



HAL
open science

Evidence for pseudospin-chiral quartet bands in the presence of octupole correlations

S. Guo, C.M. Petrache, D. Mengoni, Y.H. Qiang, Y.P. Wang, Y.Y. Wang, J. Meng, Y.K. Wang, S.Q. Zhang, P.W. Zhao, et al.

► **To cite this version:**

S. Guo, C.M. Petrache, D. Mengoni, Y.H. Qiang, Y.P. Wang, et al.. Evidence for pseudospin-chiral quartet bands in the presence of octupole correlations. *Phys.Lett.B*, 2020, 807, pp.135572. 10.1016/j.physletb.2020.135572 . hal-02934117

HAL Id: hal-02934117

<https://hal.science/hal-02934117>

Submitted on 16 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Evidence for pseudospin-chiral quartet bands in the presence of octupole correlations

S. Guo^{a,b,*}, C. M. Petrache^{c,*}, D. Mengoni^{d,e}, Y. H. Qiang^a, Y. P. Wang^f, Y. Y. Wang^f, J. Meng^{f,g}, Y. K. Wang^f, S. Q. Zhang^f, P. W. Zhao^f, A. Astier^c, J. G. Wang^{a,b}, H. L. Fan^a, E. Dupont^c, B.F. Lv^c, D. Bazzacco^{d,e}, A. Boso^{d,e}, A. Goasduff^{d,e}, F. Recchia^{d,e}, D. Testov^{d,e}, F. Galtarossa^{h,i}, G. Jaworski^h, D. R. Napoli^h, S. Riccetto^h, M. Siciliano^h, J. J. Valiente-Dobon^h, M. L. Liu^{a,b}, G. S. Li^{a,b}, X. H. Zhou^{a,b}, Y. H. Zhang^{a,b}, C. Andreoiu^j, F. H. Garcia^j, K. Ortner^j, K. Whitmore^j, A. Ataç-Nyberg^k, T. Bäck^k, B. Cederwall^k, E. A. Lawrie^{l,m}, I. Kutiⁿ, D. Sohlerⁿ, T. Marchlewski^o, J. Srebrny^o, A. Tucholski^o

^aKey Laboratory of High Precision Nuclear Spectroscopy and Center for Nuclear Matter Science, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China

^bSchool of Nuclear Science and Technology, University of Chinese Academy of Science, Beijing 100049, People's Republic of China

^cCentre de Sciences Nucléaires et Sciences de la Matière, CNRS/IN2P3, Université Paris-Saclay, Bât. 104-108, 91405 Orsay, France

^dDipartimento di Fisica e Astronomia, Università degli Studi di Padova, I-35131 Padova, Italy

^eINFN, Sezione di Padova, I-35131 Padova, Italy

^fState Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China

^gYukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

^hINFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy

ⁱDipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy

^jDepartment of Chemistry, Simon Fraser University, Burnaby, BC V5A 1S6, Canada

^kKTH Department of Physics, S-10691 Stockholm, Sweden

^lThemba LABS, National Research Foundation, PO Box 722, 7131 Somerset West, South Africa

^mDepartment of Physics & Astronomy, University of the Western Cape, P/B X17, Bellville ZA-7535, South Africa

ⁿInstitute of Nuclear Research, Hungarian Academy of Sciences, 4001 Debrecen, Hungary

^oUniversity of Warsaw, Heavy Ion Laboratory, Pasteura 5a, 02-093 Warsaw, Poland

Abstract

Three nearly degenerate pairs of doublet bands are identified in ^{131}Ba . Two of them, with positive-parity, are interpreted as pseudospin-chiral quartet bands. This is the first time that a complete set of chiral doublet bands built on the pseudospin partners $\pi(d_{5/2}, g_{7/2})$ is observed. The chiral bands with opposite parity built on 3-quasiparticle configurations are directly connected by many $E1$ transitions, without involving an intermediary non-chiral configuration. The observed band structures in ^{131}Ba have been investigated by using the reflection-asymmetric particle rotor model. The energies and the electromagnetic transition ratios of the three pairs of doublet bands observed in ^{131}Ba

*Corresponding authors

Email addresses: gs@impcas.ac.cn (S. Guo), petrache@csnsm.in2p3.fr (C. M. Petrache)

are reproduced and they are interpreted as chiral doublet bands with three-quasiparticle configurations. It is the first time that multiple chiral bands are observed in the presence of enhanced octupole correlations and pseudospin symmetry.

Key words:

Nuclear structure, Pseudospin, Chirality, Octupole correlation, reflection-asymmetric particle rotor model, tilted axis cranking covariant density functional theory

PACS: 21.10.Re, 21.60.Ev, 23.20.Lv, 27.60.+j

1. Introduction

Near degeneracy between two quantum states is usually associated with fundamental symmetries and symmetry breakings in complex many-body systems like atomic nuclei. Pseudospin symmetry was introduced to describe energy degeneracy between single-particle states with quantum numbers $(n, l, j = l + 1/2)$ and $(n - 1, l + 2, j = l + 3/2)$ [1–4]. After proving itself to be critical for many phenomena such as quantized alignment [5], identical bands [6], and pseudospin partner bands [7], the pseudospin was found to be fundamental as a relativistic symmetry of the Dirac Hamiltonian [8]. The concept of pseudospin was first proposed in spherical nuclei and later on extended to axially deformed nuclei [9, 10]. For triaxially deformed nuclei, it has been predicted to remain an important physical concept [11, 12]. However, this prediction has not been confirmed experimentally.

