Nuclear Schiff moment and time-reversal symmetry violation

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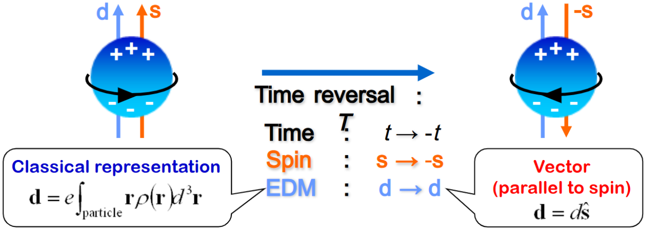
New question:

- Matter - Antimatter asymmetry in our Universe;
- The CP violation within the Standard Model(SM) cannot account for the observed asymmetry;
- Find new sources of CP violation or time reversal invariance (T) violation (Since CPT=1) beyond the SM;
- Search for evidence: electric dipole moments (EDMs) of atom, neutron, and electron.

Non-zero EDM associated with spin is direct evidence of time reversal symmetry violation



$\boxed{d \neq 0 \ : \ T\text{-violation} \longrightarrow CP\text{-violation (by } CPT \text{ theorem)}}$

Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	9×10^{-29}	ThO in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

Nuclear Schiff moment and PT-odd interaction

- At the nuclear level: The EDM of an atom originates from the contribution of the nuclear Schiff moment:

  E. F. Zhou, J. M. Yao, Int. J. Mod. Phys. E (2023)=

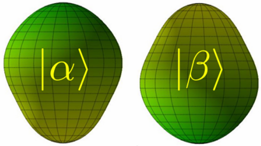
$$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle \langle ez\rangle}{6}$$

$$S \equiv \langle\Psi_0|\, S_z\, |\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z\, |\Psi_k\rangle \langle\Psi_k|\, V_{PT}\, |\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

Choose an isotope with large deformations

Unknown

Parity Doublet



$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

55 keV

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

- Nearly degenerate parity doublet; **[Haxton, Henley PRL 51:1937 (1983).]**
- Large intrinsic Schiff moment due to octupole deformation;

  [Auerbach, Flambaum, SpevakPRL 76:4316 (1996)]

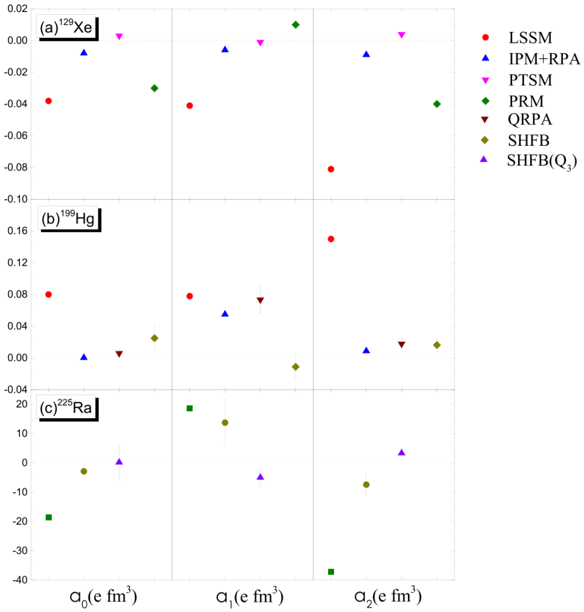
  Total Enhancement Factor: EDM (225Ra) / EDM (199Hg)

Skyrme Model	Isoscalar	Isovector
SIII	300	4000
SkM*	300	2000
SLy4	700	9000

^{225}Ra: **[Dobaczewski, Engel PRL 94:232502 (2005)**;

^{199}Hg: **[Ban et al. PRC 82:015501 (2010)**;

- The values of a_i in the Schiff moment by different nuclear models differ by a factor up to two to three orders of magnitude and even with different signs;
- The discrepancy causes large uncertainty in the constrains on the low-energy constants $\bar{g}_i$ of the PT-odd interaction.



This work

Motivation

- It is highly important to develop a state-of-the-art nuclear model, which is suitable for the low-lying states of odd-mass nuclei with octupole deformation,
- and apply it to nuclear Schiff moments.

Goal

- Development of multi-reference covariant density functional theory (MR-CDFT) for odd-mass octupole-deformed nuclei.
- Application of the MR-CDFT to nuclear Schiff moment, providing a key input to constrain the LECs of PT-odd interaction.

