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Spin assignments of rotational bands in ^{128}La

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Previous to the present study, three isolated rotational bands with tentative spin assignments had been reported in the literature and the authors estimated that, to meet the predicted alignments, the spin of these bands has to be increased by $4\hbar$ to $5\hbar$. Based on the linking transitions observed in the present work, through the reaction ^{118}Sn(^{14}N,4n)^{128}La, and the $I^{\pi} = 5^{+}$ assignment for the bandhead of the yrast band proposed by Hayakawa, Lu, Mukai, Saitoh, Hasimoto, Komatsubara, and Furuno [Z. Phys. A **352**, 241 (1995)] from β-decay studies, the spins of these bands are reassigned. The alignments of bands in ^{128}La deduced from the present spin assignments are consistent with the alignments of relevant bands observed in neighboring odd-A nuclei ^{127}La, ^{127}Ba, and ^{131}La. Additionally, a new band with a tentative configuration assignment $\pi h_{11/2} \otimes d_{3/2}$ is reported.

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The high spin states of ^{128}La had previously been studied by several groups [1–5]. In the studies of Godfrey *et al.* [3,4] three isolated rotational bands with tentative spin assignments were reported and discussed in terms of the cranked shell model, odd-odd particle-rotor model, and total Routhian surface calculations, and as results of these discussions, the particle configuration of these rotational bands were interpreted as $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi h_{11/2} \otimes \nu g_{7/2}$, and $\pi h_{11/2} \otimes \nu(h_{11/2})^3$, correspondingly. The authors of [4] estimated that, to meet the predicted alignments, the tentative spin assignments of these rotational bands have to be increased by $4\hbar$ to $5\hbar$ (p. 683 of Ref. [4]). After the work of [3,4], $I^{\pi} = 5^{+}$ was assigned to the bandhead of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band by Hayakawa *et al.* [6] based on the studies of β decays of ^{128}La and ^{128}Ce. The purpose of the present work is to try to establish connections between these bands by identifying linking transition between them, and to reassign spins of levels in ^{128}La on the basis of the configuration assignments, and thus the parity assignments of [3,4], the $I^{\pi} = 5^{+}$ assignment for the bandhead of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band of [6], and the linking transitions observed in the present work.

In the present study, states in ^{128}La were populated through the reaction ^{118}Sn(^{14}N,4n)^{128}La at a beam energy of 69 MeV. The beam was provided by the HI-13 tandem accelerator at CIAE in Beijing. The γ-γ coincidence data were recorded by use of the detecting system consisting of 14 Compton-suppressed HPGe detectors and two HPGe planar detectors. The γ-γ coincidence matrix and DCO (directional correlation ratios of oriented states) matrix were constructed, and the DCO ratios were obtained from spectra gated either on quadrupole or dipole transitions. For our detector array, when gating on a stretched quadrupole transition, the DCO ratio of the measured transition is around 1 for a stretched quadrupole transition or nonstretched dipole transition and around 0.6 for a stretched dipole transition, and when gating on a stretched dipole transition, the DCO ratio of the measured transition becomes around 1 for a stretched dipole transition and around 1.7 for a stretched quadrupole transition.

