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Positive-parity rotational band in ^{158}Tb

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Excited states of the odd-odd nucleus ^{158}Tb have been studied via the ^{154}Sm(^{7}Li,3n)^{158}Tb reaction at a beam energy of 27 MeV. The new level scheme of ^{158}Tb involving a positive parity rotational band is established up to excitation energy ~2.3 MeV and spin ~17$\hbar$. By comparing with the rotational bands in the neighboring nuclei ^{157}Tb and ^{157}Gd, the configuration was tentatively assigned as $\pi d_{5/2} \otimes \nu i_{13/2}$, and the phenomenon of signature inversion is discussed.

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I. INTRODUCTION

Extensive experimental information is available for high-spin structures in doubly odd nuclei in the rare-earth region [1–4]. This area has proven to be fascinating in nature because of the various structures resulting from active quasiparticle orbits and the softness of the nuclei. A lot of high-spin phenomena have been investigated, such as band crossings [2], rotational alignments [5], and signature splitting and inversion [6]. However, very little high-spin information is available regarding ^{158}Tb [7], because it is not easy for this neutron-rich nucleus to be populated to high angular momentum by heavy-ion fusion evaporation reactions, and it is hard to distinguish γ rays belonging to ^{158}Tb from signal contamination of ^{157}Tb [8]. The direct consequence of this lack of information is that high spin structure in ^{158}Tb is unknown. The motivation of the present study is therefore to investigate the properties of the rotational band in ^{158}Tb.

II. EXPERIMENTAL METHODS AND RESULTS

Excited states in ^{158}Tb were populated using the fusion evaporation reaction ^{154}Sm(^{7}Li,3n)^{158}Tb at a beam energy of 27 MeV. The experiment was performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE) in Beijing. A 0.67 mg/cm^2 thick ^{154}Sm foil, which was evaporated on a 1.49 mg/cm^2 thick gold backing, was used as the target. Nine Compton-suppressed high-purity Ge (HPGe) detectors and two planar HPGe detectors were utilized to detect the deexcited γ rays produced by the reaction residues. Three of these detectors were placed at 90°, four at 140°, and two at 40° with respect to the beam direction. The γ-ray energy and efficiency of detectors were calibrated using ^{133}Ba and ^{152}Eu standard sources. A total of about 1.6×10^7 twofold γ-γ coincidence events were collected in event-by-event mode. The data were sorted offline into a symmetrical matrix with a dispersion of 0.5 keV/channel. The matrix was analyzed using GASP software (from the National Laboratory of Legnaro, Italy). To obtain information concerning the γ rays' multipolarities, the angular distribution of the oriented states (ADO) ratios were extracted from two asymmetric matrices. These two matrices were created by sorting the data with the detectors for all angles on one axis and the detectors for ~140° or ~90° on the other axis. All the matrices were normalized with respect to the overall efficiency of the detectors determined with calibration sources at the target position. By comparing with the transitions of known multipolarities in ^{157}Tb [8], as shown in Fig. 1, the typical ADO ratio in the present geometry was found to be ~1.4 for stretched quadrupole transitions, and ~0.8 for stretched pure dipole transitions.

Prior to our work, the low-spin states of ^{158}Tb had been studied by the ^{159}Tb(d,t)^{158}Tb [9] and ^{157}Gd(^{3}He,d)^{158}Tb [10] reactions. These studies confirmed that the spin and parity of the ground state in ^{158}Tb is $I^{\pi} = 3^{-}$. Low-spin states of ^{158}Tb have been studied via the ^{154}Sm(^{7}Li,3n)^{158}Tb reaction up to 7^{+} and 7^{-} for the positive- and negative-parity levels [7], respectively; however, no state above the 395 μs isomer was reported. Owing to the better detection conditions, the level scheme of ^{158}Tb in this paper is dramatically extended by adding 17 new γ rays and 10 new levels. The rotational band is first completed up to $(I^{\pi}) = (17^{+})$. The level scheme of ^{158}Tb proposed from this experiment is shown in Fig. 2. As can be seen in Fig. 3, there are many new-found γ peaks (labeled with numbers). According to coincidence relationships, intensity balances, and energy sums, a rotational band based on the 4^{+} state is established.