Outline

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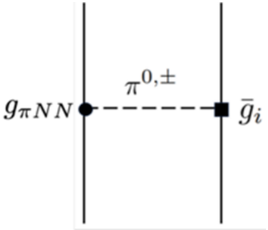
In a meson-exchange model, the P,T-violating nucleon-nucleon interaction is given by one weak P,T-violating N$\rightarrow$NM vertex and one strong P,T-conserving N$\rightarrow$NM vertex with a meson exchanged between the two.



$$\mathcal{L}^{(I=0)}_{\pi NN} = \bar{g}^{(0)}_{\pi NN}\bar{N}N\vec{\tau}\cdot\vec{\pi} \tag{1}$$
$$\mathcal{L}^{(I=1)}_{\pi NN} = \bar{g}^{(1)}_{\pi NN}\bar{N}N\pi_z \tag{2}$$
$$\mathcal{L}^{(I=2)}_{\pi NN} = \bar{g}^{(2)}_{\pi NN}\bar{N}N(3\tau_z\pi_z - \vec{\tau}\cdot\vec{\pi}) \tag{3}$$

where $\bar{g}^{(I)}_{\pi NN}$ are coupling constants, N nucleon fields, and π pion fields. The strong interaction vertex is

$$\mathcal{L}_{\pi NN} = ig_{\pi NN}\bar{N}\gamma_5 N\vec{\tau}\cdot\vec{\pi} \tag{4}$$

where $g_{\pi NN}$ is the strong pion-nucleon coupling constant, and the τ is the Pauli isospin matrix.

Second quantization, the nuclear matrix of the V_{PT} in nuclear Schiff moment can be written as,

$$M^{V_{PT}} = \sum_{ijkl} \langle jl|V_{PT}|ik\rangle \langle \Psi_f | c_j^\dagger c_l^\dagger c_k c_i | \Psi_i \rangle. \tag{5}$$

In the above expression, we have implemented the nuclear many-body wave functions for both initial Ψ_i and the final states Φ_f,

$$\Psi_{i/f} = \sum_{q,K} f_\alpha^{J\pi}(q) |\tilde{\Phi}_k^{(\mathrm{OA})}(q)\rangle, \quad |\tilde{\Phi}_k^{(\mathrm{OA})}(q)\rangle = \sum_{q,K} \hat{P}^J_{MK} \hat{P}^{N_\tau} \hat{P}^\pi |\Phi_k^{(\mathrm{OA})}(q)\rangle. \tag{6}$$

We can prove

$$M^{V_{PT}} = \sum_{q_f K_f q_i K_i} f_{\alpha_f}^{J_f}(q_f) f_{\alpha_i}^{J_i}(q_i) \sum_{ijkl} \langle jl|V_{PT}|ik\rangle (\rho_{ij}\rho_{kl} - \rho_{kj}\rho_{il} + \kappa_{jl}^{01*}\kappa_{ik}^{10}) \tag{7}$$

E.F.Zhou,X.Y.Wu,J.M.Yao,PRC109. 034305(2024)

The Schiff moment from the contribution of the nuclear charge distributions,

$$S_0 = \langle \Psi_i | \hat{S}_z | \Psi_f \rangle = \sum_{q_f K_f q_i K_i} f^{J_f}_{\alpha_f}(q_f) f^{J_i}_{\alpha_i}(q_i) \sum_{ijkl} \langle j | \hat{S}_z | i \rangle \langle \tilde{\Phi}^{(OA)}_{k_i}(q_i) | c^\dagger_j c_i | \tilde{\Phi}^{(OA)}_{k_f}(q_f) \rangle \tag{8}$$

where $\hat{S}_z$ is

$$\hat{S}_z = \frac{e}{10} \sum_0^Z \left(\hat{r}^2_p - \frac{5}{3} R^2_c \right) \hat{\mathbf{r}}^p_z \tag{9}$$

Here R^2_c is the mean squared radius of the nuclear charge distribution.

$$R^2_c = \frac{1}{Z} \int d^3 r r^2 \rho(r) = (1.2 Z^{1/3})^2 \tag{10}$$

Finally, the nuclear Schiff moment ,

$$S \approx 2 \frac{M^{V_{PT}} \cdot S_0}{E_i - E_f} = g_{\pi NN} (a_0 \bar{g}^{(0)} + a_1 \bar{g}^{(1)} + a_2 \bar{g}^{(2)}). \tag{11}$$

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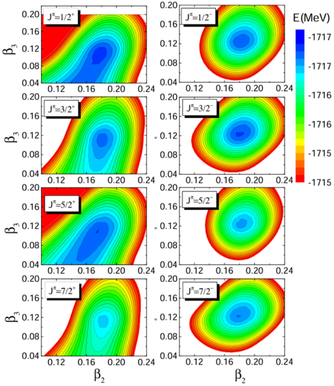
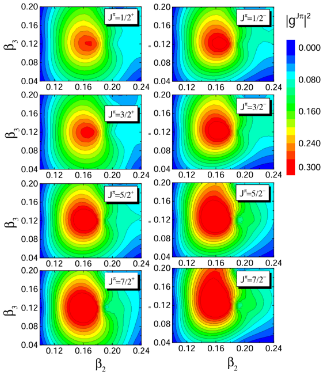
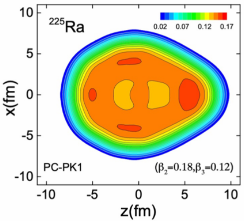
- Extension of mutil-reference covariant density functional theory (MR-CDFT) to low-lying states of odd-mass nuclei with quadrupole octupole deformations;

E.F.Zhou,X.Y.Wu,J.M.Yao,PRC109. 034305(2024)

