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Candidate chiral doublet bands in ^{128}La

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The candidate chiral doublet bands in ^{128}La have been searched for through the ^{118}Sn(^{14}N, 4n)^{128}La reaction at a beam energy of 69 MeV. A positive-parity sideband with the same configuration as that of the yrast band has been identified. The positive-parity and spins of the sideband have been assigned based on the $\Delta I = 1$ mixed $M1/E2$ and $E2$ characters of the linking transitions between the sideband and the yrast band. The properties of the sideband and the yrast band are discussed. The newly identified sideband and the yrast band are suggested to form the candidate of the near degenerate chiral doublet bands.

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Chiral doublet bands were predicted to appear in odd-odd nuclei in the $A \sim 130$ mass region 14 years ago [1], and since then candidates of chiral doublet bands based on $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration have been reported in more than ten odd-odd nuclei in this mass region. For a deeper understanding of the systematically appeared chiral doublet bands in this mass region, it is important to try to experimentally define the boundaries of the Z, N region where chiral candidate doublet bands appear in this mass region. For this purpose, the present work will try to extend the study of candidate chiral doublet bands to ^{128}La.

In the present study, high-spin states in ^{128}La were populated through the ^{118}Sn(^{14}N, 4n)^{128}La reaction at a beam energy of 69 MeV. The ^{14}N beam was provided by the HI-13 tandem accelerator at CIAE in Beijing. The ^{118}Sn target, with an enrichment of 92.8% and a thickness of 2.4 mg/cm^2, was rolled onto a lead backing. γ-γ coincidence measurements were performed using the detecting system consisting of 14 Compton-suppressed HPGe detectors and two planar HPGe detectors. The γ-γ coincidence matrix and DCO matrix have been constructed and a total of 3.6×10^6 coincidence events were collected.

The partial level scheme deduced from the present study is presented in Fig. 1. The level structure of the yrast band is consistent with that of [2] except that the spin values of all levels of the yrast band are increased by $3\hbar$ as suggested by [3,4]. The sideband and linking transitions are established in the present study. A sample γ-γ coincidence spectrum is shown in Fig. 2. γ rays assigned to the partial level scheme of Fig. 1 are listed in Table I, including their energies, intensities, DCO ratios, and multipolarities. The DCO ratios are obtained by setting the gates on $\Delta I = 1$ mixed $M1/E2$ transitions in yrast band, and the multipolarities of the newly observed transitions are determined by taking the multipolarities and DCO ratios of transitions in the yrast band as reference. In the present detector array geometry, assuming a negligible mixing ratio δ for the $\Delta I = 1$ transitions, when the gate is set on a stretched dipole transition, the DCO ratio of the measured transition is expected to be around 1.7 for stretched quadrupole transition and around unity for $\Delta I = 1$ stretched dipole transition. The DCO ratios are plotted in Fig. 3, which shows that the DCO ratios of the 704.1 and 836.3 keV linking transitions fall into the group of $E2$ transitions of the yrast band and the 565.7 and 766.1 keV linking transitions fall into the group of $\Delta I = 1$ mixed $M1/E2$ transitions of the yrast band. This suggests that 704.1 and 836.3 keV linking transitions are of $E2$ multipolarity and 565.7 and 766.1 keV linking transitions are of $\Delta I = 1$ mixed $M1/E2$ multipolarity. The existence of linking transitions with multipolarities $E2$ and $M1/E2$ leads to the positive parity and spin assignments for the sideband, as shown in Fig. 1.

The same $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration as that of the yrast band is usually assigned to the sideband reported in odd-odd nuclei in the $A \sim 130$ mass region due to the observation of $\Delta I = 1$ mixed $M1/E2$ linking transitions between the sideband and the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band [5]. This is because other low-lying positive-parity configurations in odd-odd nuclei in the $A \sim 130$ mass region must involve both a positive-parity proton and a positive-parity neutron orbital. The selection rules for the $M1$ and $E2$ operators yield vanishing matrix elements between such configurations and the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. As a consequence, the linking transitions should be strongly hindered unless the sideband is build on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration.

The separation energy between the states in the sideband and the yrast band at the same spin I, $\Delta E(I) = E(I)_{\text{side}} - E(I)_{\text{yrast}}$, is an important quantity for the interpretation of the sideband. Level energies of the sideband and the yrast band of ^{128}La are shown in Fig. 4 together with those of ^{130}La [6], ^{132}La [5], and ^{134}La [7] for comparison. Figure 4 exhibits the separation energies of the states in the sidebands and the yrast bands for these isotopes. Similar to the cases of ^{130}La and ^{132}La, $\Delta E(I)$ in ^{128}La stays roughly constant within a wide range of spin, and $\Delta E(I)$ of ^{128}La is about 500 keV, which is ~100 keV higher than those of ^{130}La [6]

