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Detailed spectroscopy of the chiral-twin candidate bands in ^{136}Pm

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The chiral-twin candidate bands recently observed in ^{136}Pm have been extended to high spins $[I=(21)]$ using the Gammasphere γ-ray spectrometer and the Microball charged-particle detector array. A more-detailed spectroscopy of the bands was possible, where the rotational alignments and $B(M1)/B(E2)$ ratios confirm that both sequences have the $\pi h_{11/2}\nu h_{11/2}$ configuration. Particle-rotor calculations of intraband and interband transition strength ratios of the chiral-twin bands are compared with experimental values for the first time. Good agreement was found between the predicted transition strength ratios and the experimental values, thus supporting the possible chiral nature of the $\pi h_{11/2}\nu h_{11/2}$ configuration in ^{136}Pm.

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Triaxially deformed odd-odd nuclei can rotate in a left-handed and right-handed geometrical configuration, which is the manifestation of chiral symmetry breaking recently proposed by Frauendorf and Meng [1]. The basic mechanism for chiral symmetry breaking entails that the angular momentum vectors of the valence proton, valence neutron, and even-even core are mutually perpendicular to each other. The vector sum, i.e., the total angular momentum that fixes the rotational axis, lies outside any of the three principal planes determined by the triaxial core deformation. The angular momenta of the odd particles and of the core can form either a left-handed or a right-handed combination. Both possibilities are energetically equivalent and cannot be transformed into each other by a simple rotation. Rather, a combined (chiral) operation $\chi=\mathcal{TR}(\pi)$, implying both a time reversal and a rotation of 180°, is necessary to change the handedness (chirality) of the system. Since, in the ideal case, the two equivalent chiral arrangements are not interacting with each other, two degenerate bands with the same quasiparticle configuration are expected to exist. Tilted axis cranking (TAC) [2,3] calculations presented in Ref. [4] indicate that two of the best cases for observing this exotic symmetry breaking are in $^{134}_{59}\mathrm{Pr}_{75}$ and $^{136}_{61}\mathrm{Pm}_{75}$.

Starosta *et al.* [4] recently published the first possible experimental evidence for a series of chiral-twin bands in odd-Z $N=75$ isotones. Excited sequences were observed in the ^{130}Cs, ^{132}La, ^{134}Pr, and ^{136}Pm nuclei that feed the $\pi h_{11/2}\nu h_{11/2}$ yrast band. Except for ^{134}Pr [5], only a few states in each of the excited bands had been observed. Arguments were given to suggest that these sequences have the same $\pi h_{11/2}\nu h_{11/2}$ configuration, but were based solely on selection rules for the linking transitions, rather than in-band properties. Clearly more information is needed in order to verify the configuration of the excited bands and to compare experimental observables with theoretical predictions of a chiral-twin sequence.

In this Rapid Communication, we report on the significant extension of the possible chiral-twin band in ^{136}Pm. The additional information allows for the detailed study of the rotational alignment and $B(M1)/B(E2)$ ratios such that a configuration assignment can be based upon characteristic band properties. Particle-rotor model (PRM) [6] calculations of the twinned bands from the chiral solution were also performed and compared with experimental results for the first time.

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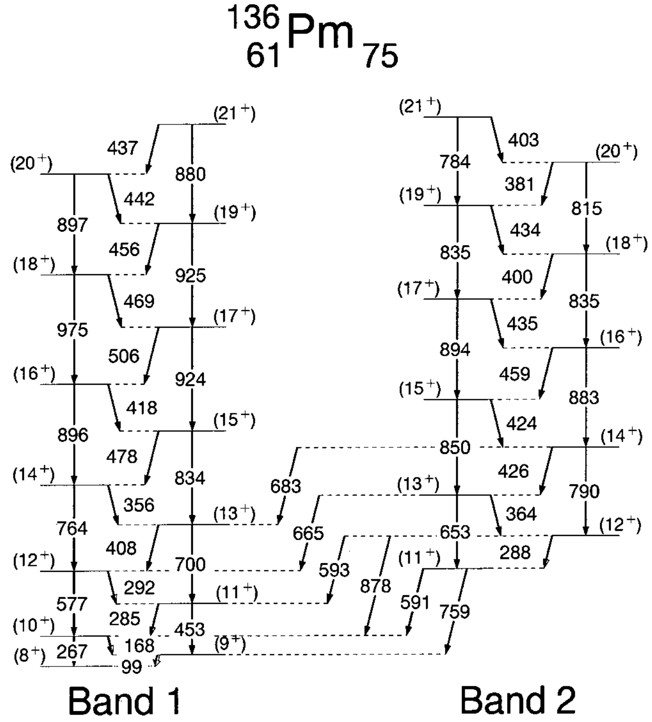

