

Multi-chiral doublets in one single nucleus Post-print

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Abstract

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Full Text

Preamble

Multi-chiral doublets in one single nucleus

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Abstract

Adiabatic and configuration-fixed constraint triaxial relativistic mean field (RMF) approaches are developed for the first time, and a new phenomenon—the existence of multi-chiral doublets (MD), i.e., more than one pair of chiral doublet bands in a single nucleus—is suggested for ^{106}Rh based on triaxial deformations together with their corresponding proton and neutron configurations.

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The concept of handedness or chirality is a subject of general interest in molecular physics, elementary particle physics, and optics. The occurrence of chirality in nuclear physics was first suggested in 1997 [?] and the predicted spectral patterns exhibiting chirality—i.e., chiral doublet bands—were experimentally observed in 2001 [?].

Since this pioneering work on chirality in nuclear physics, considerable effort has been devoted to understanding this novel phenomenon and exploring its possible existence throughout the nuclear chart [?, ?, ?, ?, ?, ?, ?, ?]. Experimentally, chiral doublet bands have been identified in many nuclei with $A \approx 100$ having $g_{9/2}^{-1} h_{11/2}$ configurations, as well as in the $A \approx 130$ mass region with the earlier suggested configuration $h_{11/2} h_{11/2}$ and $A \approx 190$ with $h_{9/2} i_{13/2}$. On the theoretical side, chiral symmetry breaking was first predicted in the particle-rotor model (PRM) and the tilted axis cranking (TAC) approach for triaxially deformed nuclei [?]. It has subsequently been investigated in hybrid Woods-Saxon and Nilsson models combined with the shell correction method [?] as well as the Skyrme-Hartree-Fock cranking approach [?], and its selection rules for electromagnetic transitions have been discussed in a simple PRM [?].

For a triaxially deformed rotating nucleus, the collective angular momentum favors alignment with the intermediate axis, which possesses the largest moment of inertia. Meanwhile, the valence particle and hole angular momentum vectors align along the nuclear short and long axes, respectively. These orientations maximize the overlap of the particle densities with the triaxial core and minimize the interaction energy. The three mutually perpendicular angular momenta can be arranged to form two systems with opposite chirality—left- and right-handedness—that are transformed into each other by the chiral operator combining time reversal and a spatial rotation of 180° , $\hat{C} = \text{TR}(\hat{R})$. The breaking of chiral symmetry in atomic nuclei is observed due to quantum tunneling between these opposite-chirality systems.

The description of quantum tunneling between chiral partners lies beyond the mean-field approximation, as the usual cranking approach is a semiclassical model in which the total angular momentum is not a good quantum number [?]. In contrast, the PRM is better suited for this purpose, though it has so far been confined to one-particle, one-hole configurations only [?, ?, ?]. Its generalization to multi-particle and/or multi-hole configurations remains under development. Furthermore, the deformation and configurations in the PRM are not self-consistent but rather serve as model inputs.

The relativistic mean field (RMF) theory has received wide attention due to its success in describing nuclear properties and numerous nuclear phenomena over the past years [?, ?]. It is therefore of interest to search for nuclei with triaxial deformation and configurations suitable for chirality in RMF theory, including not only one-particle, one-hole configurations but also multi-particle, multi-hole ones. A multi-dimensional microscopic cranking RMF model is computationally very demanding and has only been applied to magnetic rotation thus far [?].

In this Letter, we develop adiabatic and configuration-fixed constraint triaxial RMF approaches to investigate triaxial shape coexistence and possible chiral doublet bands in the $A \approx 100$ mass region. The existence of multi-chiral doublets (M D)—i.e., more than one pair of chiral doublet bands in a single nucleus—is suggested through examination of the deformation and corresponding configurations.