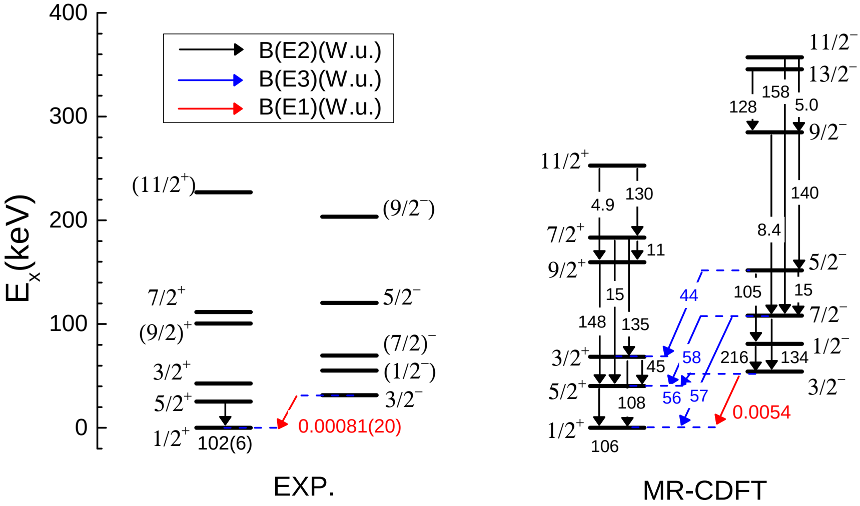
- Application to the nucleus ^{225}Ra of candidate atom, showing strong octupole correlation.



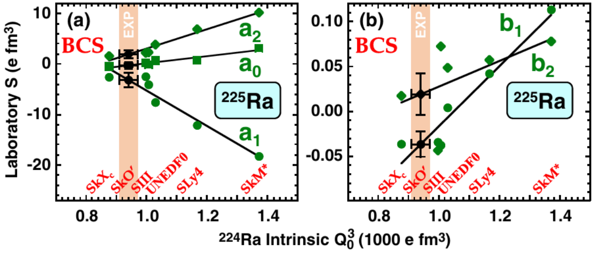




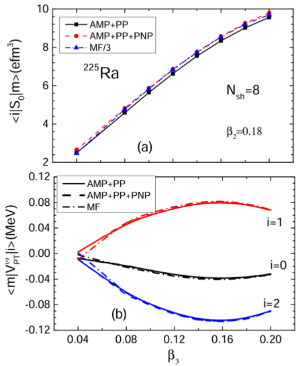
The low-lying state of ^{225}Ra

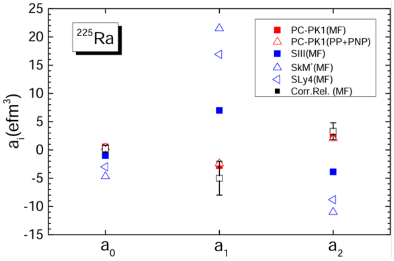


- After taking into account shape-mixing effect in the MR-CDFT, the low-lying states are in better agreement with the data.



J. Dobaczewski et al., PRL121, 232501 (2018).





- At the mean-field level, the values of ai by the relaitivistic EDF PC-PK1 are consistent with those by the Skyrme EDFs;
- The restoration of particle numbers has 10% -20% impact on the structure factors a_i.

Outline

Summary

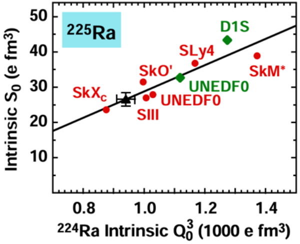
- We have extended the quantum-number projected GCM approach based on CDFT for odd-mass nuclei with octupole deformation and successfully applies it to study the low-lying states of ^{225}Ra.
- Additionally, we developed a method for calculating the nuclear Schiff moment and compared with previous studies based on non-relativistic EDF. The results show that our MF calculations give similar results for the regression analysis based on the Skyrme EDF. Additionally, when PP+PNP is added, a_i shows a variation of about 10% to 20%.

Outlook

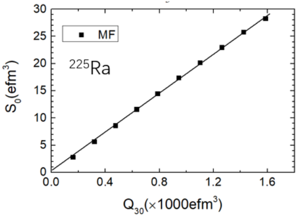
- In the next steps, we will examine the effects of angular-momentum projection and configuration mixing on nuclear Schiff moments.
- Besides, we will provide constraints on the LECs of PT-odd interaction using our calculated Schiff moments, together with the latest measurements on the atomic EDMs.

Thanks for your attention!

- There is a strong linear correlation between S_0 and octupole deformation β_3 and moment Q_3.
- Comparing our results with the literature fit, we find that our calculated slope is very close to their value, corresponding to an angle between 86.6^0 and 88.7^0; however, there is a significant difference in the intercept.



J. Dobaczewski et al., PRL121, 232501 (2018)



Method	PC-PK1	PRL 121, 232501 (2018) /Correlated with		
		^{224}Ra	^{226}Ra	^{220}Rn
Slope	18.1	37.3	44.2	17.0
Intercept	0.12	-8.6	-16.1	21.2