As for triaxiality, it provides the prerequisite for the well-known chiral symmetry breaking in nuclei [13]. So far, more than 60 chiral doublet bands have been reported in $A \sim 80, 100, 130,$ and 190 mass regions [14], which are regarded as the fingerprints of triaxial deformation. Therefore, it is possible to observe quartet bands with both pseudospin and chiral symmetries involved. If the effect of one symmetry is much stronger than the other, two well-divided pairs of energetically nearly degenerate bands are expected, otherwise it would behave as quartet bands which are difficult to divide in two groups by excitation energies and interband transitions. Since chiral geometry requires at least one particle and one hole in high- j orbitals which are usually intruder orbitals without pseudospin partner, pseudospin-chiral quartet bands are generally expected to be built on at least 3-quasiparticle configurations. Recently the predicted multiple chiral doublets ($M\chi D$) [15–18] triggered several experimental studies which led to the observation

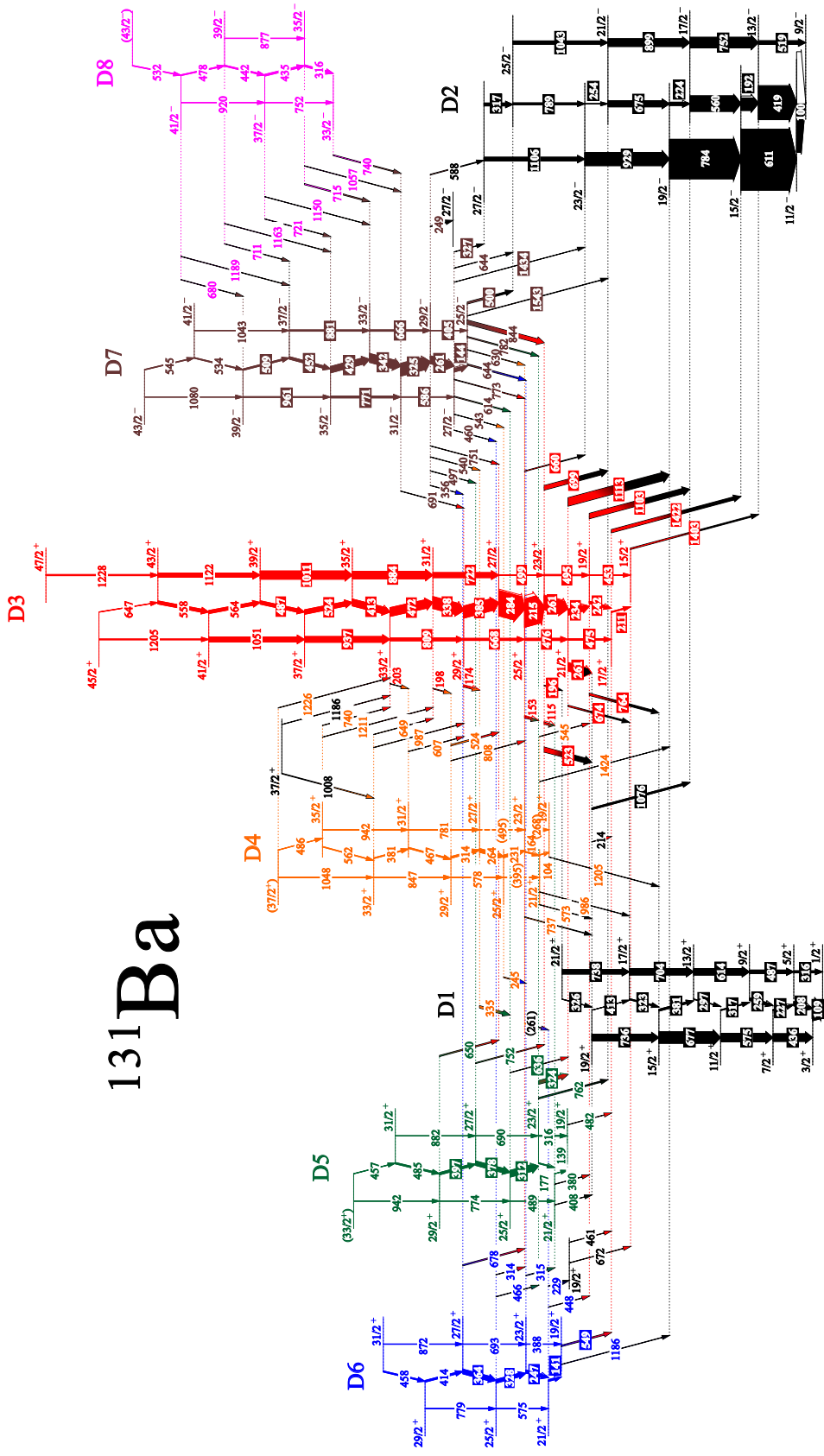


Figure 1: (Color online) Partial level scheme of ^{131}Ba deduced from the present work. Transition energies are given in keV and their measured relative intensities are proportional to the widths of the arrows. The labels of the newly identified transitions are on white background, while those of the previously known transitions are on a colored background. Levels and intraband transitions are colored in group by bands. The energies and ends of linking transitions are colored by their initial states while the tips are colored by their final states. Uncertain spin and parity assignments are given in brackets.

of several multi-energy-degenerate bands built on three or more quasiparticle configurations [19–23]. A recent theoretical work reported the coexistence of chiral symmetry and pseudospin symmetry in ^{105}Ag , and predicted the existence of pseudospin-chiral quartet bands, which has not been reported so far [24].

On the other hand, the coexistence of chirality and octupole correlations has been reported in ^{78}Br [25]. Octupole interaction is derived from intrinsic reflection symmetry breaking, and reaches maximum for octupole partner orbitals (l, j) and $(l \pm 3, j \pm 3)$. For normal deformed systems, strong octupole correlations are achieved when particle numbers are around 34, 56, 88, or 134 [26]. In ^{78}Br two chiral systems built on the $\pi g_{9/2} \otimes \nu g_{9/2}$ and $\pi f_{5/2} \otimes \nu g_{9/2}$ configurations, are linked by $E1$ transitions, which are enhanced by octupole correlations between the $\pi g_{9/2}$ and mixed $\pi(p_{3/2}, f_{5/2})$ orbitals, showing that chirality can be robust against the octupole correlations in nuclei. It is worth noting that the non-chiral $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration in ^{78}Br plays an important role in the link between two chiral systems built on $\pi g_{9/2} \otimes \nu g_{9/2}$ and $\pi f_{5/2} \otimes \nu g_{9/2}$ configurations. It is therefore interesting to search for chiral systems linked by “direct” octupole correlations without any intermediary non-chiral configuration involved.

Odd- A Ba isotopes provide ideal circumstances for the existence of the pseudospin-chiral quartet bands and direct octupole correlations between chiral systems. As $^{123-133}\text{Ba}$ are located in the $A \sim 130$ region of triaxially deformed nuclei, one expects the presence of chiral doublet bands. However, no chiral doublet candidates were reported previously in the Ba isotopes. As the proton Fermi surface for the Ba isotopes with $Z = 56$ is located between the $h_{11/2}$ and $(d_{5/2}, g_{7/2})$ orbitals, one also expects the presence of octupole correlations and octupole soft deformations, as well as pseudospin-chiral quartet bands.