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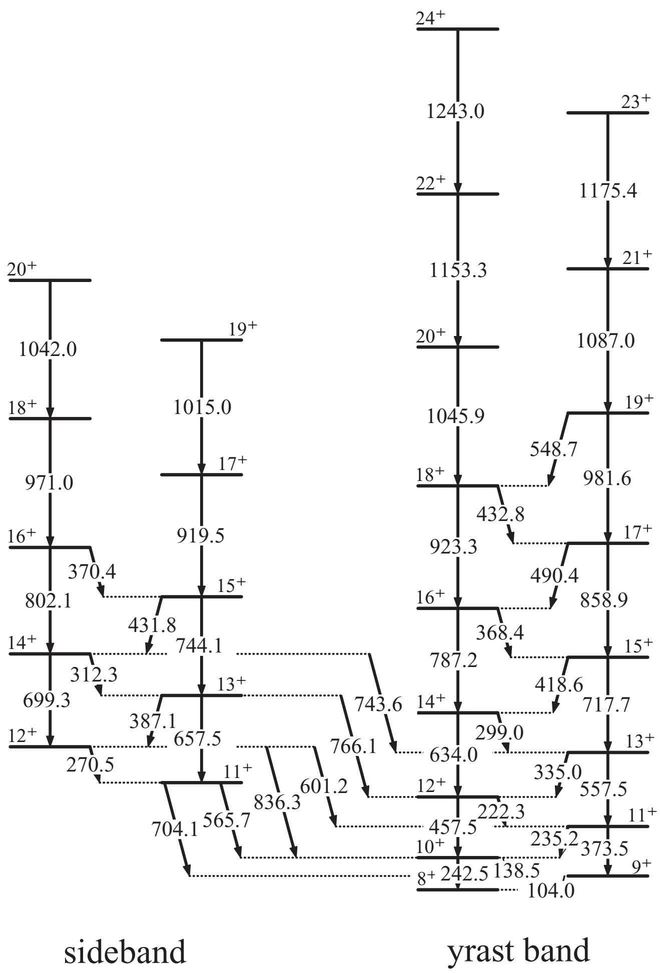

FIG. 1. Partial level scheme of ^{128}La presenting the yrast band and the newly identified sideband, and linking transitions between them.

and ^{132}La [5]. A possible interpretation of the sideband is that it may result from the coupling between the unfavored signature of the $\pi h_{11/2}$ orbital and the two signatures of the $\nu h_{11/2}$ orbital. The difference between the lowest $\pi h_{11/2}$ quasiparticle Routhian had been calculated to be 700–800 keV, as shown in Fig. 8 of Ref. [2], and this is consistent with

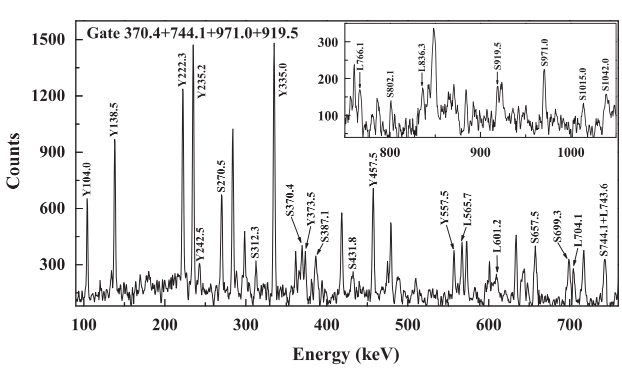

FIG. 2. Sample γ-γ coincidence spectrum supporting the partial level scheme of ^{128}La. Y, S, and L stand for transitions in the yrast band, the sideband, and the linking transitions, respectively.

TABLE I. Energies, intensities, and DCO ratio for transitions related to doublet bands in ^{128}La. Uncertainties on the relative intensities listed in the table vary from 10% for strong transitions up to 30% for weaker transitions.

