Chiral Doublet Structures in Odd-Odd N = 75 Isotones: Chiral Vibrations

著者	Starosta K., Koike T., Chiara C. J., Fossan D. B., LaFosse D. R., Hecht A. A., Beausang C. W., Caprio M. A., Cooper J. R., Krucken R., Novak J. R., Zamfir N. V., Zyromski K. E., Hartley D. J., Balabanski D. L., Zhang Jing-ye, Frauendorf S., Dimitrov V. I.
journal or publication title	Physical Review Letters
volume	86
number	6
page range	971-974
year	2001
URL	http://hdl.handle.net/10097/52540

doi: 10.1103/PhysRevLett.86.971

Chiral Doublet Structures in Odd-Odd $N = 75$ Isotones: Chiral Vibrations

K. Starosta,[1,*] T. Koike,[1] C. J. Chiara,[1] D. B. Fossan,[1] D. R. LaFosse,[1] A. A. Hecht,[2] C. W. Beausang,[2] M. A. Caprio,[2] J. R. Cooper,[2] R. Krücken,[2] J. R. Novak,[2] N. V. Zamfir,[2,†] K. E. Zyromski,[2] D. J. Hartley,[3] D. L. Balabanski,[3,‡] Jing-ye Zhang,[3] S. Frauendorf,[4] and V. I. Dimitrov[4,‡]

[1]*Department of Physics and Astronomy, SUNY at Stony Brook, Stony Brook, New York 11794*
[2]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
and Institute for Nuclear and Hadronic Physics, Research Center Rossendorf, 01314 Dresden, Germany
(Received 24 July 2000)

New sideband partners of the yrast bands built on the $\pi h_{11/2} \nu h_{11/2}$ configuration were identified in $_{55}$Cs, $_{57}$La, and $_{61}$Pm $N = 75$ isotones of ^{134}Pr. These bands form with ^{134}Pr unique doublet-band systematics suggesting a common basis. Aplanar solutions of 3D tilted axis cranking calculations for triaxial shapes define left- and right-handed chiral systems out of the three angular momenta provided by the valence particles and the core rotation, which leads to spontaneous chiral symmetry breaking and the doublet bands. Small energy differences between the doublet bands suggest collective chiral vibrations.

DOI: 10.1103/PhysRevLett.86.971 PACS numbers: 21.10.Re, 23.20.Lv, 23.90.+w, 27.60.+j

Static chirality exists in molecules composed of four different atoms and is common for biological and pharmaceutical molecules with important consequences. In particle physics, chirality is a dynamic property which distinguishes for massless fermions the parallel or antiparallel orientation of spin and momentum. Intriguing nuclear structure effects associated with spontaneous chiral symmetry breaking have been predicted recently from angular momentum coupling considerations in odd-odd nuclei having triaxial shapes [1]. These predictions relate to configurations where the angular momenta of the valence proton, the valence neutron, and the core rotation are mutually perpendicular. This can occur when the Fermi level is located in the lower part of a valence proton high-j subshell resulting in its angular momentum oriented along the short axis of the triaxial core and in the upper part of a valence neutron high-j subshell with its angular momentum aligned with the long axis. These orientations maximize the overlap of the valence-particle wave functions with the triaxial nuclear shape, minimizing the interaction energy. The angular momentum of the rotating core itself is oriented along the intermediate axis because it has the largest moment of inertia for irrotational-like flow [2], which minimizes the rotational energy. These three mutually perpendicular angular momenta can be arranged to form two systems which differ by intrinsic chirality, a left- and a right-handed system; they are related by the chiral operator which combines time reversal and rotation by 180°, $TR_y(\pi)$. When chiral symmetry is thus broken in the body-fixed frame, the restoration of the symmetry in the lab frame is manifest as degenerate doublet $\Delta I = 1$ bands from the doubling of states [1].

