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Candidate chiral doublet bands in ^{138}Pm

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High-spin states of ^{138}Pm have been populated using the ^{124}Te(^{19}F, 5n)^{138}Pm reaction at a beam energy of 105 MeV. A new positive-parity side band with the same $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration as that of the yrast band is observed in ^{138}Pm. The properties of the two positive-parity bands show general agreement with the fingerprints of chiral rotation and thus these two bands are suggested to be candidates for near degenerate chiral doublet bands. Besides, odd-even spin staggering of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands is studied systematically in odd-odd Cs, La, Pr, and Pm isotopes. As a result of this study we suggest that the spin value of lowest observed state of the yrast band be reassigned as 9 in ^{138}Pm. This new spin assignment is also supported by the argument of alignment additivity.

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I. INTRODUCTION

The manifestation of chirality in atomic nuclei was originally suggested in Ref. [1], and vigorously investigated over the last 20 years. Chiral rotation is generated in special circumstances, when the total angular momentum vector of a rotating triaxial nucleus lies outside the three principal planes. Thus, its components along the principal axes can be oriented in left- and right-handed ways. In the laboratory frame, the restoration of spontaneous chiral-symmetry breaking can be observed as a pair of $\Delta I = 1$ nearly degenerate bands with the same parity. Up to now, such candidate chiral doublet bands have been proposed in a number of odd-odd nuclei, in the $A \sim 130$ mass region with the suggested configuration $\pi h_{11/2} \otimes \nu h_{11/2}$ [2–13], $A \sim 110$ region with $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}$ [14–16], $A \sim 190$ region with $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$ [17], and $A \sim 80$ region with $\pi g_{9/2} \otimes \nu g_{9/2}^{-1}$ [18,19]. Furthermore, a few more candidates with more than one valence particle and hole were also reported in odd-A and even-even nuclei [20–25].

Since the first candidate chiral doublet bands were reported in the $A \sim 130$ mass region, extensive experimental studies have been made to search for such bands. As a result, candidate chiral doublet bands have been reported in more than ten odd-odd nuclei, i.e., several $N = 77$ (^{132}Cs, ^{134}La, ^{140}Eu) [5,8,12], $N = 75$ (^{130}Cs, ^{132}La, ^{134}Pr, ^{136}Pm, ^{138}Eu) [4,7,13], $N = 73$ (^{128}Cs, ^{130}La, ^{132}Pr) [2,4], and $N = 71$ (^{126}Cs, ^{128}La) [10,11] isotones. These provide support for the existence of a small island of chiral structures in the $A \sim 130$ mass region. For a deeper understanding of the systematically appearing chiral doublet bands, it is important to try to experimentally define the boundaries of this island where chiral candidate doublet bands appear in this mass region. For this purpose, the odd-odd ^{138}Pm ($N = 77, Z = 61$) nucleus lying at the extremes of both the N and Z ranges, is suggested to be a good case for testing the limits of this region of chiral symmetry. Previously, the candidate chiral doublet bands have been reported in neighboring isotope ^{136}Pm ($N = 75, Z = 61$) [3,6,7]. Meanwhile, the doublet bands have also been observed in the ^{132}Cs and ^{134}La [5,12], which are $N = 77$ isotones of ^{138}Pm. Hence, we infer that the odd-odd nucleus ^{138}Pm may be considered as a possible candidate of a chiral nucleus.

II. EXPERIMENTAL METHODS AND RESULTS

High-spin states of ^{138}Pm were populated through the ^{124}Te(^{19}F, 5n)^{138}Pm reaction at a beam energy of 105 MeV. The ^{124}Te target, with a thickness of 1.91 mg/cm^2, was rolled onto a 15.4 mg/cm^2 lead backing. The beam was provided by the HI-13 tandem accelerator at CIAE in Beijing. The γ-γ coincidence data were recorded by the use of the detecting system consisting of ten compton-suppressed HPGe detectors, one HPGe planar detector, and one clover-type detector. A total of 6.5×10^8 γ-γ coincidence events were recorded. The data were sorted into a symmetrized γ-γ coincidence matrix and a DCO (directional correlation from oriented states) matrix. DCO ratios [26] were obtained from spectra gated either on quadrupole or dipole transitions. For our detector array, when gating on a quadrupole transition, the DCO ratio of the measured transition is around 1.0 for quadrupole transition and around 0.6 for dipole transition, and when gating on a dipole transition, the DCO ratio of measured transition becomes around 1.0 for dipole transition and around 1.7 for quadrupole transition.

