Selection rules of electromagnetic transitions for chirality-parity violation in atomic nuclei

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Introduction

Symmetry and symmetry breaking in atomic nuclei

- As a microscopic quantum many-body system, the atomic nucleus carries a wealth of information on fundamental symmetries and symmetry breakings, which are usually manifested in energy spectra, electromagnetic transitions and their selection rules.

Reflection symmetry and its breaking

- In pear-shaped nuclei, the spontaneous breaking of reflection symmetry occurs and manifests itself by the occurrence of the interleaved positive and negative parity bands, the parity doublet bands, and the enhanced $E1$ transitions.

  P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. (1991) 68:349

Chiral symmetry and its breaking

- In triaxially deformed nuclei, the spontaneous breaking of chiral symmetry may occur and manifested by the chiral doublet bands.

  S. Frauendorf and J. Meng, NPA (1997) 617:131

- The coexistence of two or more chiral doublet bands in a single nucleus, i.e., multiple chiral doublets (MχD) was predicted in 2006 and first observed in ^{133}Ce in 2013.

  J. Meng et al, PRC (2006) 73:037303

  A. D. Ayangeakaa et al., PRL (2013) 110:172504

MχD with octupole correlations

- In 2016, two pairs of positive and negative parity doublet bands together with eight strong $E1$ transitions have been identified in ^{78}Br.

  C. Liu et al., PRL (2016) 116:112501

- This observation provides the first evidence of the chiral geometry in octupole soft nuclei.

Chirality-Parity (ChP) violation in atomic nuclei

- For the nucleus with both triaxial and octupole deformations, the ChP violation, i.e., the simultaneous breaking of chiral and reflection symmetries may occur in the intrinsic frame.

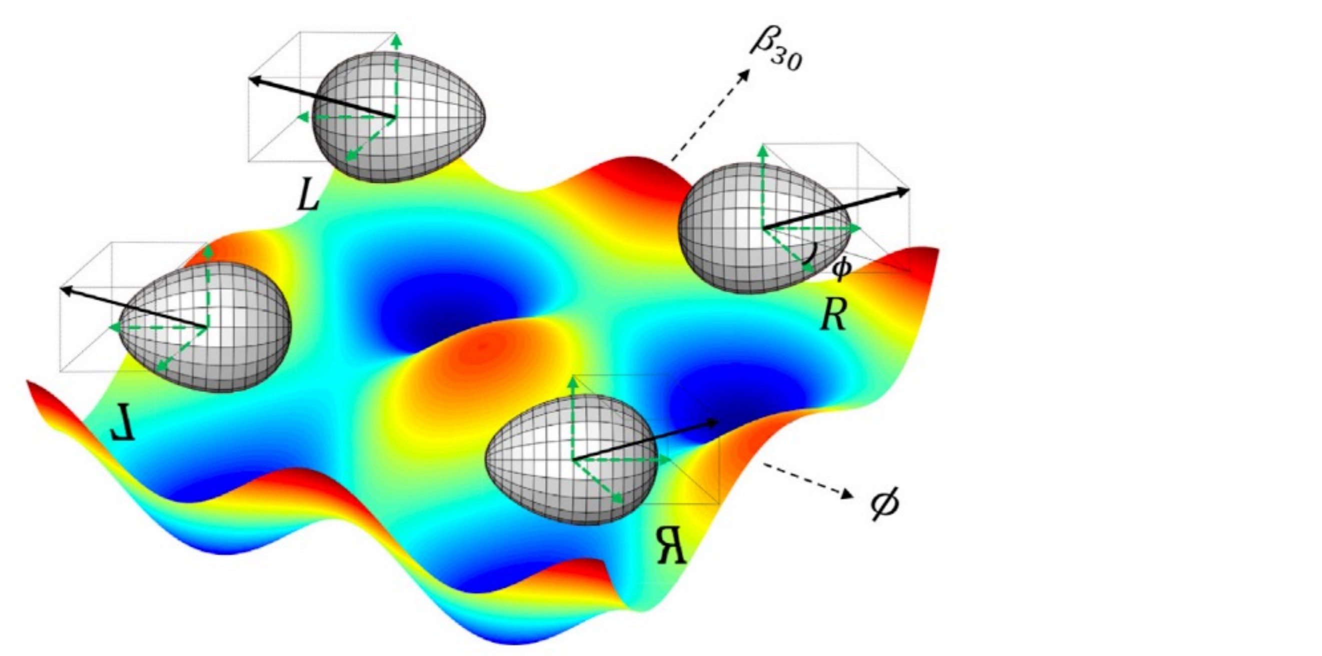

Fig.1. A schematic potential energy surface with simultaneous chiral and reflection symmetry breaking in the intrinsic (β_{30}, ϕ) plane.

- The ChP quartet bands, i.e., four nearly degenerate $\Delta I = 1\hbar$ bands may be established in the laboratory frame.

> The nuclear ChP violation has not been observed experimentally !
>
> What's the fingerprint of the nuclear ChP violation ?

