

MULTIPLE CHIRAL DOUBLET BANDS IN REFLECTION-ASYMMETRIC TRIAXIAL PARTICLE ROTOR MODEL*

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The chirality in atomic nucleus has attracted a lot of attention in the last few decades. Based on the covariant density functional theory, the multiple chiral doublets ($M\chi D$), *i.e.*, more than one pair of chiral doublet bands in one single nucleus, has further been predicted in 2006, and attracted extensive attention. In this contribution, the $M\chi D$ with octupole correlations observed in ^{78}Br are discussed within the framework of recently developed reflection-asymmetric triaxial particle rotor model (RAT-PRM). In particular, the effects of the triaxial and octupole deformation degrees of freedom are discussed.

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1. Introduction

Since the pioneering work of nuclear chirality by Frauendorf and Meng in 1997 [1], many efforts have been devoted to explore the chirality in atomic nuclei, see *e.g.*, reviews [2–6].

The experimental signature of nuclear chirality is a pair of nearly degenerate $\Delta I = 1$ bands with the same parity, *i.e.*, chiral doublet bands. In 2006, based on the self-consistent covariant density functional theory, a phenomenon named multiple chiral doublets ($M\chi D$) is suggested, which shows more than one pair of chiral doublet bands can exist in one single nucleus [7]. The first experimental evidence for $M\chi D$ is reported in ^{133}Ce [8], followed by more evidences, such as in ^{103}Rh [9], ^{78}Br [10], ^{136}Nd [11] and ^{195}Tl [12]. Up to now, 62 candidate chiral bands in 49 nuclei (including 9 nuclei with $M\chi D$) have been reported in the $A \sim 80, 100, 130$ and 190 mass regions [12–14].

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Due to the observation of eight strong electric dipole (E1) transitions linking the positive- and negative-parity candidate chiral bands [10], the $M\chi D$ observed in ^{78}Br has recently been of great interest. It provides the first example of chiral geometry in octupole soft nuclei and indicates that nuclear chirality can be robust against the octupole correlations. It also indicates that the chirality-parity quartet bands [2, 10], which are the consequence of the simultaneous breaking of chiral and space-reflection symmetries, may exist in nuclei. The observations of $M\chi D$ with octupole correlations and/or the possible chirality-parity quartet bands have brought great challenges to the current nuclear models and, thus, it requires the development of new approaches.

Theoretically, nuclear chirality has been investigated with many approaches, for example, the triaxial particle rotor model (PRM) [1, 15–19], the tilted axis cranking model (TAC) [1, 20–23], the TAC approach with the random phase approximation [24, 25], and the collective Hamiltonian [26–28], the interacting boson–fermion–fermion model [29], the generalized coherent state model [30], and the projected shell model [31–34]. The triaxial PRM is one of the most popular models for describing nuclear chirality. It is a quantal model coupling the collective rotation and the single-particle motions in the laboratory reference frame, and describes directly the quantum tunneling and energy splitting between the doublet bands.

Very recently, a reflection-asymmetric triaxial PRM (RAT-PRM) with both triaxial and octupole degrees of freedom has been developed [35]. In this contribution, the RAT-PRM descriptions for the observed $M\chi D$ with octupole correlations in ^{78}Br are presented, and the effects of the triaxial and octupole deformation degrees of freedom are discussed.

2. Results and discussion

In the RAT-PRM calculations, the quadrupole deformation parameters $\beta_2 = 0.28$, $\gamma = 16.3^\circ$ are obtained from the microscopic multidimensionally-constrained covariant density functional (MDC-CDFT) calculation [36]. The octupole deformation parameter $\beta_3 = 0.02$ is adopted to consider the effect of octupole correlations.

The intrinsic single-particle states are obtained from the diagonalization of the reflection-asymmetric triaxial Nilsson potential [37]. To simulate the proton and neutron Fermi surfaces obtained from the MDC-CDFT calculation which are close to $\pi g_{9/2}[1/2]$ and $\nu g_{9/2}[5/2]$ orbitals, respectively, we choose the proton and neutron Fermi energies $\lambda_p = 44.6$ MeV and $\lambda_n = 47.6$ MeV. The pairing gap for both proton and neutron is determined by the empirical formula $\Delta = 12/\sqrt{A}$. The single-particle space available to the odd nucleon was truncated to 13 levels, six above and six on or below

the Fermi level. Increasing the size of the single-particle space did not have a significant effect on particle-rotor bands starting below about 5.0 MeV, but an enlarged basis space would be required for higher-lying bands. For the moment of inertia and the core parity splitting parameter, the values of $\mathcal{J}_0 = 14\hbar^2/\text{MeV}$ and $E(0^-) = 3 \text{ MeV}$ are adjusted to the experimental energy data.

