Candidates for Low-Spin Members of the S Band in ^{160}Dy

Jin Gen-Ming[(a)] and J. D. Garrett
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark

and

G. Løvhøiden, T. F. Thorsteinsen, and J. C. Waddington[(b)]
University of Bergen, Bergen, Norway

and

J. Rekstad
University of Oslo, Oslo, Norway
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Candidates for the 4^+, 6^+, and 8^+ members of the S band in ^{160}Dy are established by $\nu(i_{13/2})$ pickup from the $\frac{5}{2}^+$ ground state of ^{161}Dy with use of the (^{3}He,α) reaction. The alignments and K values corresponding to this identification are discussed.

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The phenomenon of "backbending" in the yrast bands of rare-earth nuclei is thought to result from a crossing of the ground-state (g.s.) band with a "super" (S) band based on a pair of aligned $i_{13/2}$ neutrons.[1] The yrast states, composed of the g.s. band for rotational frequencies, $\hbar\omega$, below the crossing frequency, $\hbar\omega_c$, and the S band for $\hbar\omega > \hbar\omega_c$, have been the subject of numerous experimental (heavy ion,xn) studies.[2] It is possible to study the continuation of the g.s. band to $\hbar\omega > \hbar\omega_c$, e.g., by using Coulomb excitation At the lowest angular momenta, however, both the deexciting γ-ray cascades and Coulomb excitation follow the g.s. band; therefore, it is necessary to employ other experimental techniques to study the low-spin members of the S band. Candidates for such states have been suggested[3,4] for ^{156}Dy and ^{172}Yb from the systematics of rotational bands established with use of (light particle,xn) reactions. In such studies, however, it is impossible to ascertain the $[\nu(i_{13/2})]^2$ configuration of the proposed S-band members.

The present Letter proposes candidates for the low-spin members of the S band from a study of the reaction ^{161}Dy(^{3}He,α)^{160}Dy. Dysprosium 161 is one of the three stable nuclei (^{161}Dy, ^{167}Er, ^{179}Hf) that have a $\nu(i_{13/2})$ g.s. configuration. Therefore, it should be possible to study the aligned $[\nu(i_{13/2})]^2$ configurations for the neighboring even nuclei by the (^{3}He,α) and (α,^{3}He) reactions which strongly favor l_n = 5 and 6 transfer.

The experimental cross sections for the reactions ^{161,162}Dy(^{3}He,α)^{160,161}Dy were measured using the 24-MeV ^{3}He beam from the Niels Bohr Institute FN tandem accelerator. The reaction products were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsions. The targets were prepared from material enriched to 96% and 91%, respectively, in ^{161,162}Dy. An experimental ^{161}Dy(^{3}He,α) spectrum is shown in Fig. 1. Absolute cross sections were established to ± 25% by normalizing the measured yield of the elastically scattered ^{3}He (for $32.5 \leq \theta_{lab} \leq 57.5°$) to cross sections calculated from the optical model using average ^{3}He parameters.[5]

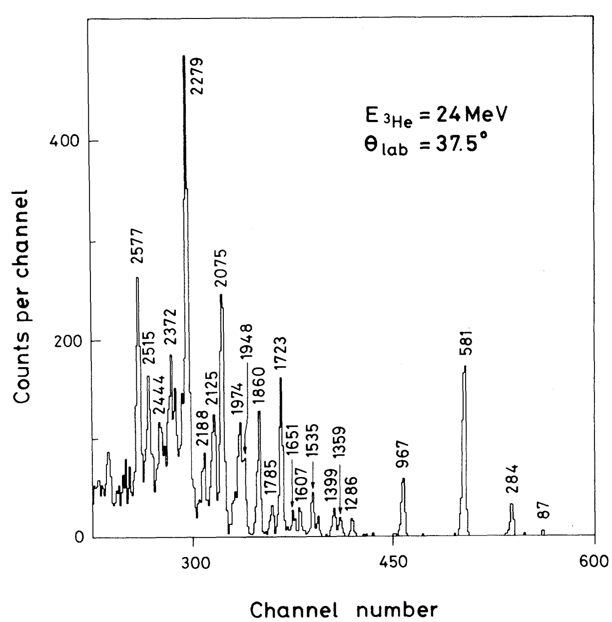

FIG. 1. α-particle spectrum for the reaction ^{161}Dy(^{3}He,α)^{160}Dy.