It has been suggested that such chiral effects might be observed in transitional $A \sim 130$ nuclei, which are known to be susceptible to triaxial deformation (see Ref. [1] and references therein). The yrast bands in odd-odd $_{55}$Cs, $_{57}$La, $_{59}$Pr, and $_{61}$Pm $N = 75$ isotones are built on a $\pi h_{11/2} \nu h_{11/2}$ configuration with the Fermi level near the bottom of the $\pi h_{11/2}$ subshell and near the top of the $\nu h_{11/2}$ subshell. Previous experimental information on the $Z = 59$ ^{134}Pr isotone [3] revealed a nearly degenerate sideband feeding into the $\Delta I = 1$ $\pi h_{11/2} \nu h_{11/2}$ yrast band and having very similar properties. This pair of $\Delta I = 1$ bands has been interpreted in Ref. [1] as a consequence of the spontaneous breaking of chiral symmetry. In this model study, a stable triaxial ($\gamma = -30°$) mean field provides the three perpendicular principal axes of the mass distribution as shown in Fig. 1. The proton and the neutron $h_{11/2}$ spins are aligned to the short (s) and long (l) axes, respectively. The core rotational angular momentum **R** is oriented outside the s-l plane toward the positive or negative directions of the perpendicular intermediate (i) axis, which can be represented by two aplanar Routhian energy minima in regard to the direction of **R**. As **R**

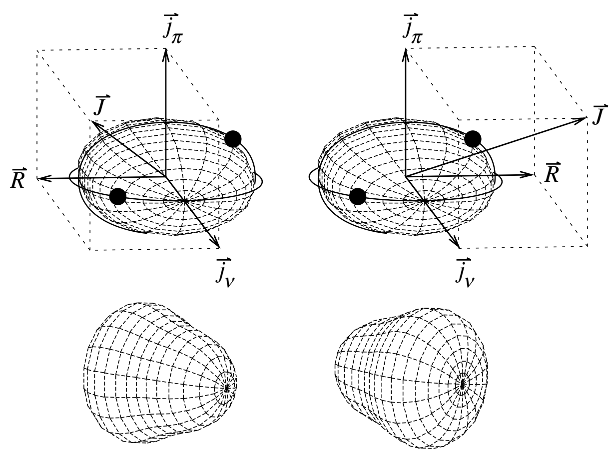

FIG. 1. Left- and right-handed chiral systems for a triaxial odd-odd nucleus in the upper part; reflection asymmetric octupole shapes in the lower part.

0031-9007/01/86(6)/971(4)$15.00

increases in going up from the bandhead, the total angular momentum I moves away from the l-s plane becoming aplanar and changing direction slightly for each band member. The two orientations of **R**, when coupled to the angular momenta of the valence nucleons, make up the left- and right-handed systems shown in Fig. 1, which differ by intrinsic chirality, and thus infer the breaking of chiral symmetry in the body-fixed frame. The required restoration of chiral symmetry for the lab frame yields the nearly degenerate doublet bands from the doubling of the spin-I band members. Detailed microscopic calculations have been carried out for ^{134}Pr using a 3D tilted axis cranking (TAC) approach [4]. The results confirm the assumptions of the model study [1] described above, namely, that the nucleus is triaxial and that **R** tends to be oriented along the (i) axis. Stable chiral solutions were found in the frequency interval $0.20 \leq \hbar\omega \leq 0.45$ MeV.

In the current work, similar sidebands have been discovered in the ^{130}Cs, ^{132}La, and ^{136}Pm isotones of ^{134}Pr with almost identical $\Delta I = 1$ energy spacings vs I as the yrast partner bands but displaced modestly in energy from the respective yrast bands. These observed systematic properties of the remarkably similar doublet $\Delta I = 1$ bands in the four $N = 75$ odd-odd isotones strongly suggest a common underlying physics interpretation, namely, that they are remnant structures related to the restoration of chiral symmetry broken in the body-fixed frame. An energy difference between the doublet bands indicates a weakening of the chiral symmetry breaking; we suggest that a lack of near degeneracy for the doublet bands implies a novel collective chiral vibration.

