Beyond mean-field correlations on nuclear Schiff moments and P,T-odd nuclear forces

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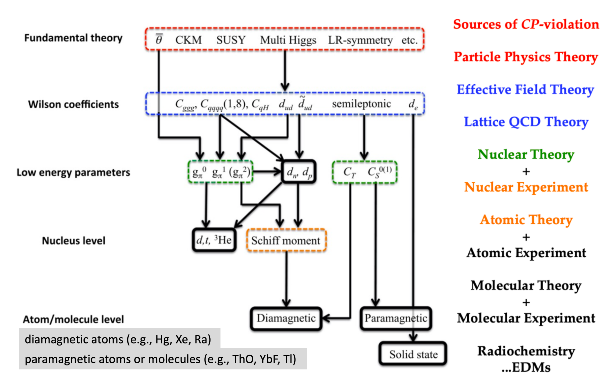
Outline

1. Introduction
   - CP violation and atomic EDMs
   - Status of studies on nuclear Schiff moments
2. The multi-reference covariant density functional theory for ^{129}Xe, ^{199}Hg, and ^{225}Ra
   - The framework of MR-CDFT
   - Application to nuclear structural properties
   - Application to nuclear Schiff moments
   - Constraints on the P,T-odd nuclear forces
3. Summary
4. Appendix: preliminary results on ^{171}Yb

- The sources of charge-parity violation (CPV) within the SM (the complex phase of the CKM matrix in weak interactions and the θ term in QCD) are not sufficient to explain the observed baryon asymmetry of the universe.
- Hypothetical new sources of CPV beyond standard model (BSM), such as SUSY, multi-Higgs models, and LR-symmetry models.



T. Chupp, et al., Rev. Mod. Phys. 91, 015001 (2019); credit to Jaideep Singh.

Observation of any sizable EDMs of elementary or composite particles would indicate new CP violation beyond the SM, potentially solving the baryon asymmetry problem.

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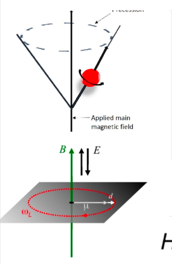
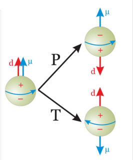
An atom with nonzero spin and EDM

Larmor precession in external B and E fields

$$\vec{\tau} = \vec{\mu} \times \vec{B} \pm \vec{d} \times \vec{E} = \frac{d\vec{L}}{dt}$$





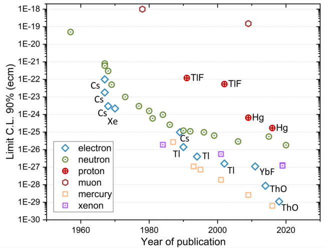
$$H_{EM} = -(\mu\cdot\mathbf{B} + \mathbf{d}\cdot\mathbf{E})$$

Change in the frequency after flipping the direction of E

$$\omega_{\pm} = \frac{2(\mu B \pm dE)}{\hbar}$$

$$\omega_{+} - \omega_{-} = \frac{4dE}{\hbar}$$

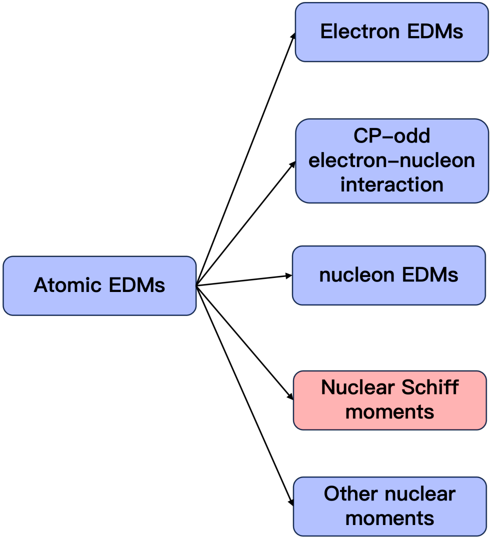
Atoms	$\lvert d_A\rvert [\times 10^{-26} e\mathrm{cm}]$	Exp. [References]
^{129}Xe	< 0.14	Sachdeva et al., PRL123, 143003 (2019)
^{171}Yb	< 1.5	Zheng et al., PRL129, 083001 (2022)
^{199}Hg	$< 7 \times 10^{-4}$	Graner et al., PRL116, 161601 (2016)
^{225}Ra	$< 5 \times 10^{4}$	Parker et al., PRL114, 233002 (2015)
^{225}Ra	$< 1.4 \times 10^{3}$	Bishof et al., PRC94, 025501 (2016)



	Standard Model	**Experiment**
^{199}Hg	10^{-33} e cm	$\leq 7.4 \cdot 10^{-30}$ e cm
electron	10^{-38} e cm	$\leq 9 \cdot 10^{-29}$ e cm
neutron	10^{-31} e cm	$\leq 1.9 \cdot 10^{-26}$ e cm
proton	10^{-31} e cm	$\leq 2.0 \cdot 10^{-25}$ e cm

best

Contributions to atomic EDMs



- Paramagnetic atoms and molecules (e.g., ThO, YbF, Tl), where the unpaired electron(s) enhance the sensitivity.
- **Relativistic effect & heavy (Z^3) atoms** amplify this contribution.

- CP-violating **semileptonic interactions** between electrons and nucleons
- Include scalar–pseudoscalar ($k_{1,3}$), tensor–tensor (k_2) operators.

- Arises from **QCD θ-term** or BSM physics (e.g., quark chromo-EDMs, CP-violating four-quark operators).
- Induce a **nuclear EDM** or contribute to the **nuclear Schiff moment**.

- Arises from nucleon EDMs or **CP-violating nuclear forces**.
- Dominant contribution to the EDM of **diamagnetic atoms** (e.g., Xe, Yb, Hg, Ra), which have all the electrons paired.

- Magnetic quadrupole moments, etc.

Atomic EDM arising from nuclear Schiff moment

- The measurements in several diamagnetic atoms are crucial for disentangling the contributions from different effective operators.
- The atomic EDMs have been calculated with different atomic many-body theories.