A partial level scheme of ^{138}Pm derived from the present work is shown in Fig. 1, where band 1 is the yrast band and

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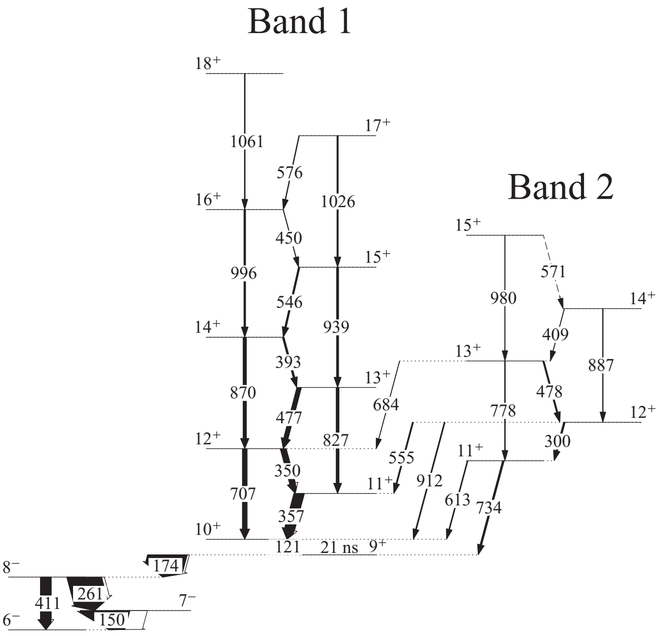

FIG. 1. Partial level scheme of ^{138}Pm deduced from the present work. Spins and parities of the states are discussed in the text. Transition energies are given in keV and their measured relative intensities are proportional to the widths of the arrows.

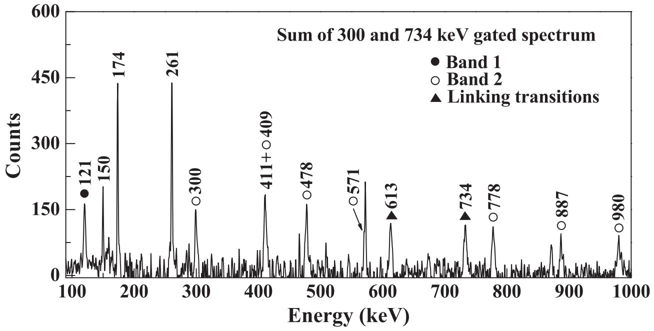

FIG. 2. Sample γ-γ coincidence spectrum supporting the partial level scheme of ^{138}Pm.

band 2 is the side band. The positive-parity yrast band 1 built on the $T_{1/2} = 21$ ns isomeric state has been assigned to $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration in the previous work [27]. In the present work, the level structure of the yrast band (band 1) is consistent with that of Refs. [27–29] except that the spin values of all levels are increased by 1 $\hbar$ based on systematic study of odd-even spin staggering and the alignment additivity. The detailed spin assignments of the yrast band 1 are discussed in later sections.

Band 2 (side band) is reported for the first time, and several new linking transitions between bands 1 and 2 are observed. Multipolarity analysis indicates that the 734 and 912 keV linking transitions are of $\Delta I = 2$ character with DCO ratios of 1.67(26) and 1.78(29) obtained by gating on the 300 and 121 keV transitions, respectively. Additionally, the 613 keV linking transition is of $\Delta I = 1$ character with DCO ratio of 1.06(19) obtained by gating on the 121 keV transition. The observation of both $\Delta I = 1$ and $\Delta I = 2$ linking transitions between bands 1 and 2 implies that band 2 has positive parity as that of band 1, and the energies and spins of band 2 are fixed, relative to the levels of band 1 as shown in Fig. 1. A sample γ-γ coincidence spectrum supporting the level scheme of Fig. 1 is shown in Fig. 2.

