Candidate chiral twin bands in the odd-odd nucleus ^{132}Cs: Exploring the limits of chirality in the mass $A\approx130$ region

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High-spin states in the doubly odd $N=77$ nucleus ^{132}Cs have been studied. The known positive-parity structures have been extended. γ-ray linear-polarization and angular-correlation measurements have been performed to establish the spin and parity assignment of these structures. A new chiral partner of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band has been proposed. Three-dimensional tilted axis cranking model calculations have been performed and compared with the experimental results.

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Chirality is a recently proposed symmetry of nuclear rotation [1]. A spontaneous breaking of chiral symmetry can take place at low spin for odd-odd nuclei when the Fermi level is located in the lower part of proton (neutron) high-j (particlelike) and in the upper part of neutron (proton) high-j (holelike) subshells, and the core is essentially triaxial. The angular momenta of the valence particles are then aligned along the short and long axes of the triaxial core, while the angular momentum of the rotational core is aligned along the intermediate axis. These three mutually perpendicular angular momenta form either a left-handed or a right-handed combination [2]. Consequently, the total angular momentum $\vec{I}$ is tilted with respect to the planes defined by the principal axes of the nucleus and has handedness introducing chirality. The experimental fingerprint for such chiral symmetry breaking is the existence of two nearly degenerate $\Delta I=1$ bands of the same parity, which are called chiral twin bands.

Chiral twin bands have been proposed in several $N=73$ [3] and $N=75$ [4–6] isotones, revealing a small island of chiral rotation centered around ^{134}Pr. All these bands are built on the $\pi h_{11/2}\otimes \nu h_{11/2}$ configuration. A near energy degeneracy is only observed for high-spin states of the twin bands in ^{134}Pr [4]. The chiral partners in other twin bands are separated by a few hundred keV. This energy difference has been understood as a consequence of a weaker violation of the chiral symmetry, the so called chiral vibration [7–9].

Despite the experimental effort concentrated on the island of chirality in the $A\approx130$ region it is still not completely clear whether the phenomenon persists for nuclei closer to $N=82$. This question is directly related to the nature of the interaction which produces the perpendicular coupling of the valence (quasi)particles. In well deformed nuclei, due to the attractive nature of the nuclear force between the core and the valence particles, the perpendicular coupling minimizes the total energy when one quasiparticle has a particle character, while the other has a hole character. However, when the deformation decreases, e.g., when the spherical limit is approached, the core-particle interaction plays a small role and the conditions for breaking the chiral symmetry are barely achieved. On the other hand, the proton-neutron interaction between valence particles and holes is repulsive and favors an angle of 90° between their angular momenta [10]. Then, if the weakly deformed core is still triaxial the chiral symmetry could be broken. However, when approaching the $N=82$ shell closure the expected shapes are "soft" with respect to deformation. This allows excitations, based on different deformations or different rotational modes, to become competitive as not all of them will necessarily preserve the chiral arrangement. The balance between the particle-(deformed)core and the particle-hole interactions along with the triaxial shape determines the existence and the stability of the chiral coupling. The study of $N=77$ isotones may allow us to address these questions. The twin bands reported in ^{134}La$_{77}$ [11] almost reach degeneracy at spin 14^+ but the sideband is not clearly developed and no chiral twin bands are reported in other $N=77$ isotones. Very recently, Koike *et al.* have identified two nonyrast positive-parity structures in ^{132}Cs [12] but the fact that they are not well developed has not allowed either of them to be included in the systematic study of the $\pi h_{11/2}\otimes \nu h_{11/2}$ chiral doublet bands in the chain of cesium isotopes. In this paper, we present evidence for chiral twin bands in ^{132}Cs which confirms the phenomenon of chiral rotation in the $N=77$ isotones.

