New candidate chiral nucleus in the $A \approx 80$ mass region: $^{82}_{35}Br_{47}$

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A pair of nearly degenerate positive-parity bands were observed in ^{82}Br for the first time using the ^{82}Se(α, $p3n$) reaction. The positive-parity doublet bands are proposed to be chiral doublet bands based on the triaxial particle rotor model and the potential energy surface calculations. The root-mean-square values of the angular momentum components and their probability distributions are discussed in detail to exhibit the chiral geometry and its evolution in ^{82}Br.

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I. INTRODUCTION

Spontaneous chiral symmetry breaking is a phenomenon of general interest not only in nuclear physics but also in other

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fields such as molecular physics, particle physics, biology, and chemistry. Chirality in nuclear physics has become a hot topic since its prediction in 1997 [1]. Spontaneous chiral symmetry breaking can take place in a rotating triaxial nucleus when its valence proton and neutron Fermi surfaces respectively locate in the high-j particle-like (hole-like) and high-j hole-like (particle-like) orbitals. Their total angular momentum vector may not lie along the principal axis or even in the principal plane. In the body-fixed frame, the projections of the angular momentum vector on the three principal axes can form a left- or right-handed system. The restoration of the symmetry in the laboratory frame results in a pair of nearly degenerate $\Delta I = 1$ bands, i.e., chiral doublet bands. Based on constrained triaxial covariant density functional theory (CDFT) calculations [2], it has been suggested that multiple chiral doublet (MχD) bands can exist in a single nucleus [3–8]. To date, the chiral doublet bands, including MχD bands, have been reported in more than 40 nuclei in the $A \approx 80$ [9,10], 100 [11–18], 130 [19–35], and 190 [36–42] mass regions. For details, see recent reviews [43–49] or data tables [50].

The $A \approx 80$ mass region is a newly identified region for the investigation of chiral symmetry breaking in rotating nuclei, with only two reports of chiral doublet bands. A pair of positive-parity doublet bands based on the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration in odd-odd ^{80}Br [9] was reported as the first evidence for chirality in the $A \approx 80$ mass region. The first evidence for MχD bands with octupole correlations was found in ^{78}Br [10], which was based on the $\pi g_{9/2} \otimes \nu g_{9/2}$ and $\pi(f_{5/2}, p_{3/2}) \otimes \nu g_{9/2}$ configurations together with several strong $E1$ transitions. Therefore, it is important to continue exploring the neighboring odd-odd nuclei for a complete definition of Z and N boundaries of the chiral nuclei in the $A \approx 80$ mass region. With a neutron in the hole-like orbital $g_{9/2}$, ^{82}Br is expected to exhibit a better chiral geometry than ^{78}Br and ^{80}Br, as the neutron Fermi surface in ^{82}Br is closer to the top of the $g_{9/2}$ subshell. However, no band structure has been observed in ^{82}Br so far [51]. In this paper, we report the candidate chiral doublet bands in the $N = 47$ odd-odd ^{82}Br nucleus.

II. EXPERIMENTAL DETAILS

The ^{82}Se(α, $p3n$) reaction at beam energies of 65 and 68 MeV was used to populate high-spin states in ^{82}Br. The α beam was delivered by the separated-sector cyclotron (SSC) at iThemba LABS, South Africa. The intensities of the beam were varied in the range 1.8–5.1 nA during the experiment. The target consisted of 0.36 mg/cm^2 ^{82}Se evaporated onto a 0.01 mg/cm^2 ^{12}C backing. Gamma rays were detected using the AFRODITE array [52], which consisted of eight Compton-suppressed clover detectors at the time of the experiment. Four clovers were positioned at 135° with respect to the beam direction, while the other four were placed at 90°. The energy and the efficiency calibrations were performed using a standard ^{152}Eu source. In the experiment, a valid event required that at least two clover detectors fired in prompt coincidence (within ≈180 ns). The average detector rate was ≈1.2×10^4 counts per second. A total of 1.45×10^9 γ-γ coincidences were accumulated during the experiment.