FIG. 1. Partial level scheme of ^{136}Pm deduced from the present work. Spins and parities of the states are discussed in the text.

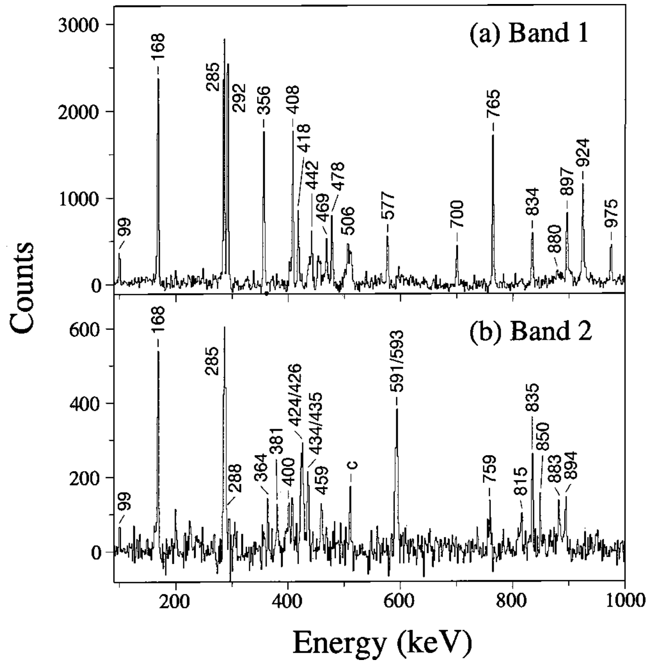

FIG. 2. (a) Spectrum of band 1 produced by the sum of many double-gated coincidence spectra. (b) Spectrum of band 2 produced by summing all the possible combinations of double gates between the 364-, 424-, 426-, and 459-keV transitions. Peaks labeled with a *c* are contaminate transitions.

High-spin states were populated in ^{136}Pm by the ^{105}Pd(^{35}Cl,2p2n) reaction, where the ^{35}Cl beam was accelerated to 173 MeV by the 88-Inch Cyclotron Facility at the Lawrence Berkeley National Laboratory. The target consisted of a 1-mg/cm^2 foil of ^{105}Pd mounted onto a 17-mg/cm^2-thick Au backing. Emitted gamma rays were collected with 97 Compton-suppressed detectors in the Gammasphere spectrometer [7], while charged-particles emitted from the compound nuclei were detected in the Microball array [8]. A total of $\sim 3 \times 10^8$ threefold or higher gamma-ray events were collected, where approximately 13% of these events were associated with the emission of two protons. Those γ rays in coincidence with two proton emission were sorted into an $E_\gamma \times E_\gamma \times E_\gamma$ cube and subsequently analyzed with the RADWARE suite of programs [9].

