Observation of a second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La

K. Y. Ma (马克岩),[1,2] J. B. Lu (陆景彬),[1,*] S. P. Ruan (阮圣平),[2] D. Yang (杨东),[1] J. Li (李剑),[1] Y. Z. Liu (刘运祚),[1] Y. J. Ma (马英君),[1] X. G. Wu (吴晓光),[3] Y. Zheng (郑云),[3] and C. Y. He (贺创业)[3]

[1]*College of Physics, Jilin University, Changchun 130023, China*

[2]*College of Electronic Science & Engineering, Jilin University, Changchun 130023, China*

[3]*China Institute of Atomic Energy, Beijing 102413, China*

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High-spin states of ^{126}La have been populated using the ^{116}Sn(^{14}N, 4n)^{126}La reaction at a beam energy of 77 MeV. A side band linking to the known yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band is observed. $B(M1)/B(E2)$ ratios and alignments of the side band and DCO ratios of linking transitions between the side band and the yrast band suggest that the side band has the same $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration as that of the yrast band, and thus the side band is a second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La. The separation energy, $\Delta E(I) = E(I)_{\text{side}} - E(I)_{\text{yrast}}$, between the side band and the yrast band at the same spin, and the energy staggering parameter $S(I)$ of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La are compared to those of other odd-odd La isotopes. The variation trends of $\Delta E(I)$ and $S(I)$ both suggest that it is reasonable to interpret the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La as an excited $\pi h_{11/2} \otimes \nu h_{11/2}$ band as proposed for ^{124}La rather than to interpret it as a partner band of a near degenerate chiral doublet band as done for $^{128-134}$La.

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A second $\pi h_{11/2} \otimes \nu h_{11/2}$ band has been reported in ^{124}La [1], ^{128}La [2], ^{130}La [3], ^{132}La [4], and ^{134}La [5]. In the cases of $^{128-134}$La [2–5], the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band and the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band were cited as partners of near degenerate chiral doublet bands resulting from chiral symmetry breaking that occurred in triaxially deformed odd-odd nuclei [6]. In the case of ^{124}La [1], the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band was considered to be an excited band of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band, where two signature components of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band were interpreted as resulting from the coupling of an unfavored signature component of the $\pi h_{11/2}$ proton orbital with two signature components of the $\nu h_{11/2}$ neutron orbital, while the two signature components of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band were interpreted as resulting from the coupling of a favored signature component of the $\pi h_{11/2}$ proton orbital with two signature components of the $\nu h_{11/2}$ neutron orbital. Up to now, no experimental data on a second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La is available. This report presents the results of our experimental study on a second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La.

High-spin states of ^{126}La were populated through the ^{116}Sn(^{14}N, 4n)^{126}La reaction at a beam energy of 77 MeV. The ^{116}Sn target, with an enrichment of 92.8% and a thickness of 3.2 mg/cm^2, was rolled onto a 12.75 mg/cm^2 lead backing. The beam was provided by the HI-13 tandem accelerator at China Institute of Atomic Energy (CIAE) in Beijing. The γ-γ coincidence data were recorded by the use of the detecting system consisting of nine Compton-suppressed high-purity germanium (HPGe) detectors, two HPGe planar detectors, and one clover-type detector. These Ge detectors in the array were placed at 90°, ±37°, ±30°, and ±60° relative to the beam direction. A total of 4.5×10^8 γ-γ coincidence events were recorded. The data were sorted into a symmetrized γ-γ coincidence matrix and a directional correlation from oriented states (DCO) matrix, and the DCO matrix was created by sorting the detectors at ±30° and ±37° on one axis and the detectors at ∼90° on the other. 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 1.0 for a stretched quadrupole transition or a 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 1.0 for a stretched dipole transition and around 1.7 for a stretched quadrupole transition.