In RMF theory, nuclei are characterized by an attractive scalar field $S(r)$ and a repulsive vector field $V(r)$ in the Dirac equation:

$$i\gamma \cdot \partial + V(r) + \beta[M + S(r)]\psi_i = \varepsilon_i\psi_i,$$

which can be solved by expanding the upper and lower components of the spinor ψ_i separately in terms of eigenfunctions of the three-dimensional deformed oscillator in Cartesian coordinates $\psi_{\alpha}(r)$ and its time-reversed state $\tilde{\psi}_{\alpha}(r) = T\psi_{\alpha}(r)$ with $T = \hat{r}_y K$:

$$\psi_i(r) = \sum_{\alpha} f_{\alpha}^{(i)} \phi_{\alpha}(r) + i \sum_{\tilde{\alpha}} g_{\tilde{\alpha}}^{(i)} \phi_{\tilde{\alpha}}(r).$$

To avoid the complex matrix diagonalization problem encountered in Ref. [?], $\phi_{\alpha}(r)$ is written as a product of three Hermite polynomials [?]:

$$\phi_{\alpha}(r) = \phi_{n_x}(x)\phi_{n_y}(y)\phi_{n_z}(z).$$

The meson fields are expanded similarly using the same deformation β_0 and β_0 for the basis, but with an oscillator length smaller by a factor of $\sqrt{2}$ than that for the nucleons ($b_B = b_0/\sqrt{2}$) to simplify calculations and avoid the need for additional parameters. The oscillator frequency is $\hbar\omega_0 = 41A^{-1/3}$ MeV.

To check the convergence of results with respect to the number of expanded oscillator shells for fermions $n_f \rightarrow \infty$, the binding energies (upper panels) and deformations (middle) and (lower) calculated with the effective interaction PK1 [?] for ^{106}Rh are presented as functions of $n_f \rightarrow \infty$ in Fig. 1 [Figure 1: see original paper]. The legends (filled circles, open circles, squares, upward triangles, downward triangles, and diamonds) represent results obtained with basis deformations of $\beta_0 = 0.0, 0.1, 0.2, 0.3, 0.4,$ and 0.5 , respectively. The results show that as long as $n_f \rightarrow \infty \approx 10$, the binding energies as well as the deformations β and β_0 obtained are almost identical. Furthermore, they are independent of the basis deformation β_0 . A similar convergence check has been performed for the bosons. In the following calculations, a spherical basis with 12 major oscillator shells for fermions and 10 shells for bosons will be used, which yields an error of less than 0.1% for the binding energy.

In general, triaxial RMF calculations yield only local minima. To obtain the ground state for a triaxially deformed nucleus, constraint calculations are necessary, which should in principle be carried out in the two-dimensional β - β_0 plane.

However, such two-dimensional constraint calculations are computationally expensive even for modern computers. Therefore, constraint calculations with $Q_{20} + \mathcal{E}Q_{22}$ (i.e., β_2) are performed to search for the ground state of triaxially deformed nuclei.

The energy surface and deformation β_2 as functions of β_3 from adiabatic constraint triaxial RMF calculations with PK1 for ^{106}Rh are presented as open circles in Figs. 2(a) and 2(b) [Figure 2: see original paper], respectively. The energy surface exhibits some irregularities, and certain local minima are too obscure to be identified clearly, making it technically difficult to determine their corresponding single-particle configurations. We therefore performed configuration-fixed constraint calculations similar to those employed in the non-relativistic case [?].

Starting from any point on the energy surface obtained from adiabatic constraint calculations, the configuration-fixed constraint calculation requires that the occupied single-particle orbits remain fixed during the constraint calculation, i.e., $\beta_{j+1} = \beta_j$. The energy surfaces and deformations β_2 from configuration-fixed calculations with PK1 for ^{106}Rh are shown as solid lines in Figs. 2(a) and 2(b) [Figure 2: see original paper], respectively. For each fixed configuration, the constraint calculation yields a continuous, smooth curve for the energy surface and deformation β_2 as functions of β_3 . The irregularities in the adiabatic energy surface disappear. In comparison, the minima in the energy surfaces from configuration-fixed constraint calculations become clearly visible, represented by stars and labeled A, B, C, D, E, F, and G. Their corresponding deformations β_2 and β_3 , together with their binding energies, are given in Figs. 2(a) and 2(b), respectively. It is interesting to note that for each fixed configuration, the deformation β_2 is approximately constant (as shown in Fig. 2(b)), indicating that β_2 is primarily determined by the corresponding configuration.