Previous studies of ^{136}Pm have determined that the yrast band is based on the $\pi h_{11/2} \nu h_{11/2}$ configuration [10]. Recently, a new sideband has been identified feeding into the yrast band at low spin [4,11]; however, only a few transitions could be observed in the excited structure. The present work significantly extends this sequence to higher spins, as shown in the partial level scheme of Fig. 1. The yrast $\pi h_{11/2} \nu h_{11/2}$ structure is labeled as band 1 and a sample spectrum is provided in Fig. 2(a). As is common with many odd-odd nuclei, the high-spin rotational structures have not been linked to the low-spin states determined by β-decay experiments [12]. Therefore, the exact spins of the states are unknown and tentative spin assignments have been given to band 1 based upon the systematic arguments of Liu *et al.* [13]. The aforementioned new sideband has been extended from (15^+) to (21^+), and a sample spectrum is provided in Fig. 2(b). Directional correlation of oriented (DCO) states analysis was performed for the 593- and 878-keV linking transitions between bands 1 and 2 (see Fig. 1). DCO ratios of ~ 0.5 and ~ 1.0 are expected for $\Delta I = 1$ and $\Delta I = 2$ transitions, respectively. The ratios $R_{DCO}(593) = 0.63(3)$ and $R_{DCO}(878) = 1.13(28)$ were determined, which confirm the relative spin assignment of band 2. Hecht *et al.* [11] performed a linear polarization measurement for the 593-keV transition and suggest that the $\Delta I = 1$ transition is a magnetic dipole, thus establishing that bands 1 and 2 have the same parity.

The extension of band 2 to high spins allows for a more detailed spectroscopic analysis to assign its relevant configuration. In the alignment plot of the data presented in Fig. 3 one observes the same large initial alignment ($\sim 6\hbar$) for bands 1 and 2. The known $\pi g_{7/2} \nu h_{11/2}$ band of ^{136}Pm, also displayed in Fig. 3, exhibits a sharp backbend at $\hbar\omega = 0.28$ MeV caused by the rotational alignment of the first pair of $h_{11/2}$ protons. The absence of a crossing at this frequency for bands 1 and 2 in Fig. 3 indicates that this alignment is Pauli blocked in both bands, which means an $h_{11/2}$ proton is involved in the configurations of these bands. There are crossings at ~ 0.44 and ~ 0.39 MeV in bands 1 and 2, respectively, which are most likely from an alignment of the second pair of $h_{11/2}$ protons. The discrepancy in the crossing frequencies is a result of band 2 lying at a higher energy than band 1; thus, the four-quasiparticle structure, which crosses bands 1 and 2, will interact with the excited sequence at a lower frequency. Since it has been determined that bands 1 and 2 have the same parity and both have an $h_{11/2}$ proton in their configuration, band 2 must also have a negative-parity neutron coupled to the proton. The only negative-parity neutron states near the Fermi surface are the high-K $h_{11/2}$ and the

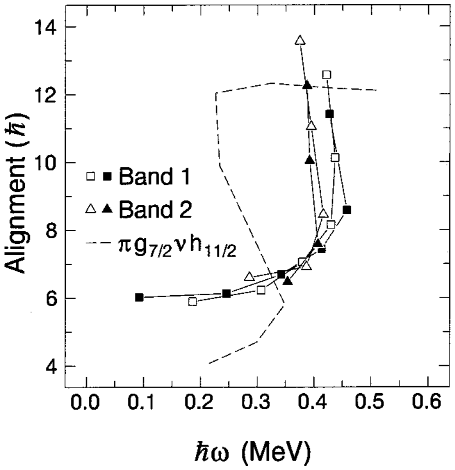

FIG. 3. Rotational alignments of bands in ^{136}Pm. Harris parameters of $\mathcal{J}_0=14\hbar^2$/MeV and $\mathcal{J}_1=15\hbar^4/\mathrm{MeV}^3$ were used to subtract the angular momentum of the core. Filled (open) symbols denote the $\alpha=0$ (1) signatures.

$K=1/2$ $h_{9/2}/f_{7/2}$ orbitals. However, the coupling of the low-K $h_{11/2}$ proton with the $h_{9/2}/f_{7/2}$ neutron would form a doubly decoupled sequence, as seen in ^{134}Pm [14]. Therefore, the $\pi h_{11/2}\nu h_{11/2}$ configuration is the only viable assignment for band 2.

