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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. Kuti [n], D. Sohler [n], T. Marchlewski [o], J. Srebrny [o], A. Tucholski [o]

[a] *Key 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*
[b] *School of Nuclear Science and Technology, University of Chinese Academy of Science, Beijing 100049, People's Republic of China*
[c] *Centre de Sciences Nucléaires et Sciences de la Matière, CNRS/IN2P3, Université Paris-Saclay, Bât. 104-108, 91405 Orsay, France*
[d] *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, I-35131 Padova, Italy*
[e] *INFN, Sezione di Padova, I-35131 Padova, Italy*
[f] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, People's Republic of China*
[g] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[h] *INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy*
[i] *Dipartimento di Fisica e Scienze della Terra, Université di Ferrara, Ferrara, Italy*
[j] *Department of Chemistry, Simon Fraser University, Burnaby, BC V5A 1S6, Canada*
[k] *KTH Department of Physics, S-10691 Stockholm, Sweden*
[l] *iThemba LABS, National Research Foundation, PO Box 722, 7131 Somerset West, South Africa*
[m] *Department of Physics & Astronomy, University of the Western Cape, P/B X17, Bellville ZA-7535, South Africa*
[n] *Institute of Nuclear Research, Hungarian Academy of Sciences, 4001 Debrecen, Hungary*
[o] *University of Warsaw, Heavy Ion Laboratory, Pasteura 5a, 02-093 Warsaw, Poland*

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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 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.

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

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* Corresponding authors.
E-mail addresses: gs@impcas.ac.cn (S. Guo), petrache@csnsm.in2p3.fr (C.M. Petrache).

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$(n-1, l+2, j=l+3/2)$ [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 (MχD) [15–18] triggered several experimental studies which led to the observation 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 $^{123-133}$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}Sn(^{13}C,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/cm^2 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 $\times 10^9$ triple- or higher-fold events have been collected. Details of the experiment and the data analysis can be found in Ref. [27].

Fig. 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 $\approx$1.5 for stretched-quadruple and $\approx$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.

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 $\pi h^2_{11/2} \otimes \nu h_{11/2}$, 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

