Nuclear Schiff Moment Calculations

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INT Workshop on EDMs and CP Violation
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Outline

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Introduction

- Permanent Electric Dipole Moments (EDMs) are a signal of **time(T)-reversal-violating physics**.
- If CPT is a good symmetry, **T-violation** $\Leftrightarrow$ **CP-violation**.
- The Standard Model accommodates some level of CP-violation in weak interactions.
  - ✓ Kaon system (1964)
  - ✓ B-meson system (2001)
  - ✗ Observed matter anti-matter asymmetry in the Universe
  - ? CP-violation in the strong sector : θ_{QCD} very small

Atomic EDMs can help !

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Experimental searches :
$|d^{\mathrm{exp}}_{^{199}\mathrm{Hg}}| < 2.1 \times 10^{-28}\ e\ \mathrm{cm}$

Standard Model prediction :
$d_{^{199}\mathrm{Hg}} \sim 10^{-33}\ e\ \mathrm{cm}$

How can this limit constrain SUSY and other extra-SM theories that predict much higher EDMs than the SM ?

Atomic → Nuclear Theory → Fundamental

When connecting atomic EDMs with underlying T-odd physics largest uncertainty is in nuclear physics.

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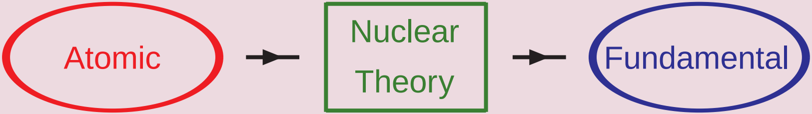

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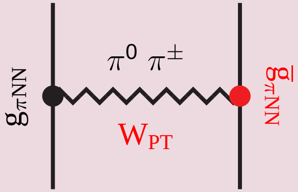
From fundamental physics to atomic EDMs

T-violation in fundamental theory induces a πNN T-odd vertex. This gives rise to a T-odd NN interaction, which induces a nuclear EDM.



The atomic EDM is induced by a nuclear EDM... **Not quite !...**
Electrons shield applied electric fields... The relevant quantity is the **Schiff operator**

$$\vec{S} \sim \sum_{p=1}^{Z} \left(r_p^2 \vec{r}_p - \frac{5}{3} \langle r_{\text{ch}}^2 \rangle \vec{r}_p \right)$$

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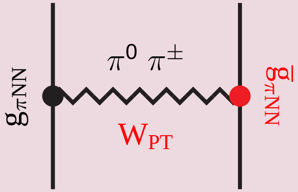

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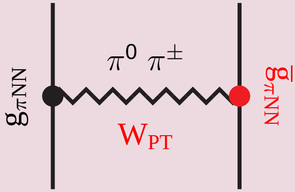

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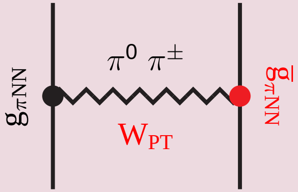

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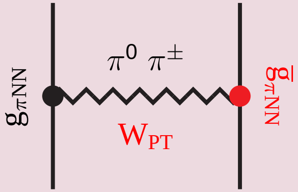

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   - Nuclear physics input
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Nuclear physics input

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_i \rangle \langle \Psi_i | W_{\rm PT} | \Psi_0 \rangle}{E_0 - E_i} + {\rm c.c.}$$

- How well do we know $\langle \Psi_0 | S_z | \Psi_i \rangle$ and $\langle \Psi_0 | W_{\rm PT} | \Psi_i \rangle$?
- $|\Psi_0\rangle$ and $|\Psi_i\rangle$ are the ground and excited states of the odd-A system... not an easy task to obtain them.
- $|\Psi_0\rangle \equiv |\Psi_0\rangle_{\rm odd-A} = a^\dagger_\nu |\Psi_0\rangle_{\rm even-A}$; it has the quantum-numbers of the valence particle because $|\Psi_0\rangle_{\rm even-A}$ has $J^\pi = 0^+$.
- S_z acts **only on protons**; in ^{129}Xe and ^{199}Hg the valence neutron is a *spectator*; in a crude approximation, we can study $\langle \Psi_0 | S_z | \Psi_i \rangle_{\rm odd} \to \langle \Psi_0 | S_z | \Psi_i \rangle_{\rm even}$.

