure of the total γ-ray energy and the number of γ rays associated with each reaction event. The data recorded by TESSA2 were two coincident suppressed germanium energies, the total γ-ray energy recorded by the BGO ball (the sum energy) and the number of ball detectors (the fold, F) which contributed to this sum energy. The beam energy was 5 MeV higher than previously in order to increase the average angular momentum in the $4n$ channel leading to ^{152}Dy without greatly decreasing its intensity relative to other channels. The target was a 1-mg-cm^{-2} foil of ^{108}Pd with a 15-mg-cm^{-2} gold backing instead of the two 0.5-mg-cm^{-2} self-supporting foils used in the first experiment. With the unbacked self-supporting targets all γ rays were emitted by the recoiling ^{152}Dy nuclei in flight and thus were fully Doppler shifted. In the present experiment the recoiling ^{152}Dy nuclei were stopped in the target plus backing and only γ rays from levels which have lifetimes plus feeding times shorter than 100 fs will be fully Doppler shifted. Decays with much longer lifetimes, the "slow" transitions, which include all the known discrete lines in ^{152}Dy up to $40\hbar$, will be emitted after the recoils have stopped, and so will exhibit no Doppler shift. As the γ rays within the superdeformed bands are expected to have lifetimes less than 100 fs (the "fast" transitions), a simple analysis technique was used to separate out the different features of the fast and slow transitions. The usual mode of presentation of E_γ-E_γ correlation matrix data is to produce spectra of $\Delta E_\gamma = |E_{\gamma 1} - E_{\gamma 2}|$ for different ranges of $\bar{E}_\gamma = \frac{1}{2}(E_{\gamma 1} + E_{\gamma 2})$. The superdeformed rotational bands will show up as a ridge at $\Delta E_\gamma = 47$ keV in the $\Delta E_\gamma - \bar{E}_\gamma$ matrix or as peaks in the ΔE_γ spectra for a series of $\bar{E}_\gamma$ values.

The ΔE_γ spectra shown in Figs. 1 and 2 are obtained with two different conditions on the sum energy and fold data of the BGO ball in TESSA2 and also for two different ways of dealing with the high-resolution germanium events. The BGO ball conditions were low fold ($5 \leq F \leq 18$) and high fold ($F \geq 19$) which correspond approximately to entry spins in ^{152}Dy of $< 50\hbar$ (low fold) and $> 50\hbar$ (high fold). The low-fold spectra also contain the majority of events from the $5n$ channel to ^{151}Dy.

The germanium detectors, which are at angles of 30°, 90°, and 150° in TESSA2, were calibrated with radioactive sources. Coincident slow transitions will have a unique ΔE_γ, independent of which pair of germanium detectors were involved, whereas coincident fast transitions will have five possible values of ΔE_γ. These will be shifted by $-2\Delta E_s$, $-\Delta E_s$, 0, ΔE_s, and $2\Delta E_s$, where ΔE_s is the full Doppler shift which has a magnitude of 25 keV for a 1-MeV γ ray. Thus with this "zero-shift" assumption for the calibration of the detectors, coincident discrete-line γ rays in ^{152}Dy below $40\hbar$ will yield a single ΔE_γ peak. These are clearly seen in Fig. 1. On the other hand any coincident γ rays from superdeformed bands will be split into five components and therefore be difficult to identify. The part of the spectra associated with very high spins in ^{152}Dy can be accentuated by subtraction of the low-fold spectra from the high-fold spectra with a relative normalization that equalizes the flux of evaporated neutrons and thus maintains similar fusion-evaporation intensities. These difference spectra are shown in Fig. 1 and the main features are negative peaks associated with ^{151}Dy γ rays and positive peaks associated with known high-spin ^{152}Dy γ rays in the spherical-oblate regime.

The second method of analysis of the data from the germanium detector yields the "full-shift" assumption spectra shown in Fig. 2. They were generated by aligning the detector gains such that fully Doppler-shifted peaks in detectors at the three different angles will occur in the same channel. The zero–Doppler-shifted peaks will be split into five components and thus become weak features in the spectra. This is indeed the case as shown in Fig. 2. The only significant feature is a peak present in the high-fold spectra at a ΔE_γ value just below 50 keV. The difference spectra in Fig. 2 were obtained in an identical way to those for the "zero-shift" spectra in Fig. 1 and a peak at 47 keV with a width of 8 keV is clearly identified in the two spectra with $\bar{E}_\gamma$ in the range 0.81 to 1.35 MeV. This peak is not seen in ΔE_γ spectra for ranges of $\bar{E}_\gamma$ greater than 1.35 or less than 0.81 MeV, although a narrow weaker peak with $\Delta E_\gamma = 50 \pm 1$ keV is present

