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LIFETIME MEASUREMENTS OF TERMINATING AND COLLECTIVE HIGH-SPIN STATES IN ^{155}DY AND ^{156}DY ☆

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Lifetime measurements for the isotopes ^{155}Dy and ^{156}Dy have been extended up to spins around 40$\hbar$ by the Doppler shift attenuation method in conjunction with γ–γ-coincidence measurements. Results have been obtained for the yrast band in ^{156}Dy and for three bands in ^{155}Dy. Strong retardations of the E2-strength were observed for intruding terminating sequences, for which specific single particle configurations are suggested.

The concept of terminating bands has been introduced in explaining the rotation-induced prolate to oblate shape transition observed at spins 30–40$\hbar$ in the $N=88$–90 region. Band termination reflects the process of gradually exhausting the maximum angular momentum that can be built by aligning the spins of particular valence nucleons. Up to now, a few terminating sequences have been suggested in rare earth isotopes with neutron numbers $N=88$–90 [1–7] by comparing the experimental high-spin level schemes with microscopic calculations. Lifetime measurements should provide a rather stringent test of this theoretical concept since drastically decreased transition rates are expected towards band termination [8], revealing the inherent rapid change of the nuclear quadrupole deformation. Therefore, we measured lifetimes in terminating bands for a sequence of transitional Dy isotopes with neutron numbers $N=88$–90. Here we report on results obtained for ^{155,156}Dy; results on ^{154}Dy have been reported in ref. [7]. We were able to extend lifetime measurements in the ^{155}Dy and ^{156}Dy isotopes up to a maximum spin of 40$\hbar$ and at the highest spins we observe strong reductions in the E2 transition strength, consistent with the picture of terminating bands. The present study illustrates the substantial impact that lifetime measurements can have in the interpretation of high-spin nuclear spectra.

To populate high-spin states in ^{155,156}Dy we chose the reaction ^{124}Sn (^{36}S, xn) at a bombarding energy of 155 MeV. De-excitation γ rays were detected in 8 Compton-suppressed Ge spectrometers which, together with an array of 14 BGO scintillators, composed the Argonne/Notre Dame γ-ray facility at the accelerator ATLAS. Three of the Ge detectors were positioned at 146°, three at 34° and two at 90° with respect to the beam axis. A 1 mg/cm^2 Sn target was used with a thick backing of natural Pb, which served to slow down the recoiling Dy ions from their initial velocity of $v=0.022c$ to rest within a mean time of 1.6 ps. Two-dimensional spectra of γ rays detected in

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prompt coincidence between two Ge detectors were recorded with the additional requirement of a minimum multiplicity and total energy observed in the BGO scintillators. A total of 28 million events of that type were accumulated. The high-spin states of interest were selected by imposing coincidence gates on appropriate low-spin γ transitions. Because of the complexity of the primary spectra, typically only five gating transitions at spins below $22\hbar$ could be used for selecting a particular band. Spectra with sufficient counting statistics could be obtained for three bands in ^{155}Dy, as well as for the positive-parity yrast band in ^{156}Dy. A partial γ spectrum obtained for ^{156}Dy is shown in fig. 1.

To extract the lifetimes from the observed Doppler broadened γ-ray lineshapes, we developed a computer code LILIFI [9] which correlates the γ decay and the slowing-down processes in the target and in the Pb backing. For the electronic stopping power we used the values given in ref. [10], while the nuclear stopping process was traced in the Monte Carlo simulation using the universal scattering formula given [11] in the code TRIM. The accuracy of the treatment, in particular the rather severe effects of lateral and longitudinal range straggling, was checked with available experimental data. We also took into account explicitly the finite solid angle of the γ detectors and the positional dependence of their efficiencies, calculated with the EGS code [12]. The energy dependence of the detector response was measured with standard radioactive sources. The history of the nuclear decay process was described by approximating the sidefeeding into each known state through a rotation-like feeder cascade. The lifetimes as well as sidefeeding times and intensities finally were derived by fitting the experimental γ-ray lineshape with those resulting from the Monte Carlo treatment; an example is presented in fig. 1. The sidefeeding via unobserved transitions was found to carry less than 40% of the intensity for all analyzed states and the sidefeeding times varied within 0.1–0.5 ps and 0.3–0.8 ps in ^{156}Dy and ^{155}Dy, respectively. These numbers seem to justify the approximation of the sidefeeding into each state by a single rotational band (3–5 steps within this band were adopted throughout the analysis). The resulting lifetimes are given in table 1. At least two successive transitions were fitted simultaneously, and therefore the errors (one standard deviation) quoted in table 1 include those due to correlations with other fit parameters. The lifetimes were transformed into quadrupole transition moments $Q_t(I)=(1.22\langle I\;020|I-2\;0\rangle\;\tau E_\gamma^5)^{-1/2}$ which are displayed in figs. 2d–2f. In addition, in figs. 2a–2c we show the excitation energies of the corresponding high-spin level after subtracting a smooth liquid drop reference energy.