The possibility of band 2 being a γ-vibrational band is highly unlikely, as discussed in Refs. [4,11]. Gamma bands are found to lie at an excitation energy of >500 keV above the ground-state sequences in nearby even-even nuclei [15,16], whereas band 2 consistently lies ~300 keV above band 1 (see Fig. 4). Also, an analogous structure in ^{134}Pr [5] is observed to actually lie lower in energy at high spins than the continuation of the yrast $\pi h_{11/2}\nu h_{11/2}$ band. Such behavior is extremely unlikely for any vibrational band.

Another consideration for the origin of band 2 is the unfavored signature of the $h_{11/2}$ proton coupled with the $h_{11/2}$ neutron. Observing the band based on the unfavored coupling of protons and neutrons in odd-odd nuclei is rare, but has been seen in ^{164}Tm [17], for example. A principal axis cranking (PAC) calculation has been performed in order to predict where the band with unfavored coupling of the $\pi h_{11/2}\nu h_{11/2}$ configuration lies with respect to the yrast band for the $N=75$ nuclei. Deformation parameters (including substantial triaxial deformation) from total Routhian surface (TRS) calculations were employed. The results are compared with the experimental Routhians of the yrast and excited positive-parity bands in Fig. 4. One may notice a trend in the PAC energy splittings of Fig. 4, where the difference increases as the proton Fermi surface changes from Pm to Cs. This is due to the proximity of the $K=1/2$ orbital, which is nearest in Cs and furthest away in Pm. However, there is not such a trend seen in the experimental Routhians since the excited sequences consistently lie ~300 keV above the yrast bands, except for ^{134}Pr, which, as stated before, crosses the yrast structure. Thus, the description of the sidebands as the unfavored coupling of the $h_{11/2}$ proton and neutron is not satisfactory.

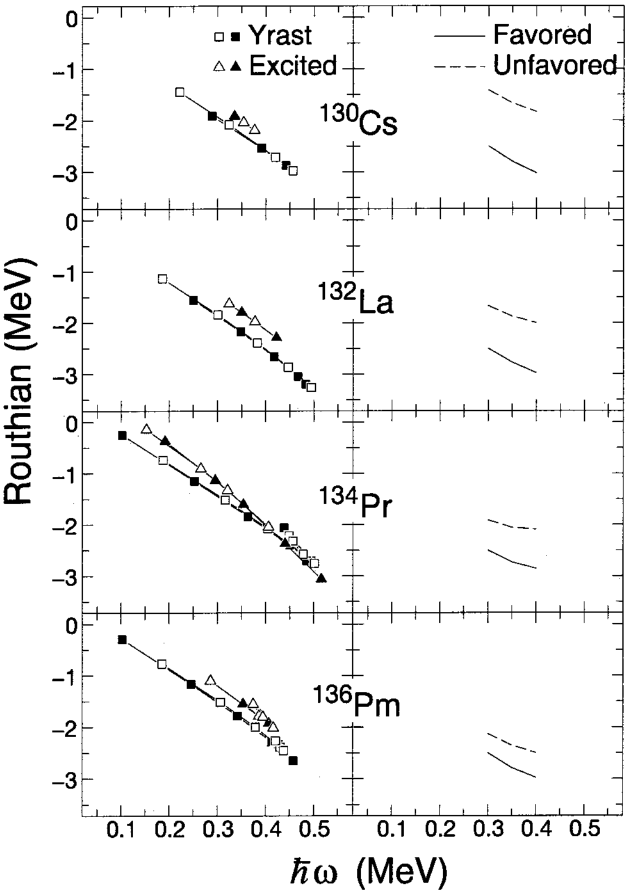

FIG. 4. Experimental Routhians (left) of the yrast and excited positive-parity candidate bands in the $N=75$ Cs, La, Pr, and Pm nuclei. Harris parameters of $\mathcal{J}_0=14\hbar^2$/MeV and $\mathcal{J}_1=15\hbar^4/\mathrm{MeV}^3$ were used. PAC calculated Routhians (right) of the favored (solid line) and unfavored (dashed line) coupling of the $h_{11/2}$ proton and neutron.