The present letter reports for the first time evidence of pseudospin-chiral quartet bands in the ^{131}Ba nucleus, linked directly to another chiral doublet bands of opposite parity via a series of $E1$ transitions enhanced by octupole correlations.

2. Experimental results

The reported results were obtained in a high-statistics spectroscopic study of Ba nuclei using the $^{122}\text{Sn}(^{13}\text{C}, \text{xn})$ reaction with a 65-MeV ^{13}C beam provided by the Tandem accelerator at the Laboratori Nazionali di Legnaro, Italy, and with a stack of two self-supporting ^{122}Sn foils with a thickness of 0.5 mg/cm² each. The γ -rays were detected

by the GALILEO spectrometer, which consisted of 25 Compton-suppressed Ge detectors placed on four rings at 90° (10 detectors), 119° (5 detectors), 129° (5 detectors) and 152° (5 detectors). Approximately 1.2×10^9 triple- or higher-fold events have been collected. Details of the experiment and the data analysis can be found in Ref. [27].

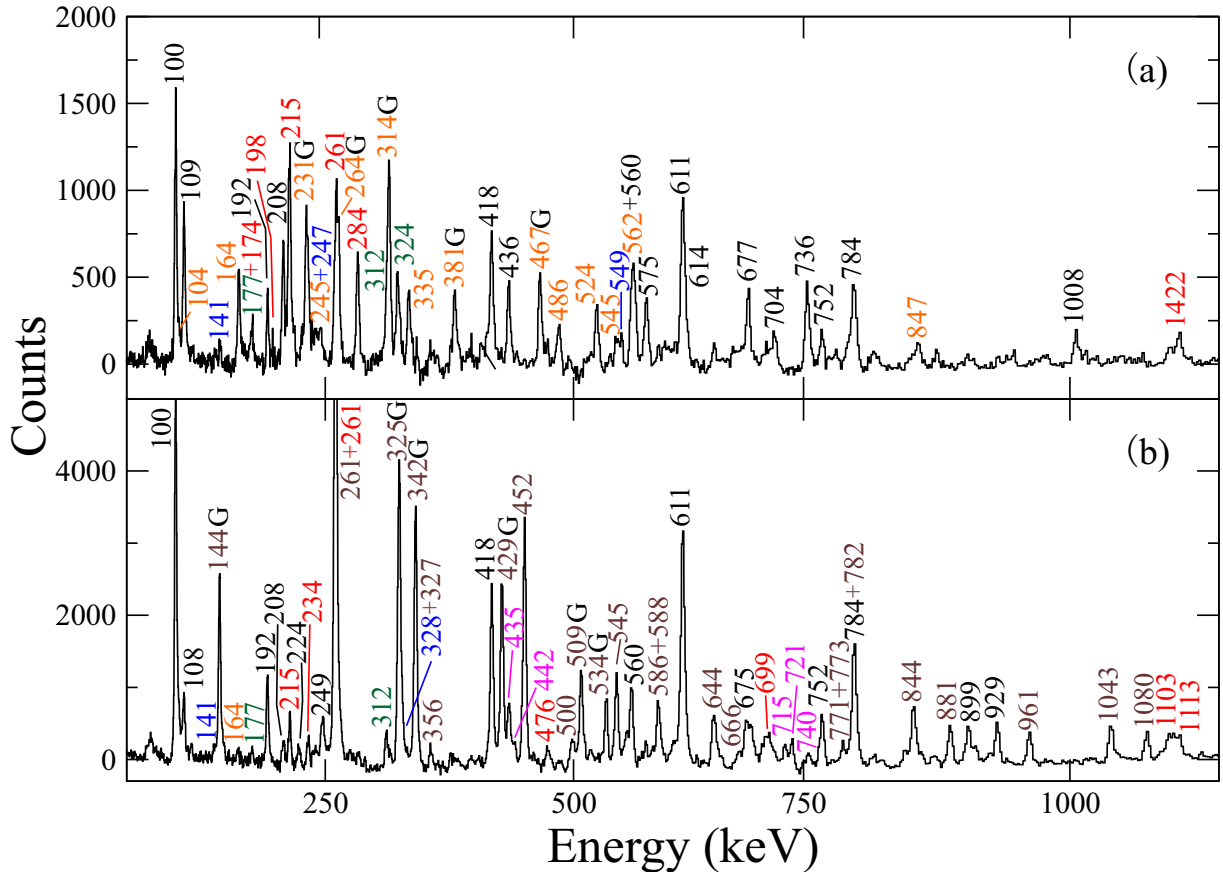


Figure 2: (Color online) Sum of background-subtracted spectra constructed by doubly-gating using any combination among strong transitions in bands D4 and D7 shown in panels (a) and (b), respectively. Energies used for gating are marked with capital letter “G”. Colors of peak energies are consistent with Fig.1.

Figure 1 shows a partial level scheme of ^{131}Ba obtained in the present work. Two bands (D4 and D8) are newly established, and four bands (D3, D5, D6, D7) have been significantly extended. Representative double-gated spectra supporting the level-scheme are shown in Fig. 2. A two-point angular-correlation ratio, R_{ac} , was deduced from a normalized ratio of γ -ray intensities extracted from spectra measured in the detectors at 152° and 90° , obtained by gating on transitions observed in all detectors. The R_{ac} ratio, which is independent of the multipolarity of the gating transition, was established to be ≈ 1.5 for stretched-quadrupole and ≈ 0.8 for stretched-dipole transitions. Some R_{ac} ratios

for typical transitions are shown in Fig. 3, in which the estimated values as function of spin for stretched-quadruple and stretched-dipole transitions are also shown with continuous lines. The deduced R_{ac} ratios for all the known $E1$ and $E2$ transitions agree with the curves within the errors. Therefore any transition with R_{ac} ratio apparently smaller than the estimated value of stretched-dipole transition is assigned to be $M1/E2$ transition with a considerable mixing ratio. The 549-keV transition linking band D6 to D3, and the 715- and 721-keV transitions linking D8 to D7 have small R_{ac} ratios, indicating that they are all $M1/E2$ transitions and the bands D6 and D8 should also same parities with D3 and D7, respectively. For bands D4 and D8, both $\Delta I = 1$ and $\Delta I = 2$ transitions are observed linking them to D3 and D7, respectively, which help to assign the spin and parities. Another angular-distribution analysis involving all the four angles was employed to deduce the mixing ratios(δ) in $M1/E2$ transitions.