In the offline analysis, the coincidence events were sorted into several symmetric and asymmetric matrices. The γ-ray coincidence relations were established by setting gates on the photopeaks of the individual transitions and projecting the coincidence spectra. Gates were also placed on the background in the vicinity of the photopeaks to remove the contributions due to the background below the photopeaks of the gating transitions. Spin and parity assignments for the observed states were deduced from the measurements of the angular distributions from the oriented states (ADO) [53] and the linear polarization measurements [54]. The ADO ratio was defined as $I_\gamma(135^\circ)/I_\gamma(90^\circ)$. Here the $I_\gamma(135^\circ)$ and I_γ (90°) were the total intensities of the γ-ray of interest observed in the detectors at 135° and 90°, respectively. I_γ (135°) and $I_\gamma(90^\circ)$ were determined under the same gating conditions on the sum of all clover detectors. For the present geometry, an ADO ratio ≈1.3 is expected for the stretched quadrupole transitions and ≈0.8 for the pure stretched dipole ones. The linear polarization measurements were performed using the four clover detectors positioned at 90° relative to the beam direction as Compton polarimeters. At this angle, the linear polarization is directly proportional to the experimental asymmetry A_p [54,55]. By assuming that each clover crystal has equal efficiency, an experimental asymmetry is defined as $A_p = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$. Here $N_\perp$ and $N_\parallel$ were the intensities of the scattered photon perpendicular and parallel to the direction of the reaction plane respectively. Positive A_p values correspond to stretched electric transitions, while negative values correspond to stretched magnetic transitions [54].

III. RESULTS AND DISCUSSION

Prior to the present work, the low-lying states in ^{82}Br had been reported in Refs. [51,56–59]. In Refs. [56–58], the 5^- ground state and the 6^- state at 376.3 keV in ^{82}Br were assigned the $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration. Furthermore, Ref. [51] reported a sequence of positive-parity levels based on the 6^+ state at 966.8 keV and assigned the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration to those levels.

A partial level scheme of ^{82}Br deduced from the present work is shown in Fig. 1. The present work confirms the previous known positive-parity sequence in Ref. [51] and extends it up to (14^+). In addition, a new band labeled as band 2 as well as several interband transitions is observed. A total of 25 new transitions and 13 new levels are added to the level scheme of ^{82}Br. Figure 2 shows the γ-ray coincidence spectrum generated from the sum of gates on 100.8, 191.9, and 966.8 keV transitions, which supports the construction of the present level scheme. All the transitions in ^{82}Br can be clearly seen from Fig. 2. The angular distributions and the linear polarization measurements of the γ rays have been performed to establish the spin and parity assignment of the levels in ^{82}Br. For example, band 2 feeds into the 6^+ state of band 1 through a 321.9 keV linking transition. The measured ADO ratio and the A_p value of the 321.9 keV transition are 0.95(0.08) and −0.05(0.01), respectively. These values indicate that the 321.9 keV linking transition has a $M1/E2$ character. We therefore assigned the spin and parity 7^+ for the

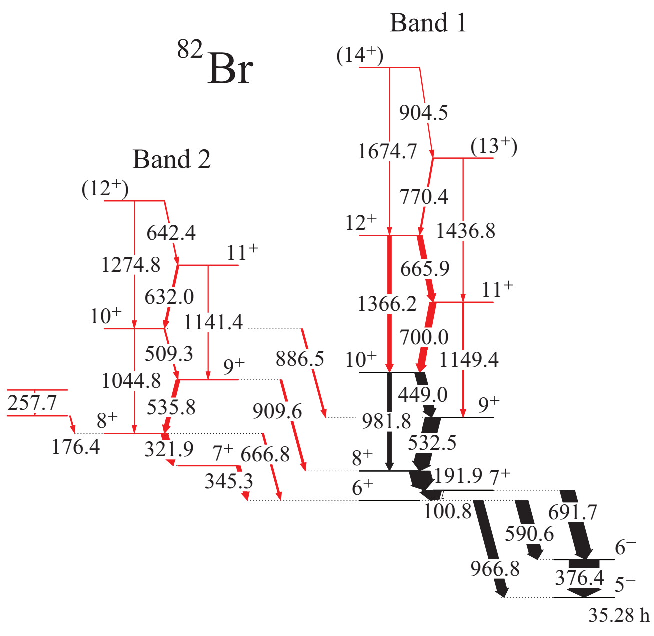

FIG. 1. Partial level scheme of ^{82}Br deduced from the present work. New transitions and levels are in red.

lowest observed state of band 2. The spin assignments for the initial and final states, transition energies, relative intensities, measured ADO ratios, and A_p values of the γ rays in ^{82}Br are listed in Table I.

