Coexistence of chiral symmetry and pseudospin symmetry in one nucleus: triplet bands in $^{105}$Ag

H. Jia, B. Qi, C. Liu, and S. Y. Wang

Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, School of Space Science and Physics, Institute of Space Sciences, Shandong University, Weihai, 264209, People’s Republic of China

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Abstract

The nearly degenerate triplet bands with the $\pi g_{9/2} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ configuration in $^{105}$Ag are studied via the relativistic mean-field (RMF) theory and the multiparticle plus rotor model (MPRM), which indicates that these bands are associated with chiral symmetry and pseudospin symmetry. The configuration-fixed constrained triaxial RMF calculations exhibit the pseudospin symmetry in single particle spectra and the triaxial shape coexistence. The experimental excitation energies and the electromagnetic transition probabilities for the triplet bands are reproduced very well by the MPRM calculations. The chiral doublet bands show the same phase in the $B(M1)/B(E2)$ staggering, while the pseudospin doublet bands hold the opposite phase. The coexistence of chiral symmetry and pseudospin symmetry in one nucleus and its corresponding characteristic of the rotational structure are discussed for the first time.

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I. INTRODUCTION

Symmetry is a fundamental concept in physics. As a many-body quantum system, the atomic nucleus occurs lots of phenomena associated with symmetries and spontaneous symmetry breaking. Thereinto, chiral symmetry and pseudospin symmetry have been extensively discussed in the past decades. Chirality in atomic nuclei was predicted by Frauendorf and Meng in 1997 \cite{1}. For a triaxially deformed nuclear core with a few high-$j$ valence particles and a few high-$j$ valence holes, the three mutually perpendicular angular momenta can be arranged to form a chiral geometry. Due to the chiral symmetry breaking, a pair of nearly degenerate $\Delta I = 1$ bands with the same parity, i.e., chiral doublet bands, should be observed in experiment. So far, more than 40 experimental candidate nuclei have been reported in the $A \sim 80, 100, 130$, and 190 mass regions, see e.g., Refs. \cite{2,19}. Theoretically, chiral doublet bands have been described successfully in many models \cite{20,36}. Based on the triaxial relativistic mean field (RMF) theory, it has been suggested that multiple chiral doublet bands ($M_{\chi D}$), i.e., more than one pair of chiral doublet bands, could exist in one single nucleus \cite{37,43}. The observations of $M_{\chi D}$ \cite{44,50} represent important confirmation of triaxial shape coexistence and its geometrical interpretation. A novel type of $M_{\chi D}$ bands with the same configuration was reported in $^{103}$Rh, which showed that chiral geometry can be robust against the increase of the intrinsic excitation energy \cite{46}. The observation of octupole correlations between the $M_{\chi D}$ bands in $^{78}$Br indicates that nuclear chirality can be robust against the octupole correlations \cite{49}.

Pseudospin symmetry in atomic nuclei was introduced in 1969 \cite{51,52}. By examining the spherical single-particle spectra, it is found that there is the near degeneracy between two single-particle states with quantum numbers $(n, l, j = l + 1/2)$ and $(n - 1, l + 2, j = l + 3/2)$. Refs. \cite{51,52} introduced the so-called pseudospin symmetry and defined the pseudospin doublets as $(\tilde{n} = n - 1, \tilde{l} = l + 1, \tilde{j} = \tilde{l} \pm 1/2)$ to explain this near degeneracy. Besides the spherical nuclei, the pseudospin symmetry remains an important physical concept in deformed nuclei \cite{53,54}. So far, lots of phenomena in nuclear structure have been interpreted by the pseudospin symmetry, including nuclear superdeformed configurations \cite{53,56}, identical bands \cite{57,58}, quantized alignment \cite{59}, magnetic moments and transitions \cite{60,61}, and $\gamma$-vibrational states in nuclei \cite{62}. A pair of nearly degenerate doublet bands with the configurations involved the pseudospin doublet states have been observed in several
nuclei, e.g., $^{108}\text{Tc}$ [63], $^{118}\text{Sb}$ [64], $^{128}\text{Pr}$ [65], $^{186}\text{Ir}$ [66], and $^{195}\text{Pt}$ [67], and suggested as pseudospin doublet bands. Pseudospin symmetry in finite nuclei has been a hot topic in nuclear physics, and an overview of these studies and open problems in the field of nuclear pseudospin symmetry is provided in Refs. [68, 69] and references therein.