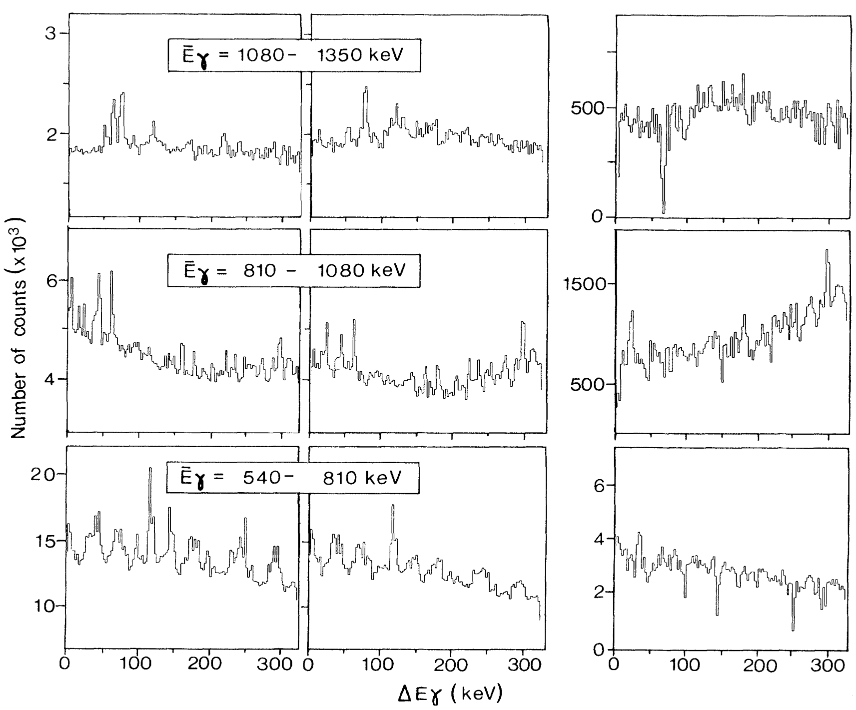

FIG. 1. Cuts across the E_γ-E_γ correlation matrix for ^{152}Dy with the detector gains aligned assuming zero Doppler shift. The spectra are of $\Delta E_\gamma = |E_{\gamma 1} - E_{\gamma 2}|$ for three regions of $\bar{E}_\gamma = \frac{1}{2}(E_{\gamma 1} + E_{\gamma 2})$. The three columns show spectra for (left to right) low fold ($5 \leq F \leq 18$), high fold ($F \geq 19$), and the difference [(high fold) − (low fold)].

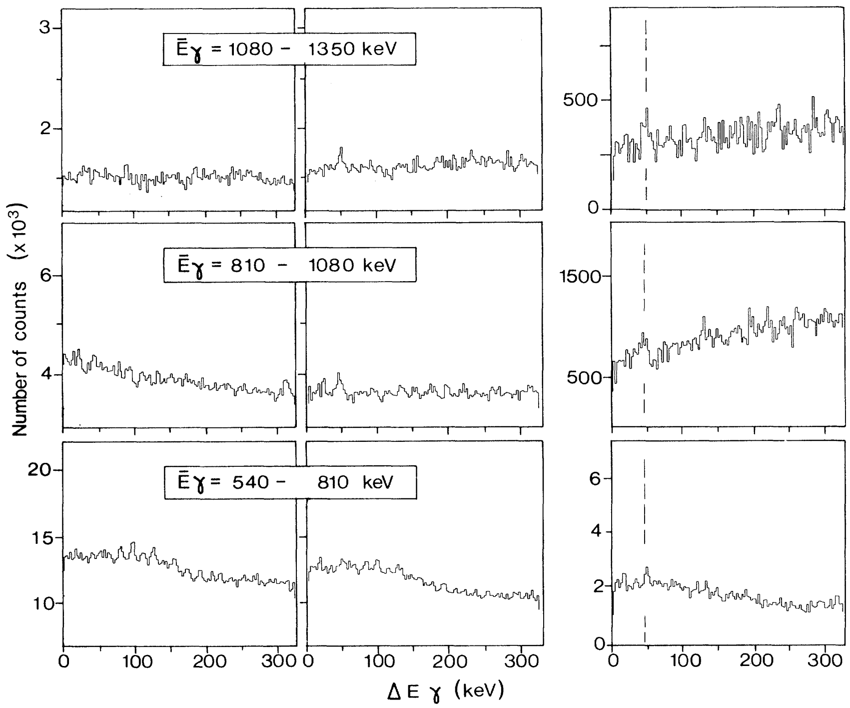

FIG. 2. Cuts across the E_γ-E_γ correlation matrix for ^{152}Dy with the detector gains aligned assuming full Doppler shift. The spectra are of $\Delta E_\gamma = |E_{\gamma 1} - E_{\gamma 2}|$ for three regions of $\bar{E}_\gamma = \frac{1}{2}(E_{\gamma 1} + E_{\gamma 2})$. The three columns show spectra for (left to right) low fold ($5 \leqslant F \leqslant 18$), high fold ($F \geqslant 19$), and the difference [(high fold) − (low fold)].

