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Simultaneous population of large and small deformation bands at very high spin in ^{152}Dy

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The lifetimes of the gamma-ray continuum at spins above $40\hbar$ were measured in ^{152}Dy via the Doppler shift attenuation technique following the ^{74}Ge(^{80}Se,2n) and ^{76}Ge(^{80}Se,4n) reactions, at beam energies of 285 and 320 MeV, respectively. Although the deduced average quadrupole moments are smaller than the value expected for superdeformed bands, the variation of the observed Doppler shift as a function of gamma-ray energy suggests that both small deformation ($\beta \sim 0.2$) and more deformed structures (possibly superdeformed) are present in the very high spin continuum of this nucleus.

Four different structures have already been established in ^{152}Dy. At low spins, the yrast levels have a quasivibrational structure,[1] while between spins $8\hbar$ and $38\hbar$ a small deformation ($\beta \sim 0.15$) prolate rotational band has been observed.[2] This band lies 0.5–1.5 MeV above the yrast levels, which themselves form a sequence of single-particle configurations[3,4] with spins aligned along the symmetry axis of an oblate shape. At higher spins, the gamma-ray continuum is dominated by a stretched $E2$ bump.[5–7] Part of this bump gives rise to ridges[8] in E_γ-E_γ correlation matrices, which indicate a moment of inertia $\mathcal{J}^{(2)} = (85 \pm 2)\hbar^2$ MeV^{-1}. This, in addition to an estimate of their lifetime,[9] has led to the suggestion[8,9] that these ridges arise from superdeformed ($\beta \sim 0.6$) bands. Very recently, Twin *et al.* have observed[10] a single discrete line band up to $60\hbar$ in this same nucleus, and with the same value of $\mathcal{J}^{(2)}$ as given by the ridges. They state that this discrete line band, which amounts to 2.2% of the total gamma-ray intensity, and has a transition quadrupole moment value of 20 e b,[10] accounts completely for the ridge structure observed previously. In this report, we present lifetime data on the bump in ^{152}Dy elucidating the nature of additional bands in this nucleus above spin $\sim 40\hbar$. Somewhat similar measurements have been carried out very recently by Radford *et al.*[11]

The states were populated using the ^{74}Ge(^{80}Se,2n) and ^{76}Ge(^{80}Se,4n) reactions, at beam energies of 285 and 320 MeV, respectively, with the beam provided by the MP tandem accelerator at Strasbourg. The targets were ~ 600 μg/cm^2 thick ^{74}Ge or ^{76}GeO$_2$. A ^{74}Ge self-supporting target allowed the full shift of the bump to be displayed and served to verify the normalization procedure, while gold-backed targets were used for the Doppler shift attenuation (DSAM) measurements proper. The gamma rays were detected with the "château de cristal" 4π array in its thirty-eight BaF$_2$ scintillation counter configuration, and with eight Compton-suppressed Ge detectors, four being at 30° to the beam axis and four at 146°.

Only Ge detector events accompanied by at least five prompt ($t < 20$ ns) and at least two delayed ($20 < t < 500$ ns) hits in the BaF$_2$ array were recorded. Because of the good timing properties of BaF$_2$ crystals, the fast decay from the $\tau = 18$ ns ($I = \frac{49}{2}$) isomer in ^{151}Dy could be clearly separated from that of the $\tau = 86$ ns ($I = 17$) isomer in ^{152}Dy in the prompt-delayed time spectrum. The selection of appropriate windows on this time spectrum and on the sum-energy and prompt-multiplicity spectra resulted in a ratio of the ^{151}Dy/^{152}Dy yields at less than 5% for the 4n reaction and of less than 15% for the 2n reaction, where the ^{151}Dy channel is much more favored. An additional 10 ns window on the Ge-prompt BaF$_2$ time spectrum eliminated all peaks due to (n,n$'\gamma$) events.

The average entry spins and energies in both reactions were estimated by comparing the BaF$_2$ prompt multiplicity and sum-energy spectra with those obtained in the ^{124}Sn(^{32}S,4n)^{152}Dy reaction at beam energies of 132, 140, and 151 MeV—the average gamma-ray multiplicities, entry spin, and energy for this last reaction having been previously established[6] at these energies. The measured average entry energies (29 and 32 ± 2 MeV for the 4n and the 2n reactions, respectively) are compatible with the values calculated for reactions at the middle of the targets and with an average neutron kinetic energy of 2 MeV (30.3 and 32.4 MeV, respectively). Compared to the ^{32}S reaction at 151 MeV, 3.4 ± 1.1 additional transitions are emitted in the present reactions. Assuming that these transitions are stretched $E2$,[6,7] the corresponding average entry spins are $(50 \pm 3)\hbar$ in the 2n as well as in the 4n reactions. This similarity does not necessarily contradict the difference in entry region deduced from the energy, since the relationship between the multiplicity and spin depends on the average change in angular momentum per transition, and this number can depend on the type of bands populated in the reaction.