The partial level scheme of ^{128}La deduced from this work is shown in Fig. 1. All the γ rays and their placements in bands 1, 2, and 3 reported in [3,4] were confirmed by the present work. The newly observed γ rays and their DCO ratios, where possible, are listed in Table I. Figures 2(a) and 2(b) are sample spectra which show the existence of linking transitions between bands 1 and 2 and those between bands 1 and 3, respectively. Band 4 is a newly observed band in the present work and the related γ rays are shown in Fig. 2(c). A positive-parity side band of the yrast band has also been observed, and it was interpreted as the partner band of the candidate chiral doublet bands and has been reported in a separate paper [7]. Before going to the spin assignments of levels in ^{128}La (the main purpose of the present work), it is appropriate to have a discussion on the configuration assignment of band 2. $\pi h_{11/2}$, $\nu h_{11/2}$, and $\pi h_{11/2} \otimes \nu h_{11/2}$ bands are the most strongly populated yrast bands in ^{127}La [8], ^{127}Ba [9,10], and ^{128}La, respectively. Band 2 is the second strongly populated band in ^{128}La while the $\nu d_{5/2}$ band is the second strongly populated band in ^{127}Ba, and the band $\nu g_{7/2}$ is very weakly populated in ^{127}Ba [9,10]. It is more likely that the configuration of band 2 in ^{128}La should be assigned as $\pi h_{11/2} \otimes \nu d_{5/2}$ instead of $\pi h_{11/2} \otimes \nu g_{7/2}$. Additionally, the new configuration assignment for band 2 is also supported by the fact that the predicted $B(M1)/B(E2)$ ratios of the geometrical model [11] are in good agreement with the experimental values before the band crossing as shown in Fig. 3.

By adopting $I^{\pi} = 5^{+}$ for the bandhead of the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band as proposed by Hayakawa *et al.*, the spins of levels in band 1 are increased by $3\hbar$ compared with those of [3,4] as shown in Fig. 1. At the bottom of band 1, 35, 48, and 85 keV γ rays are also adopted from [6]. Several linking transitions are observed between bands 1 and 2. DCO ratios of 628.4, 764.2, and 863.5 keV linking transitions, as listed in Table I, indicate that these linking transitions are of $\Delta I = 1$

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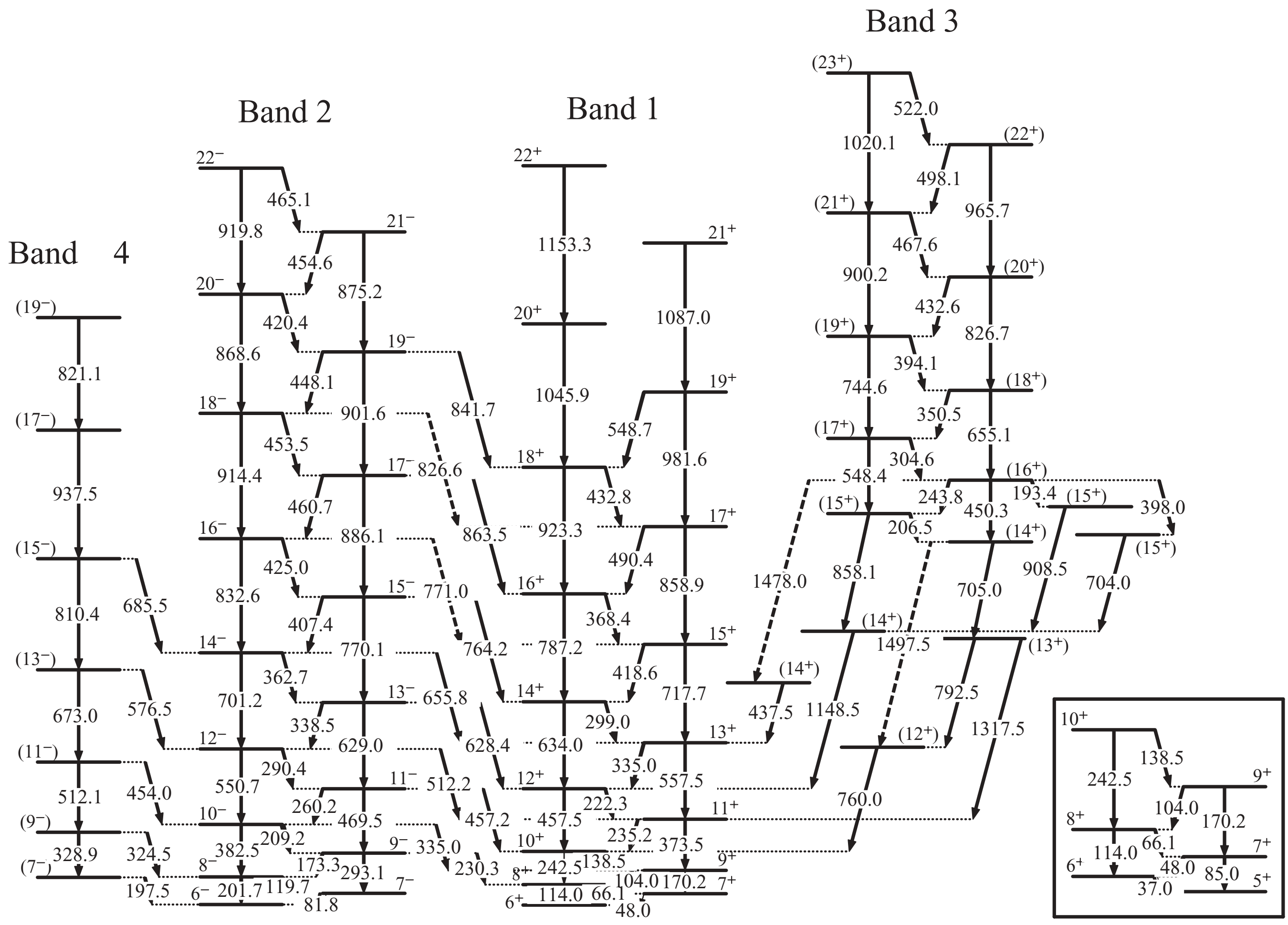