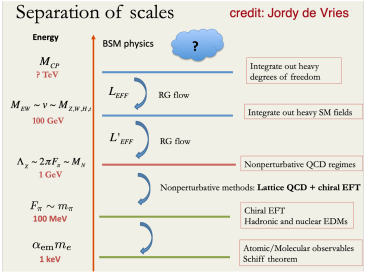
Different atomic theory calculations: differ by less than 20%

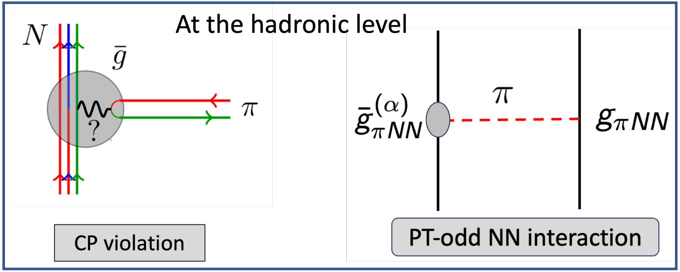
- The valence Dirac-Fock+RPA/CI+MBPT calculations: V. A. Dzuba et al., PRA80, 032120 (2009)

$$d_A(^{129}\mathrm{Xe}) = +0.38 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}),$$
$$d_A(^{199}\mathrm{Hg}) = -2.1 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}),$$
$$d_A(^{225}\mathrm{Ra}) = -8.8 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}).$$

- The relativistic coupled-cluster calculations: Latha et al, PRL 115, 059902 (2015); B.K. Sahoo, B.P. Das, PRL120, 203001 (2018);Y. Singh and B. K. Sahoo, PRA 92, 022502 (2015)

$$d_A(^{129}\mathrm{Xe}) = +0.34 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}),$$
$$d_A(^{199}\mathrm{Hg}) = -1.77 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}),$$
$$d_A(^{225}\mathrm{Ra}) = -6.79 \times 10^{-17} S (e\ \mathrm{fm}^3)^{-1} (e\ \mathrm{cm}).$$





The standard $N\pi$ coupling vertex is

$$\mathcal{L}^{(int)} = ig_{\pi NN}\bar{N}\gamma_5 N\vec{\tau}\cdot\vec{\pi}, \quad g_{\pi NN} = m_N g_A/f_\pi \simeq 12.9$$

The PT-odd $N\pi$ coupling vertex: iso-scalar, iso-vector and iso-tensor

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

J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, PPNP71, 21 (2013)

Nuclear Schiff moments and nuclear structure factors

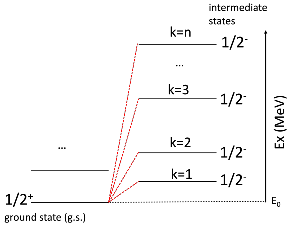
The Schiff moment can be written in terms of nuclear structure factors a_α,

$$S = \sum_{k\neq 0} \frac{\langle \Psi_0^{(N)} | \hat{S}_z | \Psi_k^{(N)} \rangle \langle \Psi_k^{(N)} | \hat{V}_{PT} | \Psi_0^{(N)} \rangle}{E_0^N - E_k^N} + c.c. \equiv g_{\pi NN} \sum_{\alpha=0}^{2} \bar{g}_{\pi NN}^{(\alpha)} a_\alpha,$$

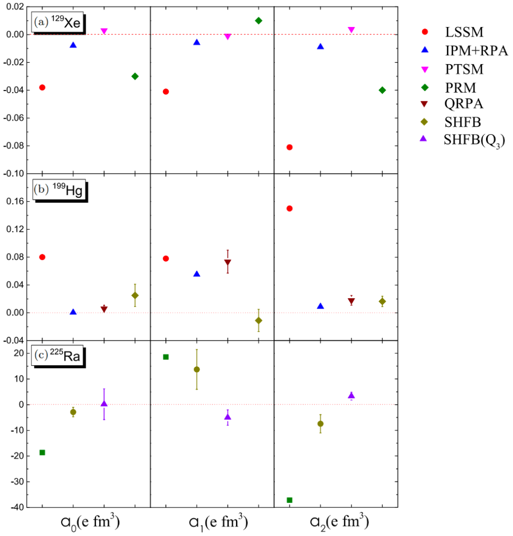
where (in units of e fm^3)

$$\hat{S}_z = \frac{e}{10} \sum_p \left(\hat{r}_p^2 - \frac{5}{3} \langle r^2 \rangle_{\rm ch} \right) \hat{z}_p,$$

$$a_\alpha = \frac{2}{g_{\pi NN}} \sum_{k\neq 0} \frac{M_S^{0k} M_{PT}^{k0(\alpha)}}{(E_0^N - E_k^N)}.$$



Accurate knowledge of nuclear Schiff moment is essential to connect experimental signatures (EDM) with the potential new physics (LECs of PT-odd nuclear forces).



E.F. Zhou, JMY, IJMPE (2024)

Table 1. The coefficients a_i ($e\,\text{fm}^3$) of nuclear Schiff moments from the calculations of different nuclear models.

