PHYSICAL REVIEW C, VOLUME 63, 051302(R)

Evidence for chiral symmetry breaking in ^{136}Pm and ^{138}Eu

A. A. Hecht,[1] C. W. Beausang,[1] K. E. Zyromski,[1] D. L. Balabanski,[2,3] C. J. Barton,[1,5] M. A. Caprio,[1] R. F. Casten,[1] J. R. Cooper,[1] D. J. Hartley,[2] R. Krücken,[1] D. Meyer,[1] H. Newman,[1] J. R. Novak,[1] E. S. Paul,[4] N. Pietralla,[1] A. Wolf,[1,5,6] N. V. Zamfir,[1,5,7] Jing-Ye Zhang,[1,2] and F. Dönau[8]

[1]*Wright Nuclear Structure Laboratory, Physics Department, Yale University, New Haven, Connecticut 06520*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[3]*Faculty of Physics, St. Kliment Ohridsky University of Sofia, BG-1164 Sofia, Bulgaria*
[4]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[5]*Department of Physics, Clark University, Worcester, Massachusetts 10610*
[6]*Nuclear Research Center—Negev, Beer Sheva 84190, Israel*
[7]*National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
[8]*Forschungszentrum Rossendorf e.V., D-01314 Dresden, Germany*

(Received 22 January 2001; published 12 April 2001)

High-spin states in the doubly odd $N=75$ nuclei ^{136}Pm and ^{138}Eu were populated following the ^{116}Sn(^{24}Mg,$p3n$) and ^{106}Cd(^{35}Cl,$2pn$) reactions, respectively. A new $\Delta I=1$ band is reported in ^{138}Eu and new data are presented for the recently reported band in ^{136}Pm. Polarization and angular correlation measurements have been performed to establish the relative spin and parity assignments for these bands. Both bands have been assigned the same $\pi h_{11/2}\otimes \nu h_{11/2}$ structure as the yrast band and are suggested as candidates for chiral twin bands.

DOI: 10.1103/PhysRevC.63.051302 PACS number(s): 21.10.−k, 23.20.Lv, 27.60.+j

Static chiral symmetries are common in nature. Well-known examples range from the macroscopic spirals of snail shells to the microscopic handedness of certain molecules. Chiral symmetry is also well known in particle physics, where it is of a dynamic nature distinguishing between the two possible orientations of the intrinsic spin with respect to the momentum of the particle. Recently, the possibility that a type of chiral symmetry breaking might exist in some doubly odd, triaxial nuclei was suggested [1,2]. For a triaxial nucleus, possessing short, intermediate, and long axes, the collective angular momentum vector R tends to align along the intermediate axis, as this axis possesses the largest moment of inertia [3]. For a suitable choice of particle numbers and deformation, the valence proton and neutron Fermi surfaces lie near the bottom and top of a high-j shell, respectively. In this case, their single particle angular momentum vectors will tend to align along the short and long nuclear axes, respectively, perpendicular to each other and to the collective angular momentum. Such a situation is encountered in the mass $A\sim 130$ region, with $Z\sim 60$, $N\sim 75$. Here, the proton Fermi surface lies low in the $h_{11/2}$ shell (high j, low Ω) while the neutron Fermi surface lies high in the same $h_{11/2}$ shell (high j, high Ω). In addition, nuclei in this mass region are predicted to be soft with respect to γ deformation, and this triaxial deformation may be stabilized by the shape driving effects of the unpaired valence particles [4]. Indeed, total Routhian surface (TRS) calculations indicate a considerable triaxiality for such low-lying $\pi h_{11/2}\otimes \nu h_{11/2}$ configurations in ^{136}Pm and ^{138}Eu.

In this case, the total angular momentum vector **I** may not lie along a principal nuclear axis or even in a principal plane. The three nuclear axes, looked at from the point of view of the total angular momentum vector, can form either a left- or right-handed coordinate system which have opposite handedness or chirality. The experimental signature of such a chiral symmetry breaking would be the existence of degenerate pairs of $\Delta I=1$ bands of the same parity. However, the degeneracy is predicted to persist only over a limited spin range [1,2]. The pairs of bands will not be degenerate at low spins near the bandhead where, since **R** is small, the total angular momentum lies close to a principal plane and chiral twin bands cannot be defined. At intermediate spins, **R** becomes comparable to the single particle angular momenta, **I** becomes aplanar, and the chiral twin states should appear. At higher spins the angular momentum slowly aligns with the rotation axis and the degeneracy is again lifted.