FIG. 1. Partial level scheme of ^{128}La deduced from the present study. The insertion shows the bottom portion of band 1.

dipole character. By adopting the configuration assignment $\pi h_{11/2} \otimes \nu d_{5/2}$ and thus the negative-parity assignment for band 2, the new spin-parity assignments of levels in band 2 are shown in Fig. 1. Compared with the tentative spin assignments of [3,4], the new spins of levels in band 2 are increased by $1\hbar$. Band 3 was interpreted as a oblate band with the configuration $\pi h_{11/2} \otimes \nu (h_{11/2})^3$ and thus with positive parity [4]. Linking γ rays between bands 1 and 3 and newly observed in-band γ rays of band 3 are listed in Table I. These γ rays are placed in the level scheme as shown in Fig. 1 on the basis of coincidence relations, intensity relations, and energy relations. DCO ratios listed in Table I indicate that the 858.0 keV transition is of $\Delta I = 1$ dipole character and the 1148.5 keV transition is of $E2$ character. By adopting the configuration assignment, and thus the positive-parity assignment of band 3 [4] and assuming that, in a decay sequence, the spin of the level increases with level energy, the I^π of the level populated by the 243.8 keV transition near the bottom of band 3 is assigned as (15^+) instead of the previous tentative assignment of (11^+). As a result of the above discussions, the spins of levels in bands 1, 2, and 3 are increased by $3\hbar$, $1\hbar$, and $4\hbar$, respectively, compared to the previous tentative spin assignments of [3,4].