The Ge spectra were unfolded[12] using ^{60}Co, ^{137}Cs, and ^{24}Na sources, and then corrected for the photoelectric peak efficiencies of the Ge detectors, as measured with calibrated sources. The unfolding procedure was tested with ^{152}Eu source spectra. All the spectra at 30° were then added together, as were those at 146°, and the discrete lines subtracted. The continuum of statistical gamma rays was fitted[6] to the function $E_\gamma^3\exp(-E_\gamma/T)$ and removed. Figure 1 displays the resulting bump for the spectra measured with the gold-backed target in the 4n reaction. The normalization factors between the 30° and 146° spectra were obtained by two different methods, either by comparing the statistical gamma-ray between 2 and 3 MeV or by treating the normalization factor as a free parameter in the fit of the average shift of the $E2$ bump between 1.1 and 1.7 MeV. After correction for the relativistic aberration,[13] both normalization factors were found to be the same within error bars, and their weighted average was used in the subsequent analysis. The Doppler shift in the two spectra was taken into account by using the recoil velocity ($v/c = 0.0430$ and 0.0447 for the 2n and 4n reactions, respectively) determined experimentally from the discrete lines.

To get the experimental average Doppler shift for each slice of the bump region, the gain of the spectrum at 30° was multiplied by the factor

$$\text{Gain shift} = \frac{1+F(\tau)\dfrac{v_0}{c}\cos(146^\circ)}{1+F(\tau)\dfrac{v_0}{c}\cos(30^\circ)} \tag{1}$$

for all values of the fraction of full shift, $F(\tau)=v/v_0$, between -0.50 and 1.50 in steps of 0.01, where v_0 is the initial recoil velocity. χ^2, the sum of the squared differences between the 146° spectrum and the shifted 30° spectrum, weighted by the squared errors on that difference, was then calculated for each $F(\tau)$ value. The resulting spectrum of χ^2 can be fitted to a second or third order polynomial. The optimum $F(\tau)$ is given at $\chi^2=\chi^2_{\min}$ of the fit, and the error bar by the values of $F(\tau)$ at $\chi^2=\chi^2_{\min}+1$. Since the normalized values of $\chi^2_{\min}$ vary between 0.75 and 0.95, this means that the errors on $F(\tau)$ are only slightly overestimated.

The average recoil velocity was thus calculated for energy bins of 0.2 MeV between 1.15 and 1.85 MeV, for the backed and self-supporting target spectra. It was verified that this procedure, applied to the self-supporting target spectra does yield a full gain shift at all energies. It should be emphasized that the observed trends discussed below are strong enough to be present even when the above Doppler shift analysis is applied to

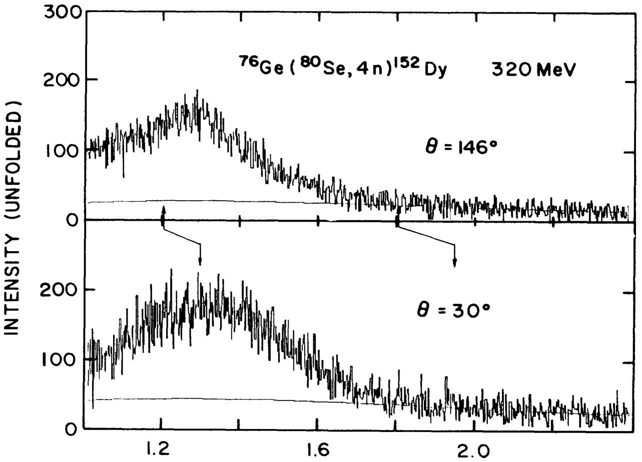

FIG. 1. Gold-backed target gamma-ray spectra measured at 30° and 146° in the ^{76}Ge(^{80}Se,4n)^{152}Dy reaction, at 320 MeV beam energy. The discrete lines have been removed, and the spectra unfolded. The lines represent the fit to the continuum of statistical transitions. The arrows indicate the magnitude of a full shift.