Empirical $l_n = 5$ and 6 angular-distribution shapes were determined from ^{162}Dy(^{3}He,α) transitions to known[6] $h_{11/2}$ and $i_{13/2}$ states at 488 and 267 keV in ^{161}Dy (Fig. 2). These empirical angular-distribution shapes are consistent with data obtained with other rare-earth targets,[7] and with the $l_n = 6$ transitions to the 6^+ and 8^+ members of the ^{160}Dy g.s. band. The empirical shapes are sufficiently different to distinguish between $l_n = 5$ and 6 transitions. In particular the $\sigma(\theta)$ for the $l_n = 6$ transitions systematically decreases more rapidly at large angles than for the $l_n = 5$ transitions. The suggested l assignments, based on the measured angular distributions of the ^{161}Dy(^{3}He,α) transitions, the relative reduced strengths, $\sigma_{\rm expt}(\theta)/\sigma_{\rm DW}(\theta)$, and the suggested configurations of the states populated in the ^{161}Dy(^{3}He,α) reaction are summarized in Table I.

The low-lying spectra of $[\nu(i_{13/2})]^2$ states populated in the ^{161}Dy(^{3}He,α) reaction are quite simple. The 4^+, 6^+, and 8^+ states of the g.s. band, $4_g{}^+$, $6_g{}^+$, and $8_g{}^+$, are populated with relative $\sigma_{\rm expt}/\sigma_{\rm DW}$ of 0.20, 1.0, and 0.33 in agreement with the angular-momentum coupling for $i_{13/2}$ pickup from an $I^\pi = \frac{5}{2}^+$ target ($\propto |\langle \frac{5}{2}, \frac{5}{2}, \frac{13}{2}, -\frac{5}{2}, | I, K = 0\rangle|^2$), which predicts relative strenghts of 0.18, 1.0, and 0.28. The remaining strong $l_n = 6$ transitions below $E_x = 2.5$ MeV are to states at $E_x = 1723$ and 1974 keV. For states with low K (i.e., aligned states), which are predicted to be populated in $l_n = 6$ pickup,[8] the angular-momentum coupling coefficients are large for $I^\pi = 6^+$, 7^+, 8^+. The 1723-keV level agrees in E_x with a state at 1722.5 keV, established[9] from γ emission following the β decay of ^{160}Ho. The large $\sigma_{\rm expt}$(^{3}He,α) of this level, together with the $E2$ and/or $M1$ and the $E2$ or $E1$ transitions from the 1722.5-keV level to $4_g{}^+$ and $6_g{}^+$ respectively [consistent with $I^\pi = 4^+$, 5^+, 6^+ (5^+ or 6^+ preferred)], suggest $I^\pi = 6^+$ for the 1722.5-keV level. The 1974-keV level was not previously known in ^{160}Dy; however, two possible candidates (both of $E2$ and/or $M1$ multipolarity[9]) exist for the γ decay of this state to $6_g{}^+$.