Assuming that the effect of the residual proton-neutron interaction on the alignment is negligible, it is expected that the alignment of the two-quasiparticle configuration band in odd-odd nuclei approximately equals the sum of the proton and neutron contributions, as observed in the neighboring odd nuclei at the same frequency. Taking band 1 in ^{128}La as example, we thus have $i_x(\pi h_{11/2} \otimes \nu h_{11/2}) \approx i_\pi(\pi h_{11/2}$ in ^{127}La$) + i_\nu(\nu h_{11/2}$ in ^{127}Ba). Because the alignment of a rotational band is sensitive to the spins of levels in the band, this alignment additive rule had been successfully applied to the spin assignments of bands in odd-odd nuclei in the mass regions of $A \sim 160$ [12] and of $A \sim 130$ [13]. The alignment i_x of band 1 deduced from the new spin assignments and the i_x deduced from the tentative spin assignments of [3,4] are compared with the sum of the alignments of $i_\pi(\pi h_{11/2}$ in ^{127}La) and $i_\nu(\nu h_{11/2}$ in ^{127}Ba) in Fig. 4(a). The alignment $i_x(\pi h_{11/2} \otimes \nu h_{11/2})$ based on the new spin assignment is closer to the sum $i_\pi(\pi h_{11/2}$ in ^{127}La$) + i_\nu(\nu h_{11/2}$ in ^{127}Ba), and thus the new spin assignment is more reasonable. A similar conclusion can also be drawn for band 2 as shown in Fig. 4(b). Band 3 was interpreted as a oblate band with the four-quasiparticle configuration $\pi h_{11/2} \otimes \nu (h_{11/2})^3$. A oblate band with the three-quasiparticle configuration $\pi h_{11/2} \otimes \nu (h_{11/2})^2$ had been observed in the