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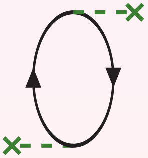
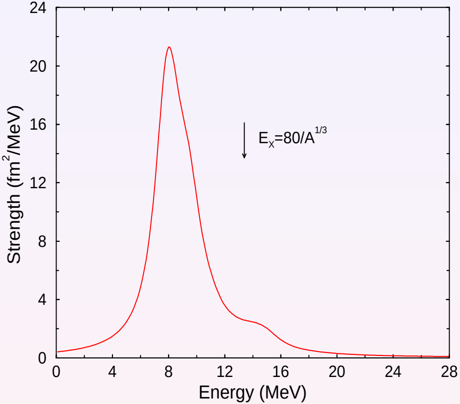
Schiff-related observables in ^{208}Pb

Isovector E-1 strength distribution

$$\vec{S} \sim \sum_{p=1}^{Z} \left(r_p^2 \vec{r}_p - \eta \vec{r}_p \right)$$

HF (SkM*)





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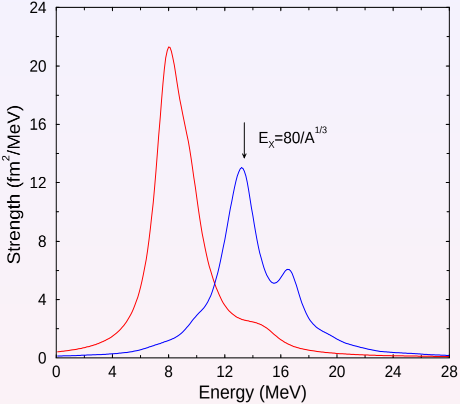

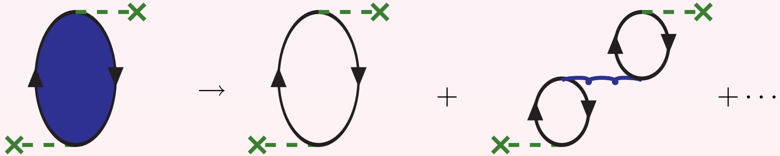

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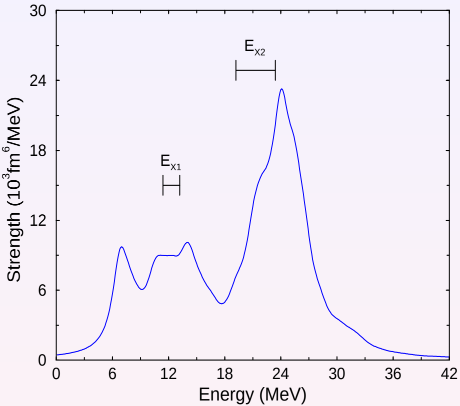

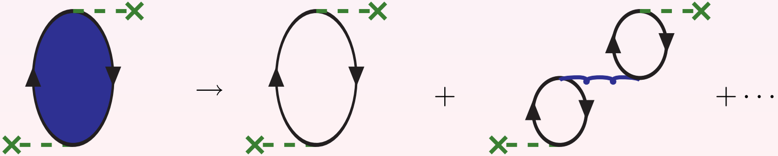

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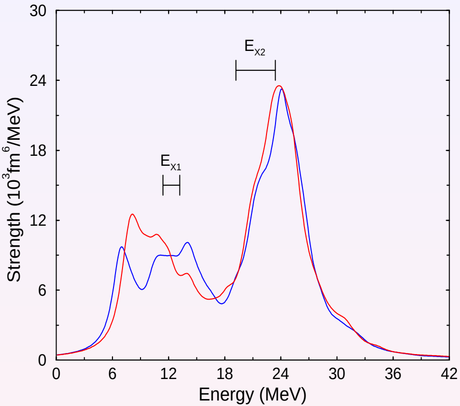