The new level scheme is built on the previously obtained 217.5 and 322.8 keV levels. The conversion coefficient of the 66.1 keV (deexciting 7^{-}) transition and the relative intensity of the 171.1 keV (deexciting 7^{-}) transition with respect to the 66.1 keV transition indicate that these are both $E1$ transitions. Thus the 322.8 and 217.5 keV levels were assigned as $I^{\pi} = 7^{+}$ and $I^{\pi} = 6^{+}$, respectively [7]. The 261.6, 123.0, and 138.6 keV transitions can be observed in spectra gated on both the 162.5 and 194.6 keV transitions, as shown in Figs. 3(a) and 3(c), respectively. However, in the coincident spectrum gated on the 261.6 keV transition [Fig. 3(d)], the 123.0 and 138.6 keV transitions cannot be seen. It is clear that the 261.6 keV

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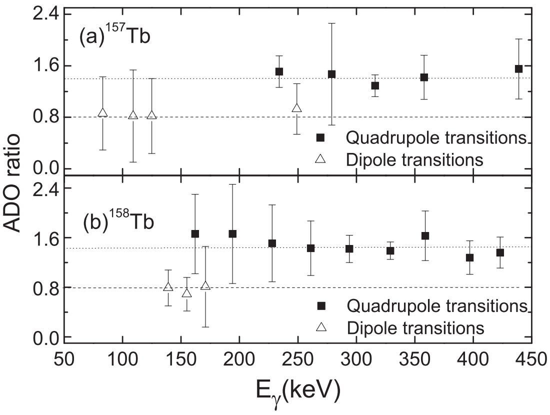

FIG. 1. ADO ratios shown as a function of γ-ray energy for (a) ^{157}Tb and (b) ^{158}Tb. The dotted and dashed lines indicate the typical values observed for the known γ rays in this experiment for stretched quadrupole and stretched pure dipole transitions, respectively.

transition is parallel to the 123.0 and 138.6 keV transitions. In the spectrum gated on the 162.5 keV transition, the 228.3 keV transition is very clear, as are the 105.3 and 123 keV transitions. The sum of 105.3 and 123.0 exactly equals 228.3; in addition, the 105.3 and 123 keV transitions cannot be observed in the spectrum gated on the 228.3 keV transition, as shown in Fig. 3(b). Thus, we fixed the positions of the 445.8 and 584.4 keV levels. The ADO ratios for the 261.6 and 228.3 keV transitions are 1.51 and 1.44, which indicate that these are $\Delta I = 2$ transitions. The spins of the 584.4 and 445.8 keV levels are tentatively assigned to $9\hbar$ and $7\hbar$, respectively.