Coincidence γ-ray experiments have been conducted to investigate possible chiral properties in ^{130}Cs, ^{132}La, and ^{136}Pm, which are $N = 75$ isotones of ^{134}Pr. The ^{130}Cs and ^{132}La nuclei were studied using the LINAC at the State University of New York at Stony Brook with suppressed Ge detectors placed at $\pm 30°$, $\pm 90°$, and $\pm 150°$ relative to the beam and a multiplicity filter. Excited states in ^{130}Cs and ^{132}La were populated via the ^{124}Sn(^{10}B, $4n$) and ^{123}Sb(^{13}C, $4n$) reactions at 47 and 64 MeV, respectively. The ^{124}Sn and ^{123}Sb targets were 2–3 mg/cm^2 thick backed with Pb. The study of ^{136}Pm was performed with the Yale tandem using the ^{116}Sn(^{24}Mg, $4n$) reaction at 130 MeV and the YRAST ball, which consisted of 28 suppressed Ge detectors including five segmented clover detectors. Two thin $\sim$800-μg/cm^2 stacked targets were used.

Partial level schemes deduced from these studies showing the $\pi h_{11/2} \nu h_{11/2}$ bands and newly identified sidebands in ^{130}Cs, ^{132}La, and ^{136}Pm are presented in Fig. 2. The information on the main yrast $\pi h_{11/2} \nu h_{11/2}$ bands is extended in comparison to that reported previously for ^{130}Cs [5], for ^{132}La [6], and for ^{136}Pm [7]. Figure 2 also includes the relevant data on ^{134}Pr from Ref. [3]. Angular correlations of γ rays from the current coincidence (± 20 ns) data uniquely identify from timing considerations that the transitions linking the sidebands and the $\pi h_{11/2} \nu h_{11/2}$ yrast bands in ^{130}Cs, ^{132}La, and ^{136}Pm are of $\Delta I = 1$ mixed $M1/E2$ character. This yields positive parity for the sidebands and the spin information shown in Fig. 2. These techniques provide relative spin assignments only; it should be stressed, however, that relative spins are sufficient for addressing chiral symmetry. The systematic patterns of the energy levels in the sidebands and the $\pi h_{11/2} \nu h_{11/2}$ yrast bands observed in the $N = 75$ isotones favor the spin information shown in Fig. 2 for a common bandhead spin of I, which is consistent with