Excited states in ^{132}Cs were populated in the ^{124}Sn(^{13}C,$4n1p$) reaction at a beam energy of 75 MeV. A

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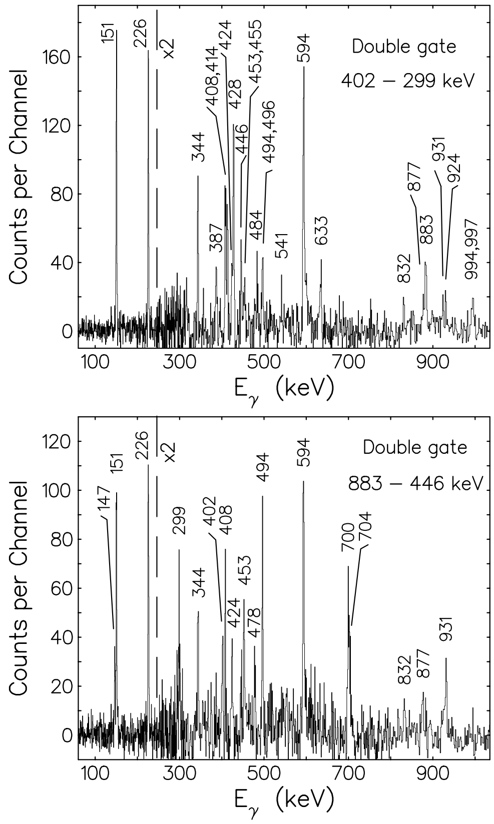

FIG. 1. Examples of doubly gated γ-ray coincidence spectra. Peaks labeled with their energy in keV are assigned to ^{132}Cs.

self-supporting ^{124}Sn target enriched to 99.96% with a thickness of 500 μg/cm^2 was used. The ^{13}C beam was provided by the VIVITRON electrostatic accelerator at IReS, Strasbourg. γ rays were recorded in prompt coincidence with the EUROBALL IV spectrometer [13]. In addition to the Ge detectors EUROBALL IV was equipped with an ''inner ball'' BGO calorimeter, comprising 110 elements, serving as a multiplicity filter. Evaporated charged particles were detected with the silicon ball EUCLIDES consisting of 40 $\Delta E - E$ telescopes [14]. Events were accepted when at least four Ge detectors and at least 12 BGO elements fired. A total of 2×10^9 events of mean γ-ray fold 3.8 were collected of which $\approx$1% were associated with the emission of one proton. The γ rays in coincidence with one proton emission were sorted into an E_γ-E_γ-E_γ cube and analyzed with the RADWARE [15] programs. Sample coincidence γ-ray spectra are shown in Fig. 1.

The events associated with one-proton emission were also used for γ-ray angular-correlation and linear-polarization analysis. To deduce the multipole order of γ rays, angular-intensity ratios, based on the directional correlation formalism [16], were analyzed. For this purpose, γ-γ coincidences between detectors placed at backward angles ($\Theta_{av}=156°$) and detectors placed close to 90° ($\Theta_{av}=90°$) were sorted into an E_γ-E_γ matrix. Coincidence intensities of transitions were extracted from this matrix and used to calculate ratios $R=I_\gamma(\Theta_{av}^{gate}=90°,\ \Theta_{av}^{spectrum}=156°)/I_\gamma(\Theta_{av}^{gate}=156°,\ \Theta_{av}^{spectrum}=90°)$. An angular intensity ratio of 1.0 is expected if the gating and observed transitions are pure stretched transitions with the same multipole order. For the present detector geometry, a value of 0.54 is expected for a pure dipole transition gated on a stretched quadrupole transition. A value of 1.85 is expected for a $\Delta I=2$ transition using a gate on a $\Delta I=1$ transition. The linear polarization of the γ rays was measured using the 24 clover detectors as Compton polarimeters [17]. Two γ-γ matrices were sorted with one axis corresponding to a single hit in any detector and the second axis corresponding to double-hit scattered event. One matrix contains events scattered parallel to the reaction plane, while the other contains the perpendicular scattered events. The experimental linear polarization is defined as $P=(1/Q)(N_\perp - N_\parallel)/(N_\perp + N_\parallel)$, where $N_\perp$ ($N_\parallel$) are the number of added-back photopeak counts scattered in the perpendicular (parallel) reaction plane and Q is the polarization sensitivity of the clover detectors [17]. Positive linear-polarization values correspond to stretched electric transitions, while negative values correspond to stretched magnetic transitions. The results from these measurements for γ rays connecting positive-parity states in ^{132}Cs are listed in Table I.