High-spin states in ^{126}La had previously been studied [7–9] and the yrast band was assigned to the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration [8,9] and thus it has positive parity. The partial level scheme of ^{126}La deduced from the present study is shown in Fig. 1. Properties and placements of related γ rays are listed in Table I. The level structure of the yrast band (band 1) is consistent with that of [9] except that the spin values of all levels in band 1 have been increased by 2 $\hbar$ according to the systematics study [10] and the "extended" total Routhian surface (TRS) calculations [11]. Band 2 and linking transitions between bands 1 and 2 are observed in the present work. DCO ratios listed in Table I indicate that 918.5 and 946.2 keV linking transitions are of $\Delta I = 1$ character and 1149.2 and 1276.3 keV linking transitions are of $\Delta I = 2$ character. The observation of both $\Delta I = 1$ and $\Delta I = 2$ linking transitions between bands 1 and 2 implies that band 2 has a positive parity like that of band 1, and energies and spin values of the levels in band 2 are fixed relative to the levels in band 1 as shown in Fig. 1. It is found that when the internal conversion is not considered, 65.1%, 63.5%, and 60.8% of the total populating γ intensities of the 9$^+$ state in ^{124}La [1], ^{126}La (present work), and ^{128}La [2] are missing, respectively. Possibly, due to the complexity of

*ljb@jlu.edu.cn

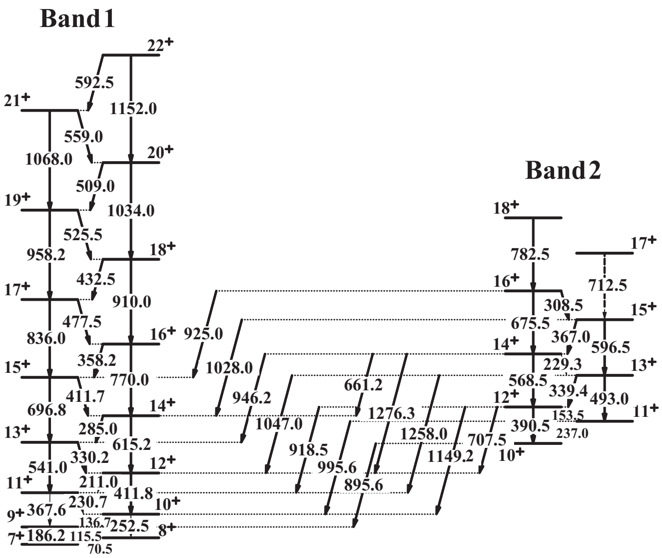

FIG. 1. Partial level scheme of ^{126}La.

the low-lying level structure in odd-odd nuclei, there are some depopulating low energy and/or highly converted γ rays were not observed. This is a problem which needs to be investigated further. A sample γ-γ coincidence spectrum supporting the level scheme of Fig. 1 is shown in Fig. 2.

As mentioned above, the configuration of the yrast band (band 1) had previously been assigned as $\pi h_{11/2} \otimes \nu h_{11/2}$ [8,9]. In order to discuss the configuration assignment of the side band (band 2), cranked shell model (CSM) calculations [12,13] were performed as shown in Fig. 3. The alignment of band 2 is shown in Fig. 4(a) along with that of band 1. The flat alignment of band 1 for $\omega < 0.45$ MeV/$\hbar$ clearly supports the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration assignment for band 1 through blocking argument; i.e., neither the theoretical ω_{EF} nor the ω_{ef} alignment of Fig. 3 are evident. The similarity of alignments between band 2 and band 1, as shown in Fig. 4(a), tentatively suggests that band 2 has the same configuration as that of band 1. The experimental $B(M1)/B(E2)$ ratios for bands 1 and 2 are shown in Fig. 4(b) along with the theoretical estimates of the geometrical model [17] for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. The general agreement between experimental results and theoretical estimates provides further support to the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration assignment for both bands 1 and 2.

The separation energy between the states in the side band and the yrast band at the same spin, $\Delta E(I) = E(I)_{\text{side}} - E(I)_{\text{yrast}}$, in $^{124-134}$La are compared in Fig. 5. Within the

TABLE I. Energies, intensities, and DCO ratio of γ rays related to bands 1 and 2 and linking γ rays between them in ^{126}La. The internal conversion is not taken into account in the present work.