The energies of these minima, including the ground state, lie within 1.3 MeV of each other but correspond to different deformations β_2 and β_3 , providing a good example of shape coexistence. This shape coexistence differs from the spherical, oblate, and prolate shape coexistence found, for example, in neutron-deficient Pt, Hg, and Pb isotopes. It represents triaxial shape coexistence: for the ground state A, the binding energy is $E = 903.92$ MeV (experimental data: 906.72 MeV), deformation $\beta_2 = 0.27$ and $\beta_3 = 24.7^\circ$; for the excited minima B: $E = 903.82$ MeV, $\beta_2 = 0.25$ and $\beta_3 = 23.3^\circ$; C: $E = 903.28$ MeV, $\beta_2 = 0.30$ and $\beta_3 = 22.9^\circ$; and D: $E = 902.69$ MeV, $\beta_2 = 0.22$, $\beta_3 = 30.8^\circ$. All states A, B, C, and D have deformations β_2 and β_3 suitable for chirality [?, ?]. Since these states exist within a single nucleus, if chiral doublet bands can be built on them, this may lead to a new phenomenon—the existence of M D in a single nucleus. Therefore, we investigate their proton and neutron configurations in detail to determine whether the particle and hole configurations required for chirality are available.

By performing configuration-fixed constraint calculations for the ground state, the single-particle levels can be obtained as functions of deformation β_2 . The differences in single-particle levels obtained by choosing other minima are neg-

ligible. The neutron and proton single-particle levels obtained in this manner are presented in Fig. 3 [Figure 3: see original paper]. Positive (negative) parity states are marked by solid (dashed) lines, and the occupations corresponding to the minima in Fig. 2 are represented by filled circles (two particles) and stars (one particle). The corresponding quantum numbers for the spherical case are labeled on the left side of the levels. As the energy curves become very stiff for small deformations in Fig. 2, the present configuration-fixed constraint calculations cannot be performed for $\beta < 0.06$. Therefore, we cannot distinguish the occupation of some low- j orbits; for example, the last occupied neutron orbit for state A may come from $2d_{5/2}$ or $2d_{3/2}$, as marked in the figures. However, since nuclear chirality is essentially determined by high- j orbits, this ambiguity does not affect our conclusions.

The binding energies, deformations β and γ , and the corresponding configurations extracted from Fig. 3 for minima A, B, C, and D in ^{106}Rh obtained from configuration-fixed constraint triaxial RMF calculations with PK1 are listed in Table I [TABLE:N]. Except for state D, which has no high- j neutron valence particle, we find high- j proton and neutron configurations for the ground state (state A) as $(1g_{9/2})^{-3} (1h_{11/2})^2$, state B as $(1g_{9/2})^{-3} (1h_{11/2})^1$, and state C as $(1g_{9/2})^{-3} (1h_{11/2})^3$. All possess high- j proton holes and high- j neutron particle configurations, which together with their triaxial deformations favor the formation of chiral doublet bands. It is interesting to note that states A and B compete strongly in energy. However, due to their different parities, states A and B do not mix and may thus produce the new M D phenomenon. Thus far, one pair of chiral doublet bands with negative parity has been observed in ^{106}Rh [?]. It would be interesting to search for other chiral doublet bands in this nucleus.