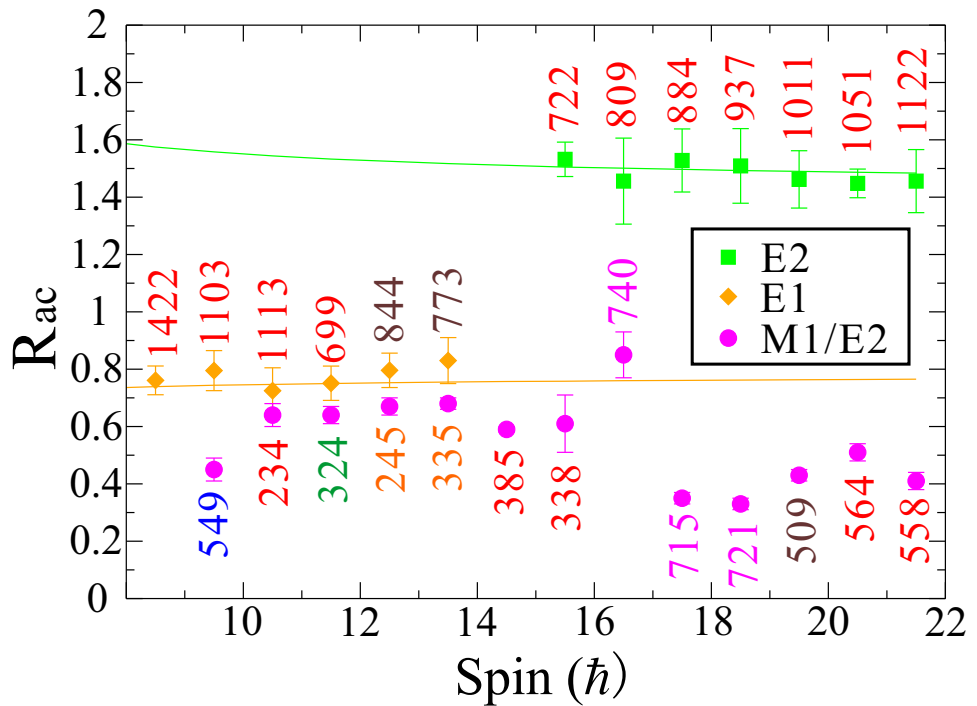


Figure 3: (Color online) R_{ac} ratios of some typical transitions deduced in the present work. Estimated values for stretched $\Delta I = 2$ and $\Delta I = 1$ transitions are shown with green and yellow continuous lines, respectively. $\sigma/I = 0.24$ is adopted in the estimation. Colors of transition energies are consistent with Fig.1.

3. Discussion

Prior to this work, band D1 based on the ground state has been established and assigned to $\nu(s_{1/2}, d_{3/2})$ configuration [28]. Band D2 is built on the $9/2^-$ isomeric state [29] and has been assigned to $\nu h_{11/2}$ configuration [30]. Bands D3 and D7 were first reported in Ref. [28] up to spin $39/2\hbar$ both, with tentative configuration assignments of $\pi h_{11/2} g_{7/2} \otimes \nu h_{11/2}$ and $\pi h_{11/2}^2 \otimes \nu h_{11/2}$, respectively. Bands D5 and D6 were first identified without spin and parity assignment in Ref. [28]. Recently, the spins and parities of band D5 have been assigned via linear polarization and angular distribution measurements [31]. The configurations of bands D5 and D6 were tentatively assigned as $\pi h_{11/2} g_{7/2} \otimes \nu h_{11/2}$ with the unfavored signature of the $g_{7/2}$ proton orbital occupied, and as $\pi h_{11/2} d_{5/2} \otimes \nu h_{11/2}$ [28], respectively, which is similar to the assignment to the corresponding bands in ^{133}Ce [32].

3.1. Interpretation based on experimental information

Four positive-parity nearly degenerate dipole bands (bands D3-D6) have been established in the present work, interconnected by many $M1/E2$ transitions and a few weak $E2$ transitions. Considering the spin and energy range, these four bands are built on three quasiparticle configurations. As the yrast band, band D3 can be safely assigned to the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration according to the systematics and previous works. The energy near degeneracy and a series of linking transitions among the four bands suggest an underlying similarity in the intrinsic quasiparticle configurations. With a normal deformation ($\beta \sim 0.2$), the quasiparticles in ^{131}Ba may occupy $\pi h_{11/2}$, $\pi g_{7/2}$, $\pi d_{5/2}$, $\nu h_{11/2}$, $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu d_{5/2}$, $\nu g_{7/2}$, $\nu h_{9/2}$, $\nu i_{13/2}$, $\nu f_{7/2}$ orbitals for states near the yrast line. Since all four bands have positive parities, the only possible competing configuration is obtained by replacing the high- Ω $\nu h_{11/2}$ orbital in the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration by the low- Ω $\nu(h_{9/2}, f_{7/2})$ one leading to the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu(h_{9/2}, f_{7/2})$ configuration. However, larger signature splitting and more intense $\Delta I = 2$ transitions are expected for this configuration, which are in contrast with the observation and therefore can be discarded. We conclude that all four bands are associated with the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configurations. This assignment is further supported by the quasiparticle alignments shown in Fig. 4. The alignments for bands D3-D6 are around 8-10 \hbar , which is approximately equal to the sum of the alignments of the $\pi h_{11/2}(g_{7/2}, d_{5/2})$ bands [31, 33, 34] ($\sim 5 - 7\hbar$) and of the $\nu h_{11/2}$ band [35] ($\sim 3\hbar$).