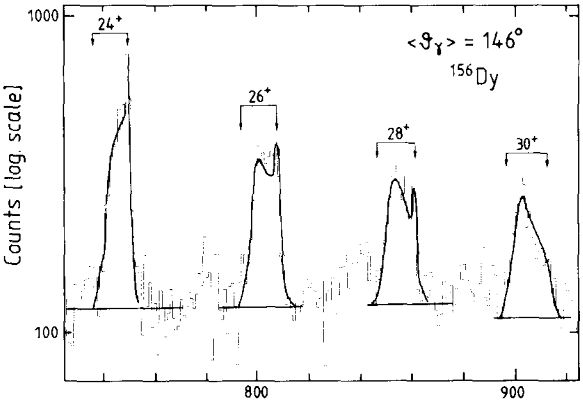

Fig. 1. Partial γ-ray spectrum for ^{156}Dy measured at 146° in coincidence with five selected γ transitions occurring at spins below $22\hbar$. Solid curves show the calculated line shapes using the best-fit parameters. The arrows indicate the energies of the γ transitions at zero and full Doppler shift.

The lifetimes in the spin range 30^+–36^+ of ^{156}Dy were too short (<0.1 ps) to be determined individually since the higher spin feeder states (38^+–42^+) have much longer lifetimes. Therefore the lifetimes of these states were extracted by fitting the respective γ-line shapes using a constant Q_t value within this spin range. For spins $I^\pi \leqslant 30^+$ lifetime data were available from an earlier recoil-distance measurement [13] performed for ^{156}Dy; they are included in table 1. The results from the two measurements are consistent within their errors, although the present DSA measurement yields values which are on the average about 35% lower.

In ^{155}Dy we have obtained results for the sequences of positive-parity yrast states (denoted as band A in the following) and the negative-parity yrast states. The latter sequence is split into two bands which – at low spin – are considered [4] to be signature partners, and which we denote below as band B ($\alpha=+1/2$) and C ($\alpha=-1/2$). In band B, Doppler-

Table 1

Lifetimes obtained from this measurement for positive- and negative-parity yrast states in ^{155}Dy and positive-parity yrast states in ^{156}Dy. Values quoted in brackets, i.e. for the topmost states in a band, include the feeding times.

^{155}Dy			^{156}Dy		
I ($\hbar$)	Band A (π^+) τ (ps)	Band B, [C] (π^-) τ (ps)	I ($\hbar$)	Yrast (π^+) τ (ps)	τ (ps) [a]
41/2	$0.39^{+1.10}_{-0.35}$		20		0.71 ± 0.06
45/2	0.19 ± 0.06	0.30 ± 0.16	22	0.46 ± 0.08	0.50 ± 0.08
49/2	$0.07^{+0.05}_{-0.03}$	$0.24^{+0.05}_{-0.09}$	24	0.21 ± 0.08	0.56 ± 0.09
53/2	0.19 ± 0.07	0.26 ± 0.06	26	0.16 ± 0.05	$0.30^{+0.10}_{-0.08}$
57/2	0.22 ± 0.06	$\leqslant 0.1$	28	0.16 ± 0.04	$0.23^{+0.10}_{-0.08}$
61/2	$0.18^{+1.10}_{-0.10}$	0.23 ± 0.12	30	0.12 ± 0.02 [b]	$0.17^{+0.08}_{-0.06}$
65/2	$0.08^{+0.40}_{-0.04}$	$0.17^{+0.10}_{-0.15}$	32	0.09 ± 0.02 [b]	
69/2	($\leqslant 1.1$)	$\leqslant 0.22$	34	0.08 ± 0.02 [b]	
71/2		$\geqslant 1.5$ [C]	36	0.06 ± 0.02 [b]	
73/2		$0.63^{+2.0}_{-0.23}$	38	0.20 ± 0.06	
75/2		$\geqslant 1.5$ [C]	40	$0.07^{+0.11}_{-0.05}$	
77/2		$\leqslant 0.2$	40 [a]	(0.60 ± 0.30)	
81/2		($0.64^{+0.35}_{-0.25}$)	42 [b]	(0.45 ± 0.15)	

[a] Values from ref. [13].

[b] Lifetimes deduced assuming a constant Q_t value (see text).