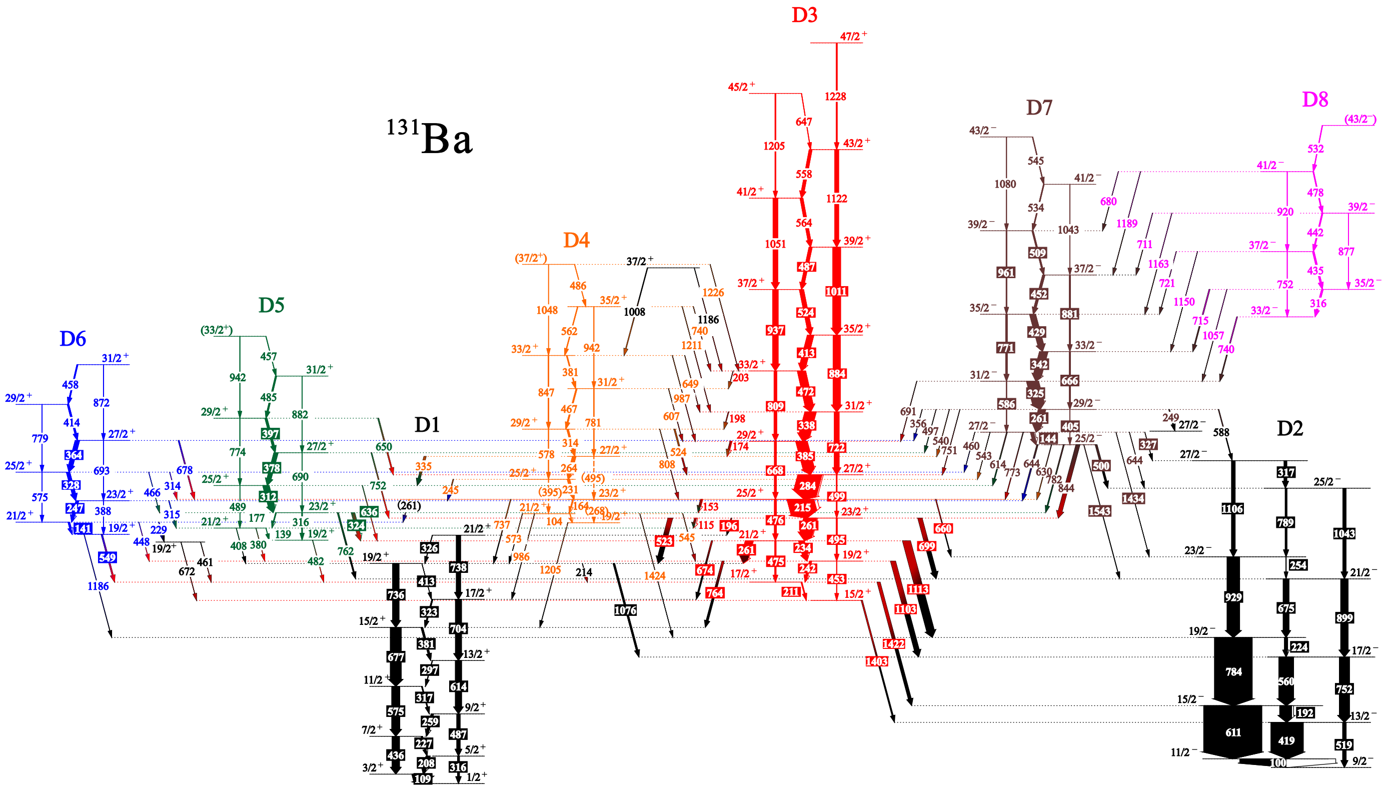

Fig. 1. Partial level scheme of ^{131}Ba deduced from the present work. Transition energies are given in keV and their measured relative intensities are proportional to the widths of the arrows. The labels of the newly identified transitions are on white background, while those of the previously known 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.

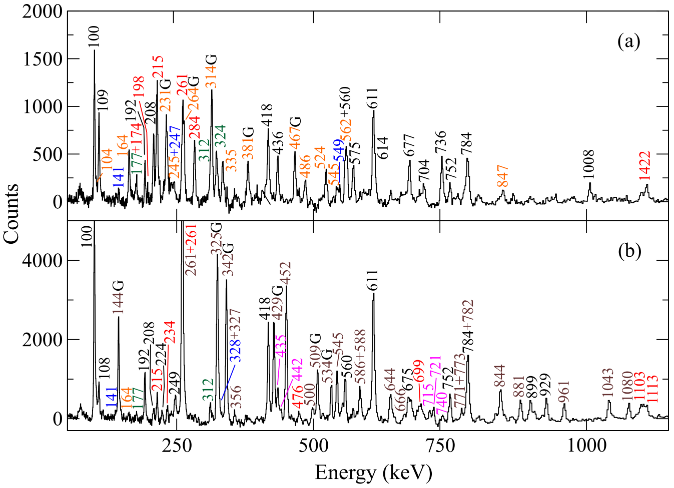

Fig. 2. Sum of background-subtracted spectra constructed by doubly-gating using any combination among strong transitions in bands D4 and D7 shown in panels (a) and (b), respectively. Energies used for gating are marked with capital letter "G". Colors of peak energies are consistent with Fig. 1.

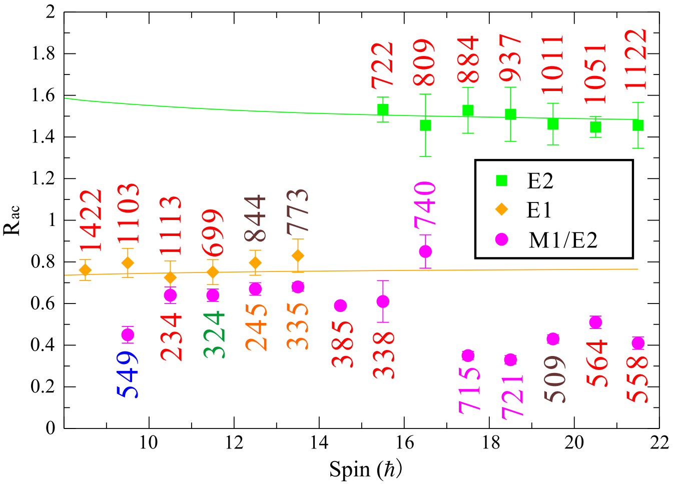

Fig. 3. R_{ac} ratios of some typical transitions deduced in the present work. Estimated values for stretched $\Delta I = 2$ and $\Delta I = 1$ transitions are shown with green and yellow continuous lines, respectively. $\sigma/I = 0.24$ is adopted in the estimation. Colors of transition energies are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

