Transition from Collective to Aligned-Particle Configurations at High Spin in ^{154}Dy

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The high-spin level structure of ^{154}Dy has been determined through the (^{34}S, $4n\gamma$) reaction. Lifetimes have been measured by use of the recoil-distance method. Both the level structure and lifetimes indicate a transition from collective to few-particle characteristics at high spin, possibly suggesting a changing shape from prolate through triaxial to oblate.

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Rapid rotation of nuclei may induce a transition to oblate shapes, marked by the occurrence of high-spin yrast isomers, among other features. Following this prediction[1] and the subsequent discovery[2] of an "island" of isomers in the $A\sim150$ region, considerable research on nuclei in this mass region ensued. For nuclei with $N=82-86$, which are spherical in the ground state, the high-spin yrast configurations have been shown to be of few-particle character, with the spins of the individual high-j nucleons aligned along a symmetry axis. The oblate mass distribution of these aligned particles, together with the resultant core polarization, leads to an overall oblate shape with $\beta\sim0.1-0.2$. However, nuclei with $N\geq90$, which are prolate in the ground state, contain no high-spin isomers[2] and appear not to become oblate. It seems that the shell effects which drive these nuclei prolate are not overcome with increasing angular momentum.

A prolate-to-oblate shape change is indeed a striking phenomenon. One might hope to observe it by examining the transitional nuclei with $N=87$ and 88, where the prolate-driving forces are just emerging at low spin and may be overcome at higher spin. In addition these nuclei provide an important testing ground for theory because effects favoring prolate and oblate shapes should compete on a roughly equal basis. Since the yrast configurations of Dy isotopes with $N=82-86$ are of aligned-particle character[3-6] and those with $N\geq90$ are collective,[7,8] we chose to investigate the high-spin structure of ^{154}Dy ($N=88$). The levels are known[9] to spin 20 and suggest a small prolate deformation, while there are predictions[10,11] of a prolate-to-oblate transition above spin 40.

We have employed the reaction ^{124}Sn(^{34}S, $4n$)^{154}Dy, using (145–165)-MeV beams from the Argonne National Laboratory superconducting linac. An extensive set of in-beam γ spectroscopic experiments was performed, including γ-γ coincidence, angular distribution, excitation function, and lifetime measurements. In these experiments a large NaI detector was used, either as a sum spectrometer or as a multiplicity filter, to enhance ^{154}Dy lines. The resulting level scheme, determined up to spin 34 or 35, is shown in Fig. 1. For the positive-parity yrast levels, a conventional plot (Fig. 2) of $2\mathscr{I}/\hbar^2$ vs $(\hbar\omega)^2$ shows two backbends at $I=16$ and 30.

Electronic timing measurements with respect to the pulsed beam revealed no nanosecond isomers in ^{154}Dy, and thus a recoil-distance technique was employed to measure the lifetimes. The data were analyzed in a manner similar to that described in Refs. 4 and 7. The complexity of the spectra (due to the presence of ^{153}Dy lines and the population of both positive- and negative-parity bands in ^{154}Dy), as well as the low intensity of many lines, limited the accuracy with which many of the lifetimes could be determined. Furthermore, the focus was on short lifetimes (<10 ps) and, thus, small target-to-stopper distances. As a consequence, it was not possible to extract accurate lifetimes for the states with $10\leq I\leq14$, particularly in the presence of slow (10–25 ps) side feeding. At higher spins the side-