Isotopes	a_0	a_1	a_2	Nuclear models
^{153}Eu	−9.62	47.3	−25.53	PRM[148]
^{129}Xe	−0.038	−0.041	−0.081	LSSM[160]
^{129}Xe	−0.008	−0.006	−0.009	IPM + RPA[151]
^{129}Xe	0.003	−0.001	0.004	PTSM[159]
^{129}Xe	−0.03	0.01	−0.04	PRM[163]
^{199}Hg	0.080	0.078	0.15	LSSM[160]
^{199}Hg	0.0004	0.055	0.009	IPM + RPA[151,169]
^{199}Hg	[0.002, 0.010]	[0.057, 0.090]	[0.011, 0.025]	SHFB + QRPA[155]
^{199}Hg	[0.009, 0.041]	[−0.027, +0.005]	[0.009, 0.024]	SHFB[153]
^{221}Rn	−0.04(10)	−1.7(3)	0.67(10)	SHFB(Q_3)[154]
^{223}Rn	−62	62	−100	PRM[156]
^{223}Rn	−0.08(8)	−2.4(4)	0.86(10)	SHFB(Q_3)[154]
^{223}Ra	−25	25	−50	PRM[156]
^{223}Fr	−31	31	−62	PRM[156]
^{223}Fr	−0.02	−0.02	−0.04	QOV[157]
^{223}Fr	0.07(20)	−0.8(7)	0.05(40)	SHFB(Q_3)[154]
^{225}Ra	−18.6	18.6	−37.2	PRM[156]
^{225}Ra	[−1.0, −4.7]	[6.0, 21.5]	[−3.9, −11.0]	SHFB[152]
^{225}Ra	0.2(6)	−5(3)	3.3(1.5)	SHFB(Q_3)[154]
^{227}Ac	−26	129	−69	PRM[148]
^{229}Pa	−1.2(3)	−0.9(9)	−0.3(5)	SHFB(Q_3)[154]
^{235}U	−7.8	38.7	−20.7	PRM[148]
^{237}Np	−15.6	77.4	−41.4	PRM[148]

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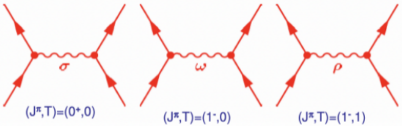
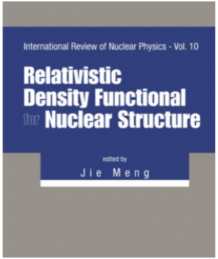
- The covariant density functional theory (CDFT)

★Meson-exchange models



$S(\mathbf{r}) = g_\sigma \sigma(\mathbf{r})$ $\quad V(\mathbf{r}) = g_\omega \omega(\mathbf{r}) + g_\rho \vec{\tau}\vec{\rho}(\mathbf{r}) + eA(\mathbf{r})$



★Point-coupling models

$(\bar\psi\Gamma\psi)^2$ $\quad D\ (\bar\psi\psi)\Delta(\bar\psi\psi)$

$G_\sigma(\rho)$ $\quad G_\omega(\rho)$ $\quad G_\rho(\rho)$

"No-sea" and "mean-field" approximations

Kohn-Sham DFT

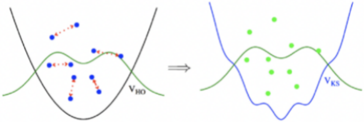
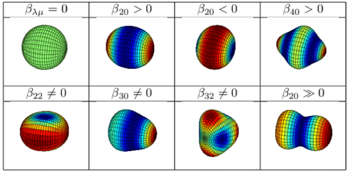


Figure from Drut PPNP 2010

The framework of MR-CDFT: symmetry restoration

- Symmetry-breaking and restoration methods



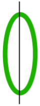
With the courtesy of B.N. Lu

Mean-field solution (variation in a limited Hilbert space):

- Onset of different shapes
- Breaking of symmetries of Hamiltonian (rotation, parity, etc)
- Restoration of symmetry with projection operators

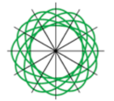
JMY, symmetry restoration methods, arXiv:2204.12126v1 (2022)

"Deformed " mean-field



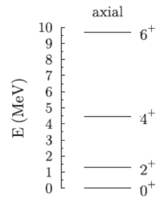
$|\Phi(\mathbf{q})\rangle$

Rotated mean-field



$\hat{R}(\Omega)|\Phi(\mathbf{q})\rangle$

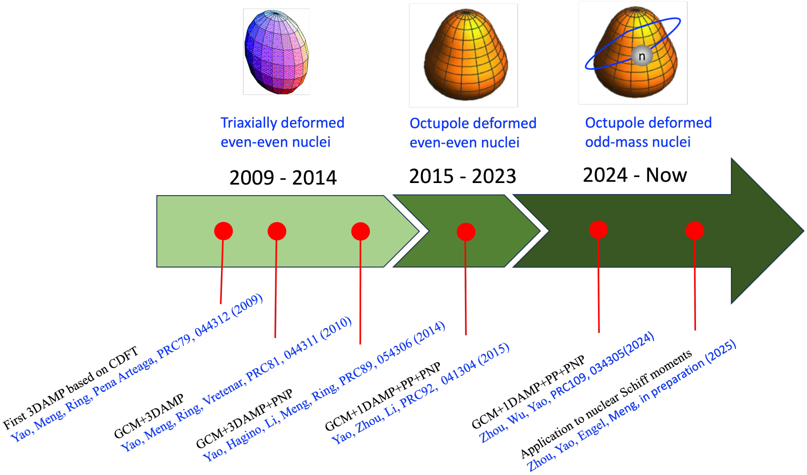
Nuclear low-lying states



$$|\Phi_{JM}(\mathbf{q})\rangle = \sum_K g_K^J \hat{P}_{MK}^J |\Phi(\mathbf{q})\rangle$$

$$\hat{P}_{MK}^J \equiv \frac{2J+1}{8\pi^2} \int_0^{2\pi} d\alpha \int_0^{\pi} \sin\beta d\beta \int_0^{2\pi} d\gamma D_{MK}^{J*}(\Omega)\hat{R}(\Omega)$$

Development of the MR-CDFT for nuclear spectroscopy



- Wave function for nuclear low-lying states

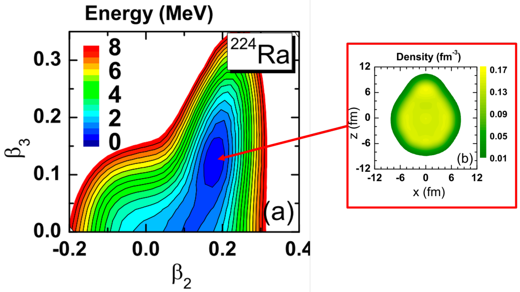
$$|JMK\pi, \alpha\rangle = \sum_{\mathbf{q}} f_{\alpha}^{JK\pi}(\mathbf{q}) \, |NZJK\pi; \mathbf{q}\rangle \,, \quad |NZJK\pi; \mathbf{q}\rangle = \hat{P}^J_{MK} \hat{P}^N \hat{P}^Z \hat{P}^{\pi} \left|\Phi_k^{(\mathrm{OA})}\right\rangle$$