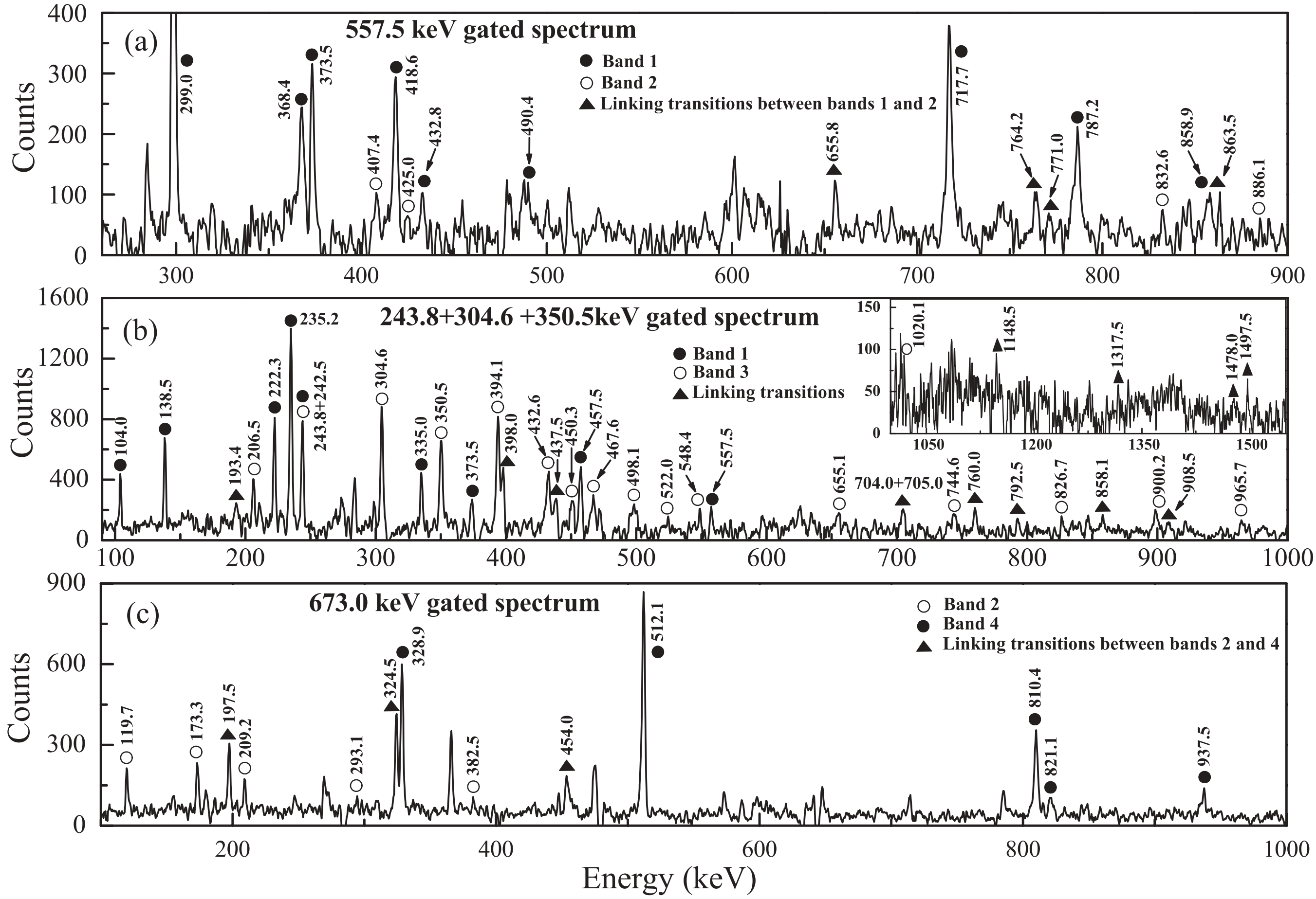

FIG. 2. Sample γ-γ coincidence spectra.

neighboring odd-A nucleus ^{131}La [14,15]. The alignment $i_x[\pi h_{11/2} \otimes \nu(h_{11/2})^3]$ of band 3 based on the new spin assignment and that based on previous tentative spin assignment of [4] are compared with the alignment $i_x[\pi h_{11/2} \otimes \nu(h_{11/2})^2]$ of the oblate band in ^{131}La. It is expected that the alignment of the four-quasiparticle band in ^{128}La should be greater than that of the three-quasiparticle band in ^{131}La. Figure 4(c) shows that the alignment of the four-quasiparticle band in ^{128}La based on the new spin assignment is indeed larger than that of the three-quasiparticle band in ^{131}La while the alignment of band 3 based on the previous tentative assignment is much smaller than that of the three-quasiparticle band in ^{131}La. (The value $10.9\hbar$ of the alignment $i_x[\pi h_{11/2} \otimes \nu(h_{11/2})^2]$ of the oblate band in ^{131}La quoted in Fig. 12 of [4] was taken from [14], and this value had been replaced with a new value $8.9\hbar$ in a later paper by the same authors [15].) This again demonstrated that the new spin assignments are more reasonable than the previous tentative spin assignments. Additionally, Fig. 4(d) shows that the alignment of band 4 is approximately equal to the sum of the alignment $i_\pi(\pi h_{11/2})$ band in ^{127}La and the $i_\nu(\nu d_{3/2})$ band in ^{127}Ba, and thus the configuration of the newly observed band 4 is tentatively assigned as $\pi h_{11/2} \otimes \nu d_{3/2}$. This configuration assignment for band 4 is consistent with the fact that the $\nu d_{3/2}$ band is the third strongly populated band, following the $\nu h_{11/2}$ and $\nu d_{5/2}$ bands, in ^{127}Ba [10].

In summary, the linking transitions between the previously reported isolated rotational bands are identified and their DCO

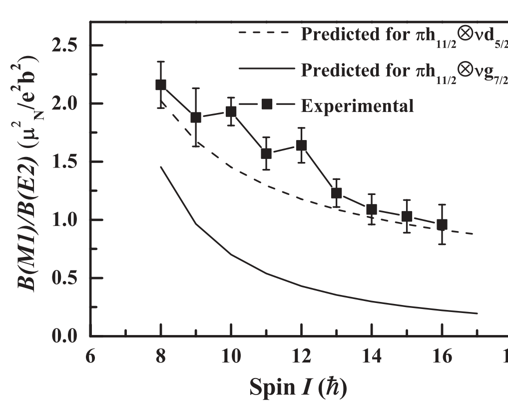

FIG. 3. Comparison of experimental and predicted $B(M1)/B(E2)$ values for band 2. Parameters used in the calculations of the predicted values: $Q_0 = 4.3$ eb, $g_R = 0.445$, $g_\pi(h_{11/2}) = 1.24$, $g_\nu(d_{5/2}) = -0.33$, $g_\nu(g_{7/2}) = 0.30$, $i_\pi(h_{11/2}) = 4.8$, $i_\nu(d_{5/2}) = 1.0$, and $i_\nu(g_{7/2}) = 1.0$.