The relative $l_n = 6$ pickup strengths and the

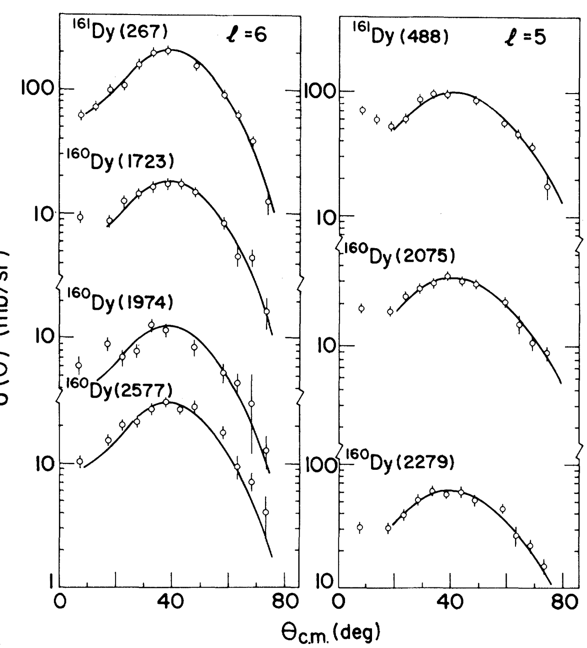

FIG. 2. Selected $l_n = 5$ and 6 angular distributions for the reaction ^{161,162}Dy(^{3}He,α)^{160,161}Dy. The $l_n = 5$ and 6 empirical shapes established from the transitions to ^{161}Dy(488) and ^{161}Dy(267) are shown by the solid curves.

TABLE I. Summary of ^{161}Dy(^{3}He,α) $l_n = 5$ and 6 transitions.

E_x [a] (keV)	I^π	l_n	$\sigma_{\rm ex}/\sigma_{\rm DW}$ [b]	Config.[c]
283	4^+	(6)	0.09	g.s.b.
583	6^+	6	0.45	g.s.b.
967	8^+	6	0.15	g.s.b.
1286	1^-			$K^\pi = 1^-$
1359	2^-		0.04[d]	$K^\pi = 1^-$
1399	3^-		0.06[d]	$K^\pi = 1^-$
1535	4^-		0.08[d]	$K^\pi = 1^-$
1607	(4^+)[e]		0.06[e]	S band
1651	(5^-)[f]		0.06[d]	$K^\pi = 1^-$[f]
1723	6^+	6	0.33	S band
1785	(5^-)[f]		0.12[d]	$K^\pi = 4^-$[f]
1860	$6^-(3-8)^-$	5	0.37	$K^\pi = 4^-$
1948	$7^-(3-8)^-$	5	0.18	$K^\pi = 4^-$
1974	$8^+(4-9)^+$	6	0.20	S band
2075	$3^-(4-8)^-$	5	0.85	$K^\pi = 3^-$
2125	(4^-)[f]	(5, 6)	0.29[d]	$K^\pi = 3^-$[f]
2188	(5^-)			$K^\pi = 3^-$
2279	$8^-(3-7)^-$	5	1.65	$K^\pi = 8^-$
2577	4^+-9^+	6	0.73	

[a]Uncertainty ± 5, 7, and 15 keV for $E_x < 1.8$, between 1.8 and 2.2, and > 2.2 MeV.

[b]$\sigma_{\rm DW}$ calculated with use of code DWUCK and average optical-model parameters, Ref. 5.

[c]The $K^\pi = 1^-$ and 4^- bands and the $K^\pi = 3^-$ and 8^- bands correspond to the $\frac{5}{2}^+[642]\otimes\frac{3}{2}^-[521]$ and the $\frac{5}{2}^+[642]\otimes\frac{11}{2}^-[505]$ Nilsson configurations, respectively.

[d]Relative strengths derived with $l_n = 5$ assumed.

[e]Assumed $l = 6$; see text.