E_γ (keV)	I_γ	R_{DCO}[a]	R_{DCO}[b]	$I_i^\pi \rightarrow I_f^\pi$	Multipolarity
Band 1					
70.5				$8^+ \rightarrow 7^+$	$(M1/E2)$
115.5	32.1(28)	0.87(18)		$9^+ \rightarrow 8^+$	$M1/E2$
136.7	76.2(54)	0.92(22)		$10^+ \rightarrow 9^+$	$M1/E2$
186.2	2.1(6)	1.68(42)		$9^+ \rightarrow 7^+$	$E2$
211.0	78.0(66)	1.07(21)		$12^+ \rightarrow 11^+$	$M1/E2$
230.7[c]	100.0(23)	1.03(21)		$11^+ \rightarrow 10^+$	$M1/E2$
252.5	17.0(34)	1.71(46)		$10^+ \rightarrow 8^+$	$E2$
285.0	30.5(32)	1.01(20)		$14^+ \rightarrow 13^+$	$M1/E2$
330.2	57.1(46)	0.92(18)		$13^+ \rightarrow 12^+$	$M1/E2$
358.2	8.5(26)	1.05(21)		$16^+ \rightarrow 15^+$	$M1/E2$
367.6	23.1(21)	1.74(41)		$11^+ \rightarrow 9^+$	$E2$
411.7	29.5(40)	0.96(19)		$15^+ \rightarrow 14^+$	$M1/E2$
411.8	53.1(51)	1.68(34)		$12^+ \rightarrow 10^+$	$E2$
432.5	2.1(11)	1.08(18)		$18^+ \rightarrow 17^+$	$M1/E2$
477.5	11.0(31)	0.95(22)		$17^+ \rightarrow 16^+$	$M1/E2$
509.0				$20^+ \rightarrow 19^+$	$(M1/E2)$
525.5	4.1(12)	0.89(28)		$19^+ \rightarrow 18^+$	$M1/E2$
541.0	34.2(72)	1.61(33)		$13^+ \rightarrow 11^+$	$E2$
559.0				$21^+ \rightarrow 20^+$	$(M1/E2)$
592.5				$22^+ \rightarrow 21^+$	$(M1/E2)$
615.2	67.1(82)	1.73(35)		$14^+ \rightarrow 12^+$	$E2$
696.8	51.2(61)	1.71(51)		$15^+ \rightarrow 13^+$	$E2$
770.0	38.1(45)	1.75(53)		$16^+ \rightarrow 14^+$	$E2$
836.0	28.1(36)	1.67(33)		$17^+ \rightarrow 15^+$	$E2$
910.0	24.3(32)	1.62(36)		$18^+ \rightarrow 16^+$	$E2$
958.2	15.1(42)	1.72(38)		$19^+ \rightarrow 17^+$	$E2$
1034.0	14.8(47)	1.77(41)		$20^+ \rightarrow 18^+$	$E2$
1068.0	5.8(21)	1.61(43)		$21^+ \rightarrow 19^+$	$E2$
1152.0	7.2(25)	1.58(36)		$22^+ \rightarrow 20^+$	$E2$
Band 2					
153.5	0.7(2)	0.96(38)		$12^+ \rightarrow 11^+$	$M1/E2$
229.3	3.1(11)	1.14(46)		$14^+ \rightarrow 13^+$	$M1/E2$
237.0				$11^+ \rightarrow 10^+$	$(M1/E2)$
308.5	1.5(5)			$16^+ \rightarrow 15^+$	$(M1/E2)$
339.4	4.8(13)	1.07(42)	0.55(13)	$13^+ \rightarrow 12^+$	$M1/E2$
367.0	3.5(11)			$15^+ \rightarrow 14^+$	$(M1/E2)$
390.5	2.1(8)			$12^+ \rightarrow 10^+$	$(E2)$
493.0	4.3(14)	1.79(52)		$13^+ \rightarrow 11^+$	$E2$
568.5	9.2(31)	1.76(60)	1.03(19)	$14^+ \rightarrow 12^+$	$E2$
596.5	5.7(19)	1.81(54)		$15^+ \rightarrow 13^+$	$E2$
675.5	4.1(14)			$16^+ \rightarrow 14^+$	$(E2)$
712.5				$17^+ \rightarrow 15^+$	$(E2)$
782.5	7.8(25)	1.74(58)		$18^+ \rightarrow 16^+$	$E2$
Linking transitions					
661.2	1.8(7)	0.89(38)		$14^+ \rightarrow 14^+$	$M1/E2$
707.5	1.4(4)	0.98(23)		$12^+ \rightarrow 12^+$	$M1/E2$
895.6				$10^+ \rightarrow 9^+$	$(M1/E2)$
918.5	4.8(16)	1.04(17)	0.56(9)	$12^+ \rightarrow 11^+$	$M1/E2$
925.0	1.6(5)			$16^+ \rightarrow 15^+$	$(M1/E2)$
995.6	2.3(8)	1.07(23)	0.63(11)	$11^+ \rightarrow 10^+$	$M1/E2$
946.2	4.3(15)	1.02(19)	0.57(8)	$14^+ \rightarrow 13^+$	$M1/E2$
1028.0				$15^+ \rightarrow 14^+$	$(M1/E2)$
1047.0	3.5(12)	1.12(25)		$13^+ \rightarrow 12^+$	$M1/E2$
1149.2	2.2(7)	1.71(45)	0.98(15)	$12^+ \rightarrow 10^+$	$E2$
1258.0	2.3(8)	1.76(42)		$13^+ \rightarrow 11^+$	$E2$
1276.3	3.1(11)	1.81(39)	1.06(16)	$14^+ \rightarrow 12^+$	$E2$