in the $\bar{E}_\gamma = 0.54$–0.81 MeV spectrum and this may be linked with the termination of the bands. The previous data showed that the superdeformed γ rays extended up to 1.35 MeV and, on the assumption that most of the feeding of these bands is above 1.1 MeV in the very high-spin regime where they are close to the yrast line, the relative intensities of the peak in the two difference spectra with $\bar{E}_\gamma = 0.81$–1.08 MeV and $\bar{E}_\gamma = 1.08$–1.35 MeV indicate that the superdeformed bands extend down to approximately 0.90 MeV. This is confirmed by a detailed analysis of ΔE_γ spectra with smaller ranges of $\bar{E}_\gamma$. We also note that a close analysis of the spectra shows that the large peaks (both negative and positive) in the difference spectra of Fig. 1 can be associated with five weak peaks in Fig. 2. We emphasize that the spectra in Figs. 1 and 2 are exactly the same data set analyzed in two different ways. These spectra demonstrate that the ridge structure previously identified[5] is composed of γ rays which are fully Doppler shifted. The ΔE_γ value is again established to be 47 keV, with a slightly larger uncertainty of 2 keV, corresponding to $I^{(2)}_{\text{band}} = (85 \pm 4)\hbar^2\ \text{MeV}^{-1}$ which is the moment of inertia expected from a superdeformed structure.

The observation of fully shifted peaks infers a Doppler-shift-attenuation F factor of greater than 0.85 (on the assumption that 50% of the peak intensity is Doppler shifted less than 4 keV in the 30° and 150° detectors) and this corresponds to a lifetime limit of < 100 fs as shown in the inset of Fig. 3. If one assumes that the feeding into the bands occurs between 1.1 and 1.35 MeV, the observed lifetime is longer than the true lifetime at γ-ray energies below 1.1 MeV and this correction approximately halves the lifetime value. The corrected lifetime limit can then be transformed to the minimum $B(E2)$ limit shown in Fig. 3. With the usual assumptions for a collective nucleus the $B(E2)$ values expected for normal deformation ($\beta = 0.2$) and superdeformation can be calculated and these are also indicated in Fig. 3. These data show that the observation of a fully shifted ridge down to $E_\gamma = 0.90 \pm 0.05$ MeV is evidence that it is composed of very enhanced collective transitions and thus definitely associated with superdeformed structures in ^{152}Dy.

In conclusion, the lifetimes of the γ rays in the rotational bands forming the ridges in the E_γ-E_γ energy correlations of ^{152}Dy have been shown to be fully Doppler shifted down to a γ-ray energy of 0.90–0.05 MeV. Their effective lifetimes are, therefore, less than 100 fs and this corresponds to very enhanced $B(E2)$ values, considerable in excess of that predicted for a normal prolate deformation of $\beta = 0.2$. The data thus provide further evidence that the rotational bands are associated with a superdeformed prolate shape in ^{152}Dy.

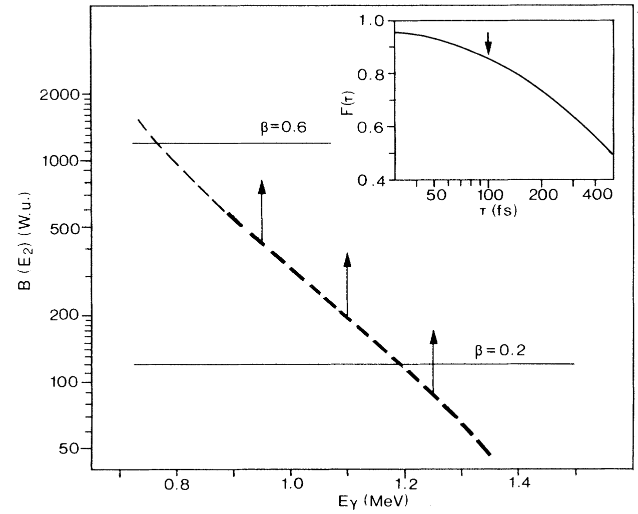

FIG. 3. The experimental lower limits on the $B(E2)$ values of the γ rays forming the rotational ridge structure in ^{152}Dy. The inset shows that the experimentally determined Doppler-shift-attenuation factor of 0.85 corresponds to a mean lifetime of 100 fs. It was assumed that the side feeding into the bands occurred above a γ-ray energy of 1.1 MeV. The predicted $B(E2)$ values are indicated for prolate deformations of $\beta = 0.2$ and $\beta = 0.6$.

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