In Ref. [51], the positive-parity level sequence has been assigned the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration. The same configuration had been assigned to the yrast positive-parity bands in the neighboring odd-odd nuclei in the $A \approx 80$ mass region [9,10,60–66]. The yrast positive-parity bands in the neighboring odd-A nuclei ^{81}Br [51] and ^{81}Kr [67] were also assigned the $\pi g_{9/2}$ and $\nu g_{9/2}$ configurations, respectively. Based on the considerations above, the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration is

TABLE I. The spin assignments for the initial and final states, energies, relative intensities, the measured ADO ratios, and the experimental asymmetries of the γ rays in ^{82}Br. The γ-ray energies are accurate to $\pm$ 0.5 keV.

E_γ (keV)	$I_i^\pi \rightarrow I_f^\pi$	I_γ	ADO ratio	A_p
100.8	$7^+ \rightarrow 6^+$	54.9(5.1)		
176.4	$\rightarrow 8^+$	3.8(0.3)		
191.9	$8^+ \rightarrow 7^+$	67.2(4.7)	0.97(0.09)	
257.7		2.1(0.2)		
321.9	$7^+ \rightarrow 6^+$	22.8(1.8)	0.95(0.08)	−0.05(0.01)
345.3	$8^+ \rightarrow 7^+$	13.8(1.3)	0.95(0.09)	−0.07(0.01)
376.4	$6^- \rightarrow 5^-$	100.0(7.0)	1.03(0.11)	−0.09(0.01)
449.0	$10^+ \rightarrow 9^+$	32.7(2.3)	0.93(0.10)	−0.16(0.02)
509.3	$10^+ \rightarrow 9^+$	4.5(0.3)	0.87(0.09)	
532.5	$9^+ \rightarrow 8^+$	51.3(3.6)	0.96(0.08)	−0.08(0.01)
535.8	$9^+ \rightarrow 8^+$	13.6(1.0)	0.97(0.10)	−0.08(0.01)
590.6	$6^+ \rightarrow 6^-$	42.4(3.0)	1.32(0.13)	0.06(0.01)
632.0	$11^+ \rightarrow 10^+$	7.2(0.6)	0.80(0.09)	
642.4	$(12^+) \rightarrow 11^+$	3.3(0.2)		
665.9	$12^+ \rightarrow 11^+$	18.4(1.3)	0.89(0.09)	−0.08(0.01)
666.8	$8^+ \rightarrow 6^+$	6.1(0.5)	1.22(0.13)	
691.7	$7^+ \rightarrow 6^-$	48.2(3.4)	0.82(0.09)	0.05(0.01)
700.0	$11^+ \rightarrow 10^+$	22.5(1.6)	0.87(0.09)	−0.09(0.01)
770.4	$(13^+) \rightarrow 12^+$	4.8(0.4)		
886.5	$10^+ \rightarrow 9^+$	5.9(0.4)	0.86(0.08)	−0.13(0.03)
904.5	$(14^+) \rightarrow (13^+)$	2.0(0.3)		
909.6	$9^+ \rightarrow 8^+$	7.4(0.5)	0.74(0.07)	−0.05(0.01)
966.8	$6^+ \rightarrow 5^-$	32.4(2.3)	0.83(0.06)	0.05(0.01)
981.8	$10^+ \rightarrow 8^+$	14.4(1.0)	1.43(0.13)	0.13(0.02)
1044.8	$10^+ \rightarrow 8^+$	⩽1.5		
1141.4	$11^+ \rightarrow 9^+$	1.7(0.2)		
1149.4	$11^+ \rightarrow 9^+$	5.0(0.4)		
1274.8	$(12^+) \rightarrow 10^+$	⩽1.5		
1366.2	$12^+ \rightarrow 10^+$	12.5(1.0)	1.45(0.15)	0.12(0.02)
1436.8	$(13^+) \rightarrow 11^+$	1.9(0.2)		
1674.7	$(14^+) \rightarrow 12^+$	1.6(0.2)		