III. DISCUSSION

Previously, the lowest observed state of the yrast band 1 has been assigned to be the band head with a tentative spin assignment $I_0 = 8$, arising from the perpendicular coupling between the valence proton and neutron [27]. However, based on this spin assignment, the phase of odd-even spin staggering is not inverted at low spin for the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band 1. It is well known that the phase of odd-even spin staggering of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in the $A \sim 130$ mass region is inverted at low spins [30]. A spin assignment of $I_0 = 8$ or of any even number to the lowest observed state of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{138}Pm will lead to the normal odd-even spin staggering without inversion at low spin, and thus the assignment of $I_0 = 8$ is not appropriate. In our previous study on spin assignments of $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast bands in odd-odd nuclei in the $A \sim 130$ mass region [30], the spin of the lowest observed state of the yrast band was suggested to be $I_0 = 9$ in ^{138}Pm, based on excitation energy systematics. To further illustrate the spin assignments of the yrast band in ^{138}Pm nucleus, the systematic odd-even spin staggering of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in several nearby doubly odd nuclei is discussed again in the present study. Figure 3 shows the staggering functions of the level energy $\Delta E = [E(I) - E(I-1)] - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ vs. spin I for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in the Cs ($Z = 55$), La ($Z = 57$), Pr ($Z = 59$), and Pm ($Z = 61$) isotopes, respectively. One can see from Fig. 3, that the phase inversion of odd-even spin staggering at low spins occurs in all nuclei except ^{138}Pm based on the previous spin assignment of $I_0 = 8$ [27,28]. In contrast, it is clear from this figure that a reassigned band head spin of $I_0 = 9$ fits well with the systematics, i.e., the yrast band based on the new spin assignments ($I_0 = 9$) in ^{138}Pm shows odd-even spin staggering in consistent with the systematic study of $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in this mass region.

Furthermore, these new spin assignments are also supported by the argument of alignment additivity. 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 band in odd-odd nuclei is approximately equal to the sum of the proton and neutron contributions, as observed in the neighboring odd-A nuclei at the same frequency. Previously, the alignment additive rule had been successfully applied to the spin assignments of bands in odd-odd nuclei in the mass regions of $A \sim 160$ [45] and of $A \sim 130$ [46]. Hence, to further confirm the spin assignments of band 1 given above, the alignment additivity of band 1 is examined in Fig. 4. It can be seen that the alignment i_x extracted from the favored cascade of band 1 with present spin ($I_0 = 9$) is closer to the sum of i_p from $\pi h_{11/2}$ band ($\alpha = -1/2$) of