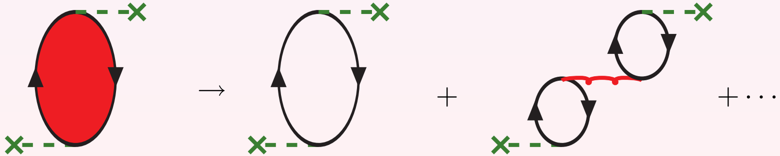

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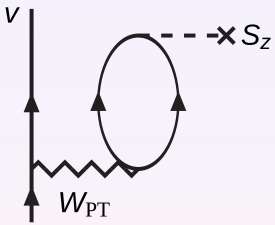

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- Ground state is $q_{\nu}^{\dagger}\,|\mathrm{BCS}\rangle$;
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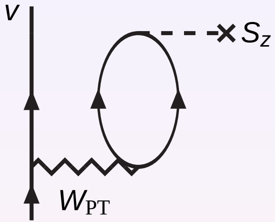

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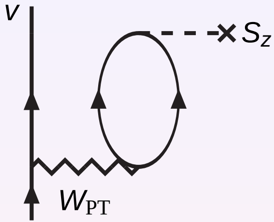

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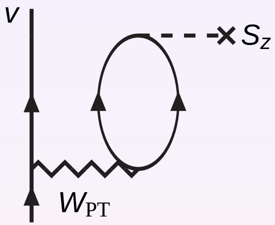

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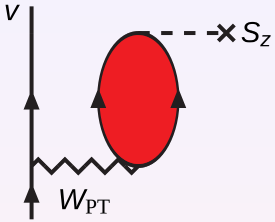

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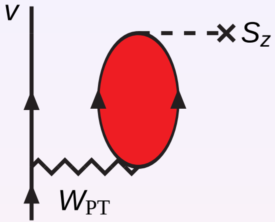

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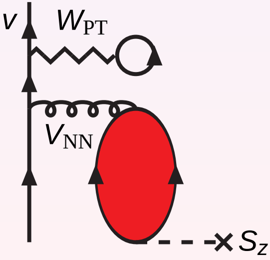

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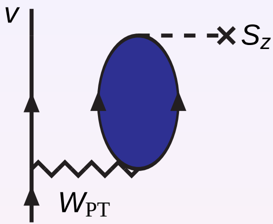

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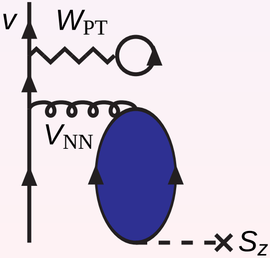
- Sensitivity to different Skyrme interactions.



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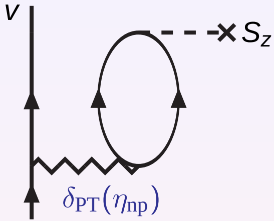

$$S\ [e\ \mathrm{fm}^3] = 0.095 g\bar{g}_0 + 0.095 g\bar{g}_1 + 0.190 g\bar{g}_2$$

$$S\ [e\ \mathrm{fm}^3] = 0.018 g\bar{g}_0 + 0.034 g\bar{g}_1 + 0.031 g\bar{g}_2$$

$$S\ [e\ \mathrm{fm}^3] = 0.010 g\bar{g}_0 + 0.074 g\bar{g}_1 + 0.018 g\bar{g}_2$$

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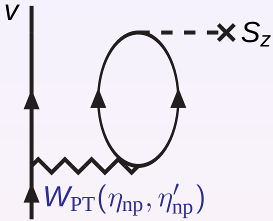