In Fig. 1, the excitation energies, the energy staggering parameters $S(I) = [E(I) - E(I - 1)]/2I$, and the $B(M1)/B(E2)$ ratios calculated by the RAT-PRM for the positive-parity doublet bands 1 and 2 as well as the negative-parity doublet bands 3 and 4 are shown in comparison with the available data [10].

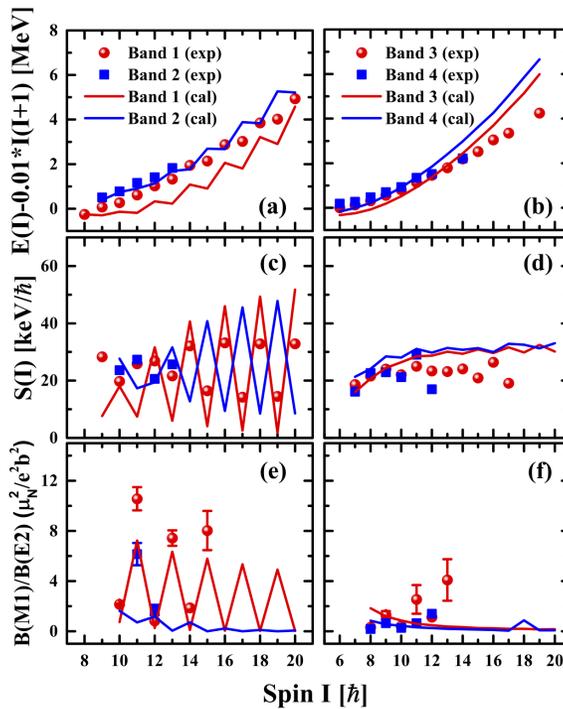


Fig. 1. The excitation energies [panels (a) and (b)], the energy staggering parameters $S(I) = [E(I) - E(I - 1)]/2I$ [panels (c) and (d)], and the $B(M1)/B(E2)$ ratios [panels (e) and (f)] for the positive-parity doublet bands 1 and 2 (left panels) as well as the negative-parity doublet bands 3 and 4 (right panels) in ^{78}Br calculated by means of the RAT-PRM (lines) in comparison with the data (symbols) [10]. The energy of band 1 at $I = 8\hbar$ is renormalized to the corresponding experimental bandhead. Taken from Ref. [35].

As shown in Figs. 1 (a) and 1 (b), the calculated excited energies give a reasonable reproduction of the data for the positive-parity doublet bands, and a better reproduction for the negative-parity doublet bands. The over-estimation of the experimental energy splittings between doublets may be due to the relatively small triaxial deformation ($\gamma = 16.3^\circ$) adopted in the present calculations. In Ref. [38], the cranked-shell-model calculations suggest the deformation parameters $(\beta_2, \gamma) = (0.32, 21.3^\circ)$ for band 1, with which a reasonable match between the calculated and experimental moments of inertia is achieved. In addition, the tilted axis cranking covariant density functional theory (TAC-CDFT) calculations [23, 39–43] also indicate that the triaxial deformation increases with the rotational frequency. In the present RAT-PRM calculations, it is found that both positive- and negative-parity doublets would be closer by using a larger triaxial deformation.

Figures 1 (c) and 1 (d) depict a reasonable agreement between the calculated $S(I)$ values and the data. For the positive-parity doublet bands, the calculated $S(I)$ values exhibit an obvious odd–even staggering behavior, while for the negative-parity doublet bands, they are quite smooth with the increasing spin up to $14\hbar$. The different $S(I)$ behaviors for the positive- and negative-parity doublet bands may be attributed to the corresponding configurations. The proton configurations are similar for both positive- and negative-parity bands, *i.e.*, a particle at the bottom of the $g_{9/2}$ shell. The neutron configurations, however, are quite different. There is a neutron hole at the top of the $f_{5/2}$ shell for the negative-parity bands, but a $g_{9/2}$ one at the middle of the shell for the positive-parity bands. In the latter case, it provides more alignments along the direction of the collective rotation and, thus, the $S(I)$ values are oscillating at even- and odd-spin states.

The experimental $B(M1)/B(E2)$ ratios are well-reproduced, as shown in Figs. 1 (e) and 1 (f). Again, there are strong odd–even staggerings for the positive-parity doublet bands, while invisible staggerings for the negative-parity bands. The similar behavior of $B(M1)/B(E2)$ ratios may be an indication for the nuclear chirality, which has been suggested in Ref. [44].