It should be noted that the configurations of the reported chiral doublet bands involve a proton or neutron pseudospin states, e.g., $\pi(f_{5/2}, p_{3/2}) \otimes \nu g_{9/2}^{-1}$ in $^{78}\text{Br}$ [49], $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ in $^{103,105}\text{Rh}$ [12, 46] and $^{105,107}\text{Ag}$ [17, 41], and $\pi h_{11/2}(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ in $^{133}\text{Ce}$ [44]. However, the coexistence of chiral symmetry and pseudospin symmetry in one single nucleus has not been discussed so far. Recently, we notice that three nearly degenerate negative-parity bands with the same $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ configuration in $^{105}\text{Ag}$ have been observed [17]. The second and third lowest energy bands (labeled G and D in Ref. [17]) of the triplet bands exhibited the expected properties of chiral doublet bands, i.e., the very small energy difference between the corresponding states and the same phase in the $B(M1)/B(E2)$ staggering. While the phase in the $B(M1)/B(E2)$ staggering of the first lowest energy bands (labeled C in Ref. [17]) was opposite to those of the bands G and D. The triplet bands in $^{105}\text{Ag}$ might provide an opportunity to investigate the coexistence of chiral symmetry and pseudospin symmetry. Therefore, it is highly interesting to study whether such nearly degenerate triplet bands in $^{105}\text{Ag}$ are associated with the coexistence of chiral and pseudospin symmetry.

Chiral symmetry and pseudospin symmetry have been successfully described by the relativistic mean-field (RMF) theory [37, 43, 68, 73] and particle rotor model (PRM) [23–25, 63, 67]. The adiabatic and configuration-fixed constrained triaxial RMF theory has been used to obtain the triaxial deformations and configurations. On the other side, the quantal calculations for the electromagnetic transition are essential to identify a pair of nearly degenerate $\Delta I = 1$ bands with the same parity belonging to chiral or pseudospin doublet bands, which could be treated fully quantally in particle rotor model. Based on these considerations, we adopt the triaxial RMF theory and multiparticle plus rotor model (MPRM) to study the triplet bands in $^{105}\text{Ag}$ and explore the possible coexistence of chiral and pseudospin symmetry.
II. RESULT AND DISCUSSION

Adiabatic and configuration-fixed constrained triaxial RMF calculations were performed to search for the possible configurations and deformations for $^{105}$Ag. The detailed formulism and numerical techniques of RMF theory can be found in Refs. [37–39]. In the present calculations, each Dirac spinor is expanded in terms of a sets of three-dimensional harmonic oscillator bases in Cartesian coordinates with 12 major shells and meson fields with 10 major shells. The effective interaction parameter PK1 [74] is adopted, and the pairing correlation is neglected here. The $\beta^2$-constrained calculations, in which the triaxial deformation $\gamma$ is automatically obtained by minimizing the energy, have also been performed.

The energy surface obtained from the adiabatic and configuration-fixed constrained RMF calculations for $^{105}$Ag is shown in Fig. 1. As shown in Fig. 1, several minima observed in the potential energy surfaces are labeled with $a, b, c, d, e, f, g$, in which states $e, f, g$ are derived from the low-lying particle-hole excitation. The total energies $E_{\text{tot}}$, triaxial deformation parameters $\beta$ and $\gamma$, the corresponding valence nucleon configurations of minima for states $a–g$, and the excitation energies are listed in Tab. I. Here, the ground state $a$ with the unpaired nucleon configuration $\pi p_{1/2}$ is consistent with the observed ground state with the spin and parity $1/2^-$ [75]. The states $e, f, g$ are the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}d_{5/2}$, $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}g_{7/2}$, and $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^2$ configurations, respectively, which correspond to the observed three-quasiparticle bands in $^{105}$Ag [17]. The excitation energies for states $e, f, g$ are 2.97, 3.47, and 4.66 MeV, respectively, which are in reasonable agreement with the experiment energies of band head $I^\pi = 15/2^-$ of band G (2.62 MeV), that of band head $I^\pi = 15/2^-$ of band C (2.47 MeV) and that of band head $I^\pi = 23/2^+$ of band E (3.91 MeV) [17]. Furthermore, states $e, f, g$ have the suitable triaxial deformation $33.9^\circ$, $24.7^\circ$ and $37.9^\circ$ together with high-$j$ particle-hole configurations. Therefore, the chiral doublet bands could be constructed on these states, which will lead to three sets of chiral doublet bands, i.e., the $\chi$D phenomenon. So far, a pair of chiral doublet bands (bands G and D) with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ configuration has been suggested in $^{105}$Ag [17]. However, the partner band of the band C with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ configuration and band F with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^2$ configuration have not been observed [17], which are interesting to search for in the future experiment of $^{105}$Ag.