The unlikelihood of the gamma vibration and unfavored coupling assignments for band 2 in ^{136}Pm opens the possibility to an alternative explanation. One such alternative is that the excited sequence is the result of a broken chiral symmetry [1]. This scenario requires that the nucleus is odd-odd with one nucleon occupying a high-j, low-K orbital, while the other nucleon occupies a high-j, high-K orbital, and that the nucleus has a triaxial deformation near $\gamma=\pm30°$. All conditions are met in the $\pi h_{11/2}\nu h_{11/2}$ configuration of ^{136}Pm and TRS calculations predict triaxial deformations of $\gamma=-25°$ for the frequency range in which band 2 is observed. Therefore, ^{136}Pm seems to be an excellent laboratory to test this new type of symmetry breaking.

A sensitive experimental observable, which can be compared with theory, is the transition strength ratio between γ rays depopulating a given state. Intraband transition strength ratios were determined from the extracted branching ratios and the γ-ray energies as described in Ref. [18] for both bands 1 and 2. The $B(M1)/B(E2)$ ratios are plotted in Fig. 5, where the filled (open) symbols indicate that the branching ratio was determined with spectra generated by gates above (below) the level of interest. The ratios for band 1 decrease as spin increases and a staggering may be observed with

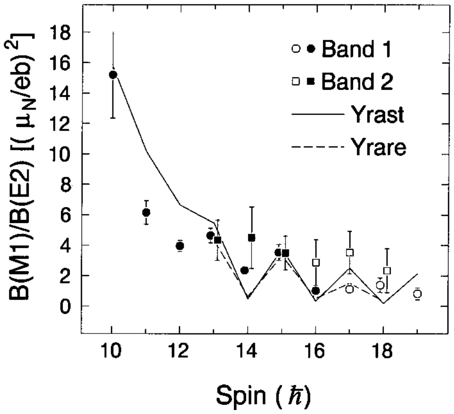

FIG. 5. $B(M1)/B(E2)$ ratios for bands 1 and 2 in ^{136}Pm. Filled (open) symbols denote that the branching ratios were determined by spectra resulting from gates above (below) the level of interest. The ratios for inband transitions found by PRM calculations for the yrast (solid line) and yrare (dashed line) $\pi h_{11/2}\nu h_{11/2}$ configurations are also displayed.

higher values for the odd spins. Band 2 has, on average, slightly higher $B(M1)/B(E2)$ ratios than band 1, and it is difficult to determine whether any staggering exists in band 2 due to large uncertainties.

Results of a TAC calculation for ^{136}Pm have been reported in Ref. [11]. The predicted $B(M1)/B(E2)$ ratios for the $\pi h_{11/2}\nu h_{11/2}$ configuration are in agreement with the experimental values shown in Fig. 5. Although the TAC model is the theoretical basis for the concept of chirality in nuclear systems [1], it bears some limitations for comparisons with experimental results. The present TAC model implementation, where the mixture between the chiral solutions has not been considered, cannot distinguish between the two bands and therefore can only give the averaged $B(M1)/B(E2)$ values from both bands. Moreover, due to the tilted cranking axis, the signature dependent effects cannot be taken into account. Finally, interband transition strengths are not easily extracted due to the fact that the chiral wave functions have imaginary components making the calculations of the overlap between the left-handed and right-handed states difficult.

Frauendorf and Meng [1] however, have demonstrated that both the TAC and the PRM can describe the chiral solution. The PRM has the advantage of working in the laboratory frame of reference. Thus, the spin *I* is a good quantum number and the chiral symmetry is restored. Therefore it is possible to distinguish between the chiral partner states of the $\pi h_{11/2}\nu h_{11/2}$ configuration such that the specific properties of the yrast and yrare bands may be explored. In particular, the conserved spin of the wave functions allows one to determine the strengths of interband transitions. It should be emphasized, however, that the PRM has its own limitations and it is not necessarily a better model to describe the chiral solution. As described more extensively in a forthcoming publication [19], it is to be considered a useful supplement to the TAC approach.

