Moment of Inertia of Dy^{158} from Excitation of the Ground-State Band to Spin 22*

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The behavior of the moment of inertia for high-spin states in Dy^{158} has been studied by populating the ground-state band up to spin 22 through the reaction $Nd^{150}(C^{13}, 5N)Dy^{158}$ at bombarding energies of up to 72 MeV. The rate of increase of the moment of inertia $\mathcal{I}$ with rotational frequency rises abruptly in the region from spin 14 to 18. In the region of spin 22, $\mathcal{I}$ tends toward a more constant value.

It is now well established that a deformed even-even nucleus exhibits a marked increase in the rate at which its moment of inertia is rising at high rotational frequencies. Such a change was first reported by Johnson, Ryde, and Sztarkier[1] for the Dy^{160} nucleus and suggested for the Dy^{158} nucleus, and typically begins to appear near the spin $I=14$ state of the ground-state (g.s.) band. They attributed this behavior to a breakdown of the pairing correlations as first anticipated[2] by Mottelson and Valatin. As the pairing correlations are broken by the coriolis force at high rotational frequencies, the moment of inertia $\mathcal{I}$ tends[2] toward the value $\mathcal{I}_{rigid}$. Johnson and coworkers[1,3] investigated this behavior in several rare-earth nuclei through the use of (α, XN) reactions leading to rotational states which have been identified with certainty to spin 18. At such spin values the moment of inertia has not yet reached the rigid value which would be deduced from the ground-state deformation. Since the pairing gap may disappear first for neutrons,[4] it may prove possible to observe separately the breakdown of neutron and proton pairing. Therefore, it seemed especially interesting to follow the trend of the moment-of-inertia behavior to higher frequencies by exciting states of still higher angular momentum in the rotational spectrum.

The use of (heavy ion, XN) reactions is certainly one of the most productive ways for populating such high spin states of the residual system. Large amounts of angular momentum are transferred in the reaction, which leaves the residual system highly aligned[5] relative to the beam direction. Individual γ rays of the resulting cascade to the ground state exhibit highly anisotropic angular distributions which provide a basis for identification of γ-ray multipolarities. In this experiment, the reactions $Nd^{150}(C^{12}, 4N)Dy^{158}$ and $Nd^{150}(C^{13}, 5N)Dy^{158}$ were examined[6] as a means of populating the Dy^{158} g.s. rotational band. Levels were observed to spin $I=22$, the highest nuclear spin reported to date. Carbon ions accelerated by the Brookhaven National Laboratory (BNL) three-stage MP tandem Van de Graaff facility to energies of 55 to 72 MeV were used to bombard a 3.5-mg/cm^2 Nd^{150} metal foil target. The $(C^{13}, 5N)$ reaction led to a more favorable reaction yield relative to background, and all results reported here were obtained with this reaction. The γ rays belonging to the Dy^{158} cascade were identified through high-resolution γ-γ coincidence measurements with a resolving time of $2\tau \simeq 30$ nsec, which involved transitions between known[7] low-lying Dy^{158} states. These measurements utilized a pair of large-volume (40- and 50-cm^3) Ge-Li detectors. Two-dimensional coincidences of 4096×4096 channels were event-mode recorded on magnetic tape, on line with the BNL tandem facility Σ-7 computer. Simultaneously, twelve spectra with 2048 channels each were collected live in core and displayed during the experiment for monitoring purposes. These spectra included the singles γ-ray spectrum from each counter, the coincidence sum spectra collapsed on each axis, and eight coincidence spectra corresponding to events associated with coincidence gates set by software on four known γ-ray lines of the g.s. band and four background regions adjacent to these lines. The coincidence events recorded on magnetic tape were scanned after the experiment. Coincidence gates were placed on each of the eleven Dy^{158} g.s. cascade transitions which originate from the states with spin 2 through 22. Each of these eleven gated spectra had subtracted from it a coincidence background obtained with a gate of identical width placed immediately adjacent to the line itself. These individual coincidence spectra served to definitely identify each transition as a member of the stretched cascade. Figure 1 shows the coincidence spectrum obtained by summing these eleven background-subtracted spectra. This summing was performed in order to maximize the statistics associated with the

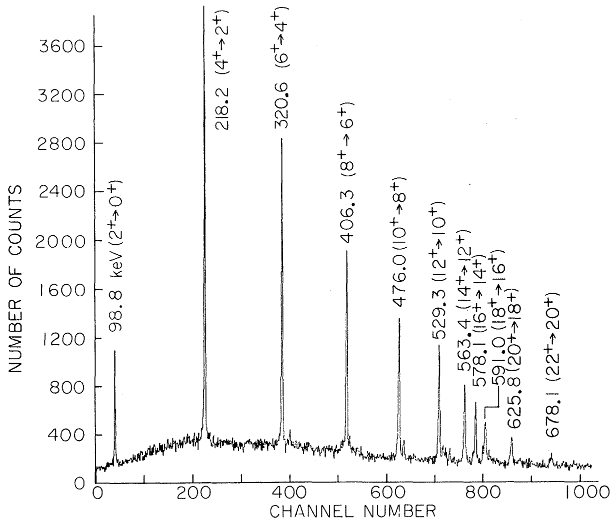

FIG. 1. Sum of eleven coincidence spectra (individually background corrected) resulting from gates placed on each transition of the g.s. rotational band of Dy^{158} up to spin 22.

weak transitions between high-spin states.

Placement of these transitions within the cascade was made on the basis of relative γ-ray intensities and excitation-function measurements with C^{13} ions from 55 to 72 MeV in energy. The yields of the Dy^{158} g.s. band transitions, normalized to the yield of the $4^+ \to 2^+$ transitions, showed a progressively steeper rise with C^{13} bombarding energy as the excitation energy and spin of the Dy^{158} state increased, and served to confirm the relative placement of the higher transitions in the cascade.

