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# Yrast Isomers and Possible Oblate Shape in $^{152}$Dy

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(Received 28 September 1978)

Excitation energies, spins, and parities have been determined for $^{152}$Dy in (HI, $xn$) reactions up to $I^\pi = 27^+$. Three isomers with $T_{1/2} = 49.5$ ns ($E_x = 5035$ keV, $I^\pi = 16^+$), 9.9 ns ($E_x = 6076$ keV, $I^\pi = 20^-$), and 1.6 ns ($E_x = 7828$ keV, $I^\pi = 26^-$) have been found. The $g$ factor of the second isomeric state was measured to be $g = 0.55 \pm 0.06$. The present experimental data compares well with microscopic calculations which imply an oblate shape for $^{152}$Dy at high angular momenta ($I^\pi \geq 16^+$).

Recently, a great deal of theoretical work has been devoted to the study of yrast traps occuring at high and very high spins. Systematic experimental search for delayed $\gamma$-ray cascades has shown the existence of high-spin isomers[1] belonging to nuclei situated around the neutron number $N = 82$. Theoretical calculations[2-4] have pointed to this region of isotopes as being especially favorable for the occurrence of yrast traps based on the oblate-coupling scheme. However, some isomers can be explained as shell-model isomeric states.[3-6] Detailed spectroscopic work on the high-spin isomers is therefore essential for a better comparison with the calculations. In this Letter we report on the existence of three high-spin isomeric states in $^{152}$Dy. Their spins, parities, lifetimes, and decay properties have been established by $\gamma$-ray spectroscopic methods. The $g$ factor of the second isomeric state ($E_x = 6076$ keV) has also been determined. The investigation of the nucleus $^{152}_{66}\mathrm{Dy}_{86}$ by Jansen *et al.*[7] has already shown the existence of an isomer of $T_{1/2} \approx 60$ ns at $E_x \approx 5$ MeV with $15 \leq I \leq 18$. Theoretical calculations of Cerkaski *et al.*[3] predict at least three yrast traps in this nucleus.

The nuclide $^{152}$Dy has been produced at high angular momenta by means of the heavy-ion reactions $^{140}\mathrm{Ce}(^{16}\mathrm{O}, 4n)^{152}\mathrm{Dy}$ ($E_{^{16}\mathrm{O}} = 88$ MeV) and $^{141}\mathrm{Pr}(^{15}\mathrm{N}, 4n)^{152}\mathrm{Dy}$ ($E_{^{15}\mathrm{N}} = 80$ MeV) at the Strasbourg MP accelerator. In-beam $\gamma$-spectroscopic experiments were performed using a variety of Ge(intrinsic), Ge(Li), and Si(Li) spectrometers,

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to measure $\gamma$-ray excitation function and $\gamma$-$\gamma$ and $n$-$\gamma$ coincidences (prompt and delayed). $\gamma$-ray angular distributions concurrent to $\gamma$-ray linear polarizations were measured using a three-Ge(Li) Compton polarimeter described elsewhere.[8] A simultaneous fit of the $A_2$ and $A_4$ angular distribution coefficients and of the linear polarization $p$ uniquely determined the angular momentum change $\Delta I$, the multipolarity $\lambda$, and the electric or magnetic character for most of the transitions. In order to reduce hyperfine-interaction effects on the angular-distribution and linear-polarization data due to the existence of long-lived states in $^{152}$Dy, the targets were evaporated on thick lead backings and heated to 260°C. The observed level scheme is shown in Fig. 1. Up to the level at $E_x = 5035$ keV the present measurements confirm essentially the level sequence reported previously[7] with the ($\alpha$, 6$n$) reaction. With the assumption of stretched cascades, spin and parity assignments given in Fig. 1 were obtained (or confirmed) from our data. For the 5035-keV state the $I^\pi = 16^+$ value is based on our present results combined with the electron-conversion measurements from Ref. 7. No evidence was found in $\gamma$-$\gamma$ coincidences done with Ge(intrinsic) and Si(Li) detectors for the presence of a low-energy transition feeding the 5053-keV level as proposed in Ref. 7. Furthermore, the $n$-$\gamma(t)$ spectrum for the 605-keV transition did not show any prompt component (Fig. 2). Above the 5035-keV level a new cascade of eight transitions was identified. The experimental $\gamma$-ray angular distribution coefficients and $\gamma$-ray linear polarizations as well as the deduced multipolarities are reported for these transitions in Table I. To overcome the difficulties met in preliminary results[9] of extracting yields of the 254- and 255-keV lines in the presence of a strong 257-keV radioactivity $\gamma$-ray line, the angular distributions and linear polarizations of the former lines were remeasured with a prompt window (~15 ns) set on the pulsed-beam-$\gamma$-ray time spectrum.