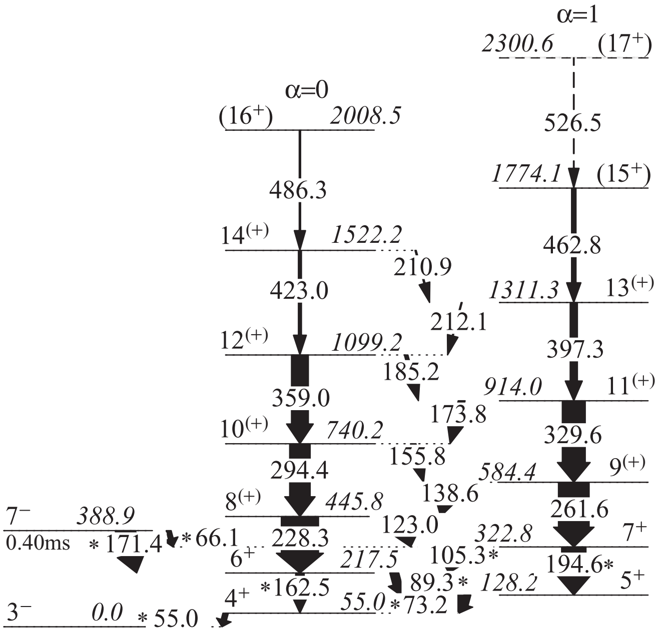

FIG. 2. The level scheme of ^{158}Tb established in the present work. The γ-ray transitions with an asterisk are obtained from previous work [7]. The decay of the 7$^-$ isomer and the 55.0 keV ($4^+ \rightarrow 3^-$), 66.1 keV ($7^- \rightarrow 7^+$) transitions, although not observed in this study, are included in the level scheme for completeness.

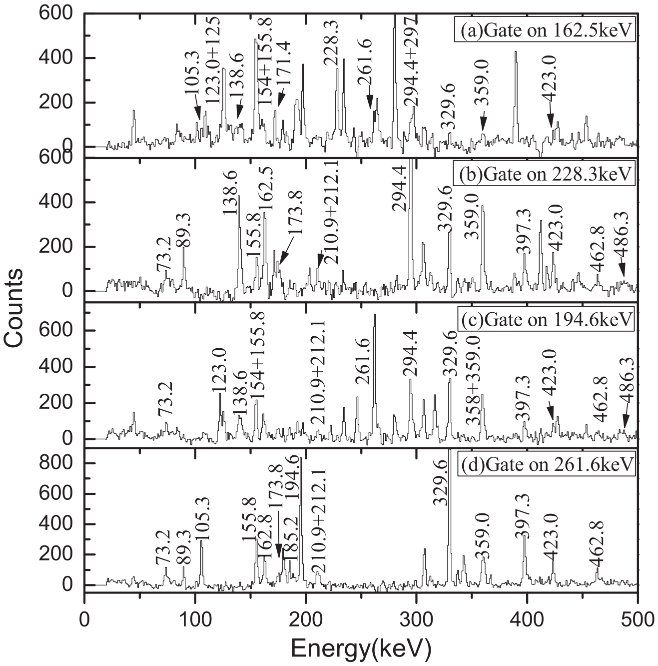

FIG. 3. Background-corrected coincidence spectrum obtained by gating on the (a) 162.5 keV, (b) 228.3 keV, (c) 194.6 keV, and (d) 261.6 keV γ-ray transitions. Peaks associated with ^{158}Tb are labeled with their energies in keV; the 125, 154, 297, and 358 keV γ rays obtained by gating on (a) the 162.5 keV γ-ray transition and (c) the 194.6 keV γ-ray transition are assigned to ^{157}Tb [8].

The ADO ratios for the 329.6 and 397.3 keV transitions are consistent with the values expected for a $\Delta I = 2$ transition; therefore, the spin and parity values of $11^{(+)}$ and $13^{(+)}$ are assigned to the 914.0 and 1311.3 keV levels. Because the ADO ratios of the 162.5, 228.3, 294.4, 359.0, and 423.0 keV transitions are close to 1.4, the placements of the 217.5 keV 6^+, 445.8 keV $8^{(+)}$, 740.2 keV $10^{(+)}$, 1099.2 keV $12^{(+)}$, and 1522.2 keV $14^{(+)}$ states are also certain. Due to the weak intensities and poor statistics of the 462.8, 486.3, and 526.5 keV transitions and some of interband γ rays, such as the 73.2, 89.3, 105.3, 123.0, 173.8, 185.2, 210.9, and 212.1 keV transitions, the ADO ratios for these transitions cannot be extracted. The properties of γ rays observed in this experiment are summarized in Table I. As shown in Fig. 3, most of transitions in ^{158}Tb observed in the previous study [7] have been confirmed and new γ rays have been identified. However, the 125, 154, 297, and 358 keV γ rays in Figs. 3(a) and 3(c) belong to another fusion reaction product, ^{157}Tb, in this experiment.

