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Signature dependence observed for $M1$ transitions between rotational levels based on an $f_{7/2}$ single-particle state in ^{163}Dy

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The ground-state rotational band in ^{163}Dy has been investigated through multiple Coulomb excitation with beams of 160-MeV ^{35}Cl and 250-MeV ^{58}Ni. Excited states up to $\frac{27}{2}^-$ were established by measuring γ-γ coincidences and γ-ray angular distributions. Nuclear lifetimes for levels up to spin $\frac{23}{2}$ have been determined by analysis of Doppler broadened γ-ray line shapes. Considerable signature dependence was observed in $M1$ transition probabilities.

The Coriolis interaction acts most effectively on particles in high-spin orbits such as $i_{13/2}$ and $h_{11/2}$, leading to strong perturbation to a rotational band. This perturbation effect was discussed mainly through the excitation energies and branching ratios. Very recently, reliable data on $E2$ and $M1$ intraband transition probabilities of such high-spin rotational bands have been reported,[1-3] which clearly show the rotational perturbation effect. In contrast, few data on transition probabilities are available for rotational bands built on lower-spin orbits; the rotational perturbation effect on such orbits are believed to be rather weak. It seems, however, desirable to study how the low-spin orbits, such as $f_{7/2}$, affect the intraband transition probabilities of the rotational levels. For this purpose we first undertook a Coulomb-excitation experiment on ^{163}Dy whose ground-state rotational band is based on an $f_{7/2}$ single-particle orbit.[4]

A self-supporting metallic target of ^{163}Dy (92.3% enriched and about 30 mg/cm^2 thick) was bombarded with beams of 160-MeV ^{35}Cl and 250-MeV ^{58}Ni from a tandem accelerator at Japan Atomic Energy Research Institute. This beam energy was rather higher than that normally used for Coulomb excitation; we intentionally chose the energy at about the Coulomb barrier to excite higher-spin states.

γ-γ coincidence measurements were performed with three conventional germanium detectors placed at 0°, 90°, and −90° to the beam. A level scheme of the ground-state rotational band of ^{163}Dy was constructed on the basis of the coincidence results as shown in Fig. 1. Levels higher than the $\frac{17}{2}^-$ member were newly established.

To make spin assignments, angular distributions of γ rays were measured at seven angles between 0° and 90° to the beam. The angular distributions were fitted with Legendre polynomials

$$W(\theta) = A_0[1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)] \ .$$

The A_2 and A_4 values corrected for geometrical attenuation factors are listed in Table I. γ-ray intensities corrected for the angular distributions and total transition intensities corrected for internal conversion are also summarized in the table, from which branching ratios have been determined up to the $\frac{23}{2}^-$ state. The weak $\frac{17}{2}^- \rightarrow \frac{15}{2}^-$ stop-over peak overlapped the strong $\frac{9}{2}^- \rightarrow \frac{5}{2}^-$ crossover one, so that the γ-ray intensity for this transition was not derived from the singles spectrum. Instead, it was derived from a γ-γ coincidence spectrum gated by the $\frac{11}{2}^- \rightarrow \frac{7}{2}^-$ transition, where the $\frac{9}{2}^- \rightarrow \frac{5}{2}^-$ peak was eliminated; the effect of angular correlation was taken into account. $E2/M1$ mixing ratios δ, which are given in the last column of Table I, have been extracted as follows. Since all crossover transitions between the band members are of pure $E2$, the ratios of the experimental A_2 values to

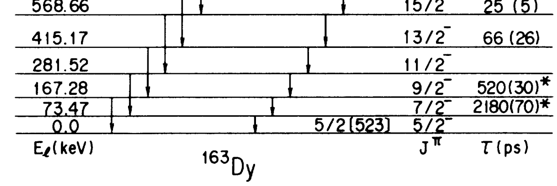

FIG. 1. A level scheme of the ground-state rotational band of ^{163}Dy. Figures at the right show nuclear lifetimes, where the asterisk is given to previously reported values (Ref. 5). Figures in parentheses denote the probable errors.