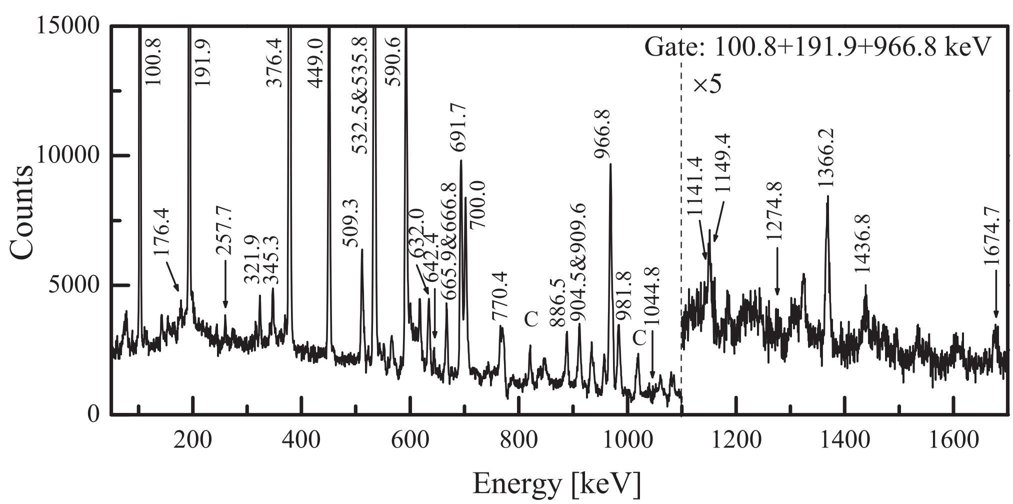

FIG. 2. The γ-ray coincidence spectrum generated from the sum of gates on 100.8, 191.9, and 966.8 keV transitions. The peaks labeled C indicate contaminations.

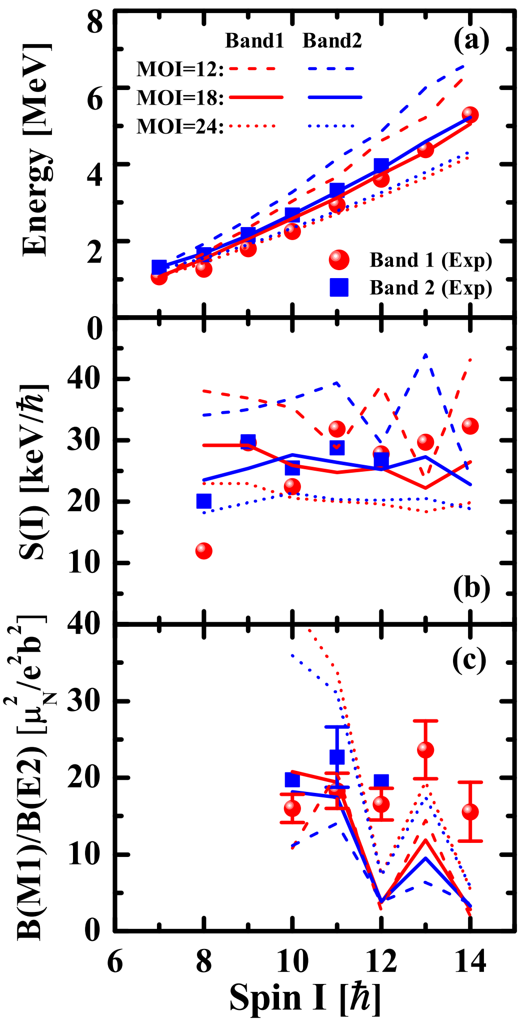

FIG. 3. Experimental excitation energies for the nearly degenerate bands (a), the energy staggering parameter $S(I) = [E(I) - E(I-1)]/2I$ (b), and experimental $B(M1)/B(E2)$ ratios (c) as a function of spin for the nearly degenerate bands in ^{82}Br in comparison with the TPRM results. The dashed, solid, and dotted lines represent the calculated results with varying moment of inertia: 12, 18, and 24 $\hbar^2$/MeV, respectively.

the most favored configuration for band 1 in ^{82}Br. In order to discuss the observed doublet bands in ^{82}Br, the excitation energies $E(I)$, energy staggering parameters $S(I) = [E(I) - E(I-1)]/2I$, and $B(M1)/B(E2)$ ratios for the doublet bands are plotted in Fig. 3 as a function of spin. As shown in Fig. 3, the doublet bands in ^{82}Br have small energy differences and almost identical $B(M1)/B(E2)$ ratios. The $S(I)$ values are independent of spin after $8\hbar$. Moreover, the $B(M1)/B(E2)$ ratios for the doublet bands show clearly odd-even staggering as a function of spin. These behaviors are consistent with the fingerprints of the chiral doublet bands [68,69]. Thus, the positive-parity doublet bands in ^{82}Br are suggested as chiral doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration.