Multipolarities of each of these γ-ray transitions were determined by γ-ray angular distribution measurements relative to the beam direction at a C^{13} bombarding energy of 71 MeV. In these measurements the 40-cm^3 Ge-Li detector was positioned 16 cm from the target on the movable arm of an automated goniometer which was programed to rotate sequentially through eight preselected angles lying between 60° and 160° relative to the beam direction. The angular distributions were fitted by the usual Legendre polynomial expansion of the form $W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$. All of the γ rays identified with the Dy^{158} cascade exhibited characteristic $L = 2$ angular distributions consistent with a stretched quadrupole cascade (with considerable side feeding) from highly aligned states.

Table I summarizes the observed γ-ray transitions, energies, intensities, their placement in the rotational cascade, and values of the angular-distribution coefficients as measured at 71 MeV C^{13} bombarding energy. In the case of the weakly excited 678.2-keV $22^+ \to 20^+$ transition, the angular-distribution measurements were complicated by the presence of a line of nearly identical energy not associated with the Dy^{158} cascade and should should be regarded as preliminary.

The manner in which the "moment of inertia" for the Dy^{158} ground-state band varies with the square of the rotational frequency is shown in

TABLE I. Summary of observed Dy^{158} γ-ray transition energies, placement in the rotational cascade, relative intensities, and measured angular-distribution coefficients.

Transition energy (keV)[a]	Assignment	Relative γ-ray intensity	A_2/A_0	A_4/A_0
98.8	$2^+ \to 0^+$	26	0.162 ± 0.018	− 0.073 ± 0.026
218.2	$4^+ \to 2^+$	100	0.226 ± 0.006	− 0.059 ± 0.009
320.6	$6^+ \to 4^+$	99	0.291 ± 0.007	− 0.075 ± 0.010
406.3	$8^+ \to 6^+$	90	0.306 ± 0.008	− 0.073 ± 0.012
476.0	$10^+ \to 8^+$	80	0.310 ± 0.009	− 0.073 ± 0.013
529.3	$12^+ \to 10^+$	59	0.322 ± 0.012	− 0.066 ± 0.018
563.4	$14^+ \to 12^+$	42	0.292 ± 0.016	− 0.117 ± 0.025
578.1	$16^+ \to 14^+$	28	0.349 ± 0.024	− 0.166 ± 0.036
591.0	$18^+ \to 16^+$	23	0.362 ± 0.029	− 0.128 ± 0.044
625.8	$20^+ \to 18^+$	13	0.280 ± 0.050	− 0.023 ± 0.076
678.1	$22^+ \to 20^+$	(6)	(0.198 ± 0.051)	(+ 0.059 ± 0.079)

[a]The transition energies are accurate to ±0.3 keV and are in good agreement with those listed to spin 18 in Ref. 3.

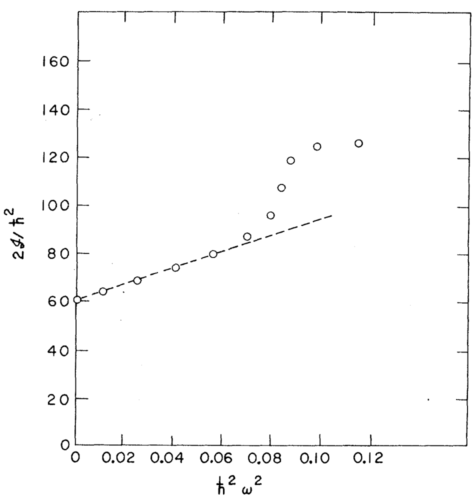

FIG. 2. Plot of $2\mathscr{I}/\hbar^2$ vs $(\hbar\omega)^2$ for the ground-state rotational band of Dy^{158}. Dashed line, variable–moment-of-inertia model (Ref. 10) fit to the first five excited states of the band.

Fig. 2. The quantities

$$\frac{2\mathscr{I}}{\hbar^2} \equiv \frac{4I-2}{E_I - E_{I-2}},$$

$$(\hbar\omega)^2 \equiv \left[\frac{E_I - E_{I-2}}{[I(I+1)]^{1/2} - [(I-2)(I-1)]^{1/2}}\right]^2$$

are obtained from the experimental data in the manner previously used[1] for the Dy^{160} g.s. band. The Dy^{158} moment of inertia deviates sharply at spin 14 from the linear increase followed up to spin 12. The large, rapid increase from spin 14 to 18 is similar to that exhibited by Dy^{160}. The progressively smaller changes from spin 18 to spin 20 and spin 22 suggest the onset of the previously unobserved "saturation" of the moment of inertia associated with the disappearance of the pairing correlations. It should be emphasized, however, that the moment of inertia has not yet reached the rigid value expected at zero rotational frequency (145 MeV^{-1}) from the Dy^{158} ground-state distortion. This may be a consequence of the nonidentity of neutron and proton pairing energies, and a further rise in the Dy^{158} moment of inertia may occur at still higher rotational frequencies.

Recently, several new theoretical attempts to explain the behavior of the moment of inertia as a function of the rotational frequency have appeared. Sorensen[4] introduces for weak pairing a generator coordinate wave function and calculates on a two-level model the moment of inertia as a function of ω^2 for various choices of the pairing-force strength. Krumlinde and Szymanski[9] introduce a model of a rotor coupled to valence particles which are distributed over two degenerate levels and interact through a pairing force. Stephens and Simon[10] calculate the coriolis effects on $I_{13/2}$ particle pairs coupled to a deformed core. All of these calculations are able to reproduce qualitatively the observed anomalies in the moment-of-inertia behavior.

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