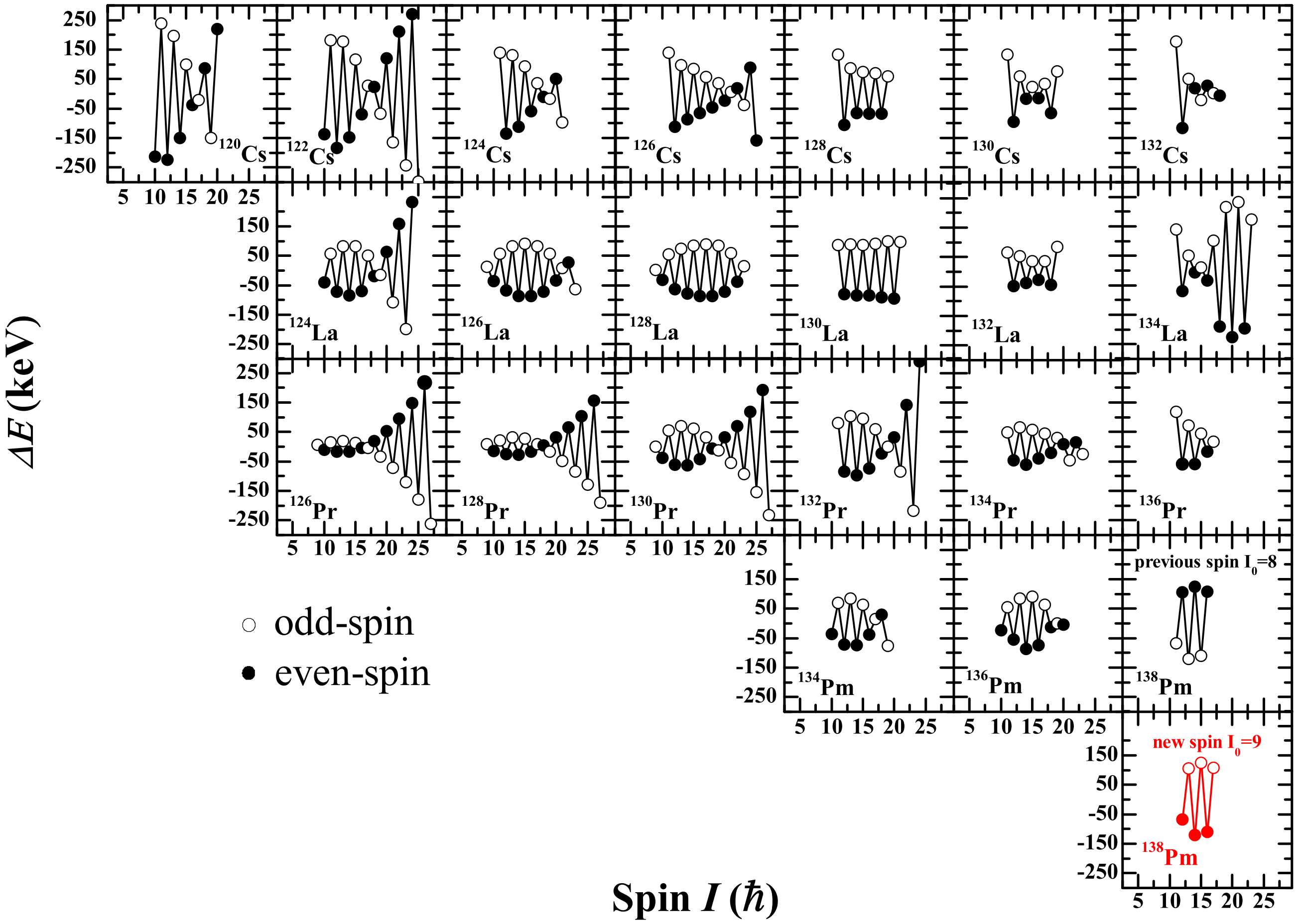

FIG. 3. Energy staggering, defined in the text, as a function of spin for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in odd-odd Cs ($Z = 55$), La ($Z = 57$), and Pr ($Z = 59$) nuclei. Level sequence with even-spin (odd-spin) is denoted by filled (open) squares. Spin assignments for all nuclei shown were adopted from ^{120}Cs [31], ^{122}Cs [32], ^{124}Cs [9,33], ^{126}Cs [10], ^{128}Cs [2], ^{130}Cs [34], ^{132}Cs [35], ^{124}La [36], ^{126}La [37], ^{128}La [38], ^{130}La [4], ^{132}La [3], ^{134}La [12], ^{126}Pr [39], ^{128}Pr [39], ^{130}Pr [40], ^{132}Pr [41], ^{134}Pr [42], ^{136}Pr [43], ^{134}Pm. [44], ^{136}Pm. [6], ^{138}Pm (previous work) [28], and ^{138}Pm (present work).

^{137}Pm (Ref. [47]) and i_n from $\nu h_{11/2}$ band ($\alpha = -1/2$) of ^{137}Nd (Ref. [48]), than the alignment i_x with previous spin value $I_0 = 8$. Thus, the new spin assignment ($I_0 = 9$) is more reasonable.