TABLE I. Summary of γ transitions in the ground-state rotational band of ^{163}Dy. I_γ shows γ-ray intensity corrected for angular distribution. I_T is transition intensity corrected for internal conversion. A_2 and A_4 are angular distribution coefficients. δ is the $E2/M1$ mixing ratio. Figures in parentheses denote uncertainties.

J^π	E_γ	I_γ	I_T	A_2	A_4	δ
$\frac{7}{2}^-$	73.43(10)	61.6(18)	618(100)	−0.002(15)	−0.002(18)	
$\frac{9}{2}^-$	93.72(10)	17.2(9)	76(4)	−0.030(15)	+0.005(18)	-2.6^{+8}_{-6} [a]
	167.32(10)	100(3)	144(4)	−0.016(4)	+0.03(5)	$E2$
$\frac{11}{2}^-$	114.27(10)	2.9(1)	7.8(3)	−0.16(4)	+0.05(6)	−1.7(4)
	208.10(10)	39(1)	47(2)	+0.071(15)	−0.009(18)	$E2$
$\frac{13}{2}^-$	133.68(10)	0.93(3)	1.83(6)	−0.21(3)	+0.047(31)	−2.9(1)
	247.82(10)	23.0(8)	25.8(9)	+0.131(15)	-0.018(19)	$E2$
$\frac{15}{2}^-$	153.52(10)	0.28(1)	0.45(2)	−0.39(5)	+0.03(7)	−1.65(15)
	287.18(10)	11.0(3)	11.8(3)	+0.165(14)	−0.026(19)	$E2$
$\frac{17}{2}^-$	171.2(3)	0.065(13) [b]	0.09(2)	. . .	. . .	−2.7(8) [c]
	324.68(10)	5.6(2)	5.9(2)	+0.193(14)	−0.038(18)	$E2$
$\frac{19}{2}^-$	190.7(2)	0.024(7)	0.031(9)	−0.40(5)	+0.07(7)	−1.7(1)
	362.28(10)	2.60(8)	2.70(8)	+0.162(22)	−0.034(28)	$E2$
$\frac{21}{2}^-$	206.4(3)	. . .	. . .	. . .	. . .	. . .
	397.09(10)	1.43(4)	1.47(4)	+0.14(4)	0.00(4)	$E2$
$\frac{23}{2}^-$	432.67(10)	0.47(2)	0.48(2)	+0.20(4)	−0.06(5)	$E2$
$\frac{25}{2}^-$	464.23(10)	0.178(16)	0.18(2)	+0.02(26)	−0.05(21)	$E2$
$\frac{27}{2}^-$	494.7(3)	. . .	. . .	. . .	. . .	$E2$

[a]From Ref. 5.
[b]From a γ-γ coincidence spectrum (see the text).
[c]Average value of δ's for $\frac{9}{2}^- \rightarrow \frac{7}{2}^-$ and $\frac{13}{2}^- \rightarrow \frac{11}{2}^-$ transitions (see the text).

the calculated ones for complete alignment give the attenuation factors of nuclear alignment for these states. Mixing ratios of the $M1+E2$ stopover transitions were extracted from the analysis of the angular distributions by utilizing the attenuation factors for individual states. For the $\frac{17}{2}^- \rightarrow \frac{15}{2}^-$ transition the mixing ratio was not available from the analysis of the angular distribution because of the situation discussed above; we assumed an average value of δ's for the $\frac{9}{2}^- \rightarrow \frac{7}{2}^-$ and $\frac{13}{2}^- \rightarrow \frac{11}{2}^-$ transitions which have the same signature change ($\alpha=+\frac{1}{2} \rightarrow \alpha=-\frac{1}{2}$) as the $\frac{17}{2}^- \rightarrow \frac{15}{2}^-$. This may be justified for the present purpose by the fact that the mixing ratios are classified into two distinct groups, i.e., the mixing ratios in the table are close to -2.7 for the transitions $\alpha=+\frac{1}{2} \rightarrow \alpha=-\frac{1}{2}$ and -1.7 for the transitions $\alpha=-\frac{1}{2} \rightarrow \alpha=+\frac{1}{2}$.