A pair of $\Delta I=1$ bands found in ^{134}Pr ($Z=59$, $N=75$), based on the $\pi h_{11/2}\otimes \nu h_{11/2}$ configuration [5], has been suggested as a candidate for this chiral doubling [1,2]. Very recently, additional chiral bands have been reported in ^{130}Cs, ^{132}La, and ^{136}Pm [6]. In this Rapid Communication we present evidence for a new pair of chiral twin bands in the neighboring $N=75$ isotone ^{138}Eu and new results for the ^{136}Pm bands.

The ^{116}Sn(^{24}Mg,$p3n$) reaction at beam energies of 130 and 135 MeV was utilized to populate high spin states in ^{136}Pm. The ^{24}Mg beam was delivered by the ESTU Tandem Van de Graaff accelerator at the Wright Nuclear Structure Laboratory at Yale University. The target consisted of two stacked foils of ^{116}Sn, each of thickness 0.8 mg/cm^2. Gamma-rays were detected using the YRAST Ball array [7], which at the time of the experiment consisted of 18 coaxial Ge detectors, each with $\sim$25% relative efficiency, three LEPS detectors, and four clover detectors of $\sim$150% relative efficiency each. A total of 6.7×10^8 $\gamma-\gamma$ coincidences were accumulated during a five-day experiment.

In the europium experiment, high-spin states in ^{138}Eu were populated following the ^{106}Cd(^{35}Cl,$2pn$) reaction at a beam energy of 150 MeV. The beam was delivered by the

 ©2001 The American Physical Society

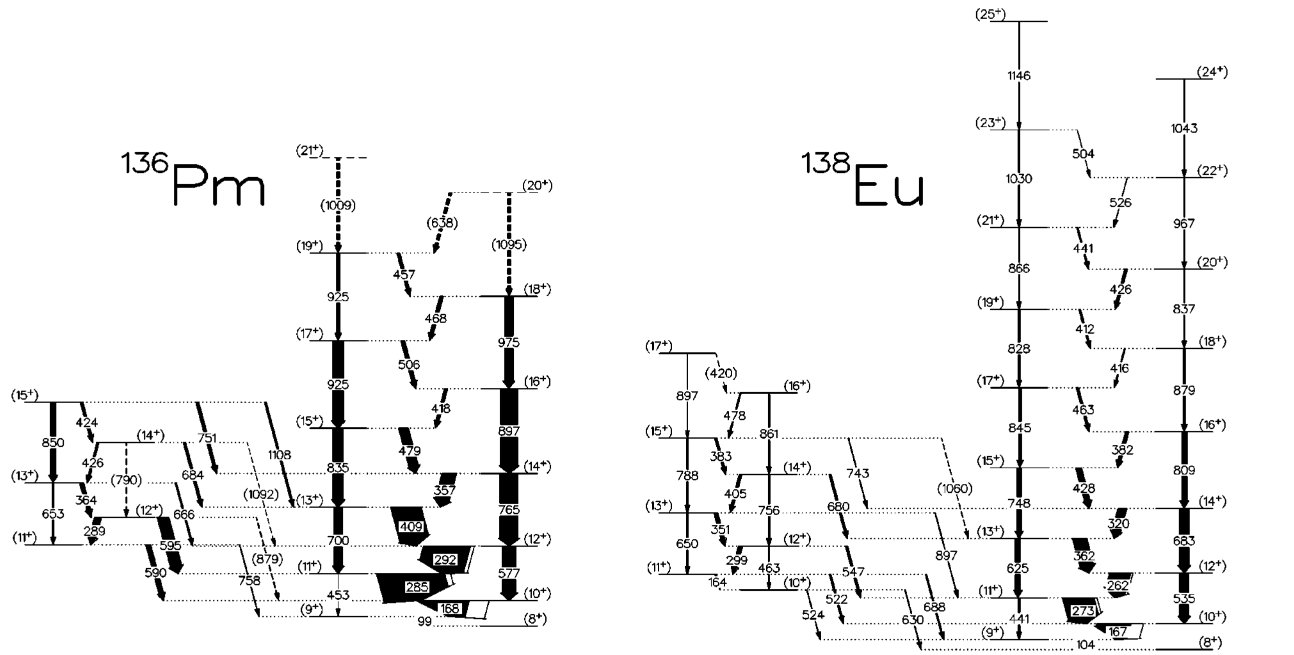

FIG. 1. Partial level schemes for ^{136}Pm and ^{138}Eu. The new $\Delta I=1$ bands are shown on the left of each nucleus. The gamma-ray energies are given in keV, arrow widths are proportional to the total intensity.