The search for lifetimes in the nanosecond range was undertaken using the delayed-coincidence method as well as the recoil-distance Doppler-shift method. Neutron-$\gamma$ and $\gamma$-$\gamma$ time-delayed coincidence spectra were recorded using a 12×5-cm NE 213 scintillation counter, allowing $n$-$\gamma$ discrimination, and a Ge(Li) spectrometer. The half-life of the 5035-keV level, determined from a least-squares fit to the shape of the delayed curve, is $T_{1/2} = 49.5 \pm 1.4$ ns (Fig. 2, upper part). From the time distributions for the 262-keV $\gamma$-ray transition (Fig. 2, lower part) and for the 525-keV transition, a value $T_{1/2} = 9.9 \pm 0.6$ ns was obtained for the half-life of the 6076-keV level. No differences, as compared to the resolution curves of the system, were observed in the time spectra of the transitions lying above this state. The recoil-distance Doppler-shift tech-

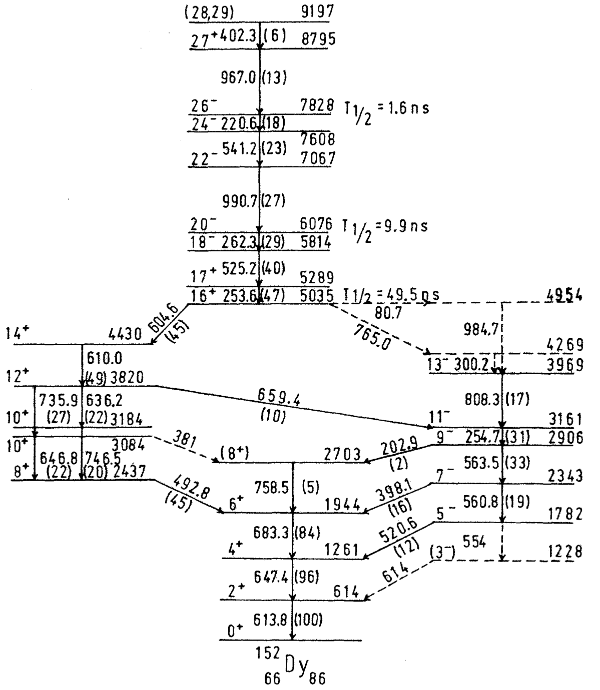

FIG. 1. Experimental level spectrum.

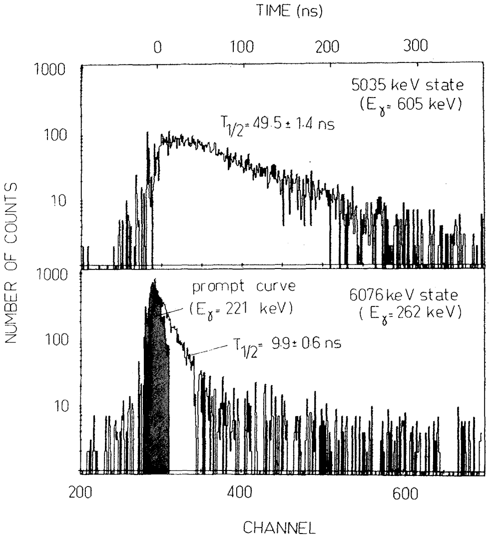

FIG. 2. Time spectra obtained in $n$-$\gamma$ coincidences.