To examine the existence of nuclear chirality in ^{82}Br, calculations based on a combination of the tilted axis cranking (TAC) approach [70,71] and the triaxial particle rotor model (TPRM) [72–76] have been performed. The TAC approach is employed to calculate the potential energy surface (PES) of ^{82}Br. The deformation parameters $(\beta_2, \gamma) = (0.31, 33^\circ)$ are obtained in the PES calculations for the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration and then adopted as inputs of the TPRM calculations. The moment of inertia is the only variable parameter in the present TPRM. All the other parameters in TPRM were fixed following those in Refs. [72–75,77] and the Coriolis attenuation factor was set to 0.7. The calculated excitation energies $E(I)$, energy staggering parameters $S(I)$, and $B(M1)/B(E2)$ ratios for the doublet bands with the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration in ^{82}Br are presented in Fig. 3 in comparison with the corresponding experimental data. To show the robustness of the calculations, calculations with varying moment of inertia (12, 18, and 24 $\hbar^2$/MeV) are also presented in Fig. 3. As shown in Fig. 3(a), the energy spectra for the doublet bands were reproduced when the moment of inertia 18 $\hbar^2$/MeV was used. With moment of inertia deviating from 18 $\hbar^2$/MeV, the calculated results deviate from the experimental values. For the calculated results with moment of inertia 18 $\hbar^2$/MeV, the small energy differences between bands 1 and 2 are reasonably reproduced, as well as the magnitude of the $S(I)$ and $B(M1)/B(E2)$ ratios. The staggering phase of the calculated $B(M1)/B(E2)$ ratios for the doublet bands also agrees with the experimental one. The agreement between the calculated values and the corresponding experimental data supports the present configuration assignment. The deviation from the data for the $S(I)$ and $B(M1)/B(E2)$ ratios in the high spin region might be attributed to the neglect of the deformation change with increasing rotational frequency in the TPRM calculations.

To exhibit the chiral geometry in ^{82}Br, the root-mean-square values of the angular momentum components for the core $R_k = \sqrt{\langle \hat{R}_k^2 \rangle}$, the valence proton $J_{pk} = \sqrt{\langle \hat{j}_{pk}^2 \rangle}$, and the valence neutron $J_{nk} = \sqrt{\langle \hat{j}_{nk}^2 \rangle}$ of the doublet bands are calculated and compared with those of ^{78}Br [10] and ^{80}Br [9] in Fig. 4, in which $k = i, l, s$ represent the intermediate, long, and short axes, respectively. References [1,73,78–80] suggested that, for an ideal case of chiral geometry, the angular momenta of the valence proton, the valence neutron, and the core rotation are mutually perpendicular, i.e., the valence proton, the valence neutron, and the core mainly align their angular momenta along the short, long, and intermediate axes, respectively. As shown in Figs. 4(a) and 4(b), the angular momentum of the core and J_p in ^{78}Br and ^{80}Br mainly lie along the intermediate and the short axes respectively. Meanwhile, the orientations of J_n show a large mixture between the three axes. It indicates that the coupling pattern of angular momenta in ^{78}Br and ^{80}Br deviates from the ideal chiral geometry. In fact, Ref. [9] has interpreted the chiral doublet bands in ^{80}Br as chiral vibration based on the analysis of the angular momentum orientations and the probability distributions. As shown in Fig. 4(c), the coupling pattern of the angular momentum in ^{82}Br is closer to an ideal case of chiral geometry than those in ^{78}Br and ^{80}Br. Based on the present calculations, the addition of the $g_{9/2}$ neutrons in ^{82}Br leads to the stabilization of chirality.