Daresbury Laboratory Tandem Van de Graaff accelerator. The decay gamma-rays were measured using the Eurogam Phase I detector array which consisted of 45 large volume Ge detectors [8,9]. A total of 5.7×10^8 unfolded $\gamma-\gamma$ coincidences were recorded. This data set had been utilized previously to establish the high spin structure of ^{138}Eu [10].

A doubles and triples analysis of these data sets resulted in the observation of new $\Delta I=1$ bands in both ^{136}Pm and ^{138}Eu. A preliminary analysis of the ^{136}Pm result has been reported previously [6,11]. Partial level schemes for ^{136}Pm and ^{138}Eu, showing the new $\Delta I=1$ bands on the left of each level scheme, are presented in Fig. 1. A double gated spectrum of the ^{138}Eu bands is shown in Fig. 2(a). The yrast bands have previously been assigned the positive parity $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration [10,12].

The new bands consist of $\Delta I=1$ $M1/E2$ transitions with $\Delta I=2$ crossover $E2$ transitions. They are connected to the yrast $\pi h_{11/2}\otimes\nu h_{11/2}$ band by both $\Delta I=1$ $M1/E2$ and ΔI

TABLE I. The results of 3D TAC calculations for the $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration in ^{136}Pm (top) and ^{138}Eu (bottom). The deformation parameters used were $\epsilon_2=0.194$, $\epsilon_4=0.028$, and $\gamma=-25°$ for ^{136}Pm and $\epsilon_2=0.202$, $\epsilon_4=0.032$, and $\gamma=-24°$ for ^{138}Eu. These were obtained from TRS calculations at a frequency of $\hbar\omega\sim0.25$ MeV for the $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration for these two nuclei. The angles θ and ϕ measure the tilt of the angular momentum vector **I** out of the principal plane.

$\hbar\omega$ (MeV)	θ (deg)	ϕ (deg)	I ($\hbar$)	$B(M1)/B(E2)$ $(\mu_N/e\text{ b})^2$
0.200	53.43	71.50	9.86	15.0
0.250	59.04	50.00	10.75	6.0
0.300	62.79	37.00	11.75	3.3
0.350	68.40	25.00	12.03	2.2
0.375	70.28	21.50	13.84	1.3
0.400	75.89	8.50	14.99	0.8
0.425	89.00	0.00	18.51	
0.200	57.17	31.00	10.53	2.9
0.225	59.04	24.50	10.95	2.5
0.250	60.91	20.50	11.45	2.1
0.275	64.66	10.00	12.07	1.6
0.300	66.53	4.00	12.59	1.3
0.325	66.53	0.50	13.00	1.3
0.350	68.40	0.00	13.50	1.2

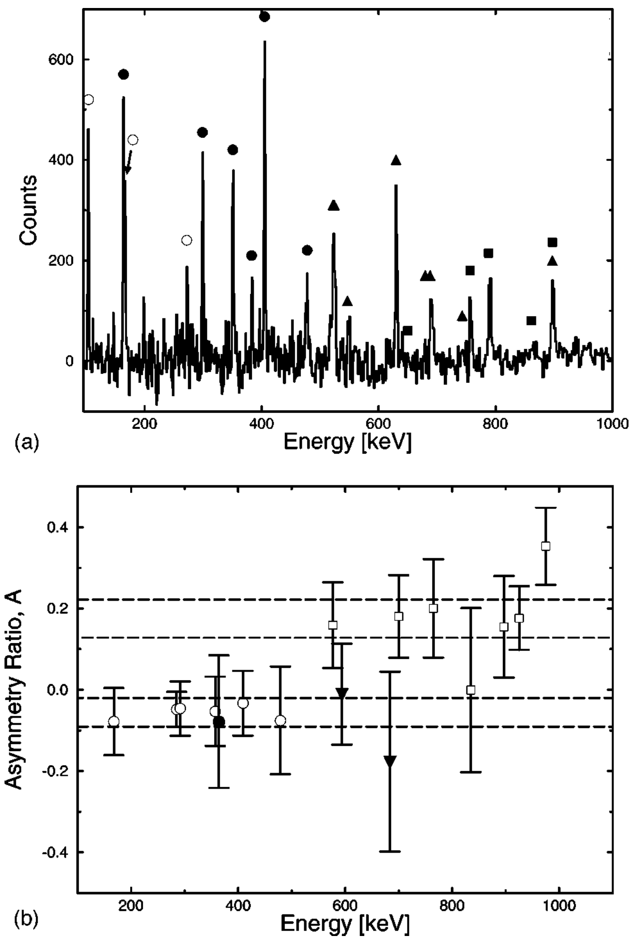

FIG. 2. (a) Background subtracted spectrum of the chiral band in ^{138}Eu with double gates set on the 164, 299, 351, and 383 keV transitions. Circles (squares) indicate $M1$ $(E2)$ transitions. Closed (open) symbols indicate transitions in the chiral (yrast) band. Closed triangles indicate interband linking transitions. (b) The measured asymmetry ratio A, for transitions in ^{136}Pm, symbols as in Fig. 2(a). The dashed lines show the error limits for averages of the known $E2$ (upper pair) and $M1$ (lower pair) transitions. Also shown are the new 364 inband, and 595 and 684 keV interband transitions.