Mean-field wave configurations:

$$E[\Phi] = \langle \Phi(\mathbf{q})| \, \hat{H} - \sum_{\tau=n,p} \lambda_\tau \hat{N}_\tau \, |\Phi(\mathbf{q})\rangle + \frac{1}{2} \sum_{\lambda=1,2,3} C_\lambda \left(\langle \Phi(\mathbf{q})| \, \hat{Q}_{\lambda 0} \, |\Phi(\mathbf{q})\rangle - q_{\lambda 0} \right)^2$$

For odd-mass nuclei,

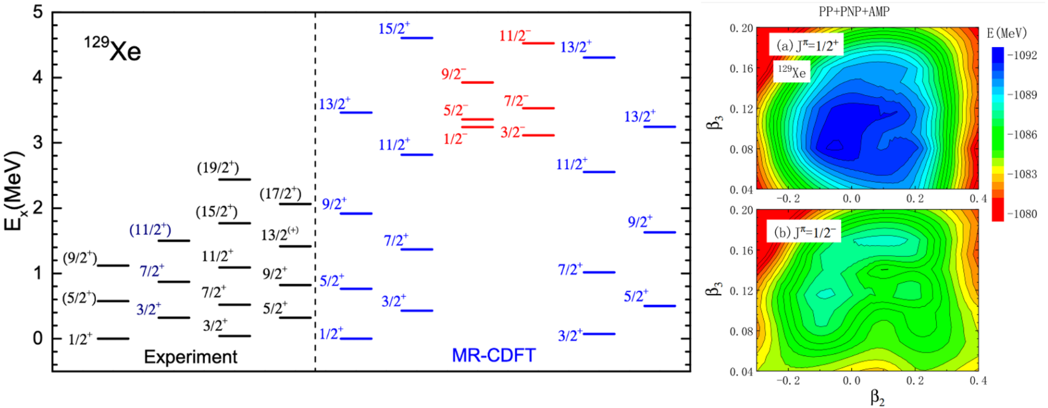
$$\left|\Phi_{\kappa}^{(\mathrm{OA})}(\mathbf{q})\right\rangle = \alpha_{\kappa}^{\dagger} \left|\Phi_{(\kappa)}(\beta_2, \beta_3)\right\rangle .$$



JMY, E.F. Zhou, Z.P. Li, PRC92, 041304(R) (2015)

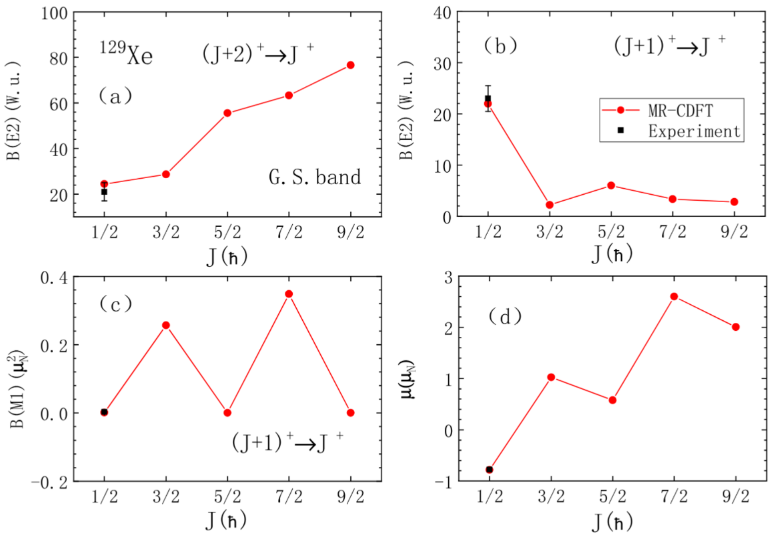
E. F. Zhou, X. Y. Wu, JMY, PRC109, 034305(2024)

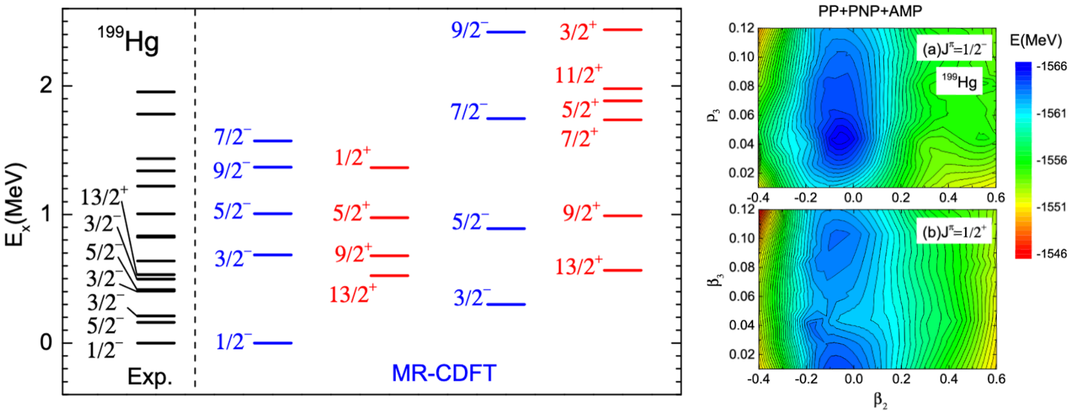
Energy spectrum and energy surfaces of ^{129}Xe



- The ground state dominated by the weakly deformed configuration with $(\beta_{20}, \beta_{30}) = (-0.08, 0.08)$.
- The excitation energy of the $1/2_1^-$ is predicted around 3.2 MeV.