The results of the PRM calculations for ^{136}Pm are shown in Fig. 5. Deformation parameters, taken from TRS calculations, of $\epsilon_2=0.194$, $\epsilon_4=0.028$, and $\gamma=-25°$ were used and kept constant. Comparing the predicted yrast $\pi h_{11/2}\nu h_{11/2}$ values with band 1 in Fig. 5, one may notice the good agreement between experiment and theory for the substantial increase in $B(M1)/B(E2)$ ratios at the lowest spin. The magnitude and decreasing trend of the transition strength ratios with spin for band 1 are also reproduced well. Although the calculated staggering in band 1 is overestimated by the PRM, the correct phase is achieved, which is consistent with the spin assignment of Liu *et al.* [13].

The chiral-twin band was also calculated to be ~ 300 keV above the yrast band, which is in good agreement with the experimental results of band 2. Once again, the predicted $B(M1)/B(E2)$ values reproduce the experimental data for band 2 in Fig. 5, although the calculated ratios are slightly lower. Thus, the experimental data for band 2 appear to satisfy the predictions of a yrare $\pi h_{11/2}\nu h_{11/2}$ band that is associated with the breaking of chiral symmetry.

TABLE I. Experimental and calculated interband transition strength ratios between band 2 and band 1 in ^{136}Pm.

	Experiment		Particle-rotor calculation					
Spin	$\frac{B(M1_{out})}{B(M1_{in})}$	$\frac{B(M1_{out})}{B(E2)}$	$\frac{B(M1_{out})}{B(M1_{in})}$	$\frac{B(M1_{out})}{B(E2)}$	$B(M1_{out})^{a}$	$B(M1_{in})^{b}$	$B(E2_{out})^{c}$	$B(E2_{in})^{d}$
$\hbar$		$(\mu_N/e\mathrm{b})^2$		$(\mu_N/e\mathrm{b})^2$	μ_N^2	μ_N^2	$(e\mathrm{b})^2$	$(e\mathrm{b})^2$
(11)		$1.08(14)^{e}$	0.120	2.62^{e}	0.204	1.698	0.078	0.154
(12)	0.101(16)	$12.7(28)^{e}$	0.194	6.44^{e}	0.264	1.348	0.041	0.188
(13)	0.067(10)	$0.298(52)^{f}$	0.234	1.01^{f}	0.285	1.219	0.031	0.283
(14)	0.209(70)	$0.94(21)^{f}$	7.20	4.64^{f}	1.080	0.150	0.049	0.233

[a] Transition strength from spin I in band 2 to spin $I-1$ in band 1.

[b] Transition strength of $I\rightarrow I-1$ in band 2.

[c] Transition strength from spin I in band 2 to spin $I-2$ in band 1.

[d] Transition strength of $I\rightarrow I-2$ in band 2.

[e] The interband $E2$ transition was used for this ratio, i.e., $B(M1)_{out}/B(E2)_{out}$.

[f] The intraband $E2$ transition (in band 2) was used for this ratio, i.e., $B(M1)_{out}/B(E2)_{in}$.

In an ideal case, the two bands would be degenerate and the corresponding chirally broken states would have no interaction. However, in reality, some mixing is always present, especially at lower spins. Therefore, determining the interaction strength between these two bands is an important issue to get information of the stability of chiral broken solutions. An experimental indicator of the interaction strength can be deduced by the transition strength ratios of the interband γ rays. Four $\Delta I = 1$ and two $\Delta I = 2$ transitions were observed linking band 2 to band 1, as seen in Fig. 1. The $B(M1_{out})/B(M1_{in})$ and $B(M1_{out})/B(E2)$ ratios were extracted from the branching ratios and γ-ray energies and are tabulated in Table I. $M1_{out}$ denotes a linking $\Delta I = 1$ transition and $M1_{in}$ is an in-band $\Delta I = 1$ transition of band 2. The linking $E2$ gamma ray was used for the $B(M1_{out})/B(E2)$ ratios from the $I = (11)$ and (12) states, while the in-band $E2$ transition (from band 2) was used for the ratios for the $I = (13)$ and (14) states. The corresponding transition strength ratios calculated by the PRM are presented in Table I for comparison, as well as the individual reduced transition strengths.