[f]Identification based on comparison of intensity with Nilsson-model predictions.

selectivity of the pickup reaction together with the γ-decay data[9] suggest a special sequence of $[\nu(i_{13/2})]^2$ states at intermediate excitation energies near that predicted for the S band from a fit of empirical data,[10] as well as from cranked shell-model[11] and particle-rotor model[8] calculations. Such states should be populated in the ^{161}Dy(^{3}He,α) reaction. Therefore, the 1723- and 1974-keV levels of ^{160}Dy are suggested as candidates for the 6^+ and 8^+ states ($6_S{}^+$ and $8_S{}^+$) of the extension of the S band to low spin. Assuming this identification, a moment of inertia ($2\mathscr{I}/\hbar^2 = 159$ MeV^{-1}) about 1.15 times the spherical rigid-body value is obtained from the $8_S{}^+$ candidate and the 18^+ state in the upbend region of the yrast band.

If the identification of the 1723- and 1974-keV levels with $6_S{}^+$ and $8_S{}^+$ is correct, a $4_S{}^+$ state should be weakly populated by a $l_n = 6$ transition somewhat lower in E_x than the $6_S{}^+$ state. A candidate for this state is the $I^\pi = 2^+$, 3^+, 4^+ (3^+ or 4^+ preferred) level at 1605.5 keV, which is known[9] to decay by $E2$ and/or $M1$ and by $E2$ transitions to the $2_g{}^+$ and $4_g{}^+$ levels, respectively. This state would correspond to the level at 1607 keV which is weakly populated in the (^{3}He,α) reaction and, therefore, cannot be definitely established as $l_n = 6$. The strengths of the suggested $I_S \to (I-2)_g$ transitions for all three S-band candidates are nearly equal, and the strengths of the suggested $I_S \to I_g$ transition from $4_S{}^+$ and $6_S{}^+$ are from 2 to 4 times less than the strength of the corresponding $I_S \to (I-2)_g$ transition.[9]

Information about the magnitudes of the projection of the spin of the "aligned" $i_{13/2}$ neutrons on the symmetry axis (K quantum number) is available from both the branching ratios for the γ decay of $I_S \to I_g$ and $\to (I-2)_g$ and $l_n = 6$ (^{3}He,α) transition strengths to I_S ($\sigma_{\rm expt}/\sigma_{\rm DW} \propto |\langle \frac{5}{2}, \frac{5}{2}, \frac{13}{2}, -\frac{5}{2}|I_S,K\rangle|^2$). In a rotating system K is not a constant of the motion; therefore, the K values obtained from experiment are an average over the values which contribute to the transition. Electric-quadrupole transitions can connect bands differing in K by 0, 1, or 2 units. Assuming no $M1$ contributions for $I_S \to I_g$ transitions (a reasonably good assumption for large E), the branching between $I_S \to I_g$ and $I_S \to I-2$ is consistent with $K = 0$. However, the relative population of the proposed members of the S band in the pickup reaction is not in agreement with the predicted population for $K = 0$. The γ-ray branching also requires that if $K \neq 0$ components are large then the ratio of $K = 1$ to $K = 2$ components must be about 1:4.

The experimental values of the γ-ray branching ratios and the relative (^{3}He,α) transition strengths are consistent with an average mixture of $K = 0$, 1, and 2 in the low-spin part of the S band in the approximate ratio of 0.34:0.13:0.53, respectively. The addition of a significant amount of higher-K components to the wave function of the low-spin portion of the S band would result in a larger pickup strength for the $8_S{}^+$ state than observed.

The experimental alignments, i, and Routhians,[11] e', corresponding to the assumed S-band members are compared in Fig. 3 with such quantities extracted for the yrast band of ^{160}Dy and the two signatures $\alpha = \pm\frac{1}{2}$ of the lowest $i_{13/2}$ bands in ^{159,161}Dy. The values shown for the S band were calculated assuming $K = 0$; however, $K \leq 2$ would not make large differences in the extracted i and e' values. The two unpaired neutrons, which