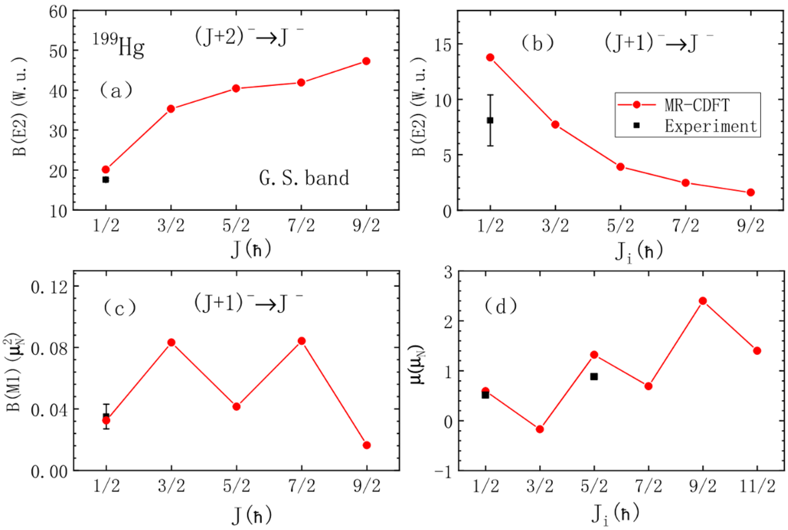
Electromagnetic properties of ^{129}Xe



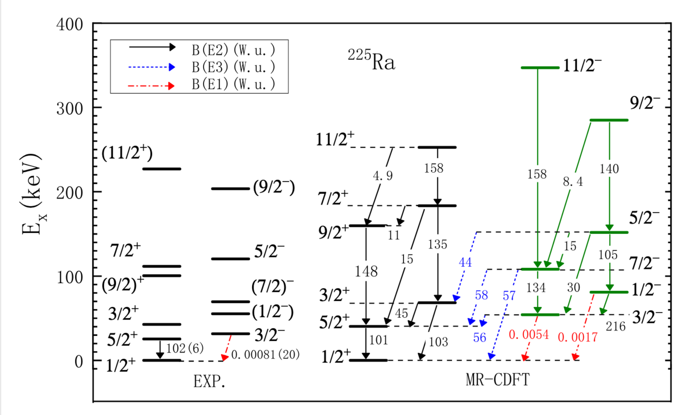


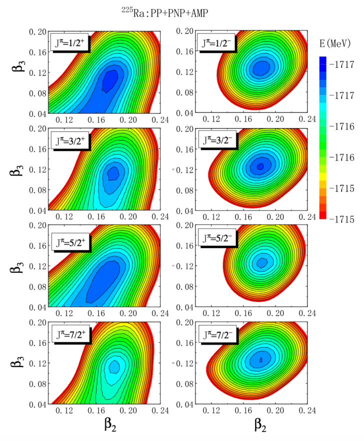
- The ground state dominated by the weakly deformed configuration with $(\beta_{20}, \beta_{30}) = (-0.05, 0.04)$.
- The first excited state $1/2^+$ is predicted around 1.6 MeV.

Electromagnetic properties of ^{199}Hg



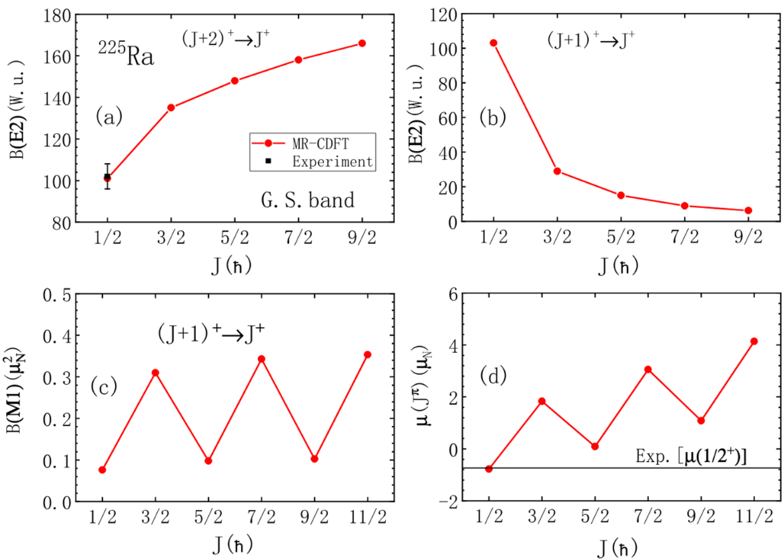
Energy spectrum and energy surfaces of ^{225}Ra





- The ground state $1/2_1^+$ is strongly octupole deformed.
- The first $1/2^-$ state is predicted around 0.069 MeV, compared to data 0.055 MeV.

Electromagnetic properties of ^{225}Ra



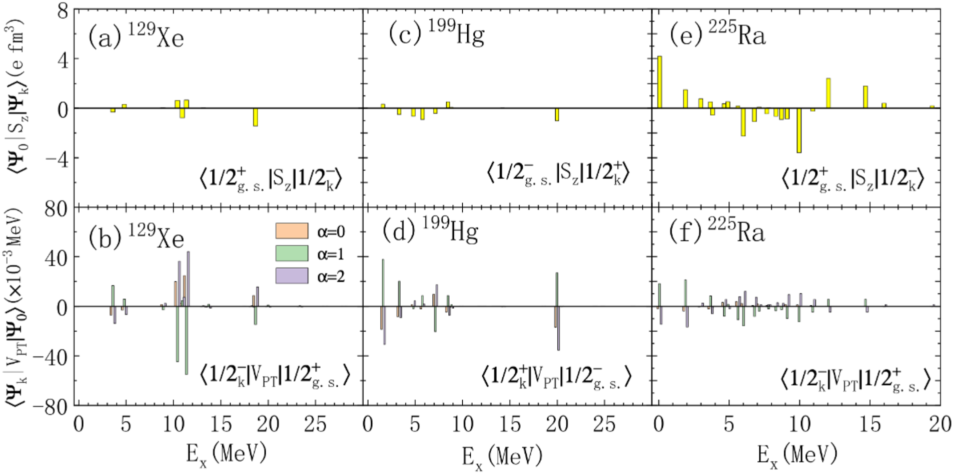
We compute the two-body matrix element of the PT-violating NN interaction in the relativistic framework directly,