Within the consideration of the octupole deformation degree of freedom, the electric dipole transition probabilities $B(E1)$ between the positive- and negative-parity bands can be calculated. As shown in Fig. 2 (a), the calculated $B(E1)/B(E2)$ ratios, in which the interband E1 transitions from band 3 to band 1 and the intraband E2 transitions in band 3, are compared with the experimental values. In general, the calculated $B(E1)/B(E2)$ ratios underestimate the experimental data. Considering the fact that the calculated $B(M1)/B(E2)$ ratios for band 3 agree with the data, the underestimation of the calculated $B(E1)/B(E2)$ ratios may result from too small $B(E1)$ values.

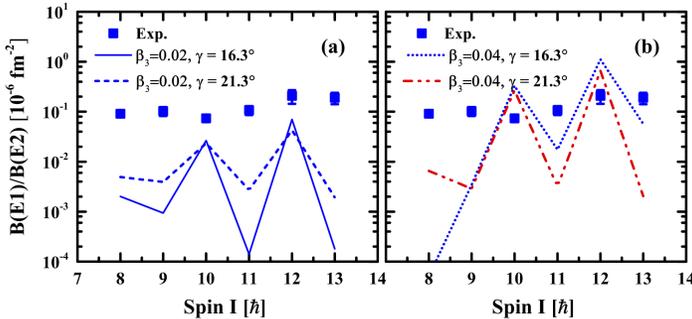


Fig. 2. The calculated $B(E1)/B(E2)$ ratios with the interband E1 transitions (band $3 \rightarrow 1$) and the intraband E2 transitions (band 3), in comparison with the available data [10] for (a) $\beta_3 = 0.01$ and (b) $\beta_3 = 0.04$. Taken from Ref. [35].

It is found that both the triaxial deformation γ and octupole deformation β_3 influence the calculated $B(E1)$ values. For $\beta_3 = 0.02$ as shown in Fig. 2 (a), the $B(E1)$ values are enhanced by changing γ from 16° to 21° (given by the cranked-shell-model calculations [38]). The same calculations with $\beta_3 = 0.04$ have no significant influence on the excited energies, staggering parameters, and $B(M1)/B(E2)$ ratios except the $B(E1)$ values. As shown in Fig. 2 (b), the $B(E1)$ values are enhanced with $\beta_3 = 0.04$ and a better agreement with the $B(E1)/B(E2)$ data can be obtained.

3. Summary and perspective

In summary, the M χ D with octupole correlations observed in ^{78}Br are discussed within the framework of the reflection-asymmetric triaxial particle rotor model (RAT-PRM). The calculated excited energies, energy staggering parameters, and $B(M1)/B(E2)$ ratios are in a reasonable agreement with the data of the chiral doublet bands with positive and negative parity. It is found that both the triaxial deformation γ and octupole deformation β_3 influence the calculated $B(E1)$ values.

The developed RAT-PRM provides a useful tool for describing a reflection-asymmetric triaxial system. For a reflection-asymmetric triaxial nucleus, the chiral and space-reflection symmetries may be broken simultaneously in the intrinsic frame. It is possible to establish the so-called chirality-parity quartet bands, *i.e.*, four nearly degenerate $\Delta I = 1$ bands, two with positive parity and two with negative parity, in reflection-asymmetric triaxial nuclei [2]. However, chirality-parity quartet bands have not been observed experimentally. It is of high scientific interest to find out the fingerprints for the experimental observations, such as energy spectra, the electromagnetic transition probabilities of the chirality-parity quartet bands theoretically.