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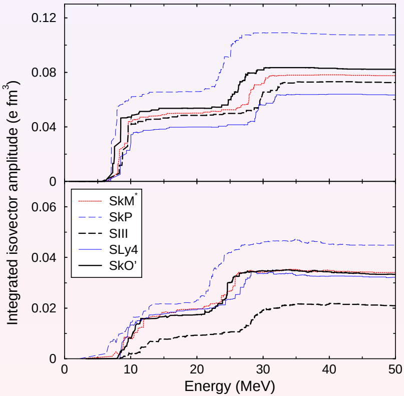

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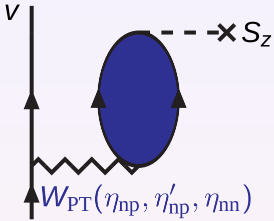

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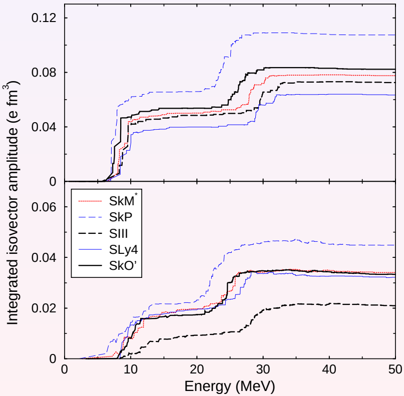

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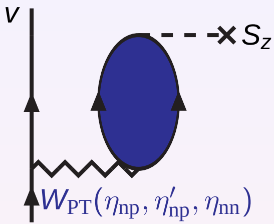

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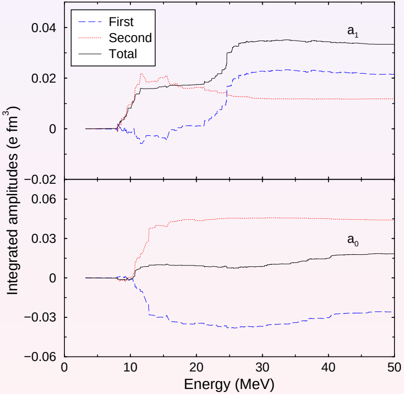

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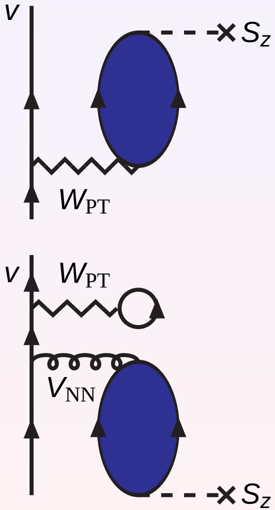

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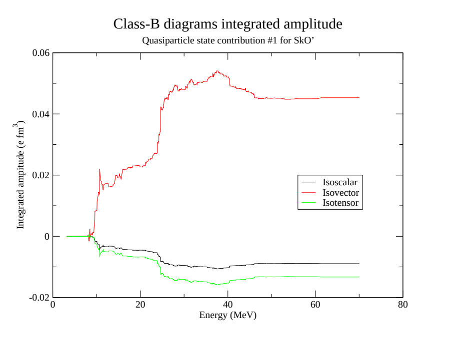

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Nuclei	a_0	a_1	a_2
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^{199}Hg (Dmitriev *et al.*)	0.0004	0.055	0.009
^{129}Xe (to be published)	-0.002	-0.034	-0.007
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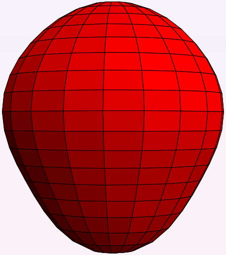

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- In spherical nuclei, $(E_0 - E_i) \sim$ MeV.
- In octupole-deformed nuclei, very low-energy state above the ground state, with opposite parity.

In ^{225}Ra, $(E_0 - E_1) = 55.3$ keV

An enhancement factor of up to 100 is expected!

More, in fact...