$$
\begin{aligned}
\langle jl|\, V_{PT}\, |ik\rangle &= \sum_{\alpha=0}^{2} \langle jl| V_{PT}^{(\alpha)} |ik\rangle \\
&= (4\pi)^2 i g_{\pi NN} \sum_{\alpha=0}^{2} \bar{g}_{\pi NN}^{(\alpha)} \sum_{LM} \int \frac{q^2 dq}{(2\pi)^3} \frac{1}{q^2 + m_\pi^2} \langle jl| V_{PT}^{(\alpha)}(q) |ik\rangle \\
&\quad + \text{exch. terms}
\end{aligned}
$$

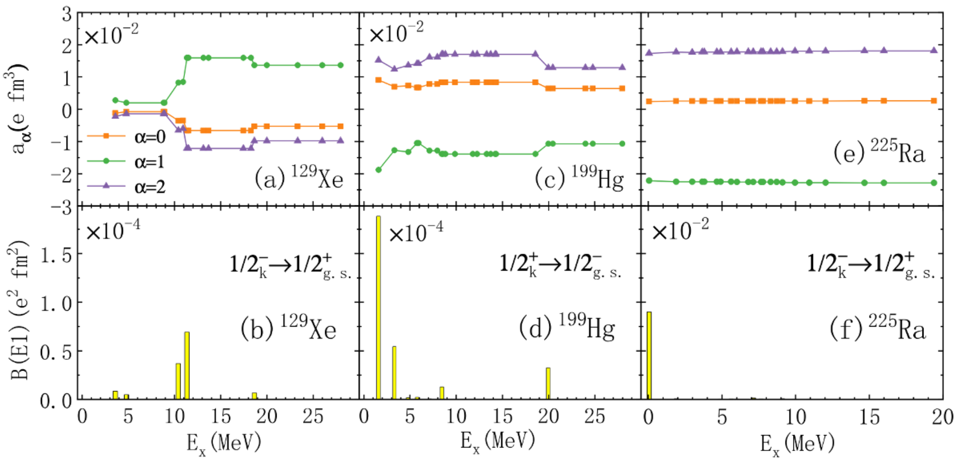
where

$$
\begin{aligned}
\langle jl| V_{PT}^{(0)}(q) |ik\rangle &= \langle j|\gamma^0\gamma_5 \vec{\tau} j_L(qr_1) Y_{LM}(\hat{\mathbf{r}}_1)|i\rangle \langle l|\gamma^0 \vec{\tau} j_L(qr_2) Y_{LM}^*(\hat{\mathbf{r}}_2)|k\rangle \\
\langle jl| V_{PT}^{(1)}(q) |ik\rangle &= \langle j|\gamma^0\gamma_5 \tau_z j_L(qr_1) Y_{LM}(\hat{\mathbf{r}}_1)|i\rangle \langle l|\gamma^0 j_L(qr_2) Y_{LM}^*(\hat{\mathbf{r}}_2)|k\rangle \\
\langle jl| V_{PT}^{(2)}(q) |ik\rangle &= 3\langle j|\gamma^0\gamma_5 \tau_z j_L(qr_1) Y_{LM}(\hat{\mathbf{r}}_1)|i\rangle \langle l|\gamma^0 \tau_z j_L(qr_2) Y_{LM}^*(\hat{\mathbf{r}}_2)|k\rangle \\
&\quad - \langle j|\gamma^0\gamma_5 \vec{\tau} j_L(qr_1) Y_{LM}(\hat{\mathbf{r}}_1)|i\rangle \langle l|\gamma^0 \vec{\tau} j_L(qr_2) Y_{LM}^*(\hat{\mathbf{r}}_2)|k\rangle
\end{aligned}
$$

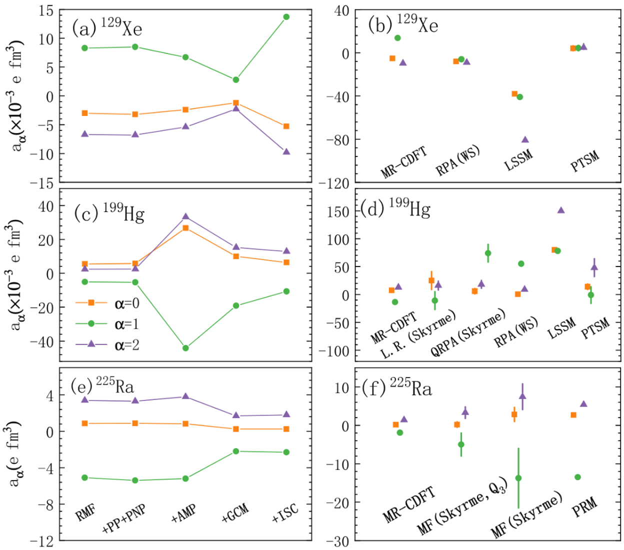
Matrix elements of Schiff operators and P,T-odd nuclear forces



Nuclear Schiff moments and E1 transition strengths



BMF correlations and comparison of NSMs



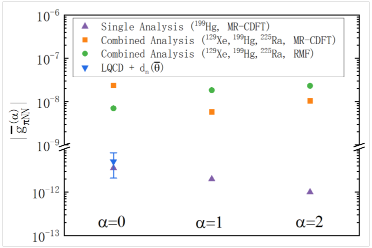
- The inclusion of parity and particle-number projection (PP+PNP) does not change significantly a_α for the three nuclei.
- The additional angular-momentum projection (AMP) modifies the values (a_0, a_1, a_2) of ^{129}Xe and ^{199}Hg by (25%, 21%, 21%) and (368%, 734%, 1228%), respectively.
- For the well-deformed ^{225}Ra, the effect of AMP is minor. However, the shape-mixing effect reduces the a_α by (71%, 58%, 55%), respectively.