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. The occupation of such low-Ω intruder orbitals induces large signature splitting due to the Coriolis splitting between the states with spin-up and spin-down, and drive the nuclei to higher deformation, leading to the enhancement of the quadrupole moment. Therefore a band built on this configuration is expected to have significant signature splitting, to be composed of two main cascades of E2 transitions, one with odd spins and one with even spins, possibly connected by weak $\Delta I = 1$ transitions, like for example the bands Q4 and Q5 in the neighboring ^{133}Ce nucleus [33]. As the positive-parity bands of ^{131}Ba have negligible signature splitting and are dominated by strong $\Delta I = 1$ transitions, one can safely discard such a configuration. We conclude that all four bands are associated with the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration. The alignments for bands D3-D6 are estimated to be around 8-10 $\hbar$, as the sum of the alignments of the $\nu h_{11/2}$ band (band D2, $\sim$ 3 $\hbar$) and of the $\pi h_{11/2}(g_{7/2}, d_{5/2})$ bands [31,34,35] ($\sim$ 5-7 $\hbar$) observed in the odd-even neighboring nuclei (see Fig. 4). An alignment of around 14 $\hbar$ can be estimated for the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu(h_{9/2}, f_{7/2})$ configuration, which is higher than that of the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration by around 4 $\hbar$, like in the case of bands 3 and 4 of ^{137}Nd [37]. The deduced alignments are therefore quantitatively in agreement with the $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ configuration, further supporting the assignments.

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}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 [38,39]. 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 [35], 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 $\pi h^2_{11/2} \otimes \nu h_{11/2}$ 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)