[a] DCO ratios listed here are obtained by setting the gate on mixed $M1/E2$ transitions.
[b] DCO ratios listed here are obtained by setting the gate on quadrupole transitions.
[c] I_γ are normalized to the 230.7 keV γ ray in band 1 as 100.

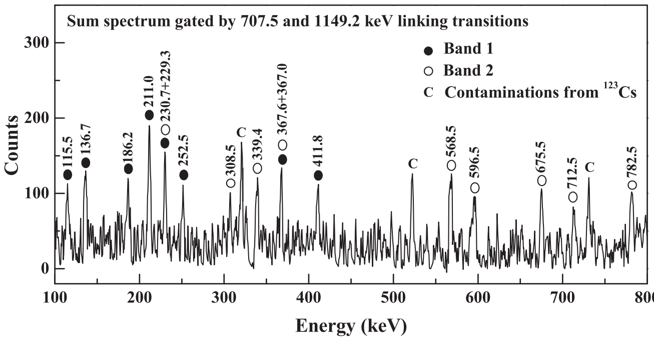

FIG. 2. Sample γ-γ coincidence spectrum supporting the partial level scheme of ^{126}La as shown in Fig. 1.

observed spin region, the magnitude and variation trend of $\Delta E(I)$ of ^{126}La is very similar to those of ^{124}La [1], and quite different from those of $^{128-134}$La [2–5]. This fact suggests that it is reasonable to interpret the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La as the excited $\pi h_{11/2} \otimes \nu h_{11/2}$ band, as proposed for ^{124}La [1], rather than to interpret it as the partner band of chiral doublet bands, as for $^{128-134}$La [2–5].

An energy staggering parameter, defined as $S(I) = E(I) - E(I-1) - 1/2[E(I+1) - E(I) + E(I-1) - E(I-2)]$, is used to display the signature inversion phenomenon of a rotational band [1]. $S(I)$ of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La [1], ^{126}La (present work), and ^{128}La [2] are shown