The predicted ratios are within a factor of 2–4 of the experimental values for the $I = (11)$, (12), and (13) states. The PRM consistently overestimates the ratios for these states except for the $B(M1_{out})/B(E2)$ value at $I = (12)$. As these are the first calculations of interband transition strengths, and little is understood about the interaction between chiral bands, such an agreement between experiment and theory is considered a significant success and supports the argument for band 2 as the chiral twin to band 1. However, large differences are found for the interband ratios of the $I = (14)$ state. This is likely due to the fact that the PRM calculated that the two bands lie nearest to each other at this spin, in contrast to the experimental observation, and it indicates the sensitivity of these quantities in the calculations.

In light of the new information on the experimental alignments and $B(M1)/B(E2)$ ratios, an $\pi h_{11/2} \nu h_{11/2}$ assignment is made for the excited positive-parity band in ^{136}Pm. Arguments were presented against band 2 being a vibrational sequence or the unfavored coupling of the $h_{11/2}$ proton and neutron. The possibility of this band being the chiral twin of the yrast $\pi h_{11/2} \nu h_{11/2}$ configuration has been explored by comparing experimental results with particle-rotor model predictions. Good agreement was achieved for both the intraband and interband transition strength ratios. Thus, we suggest that band 2 is a strong candidate as a chiral-twin partner in ^{136}Pm and that further detailed studies of the $N = 75$ nuclei, both theoretical and experimental, should be pursued to solidify other chiral candidates.

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[1] S. Frauendorf and Jie Meng, Nucl. Phys. **A617**, 131 (1997).

[2] V.I. Dimitrov, S. Frauendorf, and F. Dönau, Phys. Rev. Lett. **84**, 5732 (2000).

[3] S. Frauendorf, Nucl. Phys. **A677**, 115 (2000).

[4] K. Starosta *et al.*, Phys. Rev. Lett. **86**, 971 (2001).

[5] C.M. Petrache *et al.*, Nucl. Phys. **A597**, 106 (1996).

[6] I. Ragnarsson and P.B. Semmes, Hyperfine Interact. **43**, 425 (1988).

[7] R.V.F. Janssens and F. Stephens, Nucl. Phys. News **6**, 9 (1996).

[8] D.G. Sarantites, P.-F. Hua, M. Devlin, L.G. Sobotka, J. Elson, J.T. Hood, D.R. LaFosse, J.E. Sarantites, and M.R. Maier, Nucl. Instrum. Methods Phys. Res. A **381**, 418 (1996).

[9] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).

[10] C.W. Beausang, L. Hildingsson, E.S. Paul, W.F. Piel, N. Xu, and D.B. Fossan, Phys. Rev. C **36**, 1810 (1987).

[11] A. A. Hecht *et al.*, Phys. Rev. C **63**, 051302(R) (2001).

[12] K.S. Vierinen, J.M. Nitschke, P.A. Wilmarth, R.B. Firestone, and J. Gilat, Nucl. Phys. **A499**, 1 (1989).

[13] Y. Liu, J. Lu, Y. Ma, S. Zhou, and H. Zheng, Phys. Rev. C **54**, 719 (1996).

[14] R. Wadsworth, S.M. Mullins, P.J. Bishop, A. Kirwan, M.J. Godfrey, P.J. Nolan, and P.H. Regan, Nucl. Phys. **A526**, 188 (1991).

[15] E.S. Paul *et al.*, Phys. Rev. C **36**, 153 (1987).

[16] E.S. Paul *et al.*, Phys. Rev. C **36**, 2380 (1987).

[17] W. Reviol *et al.*, Phys. Rev. C **59**, 1351 (1999).

[18] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.

[19] Jing-ye Zhang, P. B. Semmes, F. Dönau, and L. L. Riedinger (unpublished).