A partial level scheme of ^{132}Cs deduced from the present experiment is shown in Fig. 2. In the first in-beam study of ^{132}Cs, Hayakawa *et al.* [18] identified five structures and three of them are suggested to be built on two quasiparticle excitations involving the $\pi h_{11/2}$ orbital coupled to $\nu d_{5/2}$, $\nu g_{7/2}$, $\nu h_{11/2}$ orbitals, respectively. Later on Liu *et al.* [19] suggested from smooth systematic trends of energy levels in Cs nuclei that the $\pi h_{11/2}\otimes\nu h_{11/2}$ band is built on an $I^\pi = 9^+$ state. In the present work we have considerably extended this structure (band 2 in Fig. 2) up to spin 19$^+$. A second $\Delta I=1$ band (band 3 in Fig. 2) is built on the 1729-keV level. The angular-intensity ratio of the 447.3-keV transition (see Table I) suggests that the lowest possible spin of this level is 10. In Ref. [12] the proposed sideband comprised the 162-keV, 310-keV, 167-keV, and 541-keV transitions, forming an irregular structure. Moreover, the 13$^+$ state of this structure lies 41 keV below the 13$^+$ state of the main band (band 2 in Fig. 2) which is a deviation from the smooth systematic trends of energy levels of the chiral partners in the chain of cesium isotopes [12]. In the present study, we were able to observe a new $\Delta I=1$ transition of energy 378.2 keV on top of the 2515-keV level, which together with the 313.8-keV transition more likely form the continuation of the sideband. The spectra in Fig. 1 clearly demonstrate the placement of the 483.6-keV transition which connects the 2894-keV level to the 13$^+$ state in band 2. The 483.6-keV, 518.0-keV, and 609.3-keV $\Delta I=1$ transitions have negative γ-ray linear-polarization values (see Table I), confirming the tentatively proposed positive-parity assignment for these levels in Ref. [12]. Hence, bands 2 and 3 are positive-parity bands, which are linked by $\Delta I=1$, $M1/E2$ transitions. The existence of the $M1/E2$ transitions between bands 3 and 2 strongly suggests that band 3 is built on the same unique parity orbitals as band 2—as argued in Refs. [3,7], due to the selection rules for $M1$ and $E2$ operators, the only possible configuration for band 3 is $\pi h_{11/2}\otimes\nu h_{11/2}$.

Along with the states of bands 2 and 3 up to spin 14$^+$ there is a set of states with the same spin parity: 11$^+$ at 1835

TABLE I. Measured properties of the γ-ray transitions between positive-parity states in ^{132}Cs.

E_γ (keV)	I_γ [a]	R_{dco} Q [b]	R_{dco} D [c]	Linear polarization
146.8(3)	13.8(8)			
150.5(3)	79.3(25)	0.63(5)		
152.7(4)	25.0(6)			
162.0(6)	1.7(3)		0.91(14)	
167.2(3)	5.2(5)		1.10(18)	
298.5(4)	7.9(9)		1.05(6)	−0.43(16)
304.4(4)	10.1(6)	0.46(9)		−0.32(24)
310.3(4)	7.0(6)		0.96(14)	−0.40(25)
313.8(5)	2.9(5)		0.83(20)	
343.6(3)	19.2(9)	0.61(7)		
360.6(2)	3.0(5)			
378.2(4)	2.5(6)		0.86(26)	
386.7(4)	8.5(8)	0.48(9)		
401.6(3)	27.0(7)	0.54(9)		−0.61(12)
407.8(3)	40.0(8)		1.70(9)	0.64(24)
413.7(4)	11.7(6)	0.94(9)	1.59(17)	0.65(42)
422.1(3)	8.0(3)			
424.0(4)	1.7(3)			
428.0(3)	15.4(8)	0.62(9)		−0.32(16)
445.5(4)	10.7(5)	0.50(7)		−0.88(34)
447.3(4)	2.1(4)		1.8(5) [d]	
452.9(5)	4.3(8)	0.57(9)		−0.42(15)
455.1(5)	3.4(7)	0.68(17)		−0.41(28)
478.0(4)	2.1(4)	0.48(10)		
483.6(3)	3.4(7)	0.69(15)		−0.26(21)
494.1(3)	14.4(6)	0.58(8)		0.26(15)
496.4(2)	8.9(9)		1.02(9)	−0.26(18)
518.0(4)	4.3(8)		1.20(21)	−0.36(22)
541.0(3)	4.0(9)	0.52(15)		
553.3(4)	16.2(8)		1.04(7)	−0.51(23)
593.8(2)	85.0(20)	0.59(4)		0.24(9)
609.3(4)	5.2(9)		0.96(9)	−0.35(19)
633.3(4)	19.2(8)	0.53(9)		
700.1(4)	27.1(7)	0.99(8)		0.60(31)
703.8(2)	22.7(6)	1.23(15)		0.59(27)
706.0(4)	15.7(9)	1.11(20)		0.55(27)
726.5(4)	4.7(8)		1.7(3)	
730.2(3)	9.8(11)			
759.8(5)	1.0(3)			
826.1(4)	5.6(7)	0.79(11)		
832.1(3)	4.8(6)	1.2(2)		
876.9(4)	2.0(6)	1.31(26)		
883.1(3)	9.9(8)	0.92(9)		0.51(26)
900.6(4)	8.2(9)	1.02(7)		0.66(33)
923.6(4)	4.1(7)	1.10(10)		0.65(38)
930.9(4)	7.3(6)	1.22(13)		0.53(13)
993.8(3)	26.2(7)	0.91(17)		0.65(24)
996.8(3)	14.4(6)	1.27(21)		0.40(22)
1310.2(3)	4.2(8)	1.06(14)		