Band 2 decaying to the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band is observed for the first time. In order to discuss the configuration assignment of band 2, cranked shell model (CSM) calculations [49,50] have been performed as shown in Fig. 5, where the CSM calculations predict that proton ω_{AB} and neutron ω_{ab} alignments occur at ~0.35 MeV and ~0.38 MeV, respectively. However, no crossing is found below 0.5 MeV for bands 1 and 2 in the alignment plot [Fig. 6(a)], indicating that the $h_{11/2}$ particles should be involved in the configurations of bands 1 and 2 to block the proton AB and neutron ab crossings. In addition, the experimental $B(M1)/B(E2)$ ratios for bands 1 and 2 are shown in Fig. 6(b), along with the theoretical estimates of the geometrical model for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration for comparison [54]. 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 the two bands.

As mentioned above, the experimental observations and theoretical calculations indicate that band 2 has the same $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration as that of band 1. A possible interpretation of band 2 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 principal axis cranking (PAC) calculations indicate that the unfavored signature of the $h_{11/2}$ orbital lying at an excitation energy of >400 keV above the favored signature and the energy splitting increasing with frequency in nearby nuclei [6,7]. Experimentally, observing the band based on the unfavored coupling of protons and neutrons in odd-odd nuclei in the $A \sim 130$ mass region is rare, but it has been seen in ^{128}Pr [39], where the $\pi h_{11/2} \otimes \nu h_{11/2}$ side band (band 3 of Fig. 1 in Ref. [39]) has been interpreted as resulting from the coupling between the unfavored signature of the $h_{11/2}$ proton and the two signatures of the $h_{11/2}$ neutron. Indeed, the energy difference between the side band and the yrast band at the same spin, $\Delta E(I) = E(I)_{\mathrm{side}} - E(I)_{\mathrm{yrast}}$, of ^{128}Pr increase from ~400 to ~600 keV with spin, which is consistent with theoretical prediction mentioned above. However, $\Delta E(I)$ in ^{138}Pm stays roughly constant within a wide range of spin, and

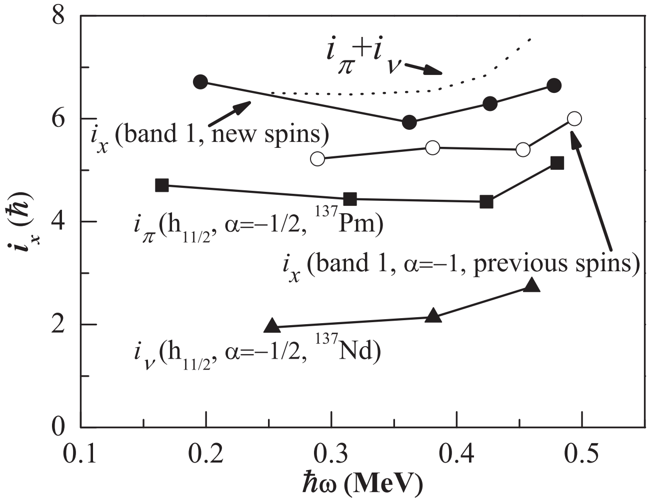

FIG. 4. Alignment of bands 1 compared to the sum $i_\pi + i_\nu$ of alignments of the relevant bands observed in neighboring odd-A nuclei ^{137}Pm [47] and ^{137}Nd [48]. Closed (open) dots for alignments based on new (previous) spin assignment. The Harris parameters are $J_0 = 8$ MeV$^{-1}\hbar^2$, $J_1 = 45$ MeV$^{-3}\hbar^4$ in ^{138}Pm [27], and $J_0 = 12.5$ MeV$^{-1}\hbar^2$, $J_1 = 16$ MeV$^{-3}\hbar^4$ for bands in ^{137}Pm [47] and ^{137}Nd [48].

$\Delta E(I) \sim 250$ keV (see Fig. 1) between the two bands is too small for the side band 2 to be interpreted as a band built on the unfavored signature of the proton orbital. Thus, the description of band 2 as the unfavored coupling of the $h_{11/2}$ proton and neutron is not satisfactory.