In order to understand the evolution of the chiral geometry with angular momentum for the candidate chiral doublet bands in ^{82}Br, we calculated the probability distributions for

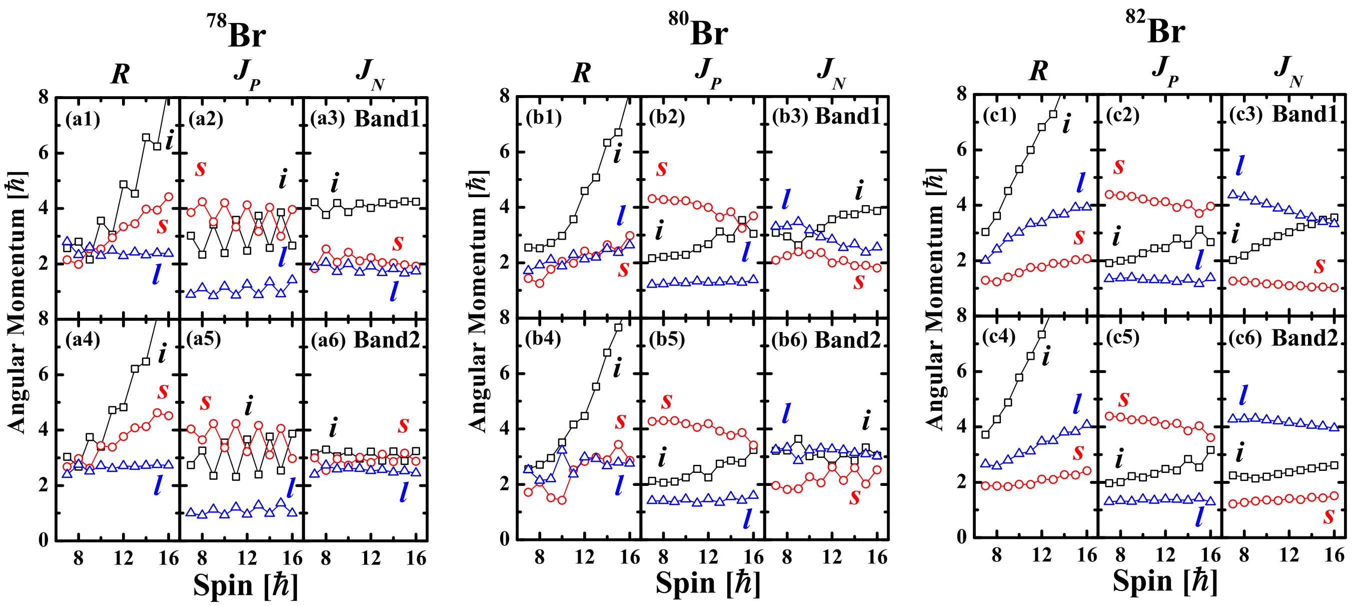

FIG. 4. The root-mean-square components along the intermediate (i, squares), short (s, circles), and long (l, triangles) axes of the core, valence proton, and valence neutron angular momenta calculated as functions of spin I by means of the TPRM for the positive-parity doublet bands in ^{78}Br (a1)–(a6), ^{80}Br (b1)–(b6), and ^{82}Br (c1)–(c6).

the projection of the total angular momentum along the l, i, and s axes [81,82]. The calculated results are illustrated in Fig. 5. For the present TPRM, the total wave function can be expanded into the strong coupling basis $|IM\rangle = \sum_{K\varphi} c_{K\varphi}|IMK\varphi\rangle$. The expression of $|IMK\varphi\rangle$ was given in Ref. [81]. The probability for the projection K of total angular