Performing the configuration-fixed and $\beta^2$-constrained calculations for the ground state,
the neutron single-particle levels as a function of deformation $\beta$ are shown in Fig. 2. The positive (negative) parity states are marked by solid (dashed) lines, and the occupations corresponding to the minima $a, e, f,$ and $g$ in Fig. 1 are represented by filled circles (two particles) and stars (one particle). For the positive parity state $g$, the two unpaired neutrons occupy the different $1h_{11/2}$ levels. For the negative parity states, the two unpaired neutrons occupy the $1h_{11/2}$ and $2d_{5/2}$ for state $e$, while occupy the $1h_{11/2}$ and $1g_{7/2}$ levels for state $f$. In fact, states $2d_{5/2}$ and $1g_{7/2}$ are mixed strongly in the deformed case, and here the configurations are denoted by the quantum numbers for the spherical case. Meanwhile, as the states $e$ and $f$ have obvious triaxial deformation $\gamma$, the third component of angular momentum is not a good quantum number. It is noted that the orbitals with $2d_{5/2}$ and $1g_{7/2}$ (denoted by bold lines) accompany each other in a large scale of the $\beta$ region, which manifests the characteristic of the pseudospin symmetry in single particle spectra. These two orbits can be considered as pseudospin doublet states $1\tilde{f}_{5/2,7/2}$. Thus pseudospin doublet bands could be constructed on the states $e$ and $f$.

In order to examine the hypothesis of the chiral doublet bands and pseudospin doublet bands in $^{105}$Ag, quantal MPRM calculations were performed to study the energy spectra and $B(M1)/B(E2)$ ratios for the triplet negative-parity bands. The detailed formulism of this model can be seen in Refs. [25, 41, 44]. The configurations and deformation parameters obtained from the RMF calculations are used as inputs to the MPRM calculations, i.e., the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} d_{5/2}$ configuration with $(\beta, \gamma) = (0.22, 33.9^\circ)$ for the doublet bands G and D, and the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} g_{7/2}$ configuration with $(\beta, \gamma) = (0.22, 24.7^\circ)$ for band C. Moment of inertia $\mathfrak{I} = 32\hbar^2/\text{MeV}$ for the triplet bands is adjusted to the experimental energy spectra. For the electromagnetic transition, the empirical intrinsic quadrupole moment $Q_0 = (3/\sqrt{5\pi})R_0^2 Z\beta$, gyromagnetic ratio $g_R = Z/A = 0.44$, $g_p(g_{9/2}) = 1.26$, $g_n(h_{11/2}) = -0.21$, $g_n(g_{7/2}) = 0.26$, and $g_n(d_{5/2}) = -0.46$ are adopted [26]. Coriolis attenuation factor $\xi = 0.7$ for the triplet bands is adopted here.