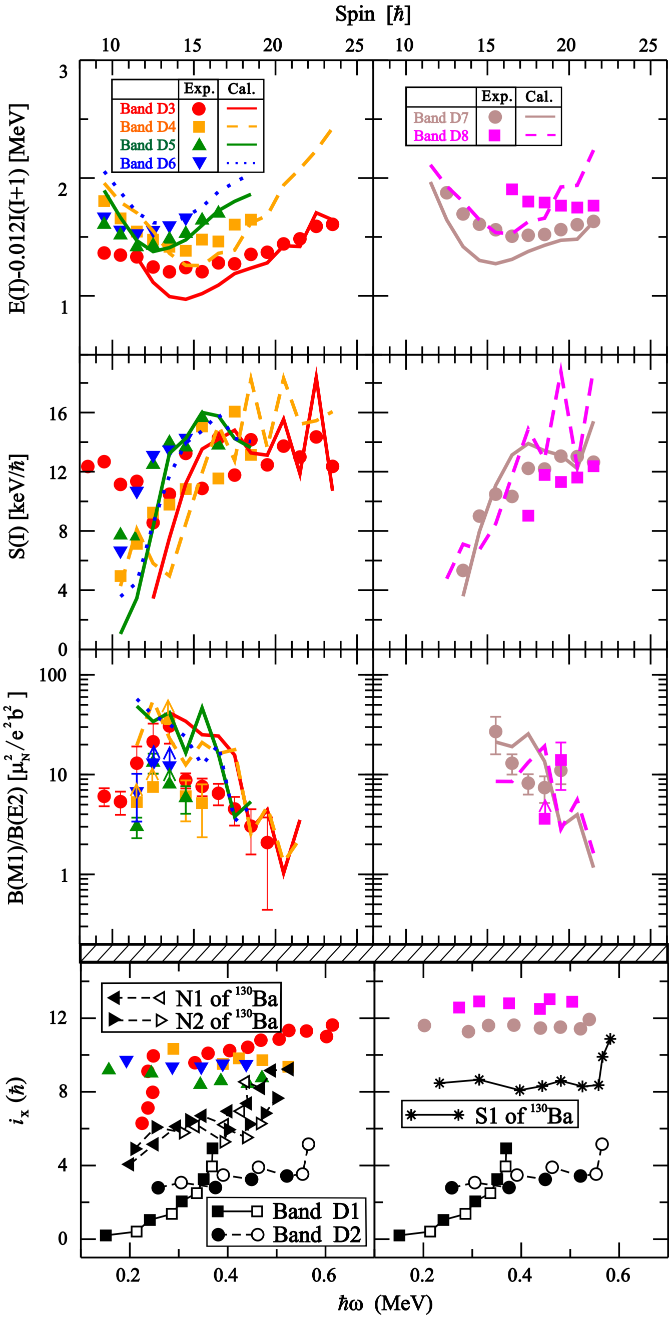

Fig. 4. The excitation energies minus a rigid-rotor reference (the first row), energy staggering parameters $S(I) = [E(I) - E(I-1)]/2I$ (the second row), $B(M1; I \to I-1)/B(E2; I \to I-2)$ ratios (the third row) in comparison with the calculated results (see subsection 3.2), and quasiparticle alignments (the fourth row) 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. The alignments of bands D1, D2 and bands N1, N2, S1 in ^{130}Ba [31,34,36] are also plotted for comparison. Bands N1, N2 are built on the $\pi h_{11/2}(g_{7/2}, d_{5/2})$ configuration, while band S1 is built on the $\pi h^2_{11/2}$ configuration. The Harris parameters used to obtain the alignments are $\mathcal{J}_0 = 11\hbar^2$ MeV^{-1} and $\mathcal{J} = 20\hbar^4$ MeV^{-3} for bands in ^{131}Ba, and $\mathcal{J}_0 = 10\hbar^2$ MeV^{-1} and $\mathcal{J} = 55\hbar^4$ MeV^{-3} in ^{130}Ba.

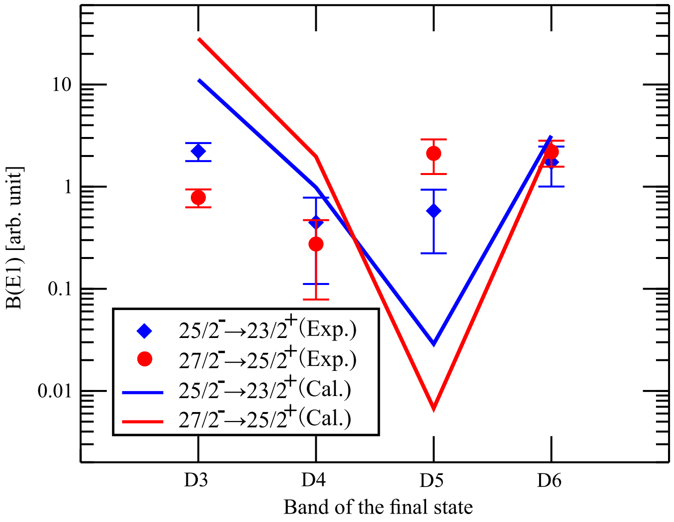

Fig. 5. Experimental relative $B(E1)$ ratios for transitions from the same initial state in band D7 to the pseudospin-chiral quartet bands (bands D3-D6) in comparison with the RAT-PRM results. For each series, the deduced ratios are normalized to their geometric mean.

[40,41] have been performed. The deformation parameters $\beta_2 = 0.22$ and $\gamma = 27.1°$ 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) [42–46] calculations with PC-PK1 parametrization [47]. The octupole deformation $\beta_3 = 0.05$ is tentatively adopted to include the effect of octupole correlations. The details will be given in Ref. [41].

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 $\pi h^2_{11/2} \otimes \nu h_{11/2}$. 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. [41], 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 [48–50], 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.

$E1$ 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 $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$. Fig. 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. The calculated transition probabilities to band D5 are significantly lower than the experimental ones. The wave functions of bands D3-D6 are highly mixed due to the pseudospin partner orbitals, and the transition probabilities are therefore, sensitive to the amplitudes of main components. If the amplitudes of two main components are opposite, the total transition probability could be reduced. D5 is located close to D6 in the low-spin region, and crosses with D4 at ($I \sim 27/2\hbar$). Therefore the amplitudes of the components of states in D5 sensitively depend on their energy differences with D4 and D6, which is difficult to be reproduced accurately by calculation.

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 $\pi h^2_{11/2} \otimes \nu h_{11/2}$ 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.

Declaration of competing interest

Acknowledgements

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