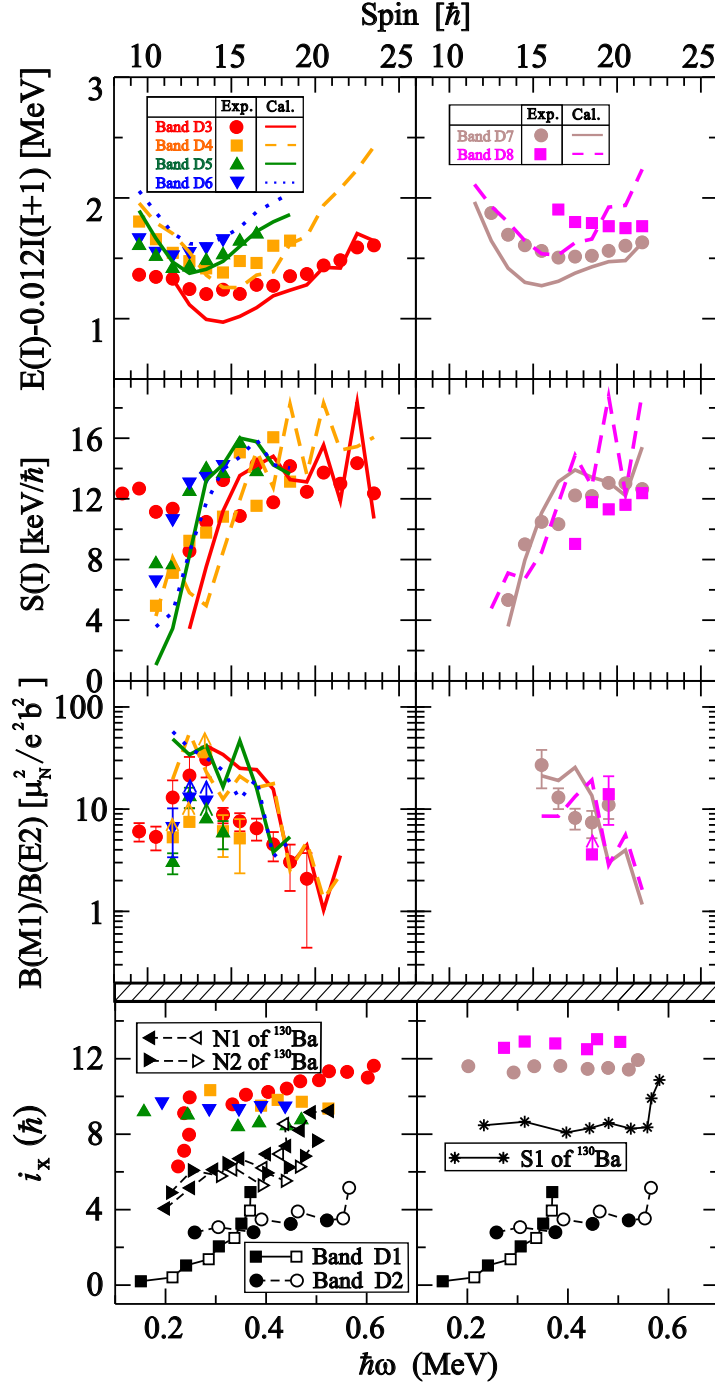


Figure 4: (Color online) The excitation energies minus a rigid-rotor reference, energy staggering parameters $S(I) = [E(I) - E(I - 1)]/2I$, $B(M1; I \rightarrow I - 1)/B(E2; I \rightarrow I - 2)$ ratios in comparison with the RAT-PRM results, and quasiparticle alignments for the positive quartet bands D3-D6 (left panel) and negative doublet bands D7, D8 (right panel). The abscissas of the lowest figures are marked in the bottom, while those for the other figures are marked in the top. To deduce the $B(M1)/B(E2)$ ratios, the mixing ratios for in-band $\Delta I=1$ transitions are deduced by angular distribution for most transitions. For a few weak ones, it is assumed to be $-0.2(1)$, which is close to the deduced values. Bands N1, N2 are two negative-parity bands in ^{130}Ba published in Refs. [31, 33], which are built on the $\pi h_{11/2}(g_{7/2}, d_{5/2})$ configuration. Band S1 of ^{130}Ba is built on the configuration $\pi h_{11/2}^2$ [35]. The Harris parameters used to obtain the alignments are $\mathcal{J}_0 = 11 \hbar^2 \text{MeV}^{-1}$ and $\mathcal{J} = 20 \hbar^4 \text{MeV}^{-3}$ for bands in ^{131}Ba , and $\mathcal{J}_0 = 10 \hbar^2 \text{MeV}^{-1}$ and $\mathcal{J} = 55 \hbar^4 \text{MeV}^{-3}$ in ^{130}Ba .

The bands D5 and D6 have been interpreted as based on the $\pi h_{11/2}g_{7/2} \otimes \nu h_{11/2}$ configuration differing by the occupation of the favored and unfavored signature of the $g_{7/2}$ proton orbital [28]. However, such an interpretation does not hold: the interband $\Delta I = 1$ transitions would be not hindered, since the quasiparticle configurations are identical and differ only by signature, leading to much stronger interband than intraband $\Delta I = 1$ transitions. This is opposite to the experimental observation.

Since the four nearly degenerate bands in ^{131}Ba involve one quasiparticle located in the $\pi(g_{7/2}, d_{5/2})$ orbital, the straightforward interpretation should involve the pseudospin symmetry. In neighboring $^{125,127,129}\text{Cs}$, the lowest-lying two branches with positive parity have been reinterpreted as based on the favored signatures of the $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals, respectively [36, 37]. The energy difference between these two branches is small (<300 keV for most spins) and their ordering varies at low spin. From the data of the present experiment, four branches are identified and assigned to the $\pi h_{11/2}(g_{7/2}, d_{5/2})$ negative-parity configuration in ^{130}Ba [34], with the two lowest-lying branches interpreted as dominated by the favored $\pi h_{11/2}g_{7/2}$ and $\pi h_{11/2}d_{5/2}$ signature branches. The energy difference between the two branches is similar to those in the Cs isotopes. Such an energy difference is similar to those between chiral doublet bands in $A \sim 130$ mass region, in particular to those in ^{133}Ce [20] and ^{135}Nd [23]. The energy degeneracy caused by the pseudo-spin doublet $\pi d_{5/2}$ and $\pi g_{7/2}$ at the Fermi surface can compete with that caused by chirality, leading to the observation of quartet bands.