Several experiments were previously performed to clarify the configurations of ^{158}Tb [7,9]. All of those experiments indicated that the configuration assignment of the positive-parity band should be $\pi 3/2^+[411] \otimes \nu 5/2^+[642]$.

III. DISCUSSION

To further understand the rotational structure of the odd-odd nucleus ^{158}Tb, we can analyze the Routhians of its neighboring nuclei ^{157}Tb and ^{157}Gd if we assume they have

TABLE I. Level energies, γ-ray energies, relative intensities, ADO ratios, and spin-parity assignments of the initial and final states in ^{158}Tb. Uncertainties in intensities are given in parentheses.

E_{lev}(keV)[a]	E_γ(keV)[a]	I_γ[b]	R_{ADO}	$I_i^\pi \rightarrow I_f^\pi$
55.0	55.0[c,d,e]			$4^+ \rightarrow 3^-$
128.2	73.2[e]	36(4)		$5^+ \rightarrow 4^+$
217.5	89.3[e]	23(3)		$6^+ \rightarrow 5^+$
	162.5	23(4)	1.66(64)	$6^+ \rightarrow 4^+$
322.8	105.3[e]	42(5)		$7^+ \rightarrow 6^+$
	194.6	65(6)	1.66(80)	$7^+ \rightarrow 5^+$
388.9	66.1[c,d,e]			$7^- \rightarrow 7^+$
	171.4	53(7)	0.81(65)	$7^- \rightarrow 6^+$
445.8	123.0[e]	47(9)		$8^{(+)} \rightarrow 7^+$
	228.3	100(7)	1.51(62)	$8^{(+)} \rightarrow 6^+$
584.4	138.6	30(4)	0.74(29)	$9^{(+)} \rightarrow 8^{(+)}$
	261.6	82(6)	1.43(44)	$9^{(+)} \rightarrow 7^+$
740.2	155.8	14(2)	0.69(27)	$10^{(+)} \rightarrow 9^{(+)}$
	294.4	55(2)	1.42(22)	$10^{(+)} \rightarrow 8^{(+)}$
914.0	173.8[e]	18(4)		$11^{(+)} \rightarrow 10^{(+)}$
	329.6	62(2)	1.39(14)	$11^{(+)} \rightarrow 9^{(+)}$
1099.2	185.2[e]	9.3(1)		$12^{(+)} \rightarrow 11^{(+)}$
	359.0	45(3)	1.63(43)	$12^{(+)} \rightarrow 10^{(+)}$
1311.3	212.1[e]	2.8(1)		$13^{(+)} \rightarrow 12^{(+)}$
	397.3	19(1)	1.28(27)	$13^{(+)} \rightarrow 11^{(+)}$
1522.2	210.9[e]	3.3(2)		$14^{(+)} \rightarrow 13^{(+)}$
	423.0	8.0(1)	1.36(25)	$14^{(+)} \rightarrow 12^{(+)}$
1774.1	462.8[e]	12(1)		$(15^+) \rightarrow 13^{(+)}$
2008.5	486.3[e]	3.6(1)		$(16^+) \rightarrow 14^{(+)}$
2300.6	526.5[d,e]			$(17^+) \rightarrow (15^+)$

[a] Uncertainties are between 0.3 and 0.7 keV depending upon their intensity.

[b] Intensities are normalized to the 228.3 keV transition.

[c] Adopted from previous work [7].

[d] Relative intensities could not be determined because of the low intensity of transitions.

[e] ADO ratios could not be extracted because of the low intensity of transitions.