TABLE I. Experimental results for the transitions decaying from the high-spin levels.

| $E_i-E_f$ (keV) | $E_\gamma$ (keV) | $I_\gamma$[a] | $A_2$ | $A_4$ | $P$[b] | Multi-polarity |
|---|---|---|---|---|---|---|
| 5289–5035 | 253.6(2) | 47(1) | −0.270(15)[c] | 0.010(17)[c] | −0.18(7)[c] | $M1+E2$ |
| 5814–5289 | 525.2(2) | 40(1) | −0.078(14) | −0.009(20) | 0.10(4) | $E1$ |
| 6076–5814 | 262.3(2) | 29(1) | 0.142(17) | −0.005(20) | 0.24(7) | $E2$ |
| 7067–6076 | 990.7(2) | 27(1) | 0.281(38) | 0.016(37) | 0.31(9) | $E2$ |
| 7608–7067 | 541.2(2) | 23(1) | 0.295(17) | −0.049(27) | 0.51(11) | $E2$ |
| 7828–7608 | 220.6(2) | 18(1) | 0.358(22) | −0.093(23) | 0.88(19) | $E2$ |
| 8795–7828 | 967.0(2) | 13(1) | −0.224(44) | 0.024(47) | 0.32(14) | $E1$ |
| 9197–8795 | 402.3(3) | 6(2) | | | | |

[a] Normalized to the 613.8-keV transition.

[b] The polarization factor $p$ is defined as $(N_\perp - N_\parallel)/(N_\perp + N_\parallel)Q$. See Ref. 8.

[c] Measurement done with a prompt window (~15 ns) set on the pulsed–$\gamma$-ray time spectrum.

nique was then used to investigate the lifetimes of the higher-lying levels. The nuclei recoiling from a self-supporting 1.2 mg/cm$^2$ Pr target and the beam itself were stopped in a thick Pb stopper. $\gamma$ rays were detected in Ge(Li) counters placed at 30° and 150° with respect to the beam direction. The intensities of the Doppler-shifted ($I_s$) and unshifted ($I_0$) $\gamma$-ray peaks were analyzed as a function of plunger-target distance. The ratios $I_0/(I_0+I_s)$ for the 221-, 541-, and 991-keV $\gamma$ rays show quantitatively the same variation. A mean value of $1.6 \pm 0.4$ ns was obtained for the half-life of the 7828-keV level. The half-life of the 8795-keV level is much shorter ($T_{1/2} < 0.2$ ns) since the 967-keV $\gamma$ ray showed no unshifted peak in the shortest-distance spectrum. The $g$ factors of the two isomeric levels at 5035 and 6076 keV have been studied with the time-differential perturbed angular correlation technique using an oxygen pulsed beam (pulse width 5 ns, burst intervals 200 ns). Enriched targets of $^{140}$Ce oxide of 1 mg/cm$^2$ were evaporated onto 0.1-mm lead foils. Lead was chosen as an appropriate cubic stopping material. The external magnetic field ($H = 9$ kOe) was applied perpendicularly to the detection plane and reversed every minute. Beam-bending effects were minimized by means of a magnetic shielding tube set along the beam axis. The $\gamma$ radiations were detected in a 10-cm$^3$ planar Ge(intrinsic) counter fixed at $\theta = -45°$ with respect to the beam direction. For the isomeric level $E_x = 6076$ keV ($T_{1/2} = 9.9$ ns), gating transitions of 262 and 525 keV have been used. Time spectra for the two transitions were combined taking into account the fact that their $A_2$ coefficients have opposite signs. A least-squares fit of the resultant curve (Fig. 3) gives the Larmor frequency $\omega_L = (8.88 \pm 0.53) \times 10^{-7}$ rad s$^{-1}$. Assuming that the implanted dysprosium atoms are most likely in a 3$^+$ charge state, the paramagnetic factor has been evaluated[10] to be $\beta = 3.75$ for a 260°C target temperature. Crystal-field effects on $\beta$ were not taken into account. The final value deduced for the $g$ factor is $g = +0.55 \pm 0.06$. Because of loss of alignment it was not possible to determine the value of the $g$ factor of the $T_{1/2} = 49.6$ ns isomeric level at 5035 keV.