Constraints on the PT-odd πNN coupling

Table: The final values for the nuclear structure factors a_α (e fm^3) by the MR-CDFT calculation with the extrapolation of $N_{\rm sh} \to \infty$.

Nuclei	a_0	a_1	a_2	$d[10^{-26} e \text{ fm}]$		$S[10^{-10} e \text{ fm}^3]$
^{129}Xe	-0.0052	$+0.0134$	-0.0097	< 0.14	Sachdeva:2019PRL	< 3.7
^{199}Hg	$+0.0075$	-0.0136	$+0.0169$	$< 7.4 \times 10^{-4}$	Graner:2016PRL	$< 3.5 \times 10^{-3}$
^{225}Ra	$+0.15$	-1.9	$+1.3$	$< 1.4 \times 10^{3}$	Bishof:2016PRC	$< 1.59 \times 10^{3}$

The ratios $a_\alpha(^{225}\mathrm{Ra})/a_\alpha(^{199}\mathrm{Hg})$ are 20, 140, and 77, respectively, significantly smaller than the previous estimation based on different nuclear models for different nuclei.



- The constraints are derived through a Monte Carlo analysis with 10^9 random samples at the 95% confidence level.
- Incorporating BMF correlations and intermediate-state contributions to the Schiff moments can change the constraints on $|\bar{g}_{\pi NN}^{(\alpha)}|$ by a factor of 2–4.

Summary

- **Nuclear Schiff Moments (NSMs)**: Essential for interpreting experiments that search for CP- (or T-) violating EDMs in certain atoms and molecules.
- **Existing calculations of NSMs**: discrepancies among different nuclear models are significant, even with different signs.
- **This work**: We have presented the **first beyond relativistic mean-field study** of NSMs in ^{129}Xe, ^{199}Hg and ^{225}Ra using the MR-CDFT. This study can in principle be applied to nuclear Schiff moments of any interesting odd-mass nuclei.
- **Our findings**: A strong correlation between the contributions of nuclear intermediate states to the **Schiff moment and the $E1$ transition** from these states and the ground state, suggesting that measurements of these transitions can help **constrain nuclear model predictions of NSMs**. Beyond-mean-field effects, together with intermediate-state contributions, can either enhance or suppress the structure factors by **50% to 400%**, and modify the allowed ranges of the LECs of P,T-odd nuclear forces by a factor up to 4.

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Collaborators

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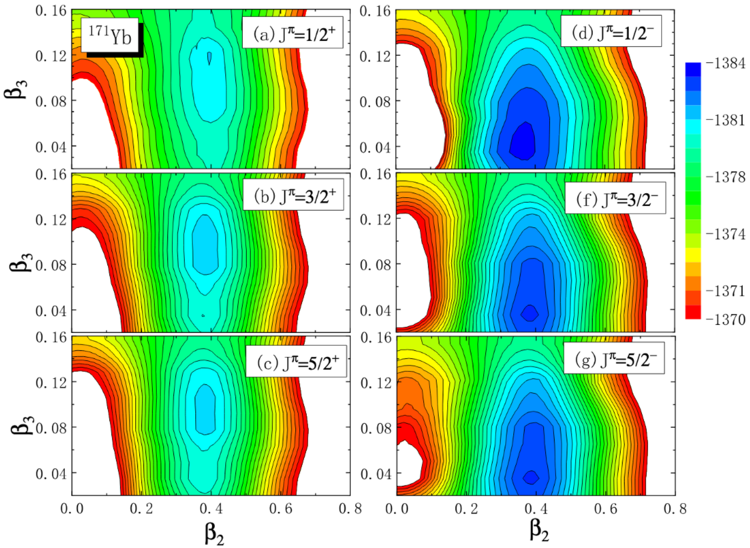
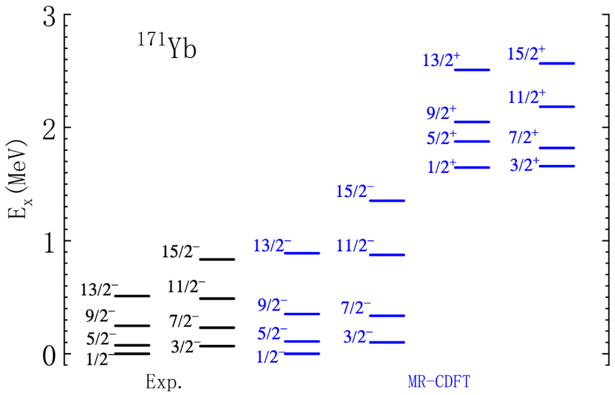
Thank you for your attention!