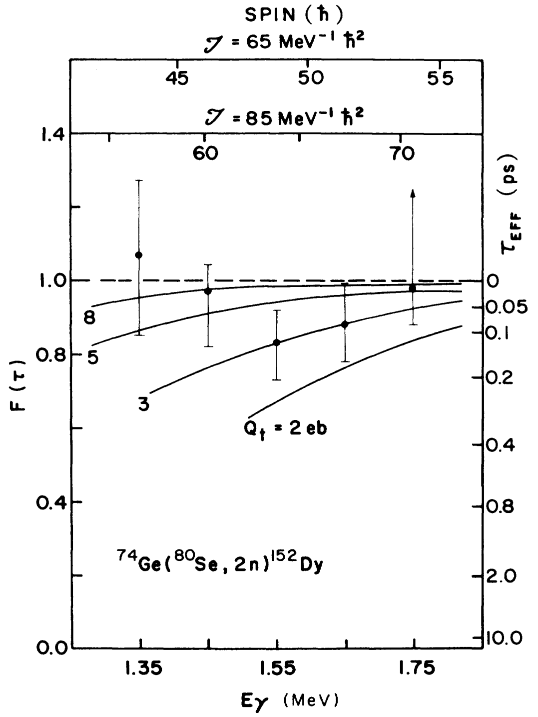

FIG. 2. Average recoil velocity [expressed as $F(\tau)$, the fraction of the full shift] as a function of gamma-ray energy for the $E2$ bump of ^{152}Dy, produced by the ^{74}Ge(^{80}Se,2n) reaction at 285 MeV beam energy. The continuum of statistical transitions has been removed. The scale on the right refers to the corresponding lifetime of the emitting state, neglecting all feeding, as calculated from the stopping powers of ^{152}Dy ions in Ge and Au. The full lines are calculated $F(\tau)$, taking into account the cascade feeding, for rotational bands with quadrupole moments (Q_t) of 2, 3, 5, and 8 e b, and moments of inertia ranging from 65 to 85$\hbar^2$ MeV^{-1}. A superdeformed nuclei would have a Q_t of $\sim$20 e b; 8 e b corresponds to a deformation of $\beta\sim0.38$ and 5 e b to $\beta\sim0.24$, or greater in case of triaxiality.

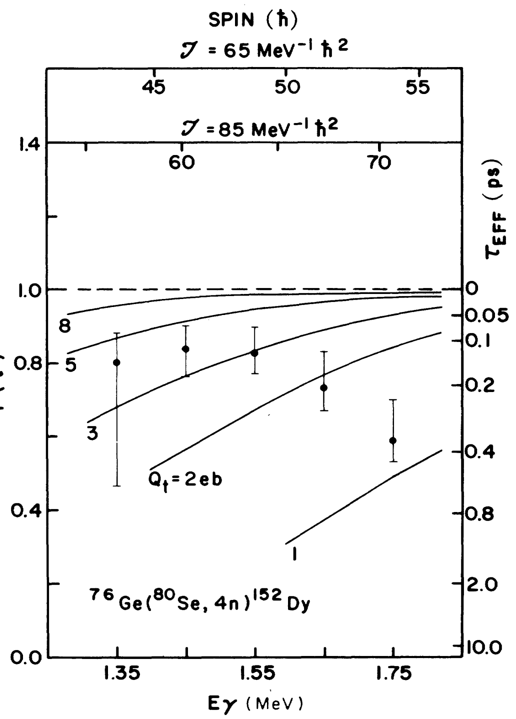

FIG. 3. Same as in Fig. 2, except for the ^{76}Ge(^{80}Se,4n)^{152}Dy reaction at 320 MeV beam energy. The triaxial structure predicted in Refs. 7 and 15 ($\beta=0.25$, $\gamma=30°$) corresponds to $Q_t \sim 3$ e b, and the small-deformation structure observed by Nyako *et al.* (Ref. 2) ($\beta=0.15$) to $Q_t \sim 2$ e b.

the spectra (i) before the subtraction of the statistical gamma-ray continuum. (ii) before the unfolding procedure, and (iii) before both corrections.

The experimental $F(\tau)$ are shown in Figs. 2 and 3 for the 2n and 4n reactions, respectively. In the 2n reaction, a fit to the data points in the 1.25 $< E_\gamma < 1.75$ MeV range yields an average electric transition quadrupole moment (Q_t) value of $5.0^{+6.0}_{-1.5}$ eb. This value corresponds to a deformation similar to that of the ground-state of the slightly heavier rare-earth nuclei,[14] and apparently excludes superdeformation ($\beta \sim 0.6$, $Q_t \sim 20$ eb). However, the data for the 4n reaction are somewhat different. A general decrease of $F(\tau)$ is observed, and, in particular, τ increases with increasing gamma-ray energy above $E_\gamma = 1.5$ MeV. In any model where the gamma-decay follows one or many collective bands of similar deformation, the E_γ^{-5} dependence of the lifetimes should cause a decrease of τ as E_γ increases. Consequently, the observed behavior in the 4n reaction can be explained only if more than one structure is postulated to exist in the high spin continuum of ^{152}Dy. The simplest hypothesis, consistent with the calculations of Ref. 15, is to assume that we are populating at spins between 40ħ and 50ħ a small-β structure (likely the continuation of the collective structure found at lower spins[8]) and, simultaneously, at spins above $\sim 50\hbar$ a much more collective structure, possibly the superdeformed one. Since, for a given spin, the gamma rays emitted in the more deformed bands will have a lower energy than those emitted in the small-deformation bands, the lifetimes of the bump at $E_\gamma > 1.5$ MeV will reflect mostly the small-β bands. Below $E_\gamma = 1.5$ MeV, there will be a mixture of both structures, with the more deformed one predominating to account for the decrease in τ. Results of average lifetime measurements do not allow more specific deductions as to the number of structures, their deformations, populations, and corresponding spin ranges.

In summary, our lifetime data suggest that the continuum of high-spin collective states in ^{152}Dy encompasses at least two different structures: a small deformation structure ($\beta < 0.2$), becoming appreciably mixed, at higher excitation energies and spins ($> 50\hbar$), with a much more collective structure, possibly the predicted superdeformed shape. This feature was revealed by comparing the average lifetimes of different slices of the $E2$ bump and for different reactions

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