$=2$ $E2$ transitions, the relative spins and transition multipole character being assigned based on the results of an angular correlation (DCO) analysis, while the bandhead spins were assigned based on the systematics of Ref. [6].

Furthermore, in the ^{136}Pm case, the polarization sensitivity of the YRAST Ball clover detectors was exploited to allow a confirmation of the electromagnetic character of several of the new transitions. The asymmetry ratio $A=(N_{\perp}-N_{\parallel})/(N_{\perp}+N_{\parallel})$ is sensitive to the electric or magnetic nature of the transitions, where $N_{\perp}(N_{\parallel})$ is the number of added-back photopeak counts which scatter between two elements of a clover detector orthogonal (parallel) to the reaction plane defined by the beam axis and the direction of the emitted gamma-ray. For this definition, magnetic transitions should have negative values, while electric transitions should have positive values of A. Figure 2(b) shows the measured values of A for various $E2$ and $M1$ transitions in the yrast and new bands in ^{136}Pm. The average values found for known $M1$ and $E2$ transitions in ^{136}Pm are $-0.055(35)$ and $0.175(47)$, respectively. Values of $A=-0.08(16)$, $-0.01(12)$, $-0.18(22)$ were measured for the 364 keV chiral inband, and 595 and 684 keV interband $\Delta I=1$ transitions, respectively, which are consistent with magnetic dipole assignments.

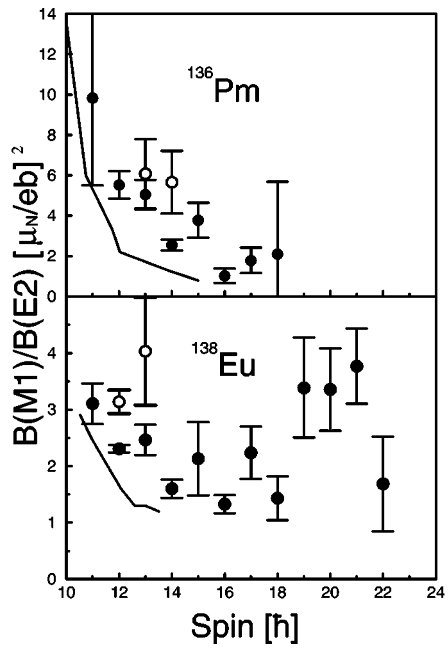

FIG. 3. Measured $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios as a function of angular momentum for the yrast (closed symbols) and chiral twin partner bands (open symbols) in ^{136}Pm and ^{138}Eu. The solid lines are the results of 3D TAC calculations [2].

The transition energies in the new bands are similar to those in the yrast bands. In addition, their alignments are essentially the same as those of the yrast bands throughout the observed frequency range. Finally, the measured inband $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ values are similar to those of the yrast band, as shown in Fig. 3. Based on these similarities, the new bands are assigned the same $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration as the yrast bands.

The new bands lie about 300 keV higher in excitation energy than the corresponding yrast band up to the limit we have currently been able to observe them. Both of these new $\Delta I=1$ bands are offered as candidates for chiral twin bands. Together with the results reported in Refs. [1,6,11], candidate chiral twin bands have now been suggested in the five $N=75$ doubly odd isotones ^{130}Cs, ^{132}La, ^{134}Pr, ^{136}Pm, and ^{138}Eu.

A traditional interpretation for the new bands, based on principal axis cranking, would invoke the unfavored signature of the $\pi h_{11/2}$ orbital coupled to both signatures of the $\nu h_{11/2}$ orbital. However, the signature splitting of the $\pi h_{11/2}$ orbital measured in odd-proton neighbors is between 400 and 500 keV [13–15], significantly larger than the observed energy splitting of about 300 keV for both ^{136}Pm and ^{138}Eu. Similarly, quasiparticle excitations and gamma-vibrational states lie at considerably higher excitation energies in this region [16,17].