Model

- The reflection-asymmetric triaxial particle rotor model (RAT-PRM) Hamiltonian is

  ***Y. Y. Wang**, X. H. Wu, S. Q. Zhang, P. W. Zhao, and J. Meng, Science Bulletin (2020) 65: 2001*

$$\hat{H} = \hat{H}_{\rm core} + \hat{H}^{\rm p}_{\rm s.p.} + \hat{H}^{\rm h}_{\rm s.p.},$$

✓ The core Hamiltonian $\hat{H}_{\rm core}$

$$\hat{H}_{\rm core} = \frac{1}{2\mathfrak{J}_0}[\hat{R}_3 + 4(\hat{R}_1 + \hat{R}_2)] + \frac{1}{2}E(0^-)(1-\hat{P}_c),$$

✓ The intrinsic Hamiltonian for the particle and hole $\hat{H}^{p(h)}_{\rm s.p.}$

$$\hat{H}^{\rm p}_{\rm s.p.} = \hat{h}_{lj} + \hbar\omega_0 r^2\left(\frac{\beta_{22}}{\sqrt{2}}[Y_{22}+Y_{2-2}] + \beta_{30}Y_{30}\right)$$

$$\hat{H}^{\rm h}_{\rm s.p.} = -\hat{h}_{lj} - \hbar\omega_0 r^2\left(\frac{\beta_{22}}{\sqrt{2}}[Y_{22}+Y_{2-2}] + \beta_{30}Y_{30}\right)$$

New symmetry

- The RAT-PRM Hamiltonian has good total parity P, good angular momentum I, and V_4 symmetry.
- A new symmetry, *chiplex* $\hat{\mathcal{B}}$, is derived,

$$\hat{\mathcal{B}} = \hat{\mathcal{R}}_3\left(\frac{\pi}{2}\right)\hat{C}\,\hat{\pi}\,\hat{P}$$

with $\hat{\mathcal{R}}_3\left(\frac{\pi}{2}\right)$ the rotation by $\pi/2$ around 3-aixs, $\hat{C}$ the exchange of particle and hole, $\hat{\pi}$ the intrinsic space reflection and $\hat{P}$ the total parity operator.

- The eigenstates of the RAT-PRM Hamiltonian can be characterized by the total parity P and the *chiplex* $\mathcal{B}$.

Selection rules of EM transitions

- The $E2$, $M1$, and $E3$ transitions are found to link the states with different $\mathcal{B}$ only.
- Starting form the yrast and yrare chiral doublets at I_0 for the positive and negative parity, the ChP quartet bands can be constructed with the $\Delta I = 2\hbar$ $E2$ transitions allowed.

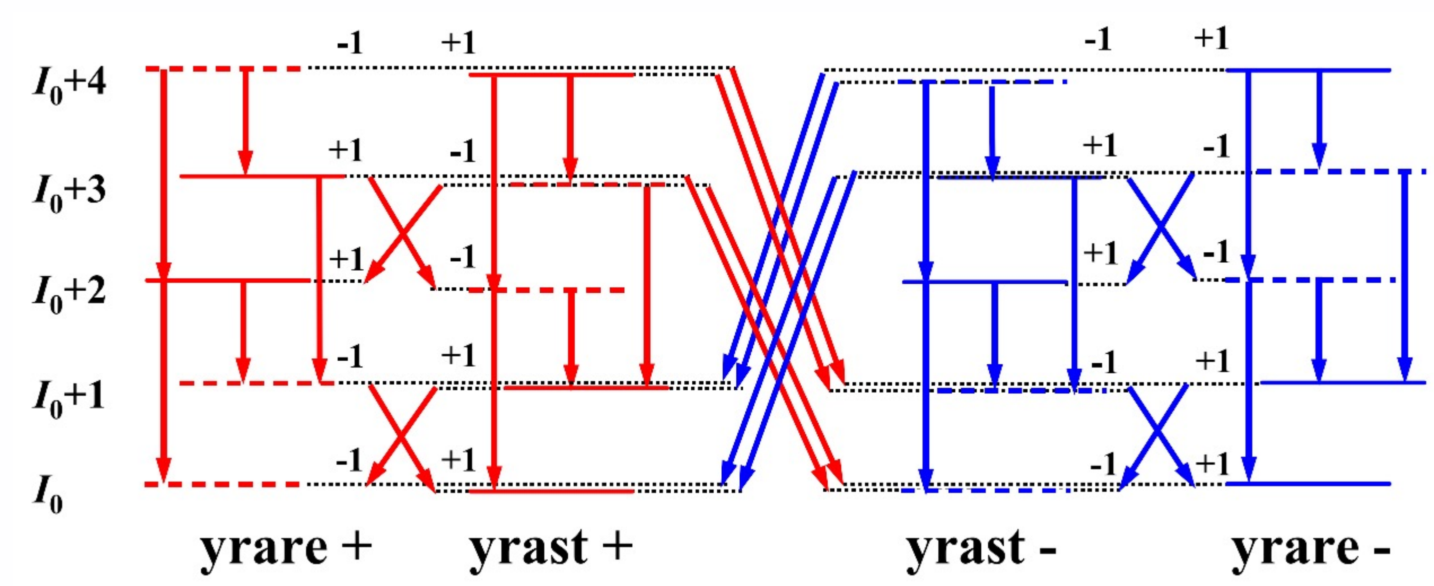

Fig.2. The ChP quartet bands organized by two pairs of chiral doublet bands with positive and negative parity. States with $\mathcal{B} = +1(-1)$ are denoted by solid (dashed) lines. Allowed $E2$, $M1$, and $E3$ transitions are denoted by arrows.