E_γ (keV)	I_γ	$R_{\rm DCO}$	$I_i^\pi \rightarrow I_f^\pi$	Multipolarity
Sideband				
270.5	2.0	0.96(0.38)	$12^+ \longrightarrow 11^+$	$M1/E2$
312.3	2.1	1.14(0.46)	$14^+ \longrightarrow 13^+$	$M1/E2$
370.4	2.0		$16^+ \longrightarrow 15^+$	$(M1/E2)$
387.1	4.3	1.07(0.42)	$13^+ \longrightarrow 12^+$	$M1/E2$
431.8	3.2		$15^+ \longrightarrow 14^+$	$(M1/E2)$
657.5	4.6	1.79(0.63)	$13^+ \longrightarrow 11^+$	$E2$
699.3	4.9	1.76(0.70)	$14^+ \longrightarrow 12^+$	$E2$
744.1	4.2	1.81(0.54)	$15^+ \longrightarrow 13^+$	$E2$
802.1	4.2		$16^+ \longrightarrow 14^+$	$(E2)$
919.5	1.2		$17^+ \longrightarrow 15^+$	$(E2)$
971.0	2.1		$18^+ \longrightarrow 16^+$	$(E2)$
1015.0	0.9		$19^+ \longrightarrow 17^+$	$(E2)$
1042.0	0.7		$20^+ \longrightarrow 18^+$	$(E2)$
Yrast band				
104.0	45.1	0.87(0.17)	$9^+ \longrightarrow 8^+$	$M1/E2$
138.5	98.0	0.92(0.18)	$10^+ \longrightarrow 9^+$	$M1/E2$
222.3	80.1	1.07(0.21)	$12^+ \longrightarrow 11^+$	$M1/E2$
235.2	100.0	1.03(0.21)	$11^+ \longrightarrow 10^+$	$M1/E2$
242.5	11.5		$10^+ \longrightarrow 8^+$	$(E2)$
299.0	28.7	1.01(0.20)	$14^+ \longrightarrow 13^+$	$M1/E2$
335.0	36.4	0.92(0.18)	$13^+ \longrightarrow 12^+$	$M1/E2$
368.4	12.2	1.05(0.21)	$16^+ \longrightarrow 15^+$	$M1/E2$
373.5	17.1		$11^+ \longrightarrow 9^+$	$(E2)$
418.6	19.8	0.96(0.19)	$15^+ \longrightarrow 14^+$	$M1/E2$
432.8	5.3		$18^+ \longrightarrow 17^+$	$(M1/E2)$
457.5	50.0	1.68(0.34)	$12^+ \longrightarrow 10^+$	$E2$
490.4	7.2	0.95(0.19)	$17^+ \longrightarrow 16^+$	$M1/E2$
548.7	2.9		$19^+ \longrightarrow 18^+$	$(M1/E2)$
557.5	15.2	1.65(0.33)	$13^+ \longrightarrow 11^+$	$E2$
634.0	43.5	1.73(0.35)	$14^+ \longrightarrow 12^+$	$E2$
717.7	18.1	1.71(0.34)	$15^+ \longrightarrow 13^+$	$E2$
787.2	32.0	1.75(0.35)	$16^+ \longrightarrow 14^+$	$E2$
858.9	15.8	1.79(0.36)	$17^+ \longrightarrow 15^+$	$E2$
923.3	24.8	1.65(0.50)	$18^+ \longrightarrow 16^+$	$E2$
981.6	8.4	1.81(0.54)	$19^+ \longrightarrow 17^+$	$E2$
1045.9	14.8		$20^+ \longrightarrow 18^+$	$(E2)$
1087.0	5.8		$21^+ \longrightarrow 19^+$	$(E2)$
1153.3	7.2		$22^+ \longrightarrow 20^+$	$(E2)$
1175.4	4.5		$23^+ \longrightarrow 21^+$	$(E2)$
1243.0	3.8		$24^+ \longrightarrow 22^+$	$(E2)$
Linking transitions				
565.7	2.5	1.12(0.45)	$11^+ \longrightarrow 10^+$	$M1/E2$
601.2	4.5		$12^+ \longrightarrow 11^+$	$(M1/E2)$
704.1	2.3	1.78(0.71)	$11^+ \longrightarrow 9^+$	$E2$
743.6	4.9		$14^+ \longrightarrow 13^+$	$(M1/E2)$
766.1	5.2	0.93(0.37)	$13^+ \longrightarrow 12^+$	$M1/E2$
836.3	2.8	1.82(0.73)	$12^+ \longrightarrow 10^+$	$E2$

the observed properties of the $h_{11/2}$ bands in the neighboring odd-Z nuclei. 700–800 keV is much larger than the separation energy $\Delta E(I) \sim 500$ keV between the sideband and the yrast

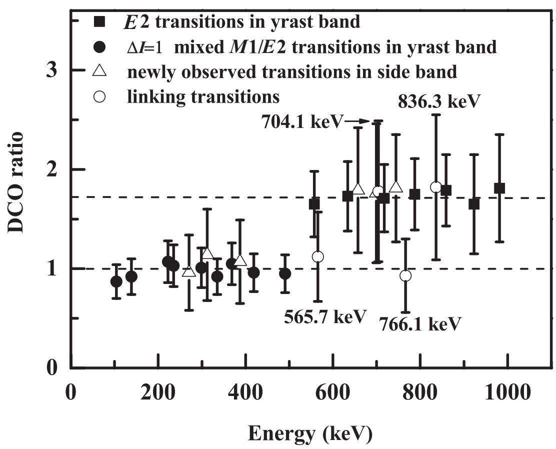

FIG. 3. DCO ratio vs γ-ray energies for most of the transitions in ^{128}La.