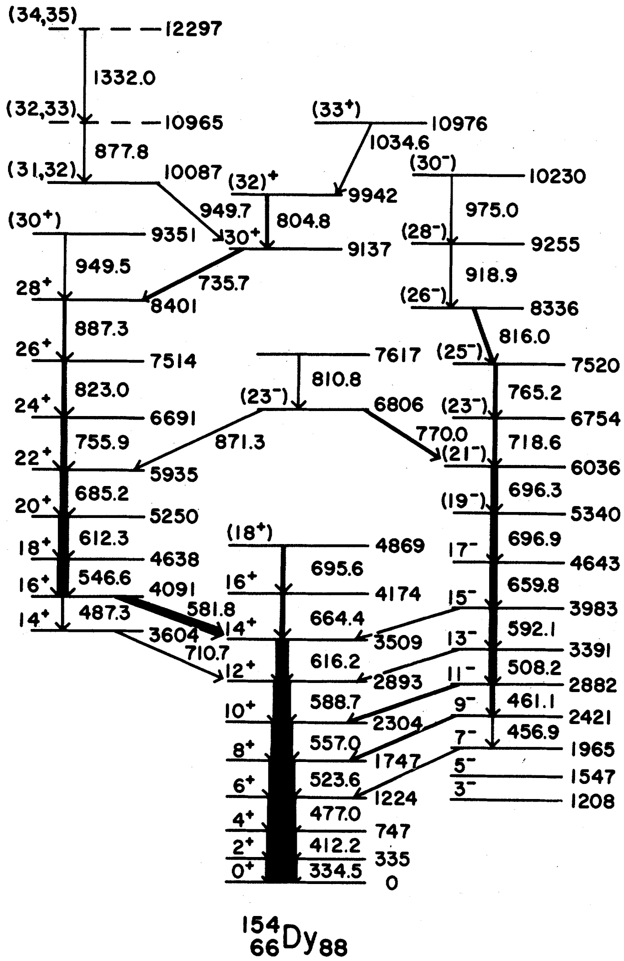

FIG. 1. Level scheme of ^{154}Dy.

feeding fraction is generally smaller (< 15%) and the feeding times shorter (< 2 ps), permitting better extraction of the state lifetimes. Details of the experimental and analytical methods will be published later.

From the measured lifetimes we have derived, for the positive-parity yrast levels, the quantity

$$Q_0(\text{eff}) = [(16\pi/5)B(E2; I \to I-2)]^{1/2}/\langle I 2 0 0 | I-2\, 0\rangle.$$

This gives the usual intrinsic quadrupole moment Q_0 for a $K=0$ band of an axially symmetric rotor, and for $I \gg K$ in general, without the constraint of axial symmetry. As seen in Fig. 3, Q_0(eff) increases between spins 2 and 6, stays high up to spin 20, and then gradually decreases. In terms of single-particle or Weisskopf units (W.u.), the $E2$ rates increase from 99 W.u. to a maximum of ~286 W.u. and then decrease to ~3.5

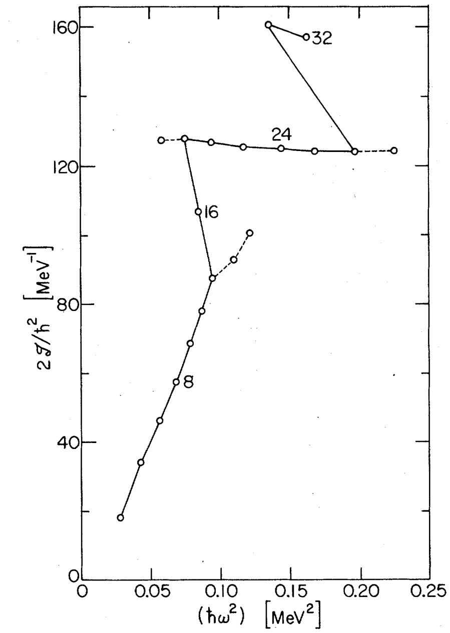

FIG. 2. Plot of moment of inertia, $2\mathscr{J}/\hbar^2$, vs $(\hbar\omega)^2$ for positive-parity levels of ^{154}Dy. Solid lines connect yrast levels, and dashed lines connect ground- or s-band members. $\hbar\omega = \frac{1}{2}(E_I - E_{I-2})$; $2\mathscr{J}/\hbar^2 = (4I-2)/(E_I - E_{I-2})$. The numbers next to some points indicate I.

W.u. between $I = 26$ and 32. The highest energy states at 11.0 and 12.3 MeV have *combined* state and feeding times of 6 ± 1 and 5 ± 1 ps, respectively.