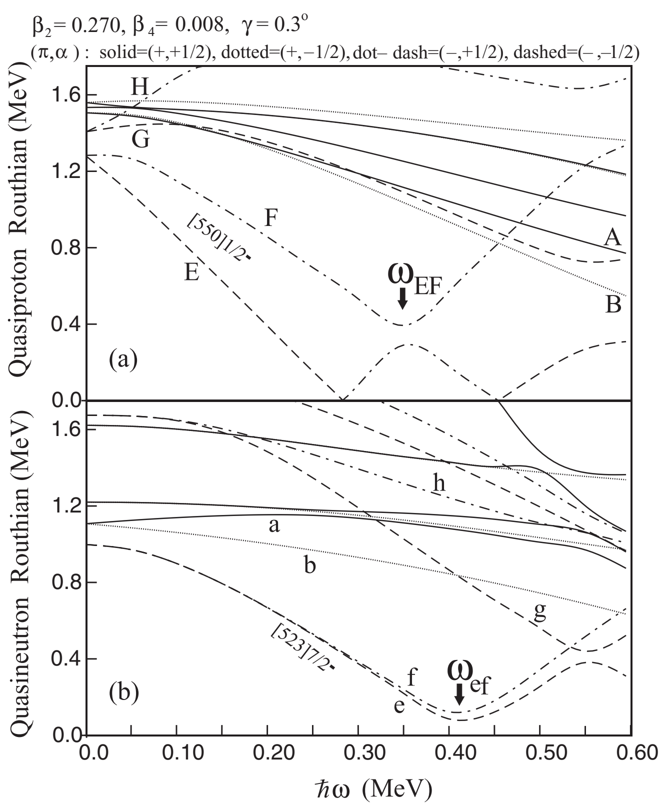

FIG. 3. Cranked shell model calculations for (a) quasiproton and (b) quasineutron Routhians. The deformation parameters shown at the top of the figure are determined by TRS calculations [14–16]. Interpretation of the lines is displayed at the top of the figure.

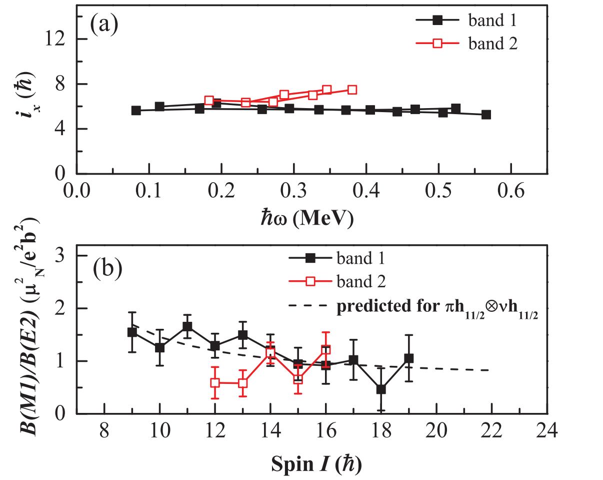

FIG. 4. (Color online) (a) Experimental alignment plots for bands 1 and 2 in ^{126}La. The Harris parameters are $J_0 = 22.7$ MeV$^{-1}\hbar^2$, $J_1 = 16.6$ MeV$^{-3}\hbar^4$ [1]. (b) Comparison of experimental and predicted $B(M1)/B(E2)$ values for bands 1 and 2. Parameters used in the calculations of the predicted values: $Q_0 = 4.63$ e b, $g_R = 0.452$, $g_\pi(h_{11/2}) = 1.17$, $g_\nu(h_{11/2}) = -0.21$, $i_\pi(h_{11/2}) = 5.0$, $i_\nu(h_{11/2}) = 3.0$.

in Fig. 6(a). $S(I)$ of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La clearly indicates that below $I_c = 18.5\,\hbar$, the expected favored signature component ($\alpha = 1$ or odd spin) lies higher in energy than the expected unfavored signature component ($\alpha = 0$ or even spin); and above $I_c = 18.5\ \hbar$, the expected favored signature component ($\alpha = 1$ or odd spin) lies lower in energy than the expected unfavored signature component ($\alpha = 0$ or even spin), i.e., signature inversion occurs below $I_c = 18.5\ \hbar$ in the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La [1]. The I_c of the yrast band in ^{126}La is about 21.5 $\hbar$. For the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La, Fig. 6(b) clearly shows that below $I_c = 18.5\,\hbar$, the expected favored signature ($\alpha = 0$ or even spin) lies lower in energy than the expected unfavored signature component ($\alpha = 1$ or odd spin); and above $I_c = 18.5\,\hbar$, the expected favored signature component ($\alpha = 0$ or even spin) lies higher in energy than the expected