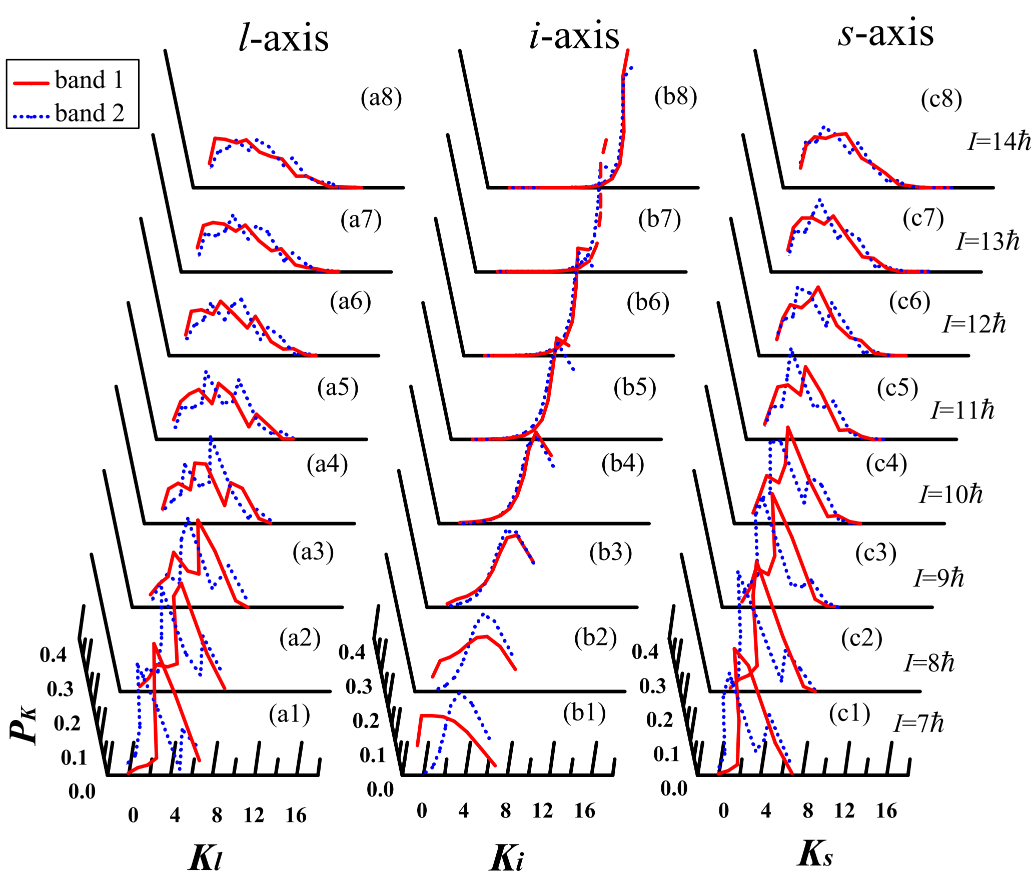

FIG. 5. The probability distributions for projection of total angular momentum on the long (l), intermediate (i) and short (s) axes in TPRM for the doublet bands in ^{82}Br.

momentum on the quantization axis is $P_k = \sum_{\varphi} |c_{K\varphi}|^2$ [81,82]. For triaxiality parameter $\gamma = 33^\circ$, the l axis is used for quantization. The distributions with respect to the s and the i axes are obtained by replacing γ with $\gamma + 120^\circ$ and $\gamma - 120^\circ$ respectively. As shown in Fig. 5(a1-a8, b1-b8, c1-c8), for $I = 7$ and $8\hbar$, the K_i of two bands is different from each other. For band 1, the maximum probability for the i axis appears at $K_i = 0$. However, the probability for band 2 is zero at $K_i = 0$; its peak appears at $K_i = 4$. It indicates an oscillation through the s-l plane and reveals the structure of the chiral vibration. For $9\hbar \leqslant I \leqslant 12\hbar$, the maximum K probabilities for the two bands along the three axes are comparable, which means the orientation of the angular momentum deviates from the s-l plane and aplanar rotation occurs. Moreover, the K probability distributions of the doublet bands are similar to each other. These features imply the appearance of static chirality in ^{82}Br. For $I \geqslant 13\hbar$, the K probability distributions of the doublet bands along the i axis are much larger than those along the l and s axes. A competition between an aplanar rotation and a rotation around the i axis might exist in ^{82}Br. Based on the present calculations, there might be a change from a chiral vibration at $7\hbar \leqslant I \leqslant 8\hbar$ to a static chirality at $9\hbar \leqslant I \leqslant 12\hbar$, and a competition between the aplanar rotation and the rotation around i axis at higher spins in ^{82}Br.

IV. CONCLUSION

High-spin states in ^{82}Br have been studied via in-beam γ spectroscopy techniques using the ^{82}Se(α, $p3n$) reaction. A pair of positive-parity doublet bands was observed for the first time and interpreted as chiral doublet bands. The interpretation was supported by the triaxial particle rotor model and the potential energy surface calculations. The calculated coupling pattern of the angular momentum suggests that the chiral geometry in ^{82}Br is more stable than those in ^{78}Br and ^{80}Br. Further probability distribution calculations show that the chiral geometry at $9\hbar \leqslant I \leqslant 12\hbar$ is approximate to the static chirality in ^{82}Br. The present work indicates that the border of the chiral nuclei in the $A \approx 80$ mass region can reach $N = 47$ when the neutron number approaches $N = 50$.

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