The states below $I^\pi = 16^+$ in $^{152}$Dy could be explained by rotational-vibrational coupling[11,12] and by two- or more-quasiparticle excitation modes assuming a small prolate shape[13] ($\beta = 0.05$). In particular, the sequence of negative-parity

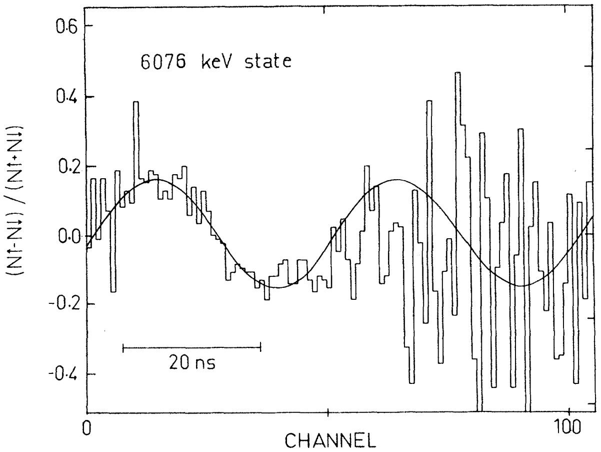

FIG. 3. Experimental time-differential perturbed angular distribution spectrum and least-squares–fitted curve.

states established in the present work can be decoupled into two bands as in $^{150}$Gd: one of vibrational character ranging up to the $I^{\pi}=9^-$ state and the other built on a two-quasiparticle $I^{\pi}=11^-$ state. The behavior of $^{152}$Dy at large angular momenta $I \geqslant 16$, i.e., the presence of the yrast isomers and irregularities in the yrast line, shows that high-spin states are built in a noncollective way. It can be interpreted as a consequence of a change in the nuclear coupling scheme from one typical of collective nature to one characteristic of the single-particle type of motion. The observed $^{152}$Dy level structure is expected in either a spherical or a deformed nucleus (prolate or oblate) spinning around its symmetry axis. The Hartree-Fock-Bogoljubov (HFB) calculation performed by Ploszajczak and Faessler[13] leads to good agreement with the experimental data with the deformation $\beta=-0.06$ to $-0.10$ for the states $I=(16-30)\hbar$. The Strutinsky-type calculations with either the Woods-Saxon or Nilsson potential[3,14] suggest $\beta=-0.16$ for these states. The isomerism of the $16^+$ state can be understood from the shape change of the nucleus and also by the fact that this state has the lowest spin and excitation of the two-quasiproton, two-quasineutron states considered at the yrast line. Since the calculations lead to definite predictions for the configurations of the yrast isomers, the magnetic moments may provide a check of these configurations. It seems that the $20^-$ state observed experimentally may correspond to one of the following configurations (Ref. 13):

$$(\pi h_{11/2})^2 \otimes (\nu i_{13/2}, \tfrac{13}{2}^+) \otimes (\nu f_{7/2}, \tfrac{7}{2}^-), \quad g=0.41;$$

$$(\pi h_{11/2})^2 \otimes (\nu i_{13/2}, \tfrac{11}{2}^+) \otimes (\nu h_{9/2}, \tfrac{9}{2}^-), \quad g=0.68.$$

If a pure HFB configuration is assumed for this state the $g$-factor value $g=0.41$ will differ from the experimental one ($g=0.55\pm0.06$), but a 30% admixture of the configuration with $g=0.68$ is sufficient to bring the calculated value within the experimental error bars. The $26^-$ state may be identified with the calculated one which contains more complicated 6- and 8-quasiparticle components. In conclusion it should be pointed out that all calculations now available[3,13,14] explain high-spin isomers in $^{152}$Dy on the basis of an oblate deformation at large angular momenta.

The authors are greatly indebted to Dr. Ploszajczak for stimulating discussions and communication of theoretical calculations prior to publication.

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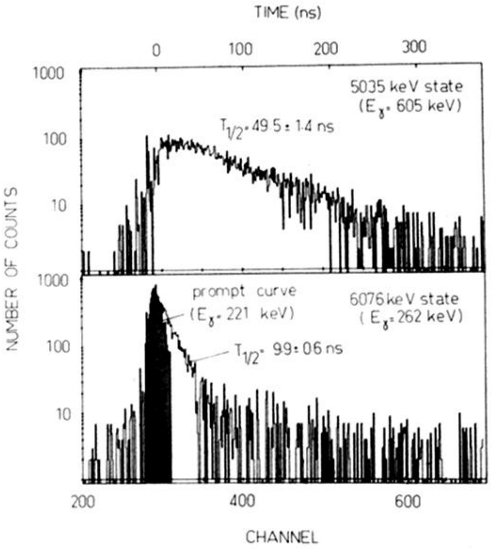

FIG. 2. Time spectra obtained in $n$–$\gamma$ coincidences.