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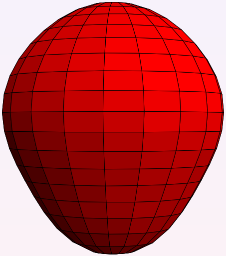

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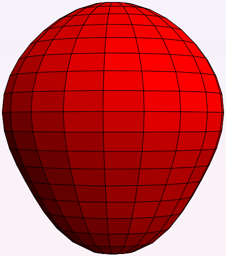

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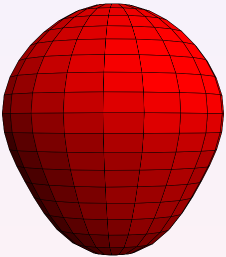

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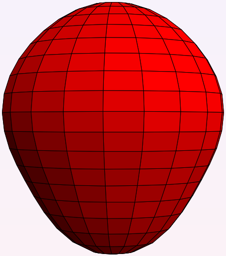

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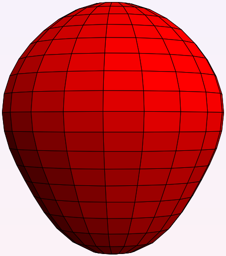

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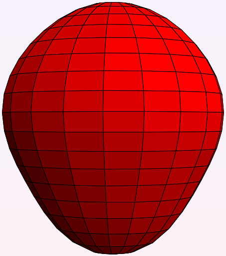

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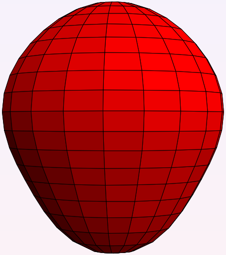

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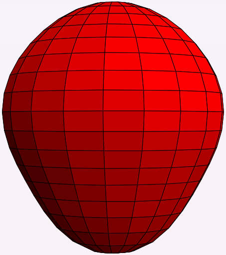

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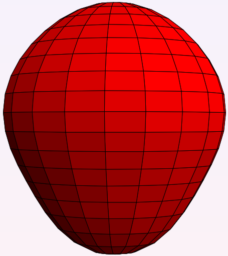

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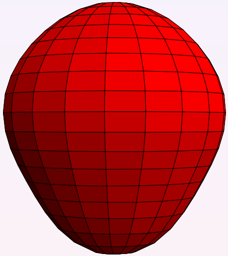

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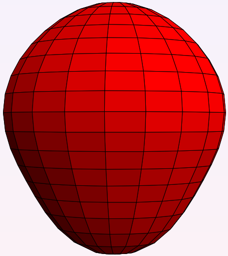

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The nuclear Schiff moment of ^{225}Ra

$$S_{^{225}\mathrm{Ra}} \sim \langle S_z \rangle_{\mathrm{intr}} \langle W_{\mathrm{PT}} \rangle_{\mathrm{intr}} / (55.3\ \mathrm{keV})$$

- Error in $\langle S_z \rangle_{\mathrm{intr}}$ is < 2.
- A first calculation was made [Engel, Bender, Dobaczewski, JHJ and Olbratowski, PRC **68**, 025501 (2003)] assuming a delta W_{PT} and direct terms only.
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2. Spherical nuclei
   - Nuclear physics input
   - Schiff-related observables in ^{208}Pb
   - The nuclear Schiff moments of ^{129}Xe and ^{199}Hg
3. Octupole-deformed nuclei
   - Octupole enhancement
   - The nuclear Schiff moment of ^{225}Ra
4. Conclusions
   - Overview

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Spherical nuclei

- Nuclear collective effects are very important in describing the nuclear Schiff response to a PT-odd NN potential.
- The isoscalar coefficient is significantly suppressed when compared to previous, less sophisticated, calculations.
- Uncertainty is a factor of 5, mainly because of our lack of knowledge about the effective PT-even NN interaction.

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Overview

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$|S_{^{225}\mathrm{Ra}}/S_{^{199}\mathrm{Hg}}|$

Skyrme interaction	a_0	a_1	a_2
SIII	100	123	177
SkM*	522	307	500
SLy4	1000	188	677
SkO′	150	81	222

... THE END!