Nevertheless, these four bands cannot be easily grouped in two pairs based on their energies and interband transitions, because the excitation energies do not show a distinct pattern and the ordering of bands D4-D6 varies with spin. Interband transitions are observed linking any two bands among them. In the present work, the deduced $B(M1)/B(E2)$ ratios are similar for the four bands, despite large uncertainties for several states. Apparent signature staggering has been observed for states with spin $> 29/2\hbar$, while the phase of bands D4 and D5 are opposite to that of band D3.

In addition to the four positive-parity bands D3-D6, we also identified the negative-parity bands D7 and D8 which are suggested as chiral doublet bands with the $\pi h_{11/2}^2 \otimes \nu h_{11/2}$ configuration, based on the similar experimental features (excitation energy, signature staggering, reduced transition probability ratios and quasiparticle alignment shown in Fig. 4) to the chiral doublet bands observed in ^{133}Ce [20] and ^{135}Nd [23]. Unlike the

corresponding bands in ^{133}Ce and ^{135}Nd which predominantly decay to the $h_{11/2}$ band, more than half of the intensity of band D7 decays to bands D3-D6 by a series of $E1$ transitions. The observation of these $E1$ linking transitions implies the existence of octupole correlations between the negative- and positive-parity bands with configurations differing by one quasiparticle on $\pi h_{11/2}$ and $\pi(g_{7/2}, d_{5/2})$ orbitals, respectively.

3.2. Support from theoretical calculation

With these configuration assignments, calculations based on the reflection-asymmetric triaxial particle rotor model (RAT-PRM) [38, 39] have been performed. The deformation parameters $\beta_2 = 0.22$ and $\gamma = 27.1^\circ$ for the configuration $\pi h_{11/2} g_{7/2} \otimes \nu h_{11/2}$ are obtained from the tilted axis cranking covariant density functional theory (TAC-CDFT) [40–44] calculations with PC-PK1 parametrization [45]. The octupole deformation $\beta_3 = 0.05$ is tentatively adopted to include the effect of octupole correlations. The details will be given in Ref. [39].

The excitation energies, energy staggering parameters $S(I) = [E(I) - E(I - 1)]/2I$, and $B(M1)/B(E2)$ ratios calculated by RAT-PRM are shown in Fig. 4, in comparison with the data. It is found that for bands D3 and D4, the dominant component of the intrinsic wavefunctions is $\pi h_{11/2} g_{7/2} \otimes \nu h_{11/2}$, while for bands D5 and D6, the valence particle wavefunction mixes up with many $\pi d_{5/2}$ components. And for the negative-parity doublet bands D7 and D8, the dominant component of the intrinsic wavefunctions is $\pi h_{11/2}^2 \otimes \nu h_{11/2}$. The small energy differences among quartet bands D3, D4, D5, and D6, as well as the difference between the doublet bands D7 and D8 are well reproduced. Especially, a band crossing between bands D4 and D5 has been reproduced, with a crossing spin ($I \sim 27/2\hbar$) in good agreement with the observation. The magnitude and trend of the energy staggering parameters and $B(M1)/B(E2)$ ratios agree with the available experimental data, which supports the present configuration assignments. The chiral geometry for these three pairs of chiral doublet bands will be further demonstrated by azimuthal plots and components of the angular momentum in Ref. [39], where a detailed discussion of the results obtained within the RAT-PRM formalism will be given.

Note that an alternative interpretation of two pairs of chiral doublet bands with the same configuration [46–48], which was employed to explain a similar structure in ^{103}Rh [21], has been excluded since the calculated quasiparticle configurations are different in ^{131}Ba .

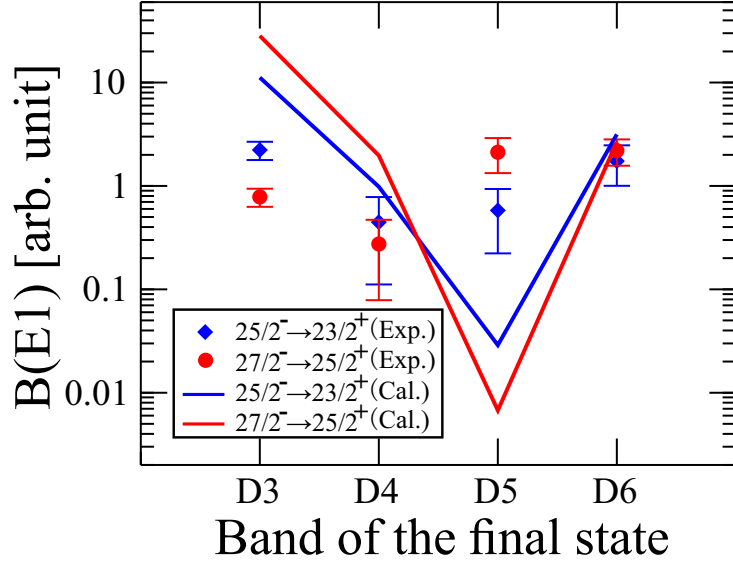


Figure 5: Experimental relative $B(E1)$ ratios for transitions from the same initial state in band D7 to the pseudospin-chiral quartet bands (bands D3-D6) in comparison with the RAT-PRM results. For each series, the deduced ratios are normalized to their geometric mean.

$E1$ transitions link band D7 not only to band D3 but also to bands D4-D6, implying the existence of octupole correlations between band D7 and all four positive-parity bands of the pseudospin-chiral quartets. The existence of the $\pi d_{5/2}$ component is therefore confirmed in all four bands, further supporting the assignment of the pseudospin-chiral quartet bands with configurations $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$. Figure 5 shows the extracted reduced relative transition probabilities among $E1$ transitions from the $25/2^-$ and $27/2^-$ states in band D7 to the four bands D3-D6 in comparison with the RAT-PRM results. The calculated trends are generally in agreement with the experimental ones, except for those feeding band D5.

4. Summary

In summary, four nearly degenerate positive-parity bands with configurations $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ are observed in ^{131}Ba , which represent the first evidence of pseudospin-chiral quartet bands. Pseudospin symmetry is found to play an important role in nuclei with stable triaxial deformation. A pair of negative-parity chiral bands associated with $\pi h_{11/2}^2 \otimes \nu h_{11/2}$ is also observed, and their decay to the pseudospin-chiral quartet bands via a series of $E1$ transitions is established, which indicates the existence of octupole correlations. Based on the reflection-asymmetric triaxial particle rotor model, the observed three pairs of nearly

degenerate doublet bands have been studied. It is the first time to observe octupole correlations between two chiral systems built on 3-quasiparticle configurations, without involving an intermediary non-chiral configuration. Such a structure, especially the linking $E1$ transitions, should be treated theoretically with chirality, pseudospin and octupole correlations involved simultaneously. Abundant experimental information on interband transitions can be used to verify theoretical models and calculations. It is of high scientific interest to search for similar structures in other nuclei and measure the lifetimes to extract reduced transitions probabilities.