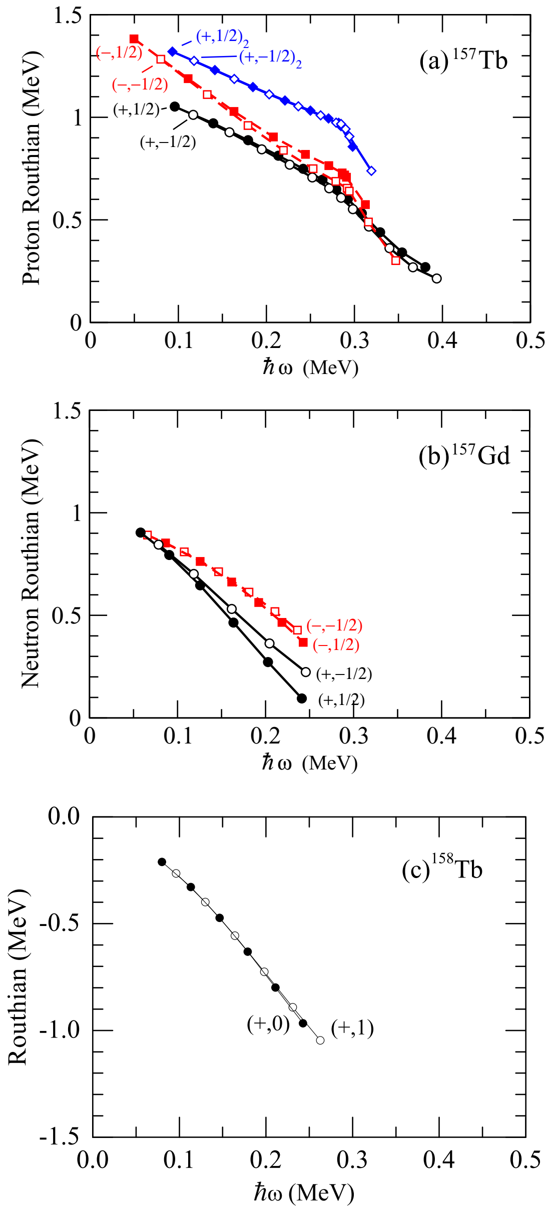

FIG. 4. (Color online) The experimental Routhians of (a) ^{157}Tb, (b) ^{157}Gd, and (c) ^{158}Tb relative to ^{156}Gd. The orbits are labeled with (π,α). Full (open) lines are used for positive (negative) parity and closed (open) symbols for signature $\alpha = 1/2$ ($\alpha = -1/2$). The orbits labeled with $(+,1/2)_2$ and $(+,-1/2)_2$ in (a) denote the second positive band ($5/2^+[413]$ band, see Ref. [8]) in ^{157}Tb. The kinks at $\omega \approx 0.3$ MeV in (a) resulted from the alignment of $i_{13/2}$ quasineutrons.

the same deformation. First, the ground band of the even-even nucleus ^{156}Gd is parametrized by the Harris polynomial [11]. The fitted Harris parameters are $J_0 = 27.3$ MeV$^{-1}\hbar^2$ and $J_1 = 256.6$ MeV$^{-3}\hbar^4$. Then, following the procedure introduced in Refs. [12,13], the experimental Routhians of ^{157}Tb and ^{157}Gd relative to the even-even nucleus ^{156}Gd are calculated and plotted in Figs. 4(a) and 4(b). The positive parity orbits are seen to be lower in energy for both protons and neutrons for most of rotational frequencies. Moderate signature splitting is observed in the neutron $(+,\pm1/2)$ orbits. For other orbits shown in Fig. 4, the signature splitting is quite small. The experimental Routhian of ^{158}Tb shows very small signature splitting [see Figs. 4(c) and 5(c)], which is similar to the positive parity band in ^{157}Tb. Thus, this band in ^{158}Tb is naturally assigned to $(\pi_p,\alpha_p)(\pi_n,\alpha_n) = (+,\pm 1/2)(+,1/2)$, which is consistent with previous assignments as $\pi 3/2^+[411] \otimes \nu 5/2^+[642]$.