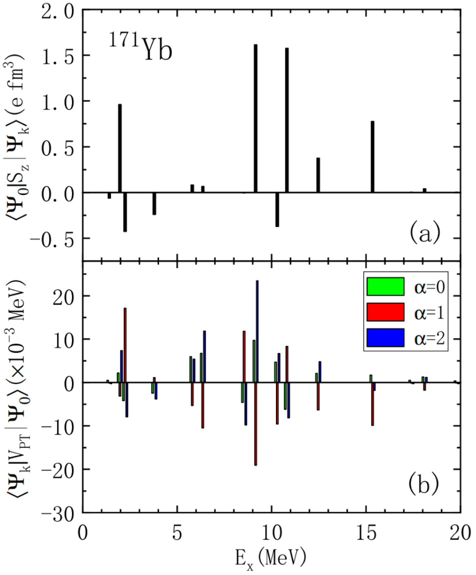
Preliminary results on ^{171}Yb

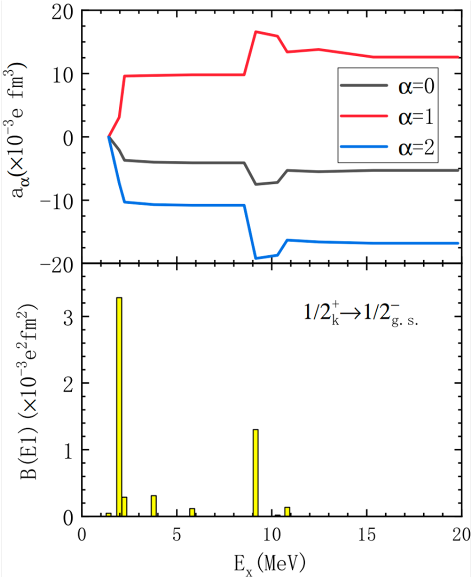


Preliminary results on ^{171}Yb



Preliminary results on ^{171}Yb





Preliminary results on ^{171}Yb

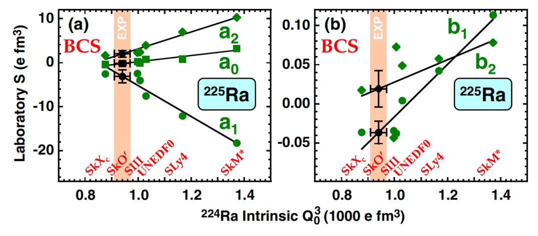
Table: The structure factors a_α (e fm^3) in the nuclear Schiff moments of ^{171}Yb from the CDFT calculation at various levels of approximation.

		$a_0(10^{-3})$	$a_1(10^{-3})$	$a_2(10^{-3})$
^{171}Yb(PC-PK1)	RMF	-1.4	4.3	-9.2
	AMP+PP+PNP	-4.8	10.2	-25.1
	PGCM(1)	0.12	-0.38	-0.54
	PGCM(all)	-5.3	12.6	-16.8

- The valence Dirac-Fock+RPA/CI+MBPT calculations: V. A. Dzuba et al., PRA80, 032120 (2009)

$$d_A(^{171}\mathrm{Yb}) = -2.1 \times 10^{-17} S(e\ \mathrm{fm}^3)^{-1}(e\ \mathrm{cm})$$

A most recent study on nuclear Schiff moments



	a_0	a_1	a_2	b_1	b_2
^{221}Rn	−0.04(10)	**−1.7(3)**	**0.67(10)**	−0.015(5)	−0.007(4)
^{223}Rn	−0.08(8)	**−2.4(4)**	**0.86(10)**	−0.031(9)	−0.008(8)
^{223}Fr	0.07(20)	−0.8(7)	0.05(40)	0.018(8)	−0.016(10)
^{225}Ra	0.2(6)	−5(3)	3.3(1.5)	−0.01(3)	0.03(2)
^{229}Pa	**−1.2(3)**	−0.9(9)	−0.3(5)	**0.036(8)**	0.032(18)

- The nuclear Schiff moment

$$S = \sum_{k\neq 0} \frac{\langle\Psi_0^{(N)}|\hat{S}_z|\Psi_k^{(N)}\rangle\langle\Psi_k^{(N)}|\hat{V}_{PT}|\Psi_0^{(N)}\rangle}{E_0^N - E_k^N} + c.c.$$

$$= a_0 g\bar{g}_0 + a_1 g\bar{g}_1 + a_2 g\bar{g}_2 + b_1\bar{c}_1 + b_2\bar{c}_2.$$

- Single-state approximation

$$S \approx -2\frac{\langle\Psi_0|\hat{S}_0|\bar{\Psi}_0\rangle\langle\bar{\Psi}_0|\hat{V}_{PT}|\Psi_0\rangle}{\Delta E},$$

- Rigid rotor approximation

$$\langle\Psi_0|\hat{S}_0|\bar{\Psi}_0\rangle_{\rm rigid} = \frac{J}{J+1}S_0,$$
$$\langle\bar{\Psi}_0|\hat{V}_{\rm PT}|\Psi_0\rangle_{\rm rigid} = \langle\hat{V}_{\rm PT}\rangle,$$

- **Correlation Reduces Uncertainty**: The strong correlation between the calculated intrinsic Schiff moment in 225Ra and the octupole moment in 224Ra helps significantly reduce systematic uncertainties associated with nuclear EDFs.
- **Sensitivity to Constraints**: Using different octupole moments to constrain model coefficients can result in notably different values, indicating sensitivity to the choice of experimental input. J. Dobaczewski, J. Engel, M. Kortelainen, and P. Becker, PRL121, 232501 (2018)

- Within the SM, the CP Violation from the topological θ term of QCD Lagrangian

$$\mathcal{L}_\theta = \frac{\bar{\theta} g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor, $\tilde{G}^{\mu\nu a} = \epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta}/2$ is its dual, and $\bar{\theta}$ is the CP-violating parameter QCD.

- This term introduces an asymmetry in the quark electric charge distribution inside the neutron, and thus induces a nonzero neutron EDM (d_n) through quark-gluon interactions, which would break ime-reversal (T) symmetry.
- The strong CP problema rises because experimental constraints (from neutron EDM searches) suggest $\bar{\theta} < 10^{-10}$, which is unnaturally small, leading to the hypothesis of axions as a possible solution.

The neutron EDM and strong CP problem

- The neutron EDM induced by the theta term of QCD is estimated as:

$$d_n = \frac{e}{m_p}\frac{g_{\pi NN}\bar{g}^{(0)}_{\pi NN}}{4\pi^2}\ln(m_\rho/m_\pi) \approx 10^{-16}\bar{\theta}\ e\cdot \mathrm{cm}$$

- The neutron EDM induced by the CKM C. Y. Seng, Phys. Rev. C 91, 025502 (2015)

$$d_n = (1-6)\times 10^{-32} e\cdot \mathrm{cm}$$

- Current experimental upper limit:

$$|d_n| < 1.8\times 10^{-26} e\cdot \mathrm{cm} = 1.8\times 10^{-13} e\cdot \mathrm{fm}$$

  This means $\bar{\theta} \lesssim 10^{-10}$, unexpectedly small if CP violation were naturally large in QCD.
- The LEC $\bar{g}^{(0)}_{\pi NN}$ originated from the θ term

$$\bar{g}^{(0)}_{\pi NN} \simeq -0.027\theta$$