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REFERENCES

- [1] S. Frauendorf, J. Meng, *Nucl. Phys. A* **617**, 131 (1997).
- [2] S. Frauendorf, *Rev. Mod. Phys.* **73**, 463 (2001).
- [3] J. Meng, S.Q. Zhang, *J. Phys. G: Nucl. Part. Phys.* **37**, 064025 (2010).
- [4] J. Meng, P.W. Zhao, *Phys. Scr.* **91**, 053008 (2016).
- [5] K. Starosta, T. Koike, *Phys. Scr.* **92**, 093002 (2017).
- [6] S. Frauendorf, *Phys. Scr.* **93**, 043003 (2018).
- [7] J. Meng, J. Peng, S.Q. Zhang, S.G. Zhou, *Phys. Rev. C* **73**, 037303 (2006).
- [8] A.D. Ayangeakaa *et al.*, *Phys. Rev. Lett.* **110**, 172504 (2013).
- [9] I. Kuti *et al.*, *Phys. Rev. Lett.* **113**, 032501 (2014).
- [10] C. Liu *et al.*, *Phys. Rev. Lett.* **116**, 112501 (2016).
- [11] C.M. Petrache *et al.*, *Phys. Rev. C* **97**, 041304 (2018).
- [12] T. Roy *et al.*, *Phys. Lett. B* **782**, 768 (2018).
- [13] B.W. Xiong, Y.Y. Wang, *At. Data Nucl. Data Tables* **125**, 193 (2019).
- [14] M. Wang *et al.*, *Phys. Rev. C* **98**, 014304 (2018).
- [15] J. Peng, J. Meng, S.Q. Zhang, *Phys. Rev. C* **68**, 044324 (2003).
- [16] T. Koike, K. Starosta, I. Hamamoto, *Phys. Rev. Lett.* **93**, 172502 (2004).
- [17] S.Q. Zhang, B. Qi, S.Y. Wang, J. Meng, *Phys. Rev. C* **75**, 044307 (2007).
- [18] B. Qi *et al.*, *Phys. Lett. B* **675**, 175 (2009).
- [19] Q.B. Chen, B.F. Lv, C.M. Petrache, J. Meng, *Phys. Lett. B* **782**, 744 (2018).
- [20] V.I. Dimitrov *et al.*, *Phys. Rev. Lett.* **84**, 5732 (2000).
- [21] P. Olbratowski *et al.*, *Phys. Rev. Lett.* **93**, 052501 (2004).
- [22] P. Olbratowski, J. Dobaczewski, J. Dudek, *Phys. Rev. C* **73**, 054308 (2006).
- [23] P.W. Zhao, *Phys. Lett. B* **773**, 1 (2017).
- [24] S. Mukhopadhyay *et al.*, *Phys. Rev. Lett.* **99**, 172501 (2007).
- [25] D. Almeded, F. Dönau, S. Frauendorf, *Phys. Rev. C* **83**, 054308 (2011).
- [26] Q.B. Chen *et al.*, *Phys. Rev. C* **87**, 024314 (2013).
- [27] Q.B. Chen *et al.*, *Phys. Rev. C* **94**, 044301 (2016).
- [28] X.H. Wu *et al.*, *Phys. Rev. C* **98**, 064302 (2018).
- [29] S. Brant, D. Tonev, G. De Angelis, A. Ventura, *Phys. Rev. C* **78**, 034301 (2008).

- [30] A.A. Raduta, Al H. Raduta, C.M. Petrache, *J. Phys. G: Nucl. Part. Phys.* **43**, 095107 (2016).
- [31] K. Hara, Y. Sun, *Int. J. Mod. Phys. E* **04**, 637 (1995).
- [32] G.H. Bhat, R.N. Ali, J.A. Sheikh, R. Palit, *Nucl. Phys. A* **922**, 150 (2014).
- [33] F.Q. Chen *et al.*, *Phys. Rev. C* **96**, 051303 (2017).
- [34] F.Q. Chen, J. Meng, S.Q. Zhang, *Phys. Lett. B* **785**, 211 (2018).
- [35] Y.Y. Wang, S.Q. Zhang, P.W. Zhao, J. Meng, *Phys. Lett. B* **792**, 454 (2019).
- [36] B.N. Lu, E.G. Zhao, S.G. Zhou, *Phys. Rev. C* **85**, 011301 (2012).
- [37] Y.Y. Wang, Z.X. Ren, *Sci. China Phys. Mech. Astron.* **61**, 082012 (2018).
- [38] E. Landulfo *et al.*, *Phys. Rev. C* **54**, 626 (1996).
- [39] P.W. Zhao *et al.*, *Phys. Lett. B* **699**, 181 (2011).
- [40] P.W. Zhao *et al.*, *Phys. Rev. Lett.* **107**, 122501 (2011).
- [41] J. Meng, J. Peng, S.Q. Zhang, P.W. Zhao, *Front. Phys.* **8**, 55 (2013).
- [42] P.W. Zhao, N. Itagaki, J. Meng, *Phys. Rev. Lett.* **115**, 022501 (2015).
- [43] P.W. Zhao, Z.P. Li, *Int. J. Mod. Phys. E* **27**, 1830007 (2018).
- [44] S.Y. Wang, S.Q. Zhang, B. Qi, J. Meng, *Chin. Phys. Lett* **24**, 664 (2007).