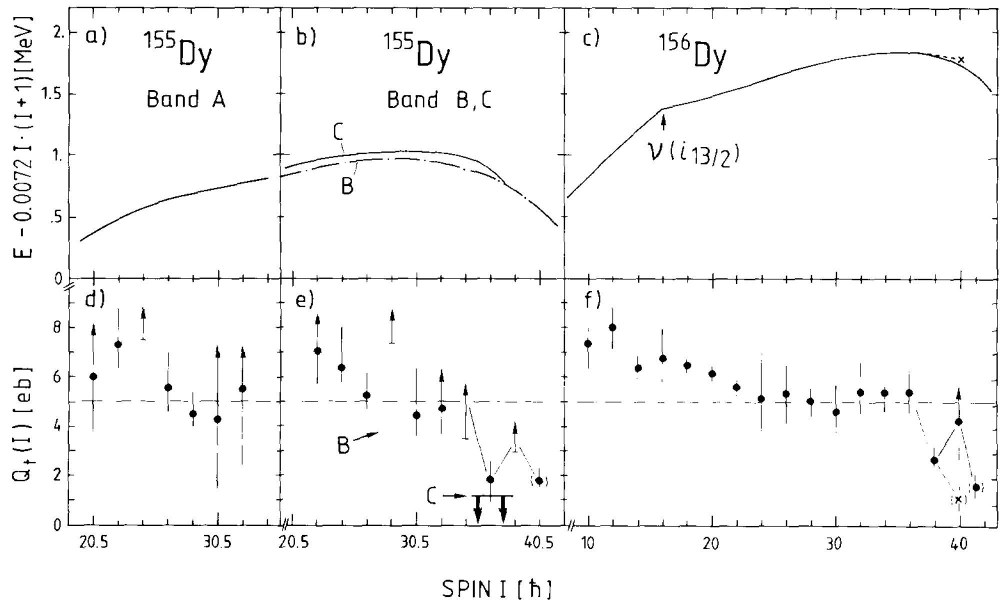

Fig. 2. (a)–(c) Excitation energies (from ref. [2]) after subtraction of a smooth reference energy for yrast states in ^{155}Dy and ^{156}Dy. In (c), the backbending due to $i_{13/2}$ neutron alignment in ^{156}Dy is indicated. (d)–(f) Quadrupole transition moments $Q_t(I)$ deduced from the measured lifetimes. For ^{156}Dy, in the spin range $I \leqslant 30\hbar$ data from ref. [13] or mean values of ref. [13] and the present measurement were used. Values given in brackets include feeding times. In (c) and (f), the values for the second 40^+ state are denoted by the symbol (×).

shifted γ-ray lineshapes are observed for transitions up to spin $81/2^-$, but all transitions in band C ($I \leqslant 75/2^-$) appear as stopped lines. This shows that either these states are long-lived with lifetimes larger than the mean stopping time of 1.6 ps, or that all feeding times involved are long. For the other bands, however, we observe only short sidefeeding times (see above) and it appears very unlikely that all the feeding into band C could be so slow. Therefore, for the topmost levels we conclude that the absence of a Doppler effect in the lineshapes must be due to long lifetimes and we deduce a lower limit of 1.5 ps for these states.

These results illustrate one striking common feature, namely, that whenever a particular level sequence exhibits downsloping behaviour it appears to be accompanied by the onset of a reduction in the E2 strength (compare fig. 2). This effect occurs at spin 38^+ in ^{156}Dy and at spin $73/2^-$ in band B of ^{155}Dy; in addition the transitions above spin $67/2^-$ in band C of ^{155}Dy are strongly retarded. Band A in ^{155}Dy exhibits no downsloping part and the corresponding Q_t values show no significant reduction. The effect of a reduced collectivity in terminating band was also observed in ^{154}Dy [7] and more recently in ^{158}Er [14].

Prior to this work, extensive microscopic calculations were performed for the isotope ^{155}Dy [4] and detailed configuration assignments were made. In these calculations if was found necessary to shift bands with a different number of $h_{11/2}$ protons indicating that the theoretical $Z=64$ gap was too small. Similarly, recent studies [15] have indicated some deficiencies in the neutron parameters. Thus, somewhat revised parameters in the $N=88$–90 region were used in ref. [16]. The main changes relative to the standard parameters [17] are a raising of the $\pi h_{11/2}$ subshell by ~500 keV, a decrease in the $\pi d_{5/2}$–$\pi g_{7/2}$ spacing and a lowering of the $\nu i_{13/2}$ subshell. We have performed calculations for ^{155}Dy using these revised parameters; partial results are shown in fig. 3. In the following, the configurations (relative to the ^{146}Gd core) will be labelled by the number n (m) of $h_{11/2}$ protons ($i_{13/2}$ neutrons) using the shorthand notation $\pi^n\nu^m = \pi[(h_{11/2})^n(g_{7/2}d_{5/2})^{2-n}]\nu[(i_{13/2})^m \cdot (f_{7/2}h_{9/2})^{7-m}]$.