[a]Relative γ-ray intensity normalized to 100% for the 225.9-keV transition ($8^- \rightarrow 7^-$).
[b]Angular-intensity ratios obtained by gating on stretched quadrupole transitions.
[c]Angular-intensity ratios obtained by gating on stretched dipole transitions.
[d]Angular-intensity ratios for nonstretched $\Delta I = 1$ transitions are the same as for $\Delta I = 2$ transitions.

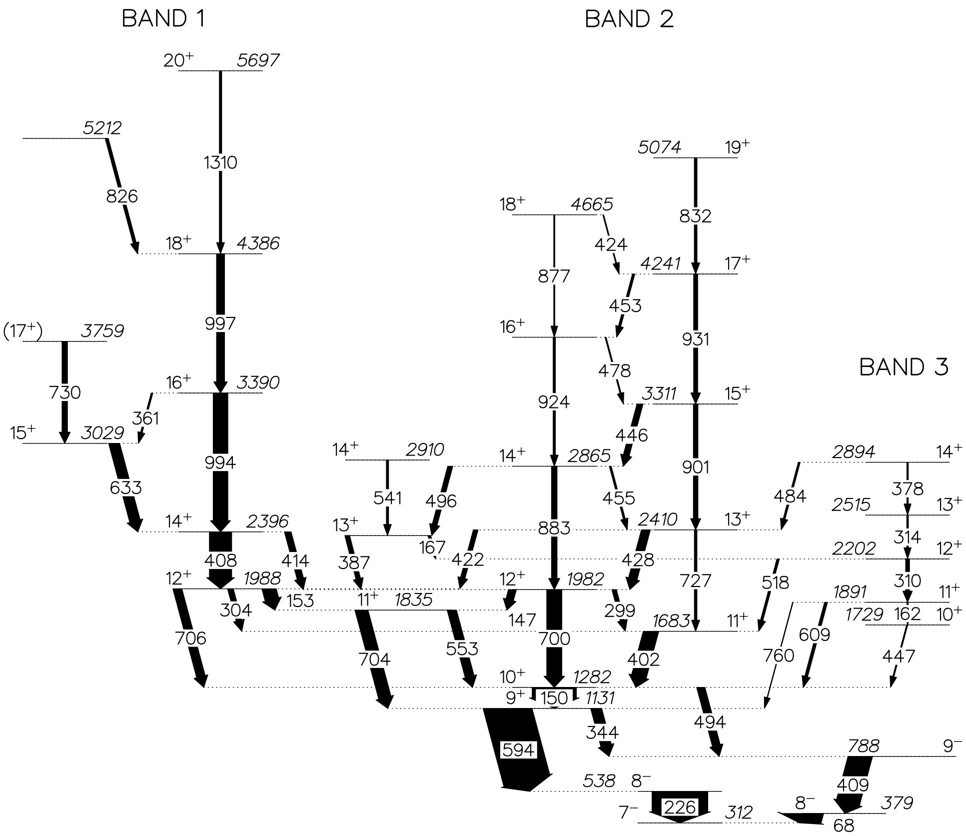

FIG. 2. Partial level scheme of ^{132}Cs showing the decay of positive-parity states. The energies of the γ transitions and of the levels are given in keV. The thickness of the arrows are proportional to the γ-ray intensities.