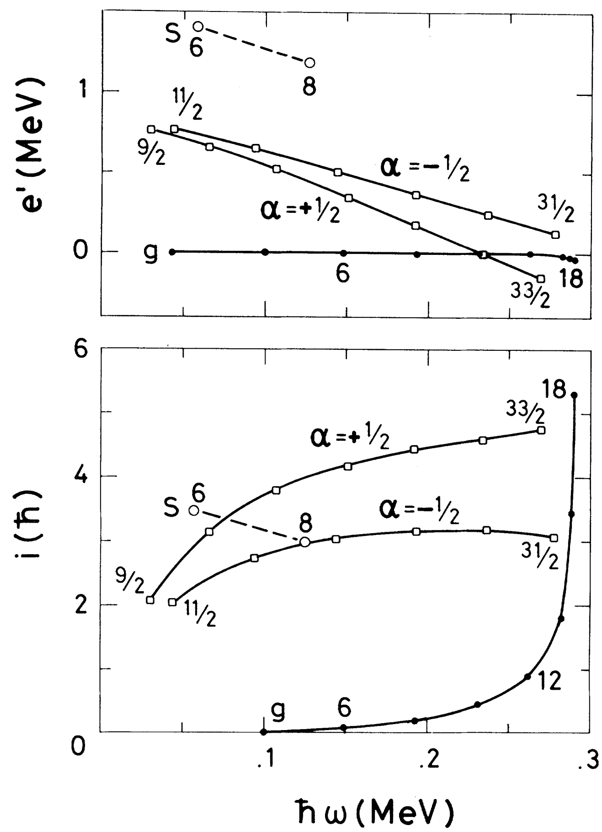

FIG. 3. Alignments, i, and experimental Routhians, e', vs rotational frequency, $\hbar\omega$ (defined in Ref. 10), for yrast (closed dots) and S (open dots) bands in ^{160}Dy and $\alpha = \pm\frac{1}{2}$ portions of the lowest $i_{13/2}$ bands in ^{159,161}Dy (squares). The spin labels given in the figure refer to $I \to I-2$ transitions.

combine to form the S band, give an i similar in magnitude[12] to a single unpaired neutron at the same $\hbar\omega$. These data, therefore, indicate that for the low-spin members of the S band the alignment along the nuclear symmetry axis is reduced by an adjustment of the angle between the quasiparticle spins. Such a recoupling of the angular momentum vectors of the quasiparticles is predicted for the low-spin members of the S band by the particle-rotor model when the "recoil terms" are treated correctly.[8] It is noted, however, that such calculations for ^{160}Dy predict[8] the low-spin members of the S band at an excitation energy that is somewhat higher than that of the suggested candidates. An average alignment of the S band between $I^{\pi}=8^{+}$ and the crossing with the g.s. band ≈ 8.5 is obtained from the experimental Routhians shown in Fig. 3 ($i=-de'/d\omega$). The crossing frequency is taken either from the $\hbar\omega$ of the upbend in ^{160}Dy or from the $\hbar\omega$ where the sum of the e''s for $\alpha=\pm\frac{1}{2}$ bands in the odd Dy's equals zero. From the experimental two-quasiparticle Routhians shown for the S band in Fig. 3 the pairing energy, Δ, is estimated[12] to be in the range of 0.75 to 0.79 MeV, depending on the procedure used to extrapolate the values of e' to $\hbar\omega=0$. This is somewhat below the odd-even mass difference (1.08 MeV) calculated with use of neutron-binding energies. Presumably this is the effect of a reduced pairing in the odd-A nuclei due to "blocking" by the unpaired neutron. Indeed, realistic calculations for ^{160}Dy place the two quasiparticle band heads (i.e. 2Δ) at about 1.5 MeV.[13]

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[(a)]Permanent address: Institute of Modern Physics, Lanchow, The People's Republic of China.

[(b)]Permanent address: McMaster University, Hamilton, Ontario L8S 4M1, Canada.

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[12]The values for i and e' extracted for the S band are sensitive to mixing with 4^{+}, 6^{+}, and 8^{+} states of other configurations. Even though such mixing may affect the details of these parameters, it probably does not make large changes in the general magnitude of i and e'.

[13]H. Sagawa, private communication.