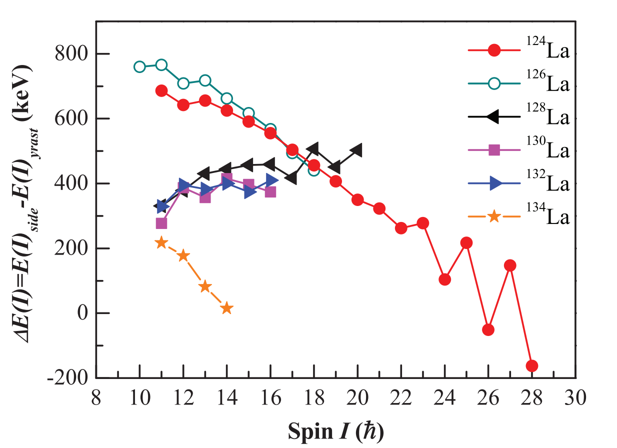

FIG. 5. (Color online) $\Delta E(I) = E(I)_{\rm side} - E(I)_{\rm yrast}$ of the two bands in ^{126}La compared with those in ^{124}La [1], ^{128}La [2], ^{130}La [3], ^{132}La [4], and ^{134}La [5].

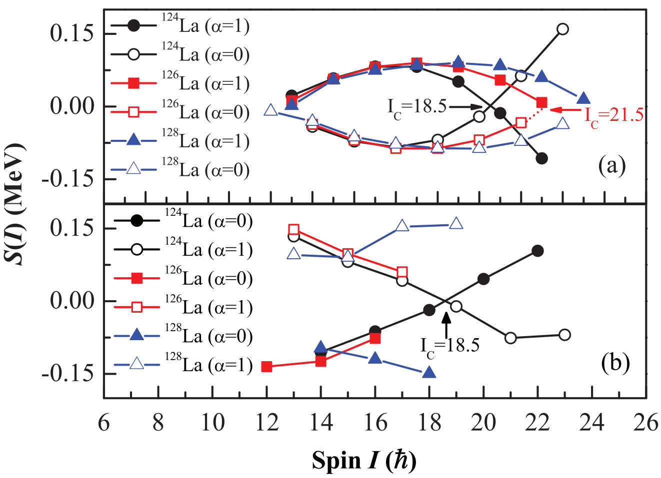

FIG. 6. (Color online) Energy staggering parameter $S(I)$ vs spin I for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in ^{124}La [1], ^{126}La (present work), and ^{128}La [2].

unfavored signature component ($\alpha = 1$ or odd spin), i.e., signature inversion of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La occurs above $I_c = 18.5\ \hbar$, in contrast to that of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band where signature inversion occurs below $I_c = 18.5\ \hbar$. $S(I)$ of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La and ^{128}La [2] is also included in Fig. 6(b). Within the observed spin region, the variation trend of $S(I)$ of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La is very similar to that of the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{124}La and quite different from that of ^{128}La. This fact once again suggests that it is reasonable to interpret the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La as the excited $\pi h_{11/2} \otimes \nu h_{11/2}$ band as proposed in ^{124}La [1] rather than to interpret it as the partner band of a chiral doublet band as done for $^{128-134}$La [2–5]. Finally, this interpretation is also supported by the TRS calculations which predict that ^{126}La has an axial quadrupole deformation, as indicated in Fig. 3, while a triaxial shape is needed for the chiral doublet bands to appear.

In summary, a second $\pi h_{11/2} \otimes \nu h_{11/2}$ band has been identified in ^{126}La through the reaction ^{116}Sn(^{14}N, $4n$)^{126}La at a beam energy of 77 MeV. It is observed that within the observed spin region, the variation trends of $\Delta E(I)$ and $S(I)$ both suggest that it is reasonable to interpret the second $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{126}La as an excited $\pi h_{11/2} \otimes \nu h_{11/2}$ band as proposed for ^{124}La rather than to interpret it as a partner band of near degenerate chiral doublet bands as proposed for $^{128-134}$La.

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