The signature inversion of the $\pi h_{11/2} \otimes \nu i_{13/2}$ band in doubly odd nuclei has been systematically observed in the neighborhood of $A \sim 160$ [6]. Many theories have been proposed to interpret the signature inversion in different mass regions [14–20]. Since in the structure observed in ^{158}Tb the unpaired proton is sitting in the $d_{5/2}$ orbit rather than the $h_{11/2}$ [7,9], it is interesting to investigate signature inversion in this and the lighter isotopes. The indicator of signature splitting $S(I)$, defined as $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$, is shown in Fig. 5 as a function of the spin I. Signature splitting in the $\pi d_{5/2} \otimes \nu i_{13/2}$ band in ^{158}Tb [Fig. 5(c)] is compared with those in the

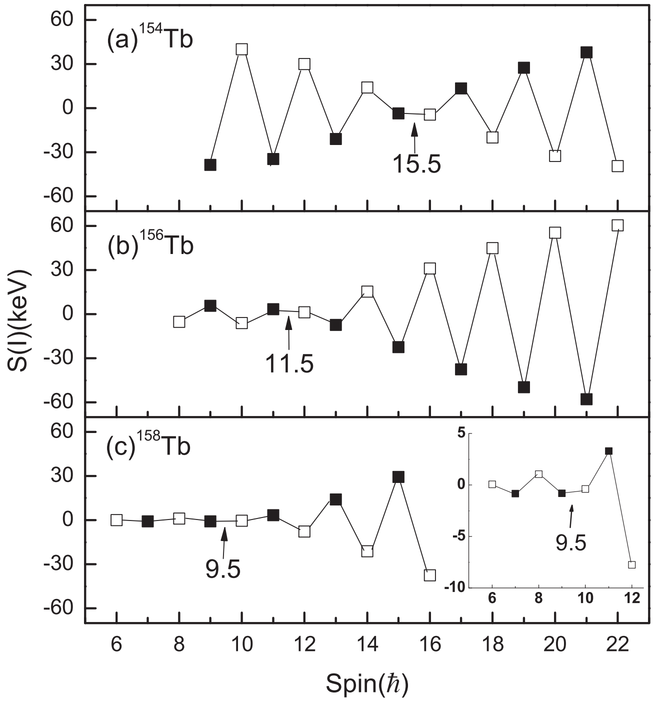

FIG. 5. Experimental energy differences $S(I)$ of the $\pi d_{5/2} \otimes \nu i_{13/2}$ band against spin I for the doubly odd isotopes with $Z = 65$. Closed (open) symbols are used for odd (even) spin. Data sources are ^{154}Tb [5], ^{156}Tb [1,6], and ^{158}Tb from this work. The inset in panel (c) shows a vertically extended plot for the spin from $6\hbar$ to $12\hbar$.

neighboring isotopes, ^{154}Tb [5] [Fig. 5(a)] and ^{156}Tb [1,6] [Fig. 5(b)]. As can be seen in Fig. 5(c), the signature splitting in ^{158}Tb seems to disappear when spin I is less than $11\hbar$, and with increasing neutron number, the magnitude of the energy splitting decreases. If we consider energies in the spin $I < 11$ region as very small signature splitting, it is interesting to find that the staggering phases of the positive-parity band in ^{158}Tb change [see partial enlargement in Fig. 5(c)]. The signature inversion point is located at approximately $9.5\hbar$ with an error no greater than $0.5\hbar$. Therefore, it can be concluded that, with increasing neutron number, the inversion point shifts toward lower spin in Tb isotopes. These features are similar to the systematic features of the signature inversion of the $\pi h_{11/2} \otimes \nu i_{13/2}$ bands in doubly odd nuclei around $A \sim 160$ summarized previously [6].

IV. SUMMARY

In summary, high-spin states in ^{158}Tb have been studied via the reaction ^{154}Sm(^{7}Li$,3n$). A rotational band is established up to excitation energy ~2.3 MeV and spin $\sim 17\hbar$ with the additional 17 new γ rays and 10 new levels. The configuration of this band was tentatively assigned as $\pi d_{5/2} \otimes \nu i_{13/2}$. By comparing the signature inversion to the similar bands with same configuration in neighboring isotopes ^{154}Tb and ^{156}Tb, it is found that, with increasing neutron number, the inversion point shifts to lower spin and the staggering magnitude before the inversion point decreases.

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