Similar detailed constraint calculations have also been performed for other isotopes in the $A \approx 100$ mass region, and the possibility of M D exists in other nuclei as well. These results will be published in detail elsewhere. Here, in Fig. 4 [Figure 4: see original paper], the deformations β and γ for ground states in $^{98-114}\text{Rh}$, $^{102-116}\text{Ag}$, and $^{100-118}\text{In}$ isotopes are presented. The shaded area represents the favorable deformation β for nuclear chirality. The nuclei ^{104}Rh and ^{106}Rh , in which chiral doublet bands have been observed [?, ?], are marked as filled circles. Apart from ^{104}Rh and ^{106}Rh , favorable deformations β for chirality are found in $^{102,108,110}\text{Rh}$, $^{108-112}\text{Ag}$, and ^{112}In , implying that more chiral doublet bands can be expected in the $A \approx 100$ mass region. For each isotopic chain, the deformation β varies with neutron number due to different occupations of the $h_{11/2}$ orbital.

In summary, adiabatic and configuration-fixed constraint triaxial RMF approaches have been developed for the first time to investigate triaxial shape coexistence and possible chiral doublet bands. A new phenomenon—the existence of multi-chiral doublets (M D), i.e., more than one pair of chiral doublet bands in a single nucleus—is suggested in ^{106}Rh by examining the deformation and corresponding configurations. Similar investigations have

also been carried out for Rh, Ag, and In isotopes and with other effective interactions. The observation of MD appears very promising in this mass region.

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TABLE I: The binding energies, deformations β_2 and β_3 , and the corresponding configurations for minima A, B, C, and D in ^{106}Rh obtained from configuration-fixed constraint triaxial RMF calculations with PK1.

| State | E (MeV) | β_2 | β_3 | Configurations |
|-------|---------|-----------|-----------|-------------------------------------------------------------------------|
| A | -903.92 | 0.27 | 24.7° | $(1g_{9/2})^{-3}$ $(1h_{11/2})^2[(2d_{5/2})^1$ or $(2d_{3/2})^1]$ |
| B | -903.82 | 0.25 | 23.3° | $(1g_{9/2})^{-3}$ $(1h_{11/2})^1[(2d_{5/2})^2$ or $(2d_{3/2})^2]$ |
| C | -903.28 | 0.30 | 22.9° | $(1g_{9/2})^{-3}$ $(1h_{11/2})^3$ |
| D | -902.69 | 0.22 | 30.8° | $(1g_{9/2})^{-3}$ $[(2d_{5/2})^3$ or $(2d_{3/2})^3]$ |

FIG. 1: Total binding energy, deformation β_2 , and β_3 calculated with PK1 for ^{106}Rh as functions of the number of expanded oscillator shells for fermions $n_f \geq 0$. The filled circles, open circles, squares, upward triangles, downward triangles, and diamonds represent results for basis deformations $\beta_0 = 0.0, 0.1, 0.2, 0.3, 0.4, \text{ and } 0.5$, respectively.

FIG. 2: (color online) Energy surfaces (a) and deformations β_2 (b) as functions of deformation β_1 from adiabatic (open circles) and configuration-fixed (solid lines) constraint triaxial RMF calculations with PK1 for ^{106}Rh . Minima in the energy surfaces are represented by stars and labeled A, B, C, D, E, F, and G. Their corresponding deformations β_2 and β_3 , together with their energies, are given in (a) and (b), respectively.

FIG. 3: (color online) Neutron and proton single-particle levels from configuration-fixed constraint triaxial RMF calculations with PK1 for ^{106}Rh as functions of deformation β_1 . Positive (negative) parity states are

marked by solid (dashed) lines. Occupations corresponding to the minima in Fig. 2 are represented by filled circles (two particles) and stars (one particle).

FIG. 4: (color online) Deformations β and γ for ground states in Rh (upper), Ag (middle), and In (lower) isotopes from constraint triaxial RMF calculations with PK1. The shaded area represents the favorable deformation β for nuclear chirality. The nuclei ^{104}Rh and ^{106}Rh , in which chiral doublet bands have been observed, are marked as filled circles.

Note: Figure translations are in progress. See original paper for figures.

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