Another consideration is that band 2 originates from a γ-vibrational band, which has been observed in even-even and odd-A nuclei in various mass regions. Assuming that band 2 is a γ-vibrational band, the aligned quadrupole phonon will contribute to the spin and may therefore account for $\sim 2\hbar$ difference in the alignments of band 2 and band 1. Actually, we note that the alignment of band 2 follows closely that of band 1 in Fig. 6(a). Additionally, γ-vibrational bands are found to lie at an excitation energy of >600 keV above the ground band in this mass region [3,5], whereas band 2 consistently lies at $\sim$250 keV above band 1. Therefore, the band 2 in ^{138}Pm is not likely to result from the coupling between a phonon and the yrast band 1.

The possibility of band 2 being a four-quasiparticle band is unlikely. As the excitation energy of the lowest observed state of band 2 at $\sim$1319 keV is less than the lowest four-quasiparticle excited state of 13^- at 2832.5 keV [29], which is also observed in the present work, but is not put in Fig. 1. Moreover, if band 2 is assumed to be a four-quasiparticle band, the alignment of the four-quasiparticle band 2 should be greater than that of the two-quasiparticle band 1 in ^{138}Pm. In fact, Fig. 6(a) shows that the alignment of band 2 is almost the same as that of band 1. Hence, the four-quasiparticle explanation of band 2 is unlikely.

The exclusion of the interpretations of unfavored coupling, γ vibration, and four-quasiparticle band provides the possibility to interpret the band 2 resulting from a broken chiral symmetry. This scenario requires that the nucleus has a triaxial deformation, and the proton and neutron Fermi levels are located in the lower part of valence proton high-j (particlelike) subshell and in the upper part of valence neutron high-j (holelike) subshell, respectively. Indeed, these requirements are met by the nucleus ^{138}Pm. The TRS calculations predict that a triaxial deformation of $\gamma = -27^\circ$ occurs in the frequency range where band 2 is observed as seen in Fig. 7, and the $\pi h_{11/2}[541]3/2^- \otimes \nu h_{11/2}[514]9/2^-$ configuration of ^{138}Pm fulfill the requirements of Fermi levels.

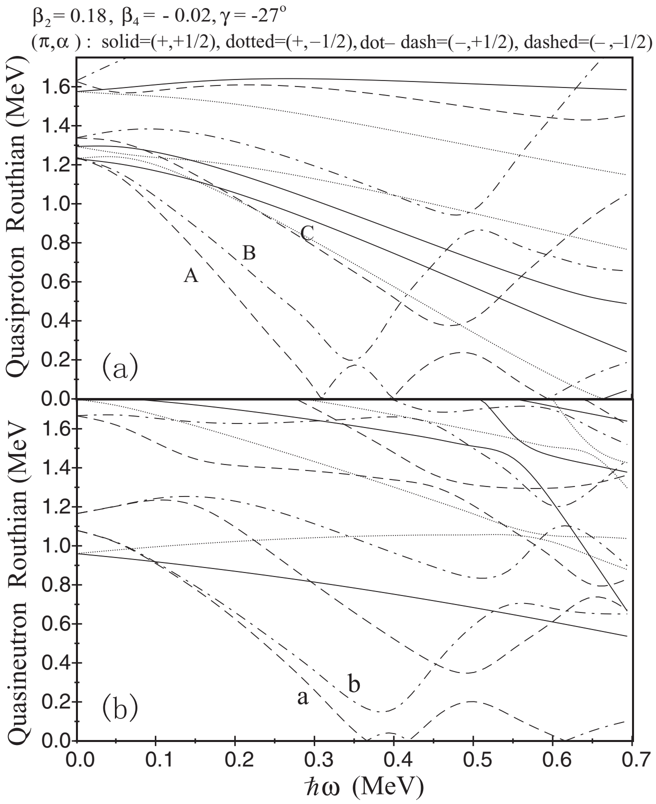

FIG. 5. Cranked shell model calculations for (a) quasiproton and (b) quasineutron Routhians. The deformation parameters shown at the top of the figure are determined by TRS calculations [51–53]. Interpretation of the lines is displayed at the top of the figure.