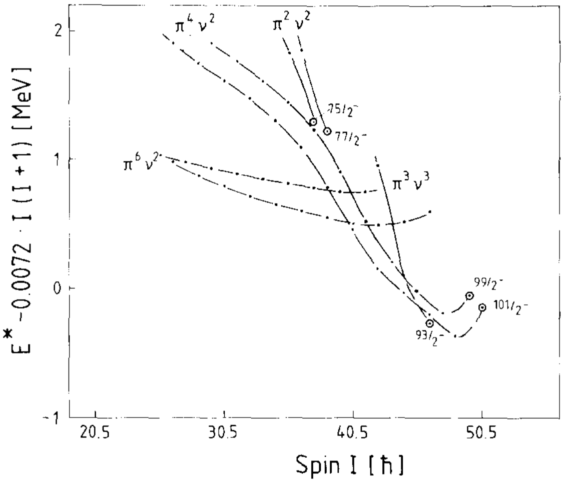

Fig. 3. High-spin configurations of negative parity in ^{155}Dy obtained from the microscopic calculations using modified parameters (see text). Only the relevant configurations are shown, i.e. those which are lowest in energy, Configurations are indicated according to the notation specified in the text. Fully aligned states are encircled.

For the positive-parity states, the calculation gives no indication of a terminating state within the spin range covered by our lifetime measurement. This is in line with the fact, that the lifetimes measured for the positive-parity yrast states (band A) show no significant retardation (figs. 2a, 2d). In ref. [4], the high-spin states of the negative-parity yrast bands B and C in ^{155}Dy were interpreted as signature partners of the configuration $\pi^4\nu^2$ with terminating spins at $101/2^-$ and $99/2^-$, respectively. This interpretation, however, appears to be in conflict with the lifetimes observed for band B and in particular for band C in ^{155}Dy. In band C, the E2-transition strength is strongly reduced already at spins $71/2^-$, while in band B only the onset of a retardation is observed. Our calculation for the negative parity states (fig. 3) show the downsloping $\pi^4\nu^2$ configuration crossing the $\pi^6\nu^2$ configuration at $I^\pi=81/2^-$. The observed downsloping and E2-strength reduction in band B can readily be ascribed to such a configuration crossing, although it does occur at a lower spin ($I^\pi=73/2^-$) than predicted. The much stronger reduction in E2 strength observed at spins $71/2^-$, $75/2^-$ in band C, however, clearly requires a configuration terminating at a much lower spin than the value obtained for $\pi^4\nu^2$ (see fig. 3). From our calculations, the only possible candidate appears to be $\pi^2\nu^2$, which terminate at spin $75/2^-$. We also note that removal of one neutron from the $\pi^2\nu^2$ $75/2^-$ state of ^{155}Dy yields an aligned 36^+ state which may be identified with the favored 36^+ state located [7] in ^{154}Dy. It should be pointed out that contrary ref. [4], the present results are obtained without any shift in energy of bands with different numbers of $h_{11/2}$ protons. However, it remains a problem that both the $\pi^4\nu^2$ and $\pi^2\nu^2$ configurations are still calculated about 500 keV too high.

In ^{156}Dy, a strong reduction occurs at spin 38^+ accompanied by the downsloping of the yrast line. Adding one more neutron to the favored $\pi^2\nu^2$ $75/2^-$ state in ^{155}Dy leads [18] to a fully aligned 40^+ state in ^{156}Dy. The second 40^+ state in ^{156}Dy, identified in ref. [2], exhibits a rather long effective lifetime and could thus be a candidate. The reduced Q_t value observed for the 38^+ yrast state indicates a bandcrossing at this spin. Most likely the intruding sequence is of $\pi^4\nu^2$ character as was assigned to band B in ^{155}Dy; the same assignment was derived in ref. [19]. The return to the more collective Q_t value of the 40^+ yrast state can readily be understood, since the $\pi^2\nu^2$ configuration terminates only at $I \sim 50\hbar$.

In summary, employing the Doppler shift attenuation method in conjunction with high efficiency γ-γ-coincidence measurements, we were able to perform lifetime measurements in the interesting high-spin region where terminating sequences compete with more collective configurations. Within the terminating sequences we observe significant reductions of the E2 strength that are generally in line with the theoretical picture. Single particle configuration assignments are suggested for the intruding bands on the basis of the experimental data, demonstrating that lifetime measurements yield information that is decisive in elucidating the microscopic nuclear structure at high spin.

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