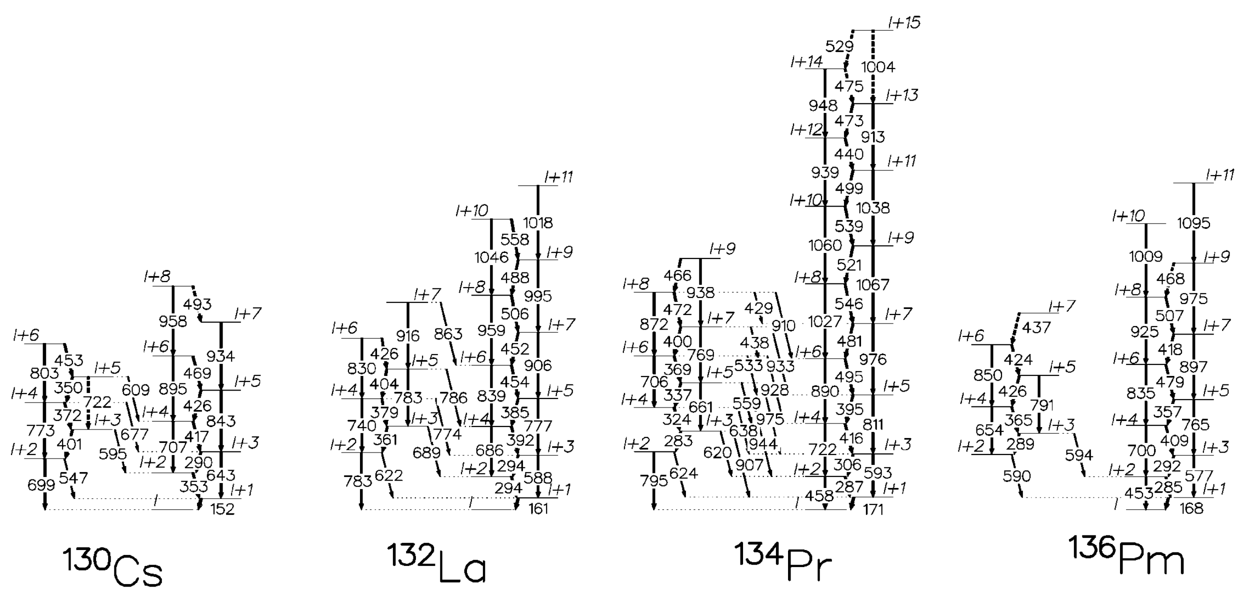

FIG. 2. Partial level schemes presenting the $\pi h_{11/2} \nu h_{11/2}$ bands and newly identified sidebands of ^{130}Cs, ^{132}La, and ^{136}Pm from the current study, and for ^{134}Pr from Ref. [3]. For each $N = 75$ isotone, the yrast $\Delta I = 1$ $\pi h_{11/2} \nu h_{11/2}$ band is shown on the right while the $\Delta I = 1$ sideband is shown on the left side of each level scheme.

$I = 9\hbar$ proposed in Ref. [8] for all four isotones. The even- and odd-spin members of the four sidebands are nearly perfectly interleaved as in the yrast bands, revealing the energy spacing similarity between the doublet bands (the splitting is not discussed using signatures, which are not good quantum numbers for triaxial aplanar TAC). The sidebands, however, are displaced modestly in energy from the yrast bands. For ^{134}Pr, the energy displacement between the doublet bands decreases from $\approx$0.19 MeV at low spin to the point where the doublet bands become nearly degenerate at $I = 14$. For the other $N = 75$ isotones, this displacement stays roughly constant at $\approx$0.25 MeV for ^{130}Cs, $\approx$0.37 MeV for ^{132}La, and $\approx$0.29 MeV for ^{136}Pm. The doublet bands in all four isotones are compared in Fig. 3.

The existence of the mixed $M1/E2$ links between the doublet bands implies that the sidebands are built on the same $\pi h_{11/2} \nu h_{11/2}$ configuration as the yrast band. Indeed, other low-lying positive-parity configurations in odd-odd nuclei in the $A \sim 130$ region must involve both a positive-parity proton and a positive-parity neutron orbital. The selection rules for the $M1$ and $E2$ operators yield vanishing matrix elements between such configurations and the yrast $\pi h_{11/2} \nu h_{11/2}$ configuration. As a consequence, the links should be strongly hindered unless the sidebands are built on the $\pi h_{11/2} \nu h_{11/2}$ configuration.

In ^{134}Pr, the members of the two band pairs with near degeneracy are interpreted as chiral restored doublet bands [1,4]. The other $N = 75$ odd-odd isotones, ^{130}Cs, ^{132}La, and ^{136}Pm (also the lower spin portion for ^{134}Pr) have similar doublet bands, as shown in Fig. 2, but which are not perfectly degenerate. The explanation that we propose for this energy displacement is related to the fact that the triaxial core deformation in these cases is not stable at $\gamma = -30°$, but perhaps more γ soft, resulting in an average moment of inertia along the i axis which is reduced closer to the values along the other two axes. In this situation, **R** is not constrained by the above Routhian minima to the two i-axis orientations, namely, the left- and right-handed systems of differing chirality; instead, **R** (and hence I) can oscillate from one chiral system to the other over (or tunnel through) the lowest saddle-point barrier E_b across the s-l plane (see Fig. 1). The related oscillation coordinate along with its canonical momentum would represent a quantum mechanical vibration, a collective chiral vibration, which produces the modest energy displacement, but retains the remnants of the chiral doublets. Such a collective chiral vibration of **R** between the left- and right-handed chiral systems in relation to chiral symmetry breaking would be analogous to the well studied collective octupole vibration between reflection asymmetric shapes in relation to parity symmetry breaking. This comparison is illustrated by the two mirror octupole shapes shown in the lower part of Fig. 1.