keV, 12^+ at 1988 keV, 13^+ at 2369 keV, and 14^+ at 2910 keV (see Fig. 2). These states do not form a certain structure but they are connected with $M1/E2$ and $E2$ transitions either to the main $\pi h_{11/2} \otimes \nu h_{11/2}$ band (band 2) or the side band (band 3). Moreover, the energies of these states are between the energies of corresponding states in the main and the sideband, except the 13^+ state at 2369 keV which is the lowest 13^+ state. Altogether, these observations suggest that these states may be built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration at different deformation, reflecting the fact that the nuclear potential for $N=77$ nuclei is more soft than for $N=73$ and $N=75$ isotones.

In contrast with the lighter cesium isotones the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration is not yrast in ^{132}Cs$_{77}$. Above spin 12^+ band 1 (see Fig. 2) is the yrast structure. This resembles the level scheme of ^{134}La where a similar band, which is associated with the $\pi g_{7/2} \otimes \nu g_{7/2} h^2_{11/2}$ structure, becomes yrast in the spin region between 14^+ and 18^+ [11]. Analogously, we have adopted the same configuration for band 1 in ^{132}Cs but further experimental information is certainly needed in order to corroborate this assignment.

Band 3 is built on top of a 10^+ level, which is 447 keV above the 10^+ level of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band (band 2). With increasing spin the states of these bands approach each other as shown in Fig. 3. The energy difference between states with spin 14 is only 29 keV. This behavior rules out the possible interpretations of band 3 as built either on the unfavored signature of the $\pi h_{11/2}$ orbital, or on a γ-phonon excitation. Neither scenarios can explain the decreasing energy difference between bands 2 and 3. Moreover, the γ-vibrational energies in this region are above 600 keV [20], while principal axis cranking calculations [21] for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration in ^{132}Cs predict that the splitting between the favored and unfavored signatures of the $\pi h_{11/2}$ orbital is larger than 1 MeV for rotational frequencies higher than 100 keV/$\hbar$ and increases with spin. The behavior presented in Fig. 3 resembles the gradual transition from weaker chiral symmetry breaking at low spin (small contribution of collective rotation) to stronger chiral symmetry breaking at high spin (large contribution of collective rota-

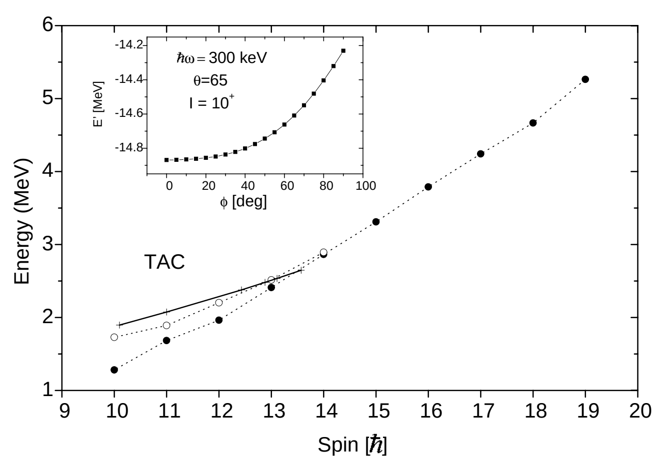

FIG. 3. Experimental energies vs spin for band 2 (filled symbols) and band 3 (open symbols) in ^{132}Cs (cf. Fig. 2). The 3D TAC energies for the chiral $\pi h_{11/2} \otimes \nu h_{11/2}$ solution with no pairing included in ^{132}Cs are shown by the solid line. The inset presents the dependence of the total routhian on the tilt angle φ when the pairing is included in the calculations.

TABLE II. The results of 3D TAC calculations with no pairing included for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration in ^{132}Cs. The deformation parameters used were $\varepsilon_2 = 0.161$, $\varepsilon_4 = 0.003$, and $\gamma = 36°$. These were obtained as self-consistence values at $\hbar\omega = 185$ keV.