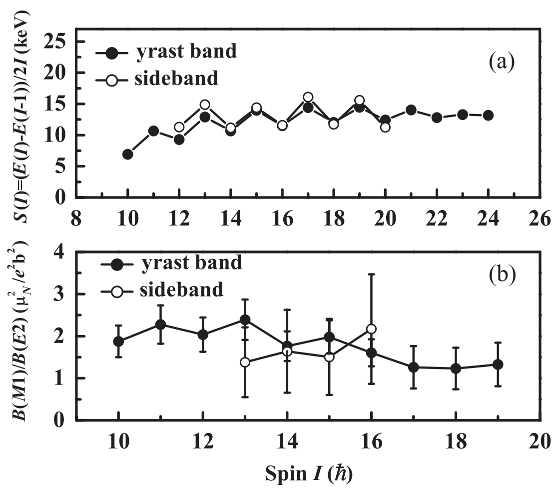

FIG. 5. (a) $S(I)$ values vs spin for the doublet bands in ^{128}La. (b) $B(M1)/B(E2)$ ratios of the sideband and the yrast band in ^{128}La.

band in ^{128}La, and thus the interpretation of the quasiparticle excitation can be ruled out. An interpretation of γ vibration coupled to the yrast band is also unlikely because the vibration energies are $\geqslant$600 keV [5] in this mass region. The exclusion of the interpretations of quasiparticle excitation and γ vibration provides the possibility to interpret the sideband as the chiral partner band of the yrast band, and thus the sideband and the yrast band form the candidate of the near degenerate chiral doublet bands.

The existence of near-degenerate $\Delta I = 1$ bands is one of the experimental indicators of chirality. Two further fingerprints, which must be observed in order to be consistent with the chiral geometry interpretation, were proposed by Koike, Starosta, and Hamamoto [8]. First, the energy staggering parameter $S(I) = [E(I) - E(I-1)]/2I$ should possess a smooth dependence with spin since the particle and hole orbital angular momentum are both perpendicular to the core rotational angular momentum in the chiral geometry. $S(I)$ of the sideband and the yrast band of ^{128}La is presented in Fig. 3(a). The relatively smooth variation of $S(I)$ should be considered as consistent with the requirement of first fingerprint. Secondly, due to the restoration of the chiral symmetry in the laboratory frame, there are phase consequences for the chiral wave functions resulting in $M1$ and $E2$ selection rules, which can manifest as $B(M1)/B(E2)$ and $B(M1)_{\text{in}}/B(M1)_{\text{out}}$ staggering as a function of spin and the odd spin members of the chiral bands have higher values relative to the even spin members for chiral bands with the configuration $\pi h_{11/2} \otimes \nu h_{11/2}$ in the $A \sim 130$ mass region. The $B(M1)/B(E2)$ of the sideband and the yrast band of ^{128}La are shown in Fig. 3(b). For the sideband, the error bar of the $B(M1)/B(E2)$ values are larger than the staggering magnitude. Therefore, the definite conclusions on the staggering phase of $B(M1)/B(E2)$ of the sideband cannot be made in the present work. However, the similar magnitude of $B(M1)/B(E2)$ of the sideband and the yrast band in ^{128}La as shown in Fig. 3(b) is consistent with the expectation for the near degenerate chiral doublet bands. This is because, for the electromagnetic properties of chiral geometry, there should be comparable strength of intraband $B(M1)$ and $B(E2)$ between the chiral partner states. This leads to the expectation that the ratio $[B(M1)/B(E2)]_{\text{yrast}}/[B(M1)/B(E2)]_{\text{side}} \approx 1$ [8].

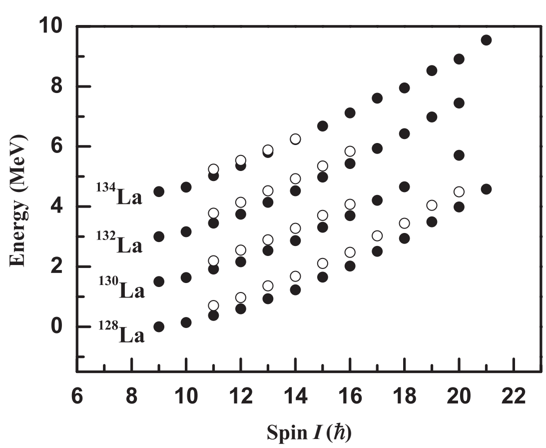

FIG. 4. Level energies for the yrast band (filled symbols) and sideband (open symbols)in the La isotopes. Bandhead energies are separated by 1.5 MeV for display.

In summary, a positive-parity sideband of the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band has been observed and linking transitions between them are identified. The properties of the sideband and the yrast band are discussed and these two bands are suggested to form the candidate of the near degenerate chiral doublet bands in ^{128}La.

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