TABLE I. New γ rays observed in the present study.

$E_\gamma (keV)$	I_γ^{c}	R_{DCO}^{a}	R_{DCO}^{b}	Assignment
Linking γ rays between bands 1 and 2				
628.4	2.2	0.65(0.20)	1.12(0.34)	$13^- \longrightarrow 12^+$
655.8	2.4	0.62(0.17)	1.09(0.29)	$14^- \longrightarrow 13^+$
764.2	1.7	0.67(0.21)	1.04(0.31)	$15^- \longrightarrow 14^+$
863.5	1.4	0.59(0.18)	0.98(0.29)	$17^- \longrightarrow 16^+$
γ rays in band 3				
206.5	4.4	0.61(0.19)	1.07(0.32)	$(15^+) \longrightarrow (14^+)$
450.3	0.9	1.07(0.24)	1.71(0.48)	$(16^+) \longrightarrow (14^+)$
548.4	1.2	1.01(0.21)	1.65(0.42)	$(17^+) \longrightarrow (15^+)$
655.1	1.4	1.11(0.26)	1.87(0.56)	$(18^+) \longrightarrow (16^+)$
Linking γ rays between bands 1 and 3				
193.4	2.2	0.68(0.18)	1.12(0.34)	$(16^+) \longrightarrow (15^+)$
398.0	5.2	0.59(0.21)	0.97(0.29)	$(16^+) \longrightarrow (15^+)$
437.5[d]	<1			$(14^+) \longrightarrow 13^+$
705.0[e]	2.3			$(14^+) \longrightarrow (13^+)$
704.0				$(15^+) \longrightarrow (14^+)$
760.0	4.4	1.05(0.17)	1.59(0.48)	$(12^+) \longrightarrow 10^+$
792.5	2.8	0.58(0.22)	1.05(0.32)	$(13^+) \longrightarrow (12^+)$
858.1	3.2	0.67(0.20)	1.02(0.31)	$(15^+) \longrightarrow (14^+)$
908.5[d]	<2			$(15^+) \longrightarrow (14^+)$
1148.5	8.1	1.12(0.23)	1.87(0.37)	$(14^+) \longrightarrow 12^+$
1317.5[d]	<2			$(13^+) \longrightarrow 11^+$
1478.0[d]	<1			$(16^+) \longrightarrow (14^+)$
1497.5[d]	<1			$(14^+) \longrightarrow (12^+)$
γ rays in band 4				
328.9	13.2	1.01(0.11)	1.59(0.21)	$(9^-) \longrightarrow (7^-)$
512.1	17.8	1.05(0.16)	1.65(0.23)	$(11^-) \longrightarrow (9^-)$
673.0	19.9	0.98(0.10)	1.68(0.25)	$(13^-) \longrightarrow (11^-)$
810.4	17.1	1.04(0.11)	1.74(0.26)	$(15^-) \longrightarrow (13^-)$
821.1	4.2	1.12(0.15)	1.61(0.29)	$(19^-) \longrightarrow (17^-)$
937.5	7.9	0.89(0.09)	1.59(0.24)	$(17^-) \longrightarrow (15^-)$
Linking γ rays between bands 2 and 4				
197.5	6.8	0.61(0.16)		$(7^-) \longrightarrow 6^-$
324.5	7.9	0.58(0.10)	1.07(0.16)	$(9^-) \longrightarrow 8^-$
454.0	5.8	0.67(0.10)	1.13(0.17)	$(11^-) \longrightarrow 10^-$
576.5	2.6	0.56(0.17)	0.98(0.29)	$(13^-) \longrightarrow 12^-$
685.5	2.2	0.64(0.19)	1.03(0.31)	$(15^-) \longrightarrow 14^-$