5. Acknowledgments

S.G. expresses his gratitude to Prof. B. Qi for discussions on the theoretical interpretation. This work has been partly supported by the National Key R&D Program of China (Contract Nos. 2018YFA0404402, 2018YFA0404400 and 2017YFE0116700), the Key Research Program of the Chinese Academy of Sciences (Grant No. XDPB09-02), the National Natural Science Foundation of China (Grant Nos. 11575255, U1932137, U1732139, 11621131001, 11875075, 11935003, and 11975031), the Cai YuanPei 2018 Project No. 41458XH, the National Research, Development and Innovation Fund of Hungary (Project no. K128947), the European Regional Development Fund (Contract No. GINOP-2.3.3-15-2016-00034), and the National Research, Development and Innovation Office - NKFIH, contract number PD124717.

References

- [1] K. T. Hecht and A. Adler. Generalized seniority for favored $j \neq 0$ pairs in mixed configurations. *Nuclear Physics A*, 137(1):129 – 143, 1969.
- [2] A. Arima, M. Harvey, and K. Shimizu. Pseudo ls coupling and pseudo su_3 coupling schemes. *Physics Letters B*, 30(8):517 – 522, 1969.
- [3] H. Z. Liang, J. Meng, and S. G. Zhou. Hidden pseudospin and spin symmetries and their origins in atomic nuclei. *Physics Reports*, 570:1 – 84, 2015.
- [4] F. Nowacki, A. Poves, E. Caurier, and B. Bounthong. Shape Coexistence in ^{78}Ni as the Portal to the Fifth Island of Inversion. *Phys. Rev. Lett.*, 117:272501, Dec 2016.

- [5] F. S. Stephens, M. A. Deleplanque, J. E. Draper, R. M. Diamond, A. O. Macchiavelli, and C. W. Beausang *et al.* Pseudospin symmetry and quantized alignment in nuclei. *Phys. Rev. Lett.*, 65:301–304, Jul 1990.
- [6] J. Y. Zeng, J. Meng, C. S. Wu, E. G. Zhao, Z. Xing, and X. Q. Chen. Spin determination and quantized alignment in the superdeformed bands in ^{152}Dy , ^{151}Tb , and ^{150}Gd . *Phys. Rev. C*, 44:R1745–R1748, Nov 1991.
- [7] C. M. Petrache, G. Lo Bianco, D. Bazzacco, S. Lunardi, R. Menegazzo, and M. Nespola *et al.* Observation of a doublet band in the nucleus ^{128}Pr . *Phys. Rev. C*, 65:054324, May 2002.
- [8] Joseph N. Ginocchio. Pseudospin as a relativistic symmetry. *Phys. Rev. Lett.*, 78:436–439, Jan 1997.
- [9] R.D.Ratna Raju, J.P. Draayer, and K.T. Hecht. Search for a coupling scheme in heavy deformed nuclei: The pseudo $su(3)$ model. *Nuclear Physics A*, 202(3):433 – 466, 1973.
- [10] D. Troltenier, J.P. Draayer, P.O. Hess, and O. Castanos. Investigations of rotational nuclei via the pseudo-symplectic model. *Nuclear Physics A*, 576(3):351 – 386, 1994.
- [11] T. Beuschel, A.L. Blokhin, and J.P. Draayer. On the validity of the pseudo-spin concept for triaxially deformed nuclei. *Nuclear Physics A*, 619(1):119 – 128, 1997.
- [12] A.L. Blokhin, T. Beuschel, J.P. Draayer, and C. Bahri. Pseudospin and nuclear deformation. *Nuclear Physics A*, 612(2):163 – 203, 1997.
- [13] S. Frauendorf and J. Meng. Tilted rotation of triaxial nuclei. *Nucl. Phys. A*, 617:131, Nov 1997.
- [14] B. W. Xiong and Y. Y. Wang. Nuclear chiral doublet bands data tables. *Atomic Data and Nuclear Data Tables*, 125:193 – 225, 2019.
- [15] J. Meng, J. Peng, S. Q. Zhang, and S.-G. Zhou. Possible existence of multiple chiral doublets in ^{106}Rh . *Phys. Rev. C*, 73:037303, Mar 2006.
- [16] J. Peng, H. Sagawa, S. Q. Zhang, J. M. Yao, Y. Zhang, and J. Meng. Search for multiple chiral doublets in rhodium isotopes. *Phys. Rev. C*, 77:024309, Feb 2008.

- [17] J. M. Yao, B. Qi, S. Q. Zhang, J. Peng, S. Y. Wang, and J. Meng. Candidate multiple chiral doublets nucleus ^{106}Rh in a triaxial relativistic mean-field approach with time-odd fields. *Phys. Rev. C*, 79:067302, Jun 2009.
- [18] Jian Li, S. Q. Zhang, and J. Meng. Multiple chiral doublet candidate nucleus ^{105}Rh in a relativistic mean-field approach. *Phys. Rev. C*, 83:037301, Mar 2011.
- [19] J. A. Alcántara-Núñez, J. R. B. Oliveira, E. W. Cybulska, N. H. Medina, M. N. Rao, and R. V. Ribas *et al.* Magnetic dipole and electric quadrupole rotational structures and chirality in ^{105}Rh . *Phys. Rev. C*, 69:024317, Feb 2004.
- [20] A. D. Ayangeakaa, U. Garg, M. D. Anthony, S. Frauendorf, J. T. Matta, and B. K. Nayak *et al.* Evidence for multiple chiral doublet bands in ^{133}Ce . *Phys. Rev. Lett.*, 110:172504, Apr 2013.
- [21] I. Kuti, Q. B. Chen, J. Timár, D. Sohler, S. Q. Zhang, and Z. H. Zhang *et al.* Multiple chiral doublet bands of identical configuration in ^{103}Rh . *Phys. Rev. Lett.*, 113:032501, Jul 2014.
- [22] C. M. Petrache, B. F. Lv, A. Astier, E. Dupont, Y. K. Wang, and S. Q. Zhang *et al.* Evidence of chiral bands in even-even nuclei. *Phys. Rev. C*, 97:041304(R), Apr 2018.
- [23] B. F. Lv, C. M. Petrache, Q. B. Chen, J. Meng, A. Astier, and E. Dupont *et al.* Chirality of ^{135}Nd reexamined: Evidence for multiple chiral doublet bands. *Phys. Rev. C*, 100:024314, Aug 2019.
- [24] Hui Jia, Bin Qi, Chen Liu and Shou-Yu Wang. Coexistence of chiral symmetry and pseudospin symmetry in one nucleus: triplet bands in ^{105}Ag . *J. Phys. G: Nucl. Part. Phys.*, 46:035102, 2019.
- [25] C. Liu, S. Y. Wang, R. A. Bark, S. Q. Zhang, J. Meng, and B. Qi *et al.* Evidence for octupole correlations in multiple chiral doublet bands. *Phys. Rev. Lett.*, 116:112501, Mar 2016.
- [26] P. A. Butler and W. Nazarewicz. Intrinsic reflection asymmetry in atomic nuclei. *Rev. Mod. Phys.*, 68:349–421, Apr 1996.