The calculated energy spectrum (right panel) in comparison with the experimental data (left panel) [17] is presented in Fig. 3. The calculated energies with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} d_{5/2}$ and $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} g_{7/2}$ configurations are shifted to coincide with the experimental energy at spin $19/2\hbar$ of bands G and C, respectively. The experimental energy spectra, the trend and amplitude of the energy separation between the same spins among the triplet bands are reproduced very well by the MPRM calculations. The calculated in-band $B(M1)/B(E2)$
ratios for bands C, G, and D in $^{105}$Ag are presented in Fig. 4 together with the available data extracted from Ref. [17]. The observed in-band $B(M1)/B(E2)$ ratios in the bands G and D are very similar, and show the same staggering phase, which are consistent with the typical characters for chiral doublet bands [7, 27]. All these features are well reproduced by the present MPRM calculations. Therefore, the present calculations support that the bands G and D with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} d_{5/2}$ configuration are chiral doublet bands. The phase of the $B(M1)/B(E2)$ staggering of the band C is opposite to those of bands G and D, which is reasonably reproduced by the MPRM calculations with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} g_{7/2}$ configuration.

To clearly exhibit the staggering phase for band C, the enhancement factor of 3 has been used for the calculated values. The calculated staggering amplitude of the $B(M1)/B(E2)$ ratios is stronger than the data for the triplet bands, which might be attributed to the neglect of the mixing between the $g_{7/2}$ and $d_{5/2}$ orbitals in the present calculations. The good agreement between the experimental and calculated $B(M1)/B(E2)$ ratios further supports the configuration assignments. Based on the above discussions, bands G, D and bands G, C in $^{105}$Ag can be interpreted as chiral doublet bands and pseudospin doublet bands, respectively.

The present study on the triplet bands in $^{105}$Ag indicates that nuclear chirality can coexist with the pseudospin symmetry. Similar triplet structure has also been observed in neighbouring nucleus $^{105}$Rh [12], in which the data of electromagnetic transitions for these triplet bands are missing. The measurement of transition probabilities in the future experiment of $^{105}$Rh would be helpful to examine the coexistence of two kinds of symmetries. In fact, when chiral symmetry and pseudospin symmetry occur simultaneously in one single nucleus, two pairs of nearly degenerate $\Delta I = 1$ bands with the same parity (“chirality-pseudospin quartet bands”) are expected. It is interesting to search for the “chirality-pseudospin quartet bands” in the future experimental investigation of $^{105}$Ag and other candidate chiral nuclei.

III. SUMMARY

In summary, the nearly degenerate triplet bands with the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} (g_{7/2}, d_{5/2})$ configuration in $^{105}$Ag are studied via the relativistic mean-field (RMF) theory and the multiparticle plus rotor model (MPRM), which suggests these bands as chiral doublet bands and pseudospin partner band. The triaxial shape coexistence and the pseudospin symmetry in single
particle spectra are obtained from the configuration-fixed constrained triaxial RMF calculations. The experimental excitation energies and the electromagnetic transition probabilities for the triplet bands are reproduced very well by the MPRM calculations. The chiral doublet bands show the same phase in the $B(M1)/B(E2)$ staggering, while the pseudospin doublet bands hold the opposite phase. The present work will motivate an experimental investigation to search for the chirality-pseudospin triplet bands or chirality-pseudospin quartet bands in the nuclei with stable triaxial deformation.

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FIG. 1. (Color online) The energy surfaces in adiabatic (open circles) and configuration-fixed (solid lines) constrained triaxial RMF calculations using effective interaction PK1 for $^{105}$Ag. The minima in the energy surfaces for the fixed configuration are represented as stars and labeled as $a$, $b$, $c$, $d$, $e$, $f$, and $g$. Their corresponding triaxial deformation parameters $\beta$ and $\gamma$ are also given. The suitable states for the appearance of the chirality are marked by the blue color and asterisks.
FIG. 2. (Color online) Neutron single-particle levels obtained in constrained triaxial RMF calculations as functions of deformation $\beta$. Positive (negative) parity states are marked by solid (dashed) lines. Occupations corresponding to the minima in Fig. 1 are represented by filled circles (two particles) and stars (one particle).
TABLE I. The total energies $E_{\text{tot}}$, triaxial deformation parameters $\beta$ and $\gamma$, and their corresponding valence nucleon configurations of minima for states $a-g$ in the configuration-fixed $\beta^2$-constrained triaxial RMF calculations for $^{105}$Ag, and compared with the experimental excitation energies $E_x$.