✓ The intraband and interband $B(M1)$ exhibit staggering behavior.

✓ The interband $B(E3)$ transitions alternate with spin.

ChP violation in two-j shell $h_{11/2}$ and $d_{5/2}$

- By taking a two-j shell $h_{11/2}$ and $d_{5/2}$ with typical energy spacing for $A = 130$ nuclei, the fingerprints for ChP quartet bands including the nearly degeneracy in energy and the selection rules of EM transitions are examined.

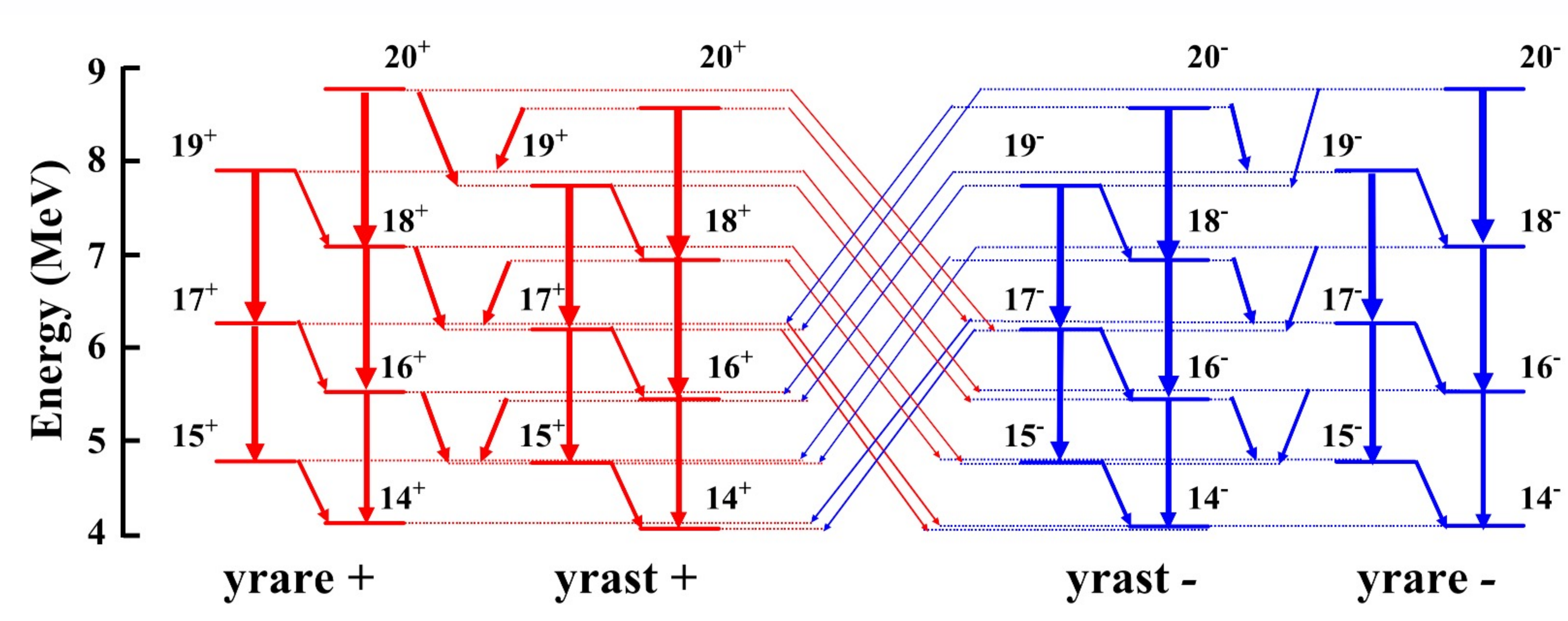

Fig.3. The ChP quartet bands in RAT-PRM and the corresponding $E2$, $M1$, and $E3$ transitions.

Summary

- The nuclear ChP violation, a simultaneous breaking of chiral and reflection symmetries is investigated with a RAT-PRM.
- A new symmetry, *chiplex* $\hat{\mathcal{B}}$, for an ideal ChP violation system is derived.
- The $E2$, $M1$, and $E3$ transitions are found to link the states with different $\mathcal{B}$ only.
- The ChP quartet bands are constructed with the $\Delta I = 2\hbar$ $E2$ transition allowed. Both the interband and intraband $B(M1)$ exhibit staggering behavior and the interband $E3$ transitions alternate with spin .
- These fingerprints for the ChP violation are examined by taking a two-j shell $h_{11/2}$ and $d_{5/2}$ with typical energy spacing for $A = 130$ nuclei.

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