$\hbar\omega$ (keV)	ϑ (deg)	φ (deg)	I ($\hbar$)	$B(M1)/B(E2)$ $(\mu_N/e\text{ b})^2$
185	55	10.3	10.09	195.1
200	60	29.2	11.02	32.0
225	65	40.6	12.43	11.7
235	65	42.7	12.88	10.9
240	65	43.7	13.11	10.5
250	65	45.5	13.57	9.9

tion). In order to check this hypothesis we have carried out two types of three-dimensional tilted axis cranking (3D TAC) calculations [2]. In these calculations the orientation of the total angular momentum with respect to the principal axes of the triaxial core ($\gamma \approx 30°$) is defined by two polar angles ϑ and φ [2], the so called tilt angles.

Calculations with pairing included did not produce a stable chiral solution; the energy in the intrinsic frame has well a defined minimum for the tilt angle $\vartheta \approx 65°-70°$, but its dependence on the tilt angle φ for angles up to about 30° is flat and very weak (see the inset in Fig. 3). This is indicative of large amplitude chiral vibrations, but the present status of the TAC model does not include the projection of the chiral symmetry before the variation, which could be a technique capable of describing such excitation modes.

Unpaired calculations did however produce a chiral band, as summarized in Table II and Fig. 3. This approximation is based on the fact that the pairing correlations are small in odd-odd nuclei close to shell closures. An aplanar solution (both tilt angles ϑ and φ are different from 0° and 90°, see Table II) for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration was found over a short spin (frequency) interval (see Fig. 3). The calculations predicted the requisite triaxiality ($\gamma = 36°$) but a moderate quadrupole deformation ($\varepsilon_2 = 0.16$) which makes the chiral geometry unstable. This explains the shortness of the observed partner band.

Experimental $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios of reduced transition probabilities for band 2 are presented in Fig. 4(a). They have a similar magnitude to the ratios deduced for the other chiral bands in the chain of $_{55}$Cs isotopes and also exhibit a clear staggering with spin [12]. The calculated ratios (see Table II) reproduce the overall decreasing trend up to spin 14 but overestimate the average experimental ratios by a factor 3–5. On the other hand it is known that the calculated $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios should be compared with the averaged ratios for the two chiral partners, since the 3D TAC model calculation cannot account for these observables in one partner band only [2]. In the framework of the core-quasiparticle coupling model it has been shown [12] that the restrictions imposed on wave functions by the chiral geometry lead to a typical behavior: the $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios in the main partner band exhibit staggering, which is in phase with the staggering in $B(M1;I\rightarrow I-1)_{in}/B(M1;I\rightarrow I-1)_{out}$ ratios in the side band [12]. This criterion for the existence of a chiral geometry is well fulfilled in ^{132}Cs, i.e., the experimental $B(M1;I\rightarrow I-1)_{in}/B(M1;I\rightarrow I-1)_{out}$ ratios for band 3 [Fig. 4(b)] exhibit well pronounced staggering, which is in phase with the staggering in the $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios [Fig. 4(a)].

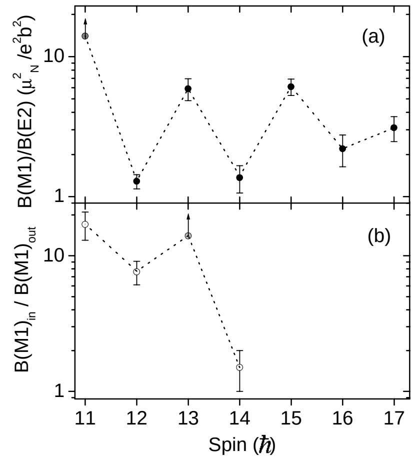

FIG. 4. (a) Measured $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios for band 2 in ^{132}Cs. (b) Measured $B(M1;I\rightarrow I-1)_{in}/B(M1;I\rightarrow I-1)_{out}$ ratios for band 3 in ^{132}Cs. The lines are drawn to guide the eye.

In summary, a candidate chiral partner of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band has been observed in ^{132}Cs, showing that the chiral symmetry is still broken for $N=77$. This is indicative of the important role of particle-hole interaction in the chiral arrangement. In contrast to the lighter $_{55}$Cs isotopes the main band built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration is not yrast in ^{132}Cs, the side partner is not well developed and other positive-parity structures develop. This reflects the fact that due to the moderate deformation the chiral structure becomes unstable and competes with other less collective structures. The instability is reflected in the 3D TAC calculations, which have predicted a short chiral solution in ^{132}Cs. These features allow us to conclude that the $N=77$ isotones form the border of the island of chirality when the neutron number approaches $N=82$.

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