- [27] Y. H. Qiang, C. M. Petrache, S. Guo, P. M. Walker, D. Mengoni, and Q. B. Chen *et al.* Identification of high- k rotation in ^{130}Ba : Testing the consistency of electromagnetic observables. *Phys. Rev. C*, 99:014307, Jan 2019.
- [28] R. Ma, Y. Liang, E. S. Paul, N. Xu, D. B. Fossan, L. Hildingsson, and R. A. Wyss. Competing proton and neutron rotational alignments: Band structures in ^{131}Ba . *Phys. Rev. C*, 41:717–729, Feb 1990.
- [29] D. J. Horen, W. H. Kelly, and L. Yaffe. Characteristics of the decay of ba^{131m} . *Phys. Rev.*, 129:1712–1715, Feb 1963.
- [30] J. Gizon, A. Gizon, and D.J. Horen. Band structure in 131,132,133ba observed by (12c,xn) reactions. *Nuclear Physics A*, 252(2):509 – 523, 1975.
- [31] Navneet Kaur, A. Kumar, G. Mukherjee, Amandeep Singh, S. Kumar, and Rajbir Kaur. High spin structure in 130,131ba. *Eur. Phys. J. A*, 50(1):5, 2014.
- [32] R. Ma, E. S. Paul, C. W. Beausang, S. Shi, N. Xu, and D. B. Fossan. Rotational bands in ^{133}Ce . *Phys. Rev. C*, 36:2322–2329, Dec 1987.
- [33] X. Sun, D. Bazzacco, W. Gast, A. Gelberg, U. Kaup and K. Schiffer *et al.* Excited states in ^{130}Ba . *Nuclear Physics A*, 436: 506 – 517, 1985.
- [34] S. Guo *et al.* to be established. *to be published*.
- [35] C. M. Petrache, P. M. Walker, S. Guo, Q. B. Chen, S. Frauendorf, and Y. X. Liu *et al.* Diversity of shapes and rotations in the γ -soft ^{130}Ba nucleus: First observation of a t -band in the $A=130$ mass region. *Physics Letters B*, 795: 241 – 247, 2019.
- [36] S. Sihotra, K. Singh, S. S. Malik, J. Goswamy, R. Palit, and Z. Naik *et al.* Band structures in ^{129}Cs . *Phys. Rev. C*, 79:044317, Apr 2009.
- [37] Ji Sun, Ying-Jun Ma, Tetsuro Komatsubara, Kohei Furuno, Yu-Hu Zhang, and Wen-Ping Zhou *et al.* Bandhead energies in ^{125}Cs . *Phys. Rev. C*, 93:064301, Jun 2016.
- [38] Y. Y. Wang, S. Q. Zhang, P. W. Zhao, and J. Meng. Multiple chiral doublet bands with octupole correlations in reflection-asymmetric triaxial particle rotor model. *Physics Letters B*, 792:454 – 460, 2019.

- [39] Y. P. Wang *et al.* to be established. *to be published*.
- [40] P. W. Zhao, J. Peng, H. Z. Liang, P. Ring, and J. Meng. Antimagnetic rotation band in nuclei: A microscopic description. *Phys. Rev. Lett.*, 107:122501, Sep 2011.
- [41] P. W. Zhao, S. Q. Zhang, J. Peng, H. Z. Liang, P. Ring, and J. Meng. Novel structure for magnetic rotation bands in 60Ni . *Physics Letters B*, 699(3):181 – 186, 2011.
- [42] Jie Meng, Jing Peng, Shuang-Quan Zhang, and Peng-Wei Zhao. Progress on tilted axis cranking covariant density functional theory for nuclear magnetic and antimagnetic rotation. *Frontiers of Physics*, 8(1):55–79, Feb 2013.
- [43] P. W. Zhao, S. Q. Zhang, and J. Meng. Impact of pairing correlations on the orientation of the nuclear spin. *Phys. Rev. C*, 92:034319, Sep 2015.
- [44] P. W. Zhao, N. Itagaki, and J. Meng. Rod-shaped nuclei at extreme spin and isospin. *Phys. Rev. Lett.*, 115:022501, Jul 2015.
- [45] P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng. New parametrization for the nuclear covariant energy density functional with a point-coupling interaction. *Phys. Rev. C*, 82:054319, Nov 2010.
- [46] Ch. Droste, S. G. Rohoziński, K. Starosta, L. Próchniak, and E. Grodner. Chiral bands in odd-odd nuclei with rigid or soft cores. *The European Physical Journal A*, 42(1):79, Sep 2009.
- [47] Q. B. Chen, J. M. Yao, S. Q. Zhang, and B. Qi. Chiral geometry of higher excited bands in triaxial nuclei with particle-hole configuration. *Phys. Rev. C*, 82:067302, Dec 2010.
- [48] Ikuko Hamamoto. Possible presence and properties of multi-chiral-pair bands in odd-odd nuclei with the same intrinsic configuration. *Phys. Rev. C*, 88:024327, Aug 2013.