The experimental branching ratios and mixing ratios were converted to the ratios of $B(M1;I \rightarrow I-1)/B(E2;I \rightarrow I-2)$ as seen in Fig. 2. Here a signature dependence is clearly observed, although an energy plot of $[E(I+1)-E(I)]/2I$ vs I^2 hardly shows even a small signature dependence. This result is very interesting because so far no significant signature dependence has been observed for bands built on such a low-spin orbit as $f_{7/2}$. In order to see which type of transition causes such a dependence, absolute transition probabilities have been deduced from nuclear lifetimes.

The nulcear lifetimes were determined from analysis of Doppler broadened γ-ray line shapes. A γ-ray singles spectrum used for the analysis was taken with a Compton-suppression spectrometer that was placed at 0° to the beam. The detailed formulation of the analysis is described in Ref. 7. The lifetimes obtained for the states from $\frac{13}{2}^-$ to $\frac{23}{2}^-$ are summarized at the right side of Fig. 1. The resultant $B(E2;I \rightarrow I-2)$ values have turned out to agree with the prediction of the Bohr-Mottelson strong coupling model within the experimental errors and there is no significant signature dependence. Thus it is concluded that the remarkable signature dependence of the $B(M1)/B(E2)$ ratios (see Fig. 2) is due to the $B(M1)$. The phase of the oscillation in Fig. 2 supports an interpretation of this phenomenon as the perturbation effect of ro-

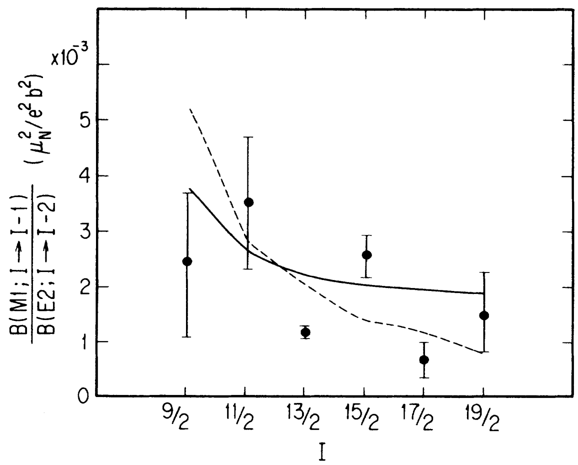

FIG. 2. $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios obtained from branching and mixing ratios. The solid line indicates a prediction of a strong coupling model which was obtained by adopting g factors (Ref. 4) of $g_K=0.25$, $g_R=0.27$ for $B(M1)$, and an intrinsic quadrupole moment of $Q_0=7.0b$ for $B(E2)$ values. The dashed line expresses a microscopic calculation by Iwasaki (Ref. 6).

tation:[8] The $B(M1)$ values of the transitions $I_i=j+2n\rightarrow I_f=j+2n-1$, where j is the single-particle angular momentum and n is an integer, become larger than those of the transitions $I_i=j+2n+1\rightarrow I_f=j+2n$. The phase in the present case ($j=\frac{7}{2}$) coincides with that for $j=\frac{11}{2}$ (Ref. 2) and is opposite to the case of $j=\frac{13}{2}$.[1,3]

The behavior of the $B(M1)$ values presents a puzzle: There is signature dependence neither in the excitation energies nor in the $B(E2)$ values. In many nuclei where the perturbation effect of rotation is expected, the signature dependence has been observed for excitation energies as well as for $B(M1)$ values.[1-3] Commonly adopted models do not predict such signature dependence for an $f_{7/2}$ orbit. For comparison, we present in Fig. 2 a calculation[6] based on a microscopic method with simultaneous projection of the angular momentum and the particle number, which has been successful in reproducing qualitatively the energies and transition probabilities for the $i_{13/2}$-orbit band.[3,9] A prediction of the strong coupling model[4] is also shown in Fig. 2.

In summary, a significant signature dependence was observed for reduced $M1$ transition probabilities in the ground-state rotational band in ^{163}Dy. It might be due to the perturbation effect of rotation of a sort. It should be pointed out that the phase of the oscillation seen in $B(M1)$ values satisfies a selection rule of this effect.[8] It is interesting to see that the signature dependence appeared only in the $B(M1)$ values but not in the excitation energies. This is certainly not the expected outcome from previously held ideas about such low-spin orbits. Similar systematic data would be valuable for studying the rotational perturbation of the nuclear system.

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