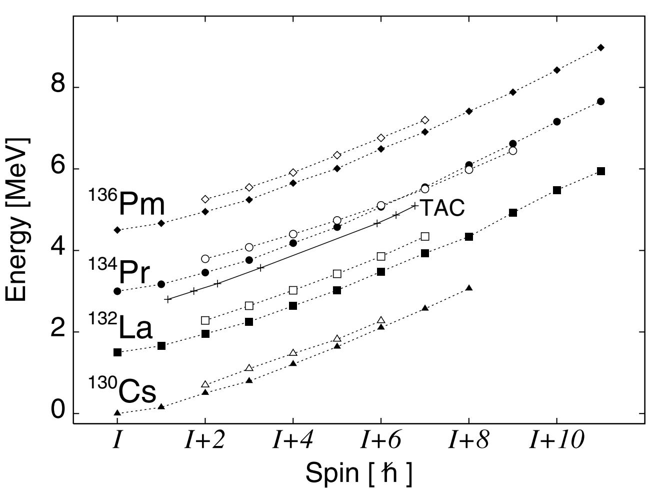

FIG. 3. Experimental energies for the $\pi h_{11/2} \nu h_{11/2}$ main band (filled symbols) and sidebands (open symbols) in the four $N = 75$ isotones. Bandhead energies are separated by 1.5 MeV for display. The 3D TAC doublet-band (relative) energies for ^{134}Pr are shown by the solid line.

An alternative interpretation of the excited band would be quasiparticle excitation. Since the parity is the same, the excitation must be within the $h_{11/2}$ shell. The difference between the lowest $h_{11/2}$ quasiparticle Routhians was calculated to be 0.75 MeV at $\hbar\omega = 0.4$ MeV for both the $h_{11/2}$ quasineutron and the $h_{11/2}$ quasiproton; this is consistent with observed properties of the $h_{11/2}$ bands in the odd-A neighboring nuclei. This energy is more than twice the experimental difference between the doublet bands; the smaller difference suggests a collective excitation. A γ vibration [9] coupled to the yrast band can be ruled out as an alternative because in this region the γ-vibration energies are $\geq$0.60 MeV. Hence, the interpretation as a collective chiral vibration appears to be the most convincing, although small admixtures of these two alternatives are possible.

We have carried out microscopic 3D TAC calculations for the $\pi h_{11/2} \nu h_{11/2}$ configuration in the $N = 75$ isotone chain for $Z = 55, 57, 59, 61, 63$. The 3D TAC model, described in Refs. [4,10], was used; it is based on a hybrid potential, where the spherical part is Woods-Saxon and the deformed part is modified harmonic oscillator. The pairing gaps Δ_p and Δ_n were fixed to 80% of the experimental even-odd mass difference, and the chemical potential was made to reproduce the particle number at $\omega = 0$ and kept constant. The calculations are the same as in Ref. [4]. Full self-consistency with respect to the tilt angles ϑ, φ and deformation parameters ε, γ was reached for $\hbar\omega = 0.35$ MeV. These values of ε, γ were then used for the other frequencies (0.20 to 0.45 MeV in steps of 50 keV), where only ϑ, φ were determined; studies showed that ε, γ depend only weakly on ω.

The results of these 3D TAC calculations as a function of Z are collected in Table I for $\hbar\omega = 0.35$ MeV, except ^{130}Cs and ^{138}Eu for $\hbar\omega = 0.30$ and 0.20 MeV, respectively; the frequency dependence for ^{134}Pr was shown in

TABLE I. Results of the 3D TAC calculations. J is the expectation value of the total angular momentum ($J \approx I + 1/2$). For aplanar chiral solutions, there are interband transitions $+ \rightarrow +$ and intraband transitions $+ \rightarrow -$ between the chiral doublet bands. If the solution is planar, there is only one band.