In an ideal chiral symmetry scenario, the band pairs are expected to be degenerate over a certain spin range [1,2]. The actual situation however is expected to be more complicated and dynamic. For example, if the barrier between the left- and right-handed orientations were finite, the bands of different chirality would mix, thus lifting the degeneracy of the levels. The 300 keV energy difference has been interpreted this way, as a tunneling between the two minima [6,11].

Table I and Fig. 3 summarize the results of calculations using the three-dimensional tilted axis cranking model (3D TAC) [2] for ^{136}Pm and ^{138}Eu, modeling the behavior for triaxial nuclei with total angular momentum away from a principal plane. For the 3D TAC calculations, constant deformation and pairing parameters were used, obtained from TRS calculations [18] at a frequency of $\hbar\omega\sim0.25$ MeV for the $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration for these two nuclei. The table shows the frequency (spin) range in which the chiral solutions exist, i.e., where both tilt angles (θ,ϕ) are essentially different from 0° or 90°. The calculated $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratio should be compared with the average ratios for the two dipole bands, since the 3D TAC calculations cannot account for the mixing between two chiral twin bands. As can be seen in Fig. 3, the calculated ratios as a function of angular momentum reproduce both the magnitude and trend of the experimental data. At higher rotational frequencies, $\hbar\omega\sim0.42$ MeV for Pm and ~0.35 MeV for Eu, the calculated tilt angles approach $\theta\sim90°,\phi\sim0°$, implying that the rotation is again about a principal axis, thus signaling the end of the chiral structure.

In summary, new $\Delta I=1$ bands have been observed in doubly odd ^{136}Pm and ^{138}Eu. Based on DCO and polarization asymmetry measurements, the relative spins of the levels and electromagnetic character of the transitions have been assigned. The measured $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ values agree with calculations for triaxial nuclei with aplanar total angular momentum. The new bands have been assigned the same $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration as the yrast bands. These bands, together with similar bands observed in ^{130}Cs, ^{132}La [6] and ^{134}Pr [5], are considered good candidates for the predicted chiral twin bands [1].

This work was partly supported by the U.S. DOE under Grant Nos. DE-FG02-91ER40609, DE-FG05-96ER40983, and DE-FG02-88ER40417 and by the DFG under Grant No. Pi393/1-1.

[1] S. Frauendorf and J. Meng, Nucl. Phys. **A617**, 131 (1997).
[2] V. Dimitrov, S. Frauendorf, and F. Dönau, Phys. Rev. Lett. **84**, 5732 (2000).
[3] A. Bohr and B. R. Mottelson, *Nuclear Structure, Vol. 2* (Benjamin, New York, 1975).
[4] E. S. Paul *et al.*, J. Phys. G **17**, 605 (1991).
[5] C. M. Petrache, D. Bazzacco, S. Lunardi, C. Rossi Alvarez, G. de Angelis, M. De Poli, D. Bucurescu, C. A. Ur, P. B. Semmes, and R. Wyss, Nucl. Phys. **A597**, 106 (1996).
[6] K. Starosta *et al.*, Phys. Rev. Lett. **86**, 971 (2001).
[7] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **452**, 431 (2000).
[8] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992).
[9] P. J. Nolan, Nucl. Phys. **A520**, 657c (1990).
[10] E. S. Paul *et al.*, J. Phys. G **20**, 751 (1994).
[11] C. W. Beausang *et al.*, Nucl. Phys. **A682**, 394c (2001).
[12] C. W. Beausang, L. Hildingsson, E. S. Paul, W. F. Piel, Jr., N. Xu, and D. B. Fossan, Phys. Rev. C **36**, 1810 (1987).
[13] R. B. Firestone, V. S. Shirley, C. M. Baglin, S. Y. F. Chu, and J. Zipkin, *Table of Isotopes*, 8th ed. (Wiley, New York, 1996).
[14] C. W. Beausang, L. Hildingsson, E. S. Paul, W. F. Piel, Jr., P. K. Weng, and D. B. Fossan, Phys. Rev. C **36**, 602 (1987).
[15] P. Vaska *et al.*, Phys. Rev. C **52**, 1270 (1995).
[16] M. O. Kortelahti, B. D. Kern, R. A. Braga, R. W. Fink, I. C. Girit, and R. L. Mlekodaj, Phys. Rev. C **42**, 1267 (1990).
[17] E. S. Paul, S. Shi, C. W. Beausang, D. B. Fossan, R. Ma, W. F. Piel, Jr., N. Xu, and P. K. Weng, Phys. Rev. C **36**, 2380 (1987).
[18] R. Wyss, private communication.