Up to spin 32, the positive-parity yrast levels are characteristic of a collective rotor with intermediate deformation: The yrast transition

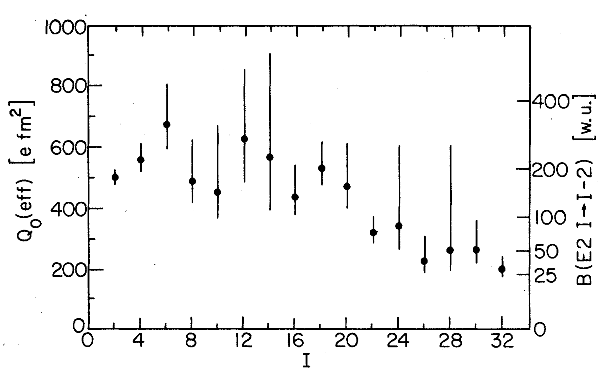

FIG. 3. Spin dependence of Q_0(eff), defined as $[(16\pi/5)B(E2; I \to I-2)]^{1/2}/\langle I 2 0 0 | I-2\, 0\rangle$. Values for $I = 10$–14 may not be reliable (see text). For $I > 10$, for which the Clebsch-Gordon coefficient is almost constant, the right-hand ordinate shows the approximate $B(E2)$ in Weisskopf units.

energies increase monotonically, except near the backbends (see Figs. 1 and 2), while the levels are connected only by stretched $E2$ transitions which are enhanced (Fig. 3). A prolate shape at intermediate spin is suggested by the systematic trends[12] in this mass region and by the first backbend, which is due to the rotational alignment[13] of a pair of neutrons in the beginning of the $i_{13/2}$ shell.

However, above spin 32 a change to few-particle structure occurs. The transition energies cease to increase smoothly. Predominantly dipole transitions (878 and 1035 keV) appear, terminating the hitherto uninterrupted cascade of stretched $E2$ gamma rays. (Gamma-ray multipolarities were deduced from angular distribution results.) In addition, the positive-parity sequence begins to fragment above spin 28, a behavior quite different from that of the typical backbending nucleus, where usually only a single yrast branch is observed at the highest spins. Finally, the combined state and feeding times of the highest observed levels with $I=(33^+)$ and $I=34$ or 35 (6 and 5 ps) are significantly slower than the typical value of $\lesssim 0.5$ ps observed at high spin in collective rotors like ^{156,158}Dy,[7,8] but are similar to those observed[4] in ^{152}Dy, which exhibits aligned-particle nature. It is likely that aligned-particle configurations similar to those in neighboring ^{152}Dy are involved, since only these would lie at sufficiently low energy. As in ^{152}Dy, these configurations would lead to an oblate mass distribution. Thus, it appears that the yrast states of ^{154}Dy are oblate above spin 32. A change from a prolate to an oblate shape is also known to occur in ^{20}Ne,[14] but has not been previously observed in heavy nuclei.

The spin dependence of Q_0(eff) shown in Fig. 3 already reflects a decrease in collectivity between $I=20$ and 32. For a rigidly rotating triaxial body Q_0(eff) is related to the parameters β and γ, characterizing quadrupole deformation and axial asymmetry, by the expression[15]

$$Q_0(\text{eff}) \propto \beta\cos(30^\circ - \gamma)\,. \qquad (1)$$

Since the shape is most likely prolate ($\gamma = 0^\circ$) for $I<20$ and oblate ($\gamma=-60^\circ$) for $I>32$, the decrease in Q_0(eff) probably has a substantial contribution from a change in γ. [If the decrease in Q_0(eff) were due to a variation of γ only, values of γ around -35° would be obtained between spins 26 and 32.] In other words, the prolate-to-oblate transition may occur gradually through a series of triaxial shapes.

A reduction in collectvity at high spin ($I \gtrsim 20$) has also been observed in ^{156}Dy and ^{158}Dy by Emling *et al.*,[8] who have similarly attributed it to the onset of triaxiality. In comparing the even Dy isotopes with $A=154-158$ the trend is that the reduction is more pronounced for the lighter isotopes; furthermore, only in ^{154}Dy has the limit of single-particle transition rates been observed. These observations are consistent with the fact that prolate-driving shell effects are more firmly established for the nuclei with $N \geq 90$.