For chiral nuclei, the existence of near-degenerate $\Delta I = 1$ bands is one of the key fingerprints of chirality. The degree of degeneracy of the two positive parity bands in ^{138}Pm is exhibited by the excitation energies of the band members as a function of spin as shown in Fig. 8(a), where the side-band 2 curve (open symbols) is displaced slightly higher in energy above the yrast-band 1 curve (closed symbols). The two curves maintain a roughly constant energy difference of $\sim$250 keV. This value is $\sim$50 keV smaller than that in the case of candidate chiral doublet bands in the neighboring ^{136}Pm isotope ($\sim$300 keV) [6,7], and this smaller energy difference of ^{138}Pm indicates that the partner bands of ^{138}Pm might have properties closer to the expected features of chiral bands than those in ^{136}Pm. Additionally, the level scheme and linking transitions between the bands 1 and 2 in ^{138}Pm are similar to the earlier reported chiral doublet bands in neighboring ^{136}Pm nucleus, indicating that such two nuclei may be similar in nature as well.

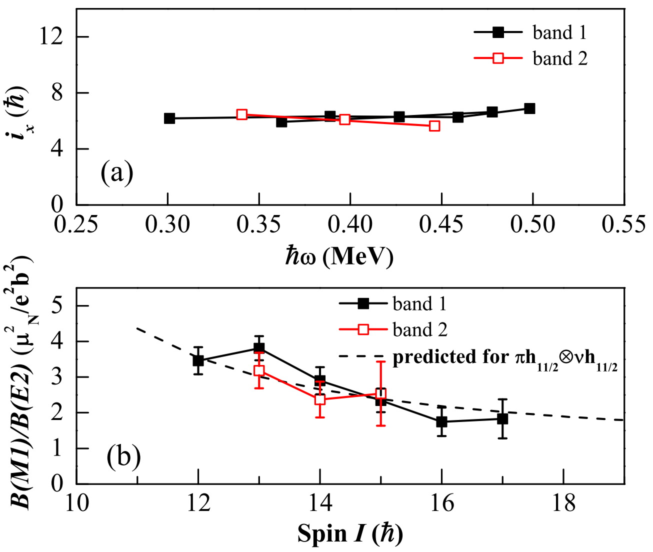

FIG. 6. (a) Experimental alignment plots for bands 1 and 2 in ^{138}Pm. The Harris parameters are $J_0 = 8$ MeV$^{-1}\hbar^2$, $J_1 = 45$ MeV$^{-3}\hbar^4$ [27]. (b) Comparison of experimental and predicted $B(M1)/B(E2)$ values for bands 1 and 2.

Furthermore, two further fingerprints of chirality were proposed by Koike *et al.* [55]. 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 bands 1 and 2 of ^{138}Pm is presented in Fig. 8(b). The relatively smooth variation of $S(I)$ should be considered as consistent with the requirement of the first fingerprint. Second, due to the restoration of the chiral symmetry in the laboratory frame, there are phase consequence for the chiral wave functions resulting in $M1$ and $E2$ selection rules, which can manifest as $B(M1)/B(E2)$ and $B(M1)_{in}/B(M1)_{\mathrm{out}}$ staggering as a function of spin. Additionally, the odd spin members of the chiral bands have higher values relative to the even spin ones 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 bands 1 and 2 of ^{138}Pm is shown in Fig. 6(b). For band 2, the error bars 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 band 2 can not be made in the present work. However, the similar magnitude of $B(M1)/B(E2)$ of bands 1 and 2 in ^{138}Pm as shown in Fig. 6(b) is consistent with the expectation of 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 $[B(M1)/B(E2)]_{\mathrm{yrast}}/[B(M1)/B(E2)]_{\mathrm{side}} \approx 1$ [11,55].

As mentioned above, the features of the two positive parity bands in ^{138}Pm, displayed in Figs. 8 and 6(b), generally fit to the fingerprints of chiral rotation. However, to confirm this suggestion, the further experimental results of absolute $B(M1)$ and $B(E2)$ transition probabilities based on lifetime measurements are desirable.