[a]DCO ratios obtained by gating on a stretched quadrupole transition.
[b]DCO ratios obtained by gating on a stretched dipole transition.
[c]I_γ are normalized to the 235.2 keV γ ray in band 1 as 100. Uncertainties of I_γ vary from 10% for stronger transitions to 30% for weaker transitions.
[d]Very weak γ rays.
[e]Intensity quoted for doublet.

ratios determined where possible by the γ-γ coincidence measurements through the reaction ^{118}Sn(^{14}N,4n)^{128}La at a beam energy of 69 MeV. Based on the configuration

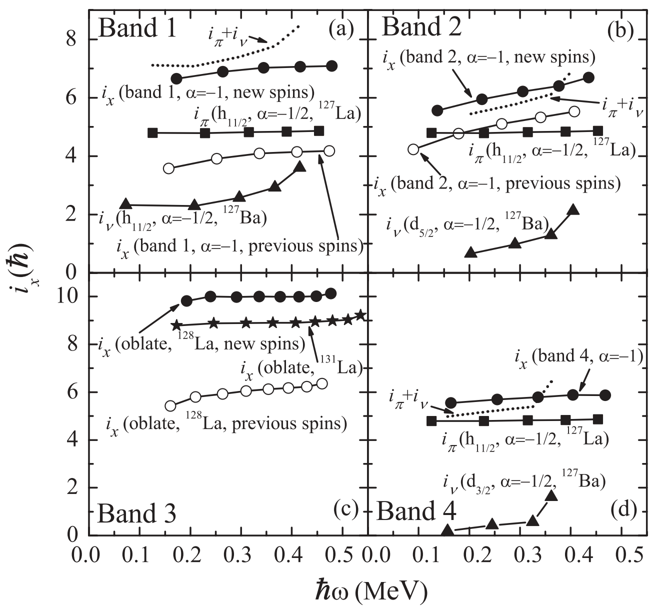

FIG. 4. (a), (b), (d) Alignments of bands 1, 2, and 4, respectively, compared to the sum $i_\pi + i_\nu$ of alignments of the relevant bands observed in neighboring odd-A nuclei ^{127}La [8] and ^{127}Ba [10]. (c) Alignment of oblate band in ^{128}La compared to the alignment of oblate band in ^{131}La [15]. Closed (open) dots for alignments based on new (previous) spin alignments. The Harris parameters are $J_0 = 17.0$ MeV$^{-1}\hbar^2$ and $J_1 = 25.8$ MeV$^{-3}\hbar^4$ for all bands in ^{128}La [3,4], ^{127}La [8], and ^{127}Ba [10], and $J_0 = 9.9$ MeV$^{-1}\hbar^2$ and $J_1 = 30.7$ MeV$^{-3}\hbar^4$ for the band in ^{131}La [15].

assignments, the I^π assignment of 5^+ for the bandhead of the yrast band proposed by Hayakawa *et al.*, and the DCO ratios of linking transitions of the present work, the spins of levels in the $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi h_{11/2} \otimes \nu d_{5/2}$, and $\pi h_{11/2} \otimes \nu (h_{11/2})^3$ bands are reassigned, and as a result, the spins of the levels in these three bands have been increased by $3\hbar$, $1\hbar$, and $4\hbar$, respectively, compared to the previous tentative spin assignments of [3,4]. The alignments of bands in ^{128}La deduced from the present new spin assignments are consistent with the alignments of relevant bands observed in neighboring odd-A nuclei ^{127}La, ^{127}Ba, and ^{131}La. Additionally, a new band with a tentative configuration assignment $\pi h_{11/2} \otimes \nu d_{3/2}$ is reported.

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