The decrease in collectivity in ^{154,156,158}Dy happens after the first backbend in all three cases. In addition, the transition to few-particle structure occurs shortly after the second backbend in ^{154}Dy. Thus, it seems likely that rotation alignment, which is responsible for the backbending, also plays a crucial role in the observed shape transition. Indeed, when the Coriolis force aligns the spin of a high-j orbit along the rotation vector, the orbit acquires an oblate mass distribution with respect to this vector. A polarization of the core follows, leading to a departure from axial symmetry. The degree of asymmetry will depend on the polarizability, which would tend to be larger in a transitional nucleus such as ^{154}Dy, particularly following rotation alignment. (The resultant decoupling in the relative motion of the high-j particle and the core results in a smaller overlap between the two than in the strong-coupled case.) Since the high-j orbit plays an important role in precipitating prolate deformation (at $N=90$) in the first place, the decoupling may well be sufficient perturbation to induce a departure from axial symmetry, especially with the prolate-driving shell effects not yet firmly established.

The transition from prolate to oblate shapes via rotation-aligned structures represents an evolutionary process. For the prolate ground band the angular momentum consists entirely of only a collective component which is perpendicular to the symmetry axis. In the rotation-aligned bands the angular momentum is generated by both aligned-particle and collective spins along the perpendicular axis. In the oblate limit this axis becomes the symmetry axis along which only particle spins align.

One reason for the transition to oblate shapes is the smaller energy increment per unit spin associated with these shapes. This is reflected in the fact that, on an E vs $I(I+1)$ plot, the average slope of the yrast line in the oblate limit (cf. $\frac{1}{147}$ MeV in ^{152}Dy) is less steep than that for the rotation-aligned $i_{13/2}$ band ($\frac{1}{124}$ MeV in ^{154}Dy).

The angular-momentum–induced transition from prolate to triaxial shapes in $^{154-158}$Dy, and ultimately to oblate shapes in ^{154}Dy, has been predicted.[10,11] The calculations of Refs. 10 and 11 suggest rather flat potential energy surfaces in the γ direction. The observed transitions set in at lower spins than predicted. This discrepancy may be removed by the inclusion of pairing, which is known to have a profound effect[16,17] on rotation alignment. It would be important to perform further calculations in order to gain a firmer understanding of the microscopic basis for the shape transition.

In summary, the level structure and lifetimes in the transitional nucleus ^{154}Dy suggest a change from collective to few-particle character with increasing spin. This is probably accompanied by a prolate-to-triaxial-to-oblate shape change. This transition is likely the outcome of the delicate interplay of prolate-driving shell effects (which dominate for $N \geq 90$) and oblate-driving effects (which prevail for $N \leq 86$).

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[1]A. Bohr and B. R. Mottelson, Phys. Scr. 10A, 13 (1974).

[2]J. Pedersen *et al.*, Phys. Rev. Lett. 39, 990 (1977).

[3]T. L. Khoo *et al.*, Phys. Rev. Lett. 41, 1027 (1978).

[4]B. Haas *et al.*, Phys. Lett. 84B, 178 (1979), and Nucl. Phys. A362, 254 (1981).

[5]M. Piiparinen *et al.*, Z. Phys. A 290, 337 (1979); P. J. Daly *et al.*, Z. Phys. 298, 173 (1980).

[6]T. Døssing, K. Neergaard, and H. Sagawa, Phys. Scr. 24, 258 (1981).

[7]D. Ward *et al.*, Nucl. Phys. A332, 433 (1979).

[8]H. Emling *et al.*, Phys. Lett. 98B, 169 (1981); H. Emling, Gesellschaft für Schwerionenforschung Report No. GSI-82-40 (to be published).

[9]H. Beuscher *et al.*, in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, Tennessee, 1974* (North-Holland, Amsterdam, 1974), Vol. I, p. 189.

[10]S. Åberg, in *Elementary Modes of Excitation in Nuclei*, edited by A. Bohr and R. A. Broglia (North-Holland, Amsterdam, 1977).

[11]C. G. Andersson *et al.*, Phys. Scr. 24, 266 (1981).

[12]R. Bengtsson, J. Zhang, and S. Åberg, Phys. Lett. 105B, 5 (1981).

[13]F. S. Stephens, Rev. Mod. Phys. 47, 43 (1975).

[14]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II, p. 98.

[15]R. J. Liotta and R. A. Sorensen, Nucl. Phys. A297, 136 (1978).

[16]B. R. Mottelson, in Proceedings of the Symposium on High-Spin Phenomena in Nuclei, Argonne, Illinois, March 1979, Argonne National Laboratory Report No. ANL/PHY-79-4 (unpublished).

[17]S. Frauendorf, Phys. Scr. 24, 349 (1981).