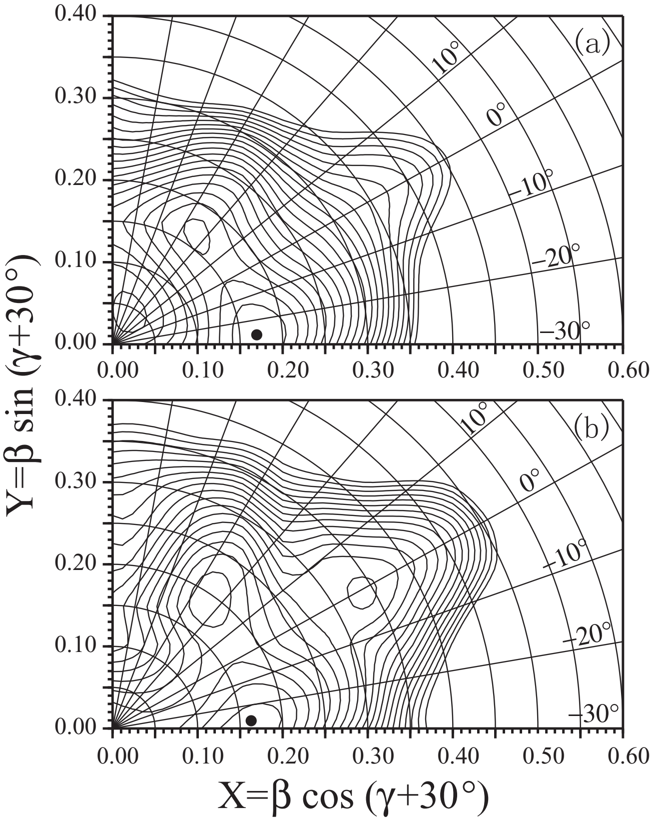

FIG. 7. Total Routhian surface (TRS) calculated for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration of ^{138}Pm. The top figure is at $\hbar\omega = 0.35$ MeV and the bottom figure is at $\hbar\omega = 0.45$ MeV, respectively. Contours are 175 keV.

IV. SUMMARY

A new positive-parity side band feeding into the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band has been observed and linking transitions between them have been identified in ^{138}Pm. The properties

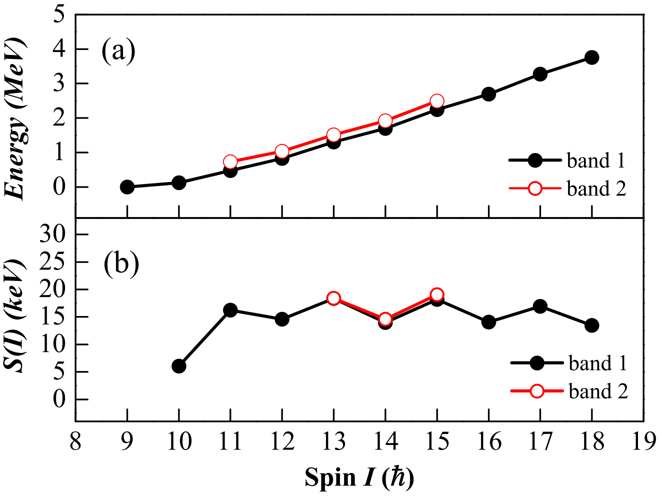

FIG. 8. Excitation energy vs. spin (top) and $S(I)$ values vs. spin for the bands 1 and 2 in ^{138}Pm.

of the two positive-parity bands show general agreement with the fingerprints of chiral rotation, and thus these two bands are suggested to be the candidate chiral doublet bands. However, to confirm this suggestion, the further experimental results of absolute transition probabilities based on lifetime measurements are desirable. Besides, the odd-even spin staggering of $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in odd-odd Cs, La, Pr, and Pm isotopes is studied systematically, and as a result we suggest that the spin value of lowest observed state of yrast band of ^{138}Pm be reassigned as 9 to replace the previous value 8. Based on this new spin assignment, the yrast band of ^{138}Pm shows odd-even spin staggering in consistent with the systematics for corresponding bands in this mass region. Meanwhile, this new spin assignment is also supported by the argument of alignment additivity.

ACKNOWLEDGMENTS

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