The configuration of the valence nucleons takes reference of 50 nucleons which occupy the states below the 50 major-shell.

| State | Valence nucleons | Unpaired nucleons | $E_{\text{tot}}$ (MeV) | $(\beta, \gamma)$ (MeV) | $E_x(\text{cal.})$ (MeV) | $E_x(\text{exp.})$ (MeV) |
|-------|------------------|-------------------|------------------------|--------------------------|--------------------------|--------------------------|
| $a$   | $\pi(g_{9/2}^{-1}p_{1/2}^{-1}) \otimes v(g_{7/2}^6 d_{5/2}^2)$ | $\pi p_{1/2}^{-1}$ | -896.20 (0.19,5.05)° | 0 0 |
| $b$   | $\pi g_{9/2}^{-2} \otimes v(g_{7/2}^6 d_{5/2}^2)$ | $\pi g_{9/2}^{-1}$ | -895.98 (0.18,0.04)° | 0.02 0.05 |
| $c$   | $\pi(g_{9/2}^{-1}g_{7/2} p_{1/2}^{-1}) \otimes v(g_{7/2}^6 d_{5/2}^2)$ | $\pi g_{7/2}^{-1}$ | -893.60 (0.24,20.3)° |
| $d$   | $\pi(g_{9/2}^{-2}g_{7/2}^{-2} p_{1/2}^{-2}) \otimes v(g_{7/2}^4 d_{5/2}^2 h_{11/2}^2)$ | $\pi g_{9/2}^{-1}$ | -892.91 (0.34,10.4)° |
| $e^*$ | $\pi g_{9/2}^{-1} p_{1/2}^{-1} \otimes v(g_{7/2}^6 d_{5/2}^2 h_{11/2}^1)$ | $\pi g_{9/2}^{-1} \otimes v h_{11/2}^1 d_{5/2}^2$ | -893.23 (0.22,33.9)° | 2.97 2.62 ♠ |
| $f^*$ | $\pi g_{9/2}^{-1} p_{1/2}^{-1} \otimes v(g_{7/2}^5 d_{5/2}^2 h_{11/2}^1)$ | $\pi g_{9/2}^{-1} \otimes v h_{11/2}^1 g_{7/2}^2$ | -892.73 (0.22,24.7)° | 3.47 2.47 ♦ |
| $g^*$ | $\pi g_{9/2}^{-1} p_{1/2}^{-1} \otimes v(g_{7/2}^5 h_{11/2}^1 h_{11/2}^1)$ | $\pi g_{9/2}^{-1} \otimes v h_{11/2}^1 h_{11/2}^1$ | -891.54 (0.24,37.9)° | 4.66 3.91 ♠ |

♣ the excitation energy of band head $I^\pi = 9/2^+$ of band A [17],

♢: the excitation energy of band head $I^\pi = 15/2^-$ of band D [17],

♡ the excitation energy of $I^\pi = 15/2^-$ of band C [17],

♠ the excitation energy of band head $I^\pi = 23/2^+$ of band E [17].
FIG. 3. (Color online) Comparison of chiral doublets (bands G and D) and pseudospin doublets (band G and band C) with the corresponding calculated results using the MPRM model. The configuration $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} d_{5/2}^{-1}$ (for bands G and D) and $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} g_{7/2}^{1}$ (for band C) with the deformation parameters obtained from RMF are adopted in the calculations. Coriolis attenuation factor $\xi=0.7$, moment of inertia $\mathcal{I}=32\hbar^2$/MeV are used. The calculated energy values in the right panel are shifted to coincide with the experimental energy at spin $19/2\hbar$ of band G and band C.
FIG. 4. (Color online) The calculated $B(M1)/B(E2)$ values by MPRM as a function of spin, in comparison with the corresponding data available in $^{105}\text{Ag}$ [17]. The same parameters as Fig. 3 are adopted. For the calculations of electromagnetic transition, the intrinsic quadrupole moment $Q_0 = (3/\sqrt{5\pi})R_0^2 Z\beta$, gyromagnetic ratio $g_R = 0.44$, $g_\mu(g_{9/2}) = 1.26$, $g_n(h_{11/2}) = -0.21$, $g_n(g_{7/2}) = 0.26$, and $g_n(d_{5/2}) = -0.46$ are adopted [26].