Z	55	57	59	61	63
ε	0.16	0.175	0.175	0.195	0.225
γ	39	32	27	27	20
$\hbar\omega$ [keV]	300	350	350	350	200
ϑ	65	65	65	70	60
φ	32	36	41	66	23
E_b [keV]	3	12	30	30	10
J	10.6	11.3	11.9	13.4	10.7
$B(M1, + \rightarrow +)[\mu_N^2]$	0.73	0.79	0.80	0.55	1.04
$B(M1, + \rightarrow -)[\mu_N^2]$	0.76	0.58	0.41	0.26	0.05
$10B(E2, + \rightarrow +)(eb)^2$	0.61	1.30	2.11	4.89	4.60
$10B(E2, + \rightarrow -)(eb)^2$	0.15	0.15	0.13	0.06	0.10

Ref. [4]. All four isotones were found to be triaxial, with ^{130}Cs and ^{138}Eu somewhat less so than the others. Chiral solutions are aplanar having both ϑ and φ substantially different from 0° and 90°. The chiral solution with degenerate doublet bands exists in ^{134}Pr for the largest frequency ω (or spin I) interval (see Fig. 3); it also has the largest E_b, the energy difference between the Routhian minima and the lowest saddle point connecting the two chiral systems. The frequency interval for chiral solutions in ^{136}Pm with a similar E_b is not as large as in ^{134}Pr. In ^{132}La, ^{130}Cs, and ^{138}Eu, chiral solutions exist for smaller ω intervals with shallower E_b values. Preliminary data for ^{138}Eu [11] suggest doublet bands similar to what was observed in ^{130}Cs. The calculations also provided the intra- and interband $B(M1)$ and $B(E2)$ transition strengths.

According to these $N = 75$ calculations, chiral solutions are the most pronounced for $Z = 59$ and 61 and disappear for Z less than 55 and greater than 63. For such a limited Z region, the best chiral characteristics should be manifest in the center with the surrounding transitional nuclei showing soft precursor vibrational modes. Such a scenario correlates well with the observation that the doublet bands are nearly degenerate for $Z = 59$. The experimental sidebands, as shown in Fig. 3, are observed for spin intervals of $7\hbar$ for ^{134}Pr, $5\hbar$ for ^{132}La, and $4\hbar$ for ^{130}Cs and ^{136}Pm, but with the latter three having energy displacements between the doublet bands. We interpret the doublet bands in the neighborhood of ^{134}Pr as soft chiral vibrations, with the related chiral vibrational energy being responsible for the modest energy displacement.

In summary, the systematic appearance of similar low-lying doublet bands of the same parity in the $N = 75$ isotones with near degeneracy in ^{134}Pr makes it likely that a small island of chiral rotation has been found which is surrounded by shores of soft chiral vibrations as is the case for other islands of broken symmetries, such as with quadrupole deformation, octupole deformation, and now rotational chirality. If the chiral doublet interpretation is correct, this would be the first direct evidence for stable triaxial shapes in nuclei. Clearly it would be interesting to study the neighboring isotone chains.

This work was supported by NSF Grant No. PHY-9870280 and DOE Grants No. DE-FG02-91ER-40609, No. DE-FG02-88ER-40417, No. DE-FG05-96ER-40983, and No. DE-FG02-95ER-40934.

*On leave from Institute of Experimental Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland.
†Also at Clark University, Worchester, MA 10610.
‡On leave from Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria.

[1] S. Frauendorf and J. Meng, Nucl. Phys. **A617**, 131 (1997).
[2] A. Bohr and B. Mottelsson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.
[3] C. M. Petrache *et al.,* Nucl. Phys. **A597**, 106 (1996); C. M. Petrache *et al.,* Z. Phys. A **344**, 227 (1992).
[4] V. I. Dimitrov, S. Frauendorf, and F. Dönau, Phys. Rev. Lett. **84**, 5732 (2000).
[5] P. R. Sala *et al.,* Nucl. Phys. **A531**, 383 (1991).
[6] J. R. B. Oliveira *et al.,* Phys. Rev. C **39**, 2250 (1989).
[7] C. W. Beausang *et al.,* Phys. Rev. C **36**, 1810 (1987).
[8] Y. Liu *et al.,* Phys. Rev. C **54**, 719 (1996); Y. Liu *et al.,* Phys. Rev. C **58**, 1849 (1998).
[9] J. Yan *et al.,* Phys. Rev. C **48**, 1046 (1993).
[10] V. I. Dimitrov *et al.,* Phys. Rev. C **62**, 024315 (2000).
[11] C. W. Beausang *et al.,* in Proceedings of "Nuclear Structure 2000," E. Lansing, MI (to be published).