#### **Nuclear Schiff Moment Calculations**

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5900

## Introduction

#### 2 Spherical nuclei

- Nuclear physics input
- Schiff-related observables in <sup>208</sup>Pb
- The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg
- Octupole-deformed nuclei
  - Octupole enhancement
  - The nuclear Schiff moment of <sup>225</sup>Ra
- ConclusionsOverview



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## Conclusions

Overview

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- Permanent Electric Dipole Moments (EDMs) are a signal of time(T)-reversal-violating physics.
- If CPT is a good symmetry, **T-violation** ⇔ **CP-violation**.
- The Standard Model accommodates some level of CP-violation in weak interactions.
  - <sup>(2001)</sup> B-meson system (2001)
  - XCObserved matter anti-matter asymmetry in the Universe.
  - CP-violation in the strong sector : θ<sub>OCD</sub> very small.

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Standard Model prediction :  $d_{
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How can this limit constrain SUSY and other extra-SM theories that predict much higher EDMs than the SM ?



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



#### From fundamental physics to atomic EDMs

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



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

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Ma A

Introduction Spherical Octupole Conclusions

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

Input

<sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg

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

Introduction Spherical Octupole Conclusions

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Spherical Octupole Conclusions

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Introduction

Spherical Octupole Conclusions

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Input

## Schiff-related observables in <sup>208</sup>Pb

24 **Isovector E-1** 20 strength distribution Strength (fm<sup>2</sup>/MeV) 8 7 91 91 E<sub>x</sub>=80/A<sup>1/3</sup>  $\vec{S} \sim \sum_{p=1}^{Z} \left( r_p^2 \vec{r}_p - \eta \vec{r}_p \right)$ 4 HF (SkM\*) 0 12 20 24 0 4 8 16 28 Energy (MeV) -X X-< D

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Input

## Schiff-related observables in <sup>208</sup>Pb



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Input

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#### Introduction

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- ConclusionsOverview

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Introduction Spherical Octupole Conclusions Input <sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg



- <sup>129</sup>Xe and <sup>199</sup>Hg are one-neutron valence nuclei;
- Ground state is  $q_v^{\dagger} | BCS \rangle$ ;
- Quasi-particle excited states;

5900

Skyrme NN interactions;

Introduction Spherical Octupole Conclusions Input <sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg



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- Nuclear collective effects;
- Higher order diagrams;





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- Ground state is  $q_{\nu}^{\dagger} |\text{BCS}\rangle$ ;
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- Skyrme NN interactions;

- Nuclear collective effects;
- Higher order diagrams;
- Sensitivity to different Skyrme interactions.



Introduction Spherical Octupole Conclusions Input <sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg

# The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg

#### $S [e \text{ fm}^3] = 0.095 g \overline{g}_0 + 0.095 g \overline{g}_1 + 0.190 g \overline{g}_2$



 $S [e \text{ fm}^3] = 0.018 g\overline{g}_0 + 0.034 g\overline{g}_1 + 0.031 g\overline{g}_2$  $S [e \text{ fm}^3] = 0.010 g\overline{g}_0 + 0.074 g\overline{g}_1 + 0.018 g\overline{g}_2$ 

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The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg

Input

Introduction Spherical Octupole Conclusions

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<sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg

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Introduction Spherical Octupole Conclusions Input <sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg

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Introduction Spherical Octupole Conclusions Input <sup>208</sup>Pb <sup>129</sup>Xe and <sup>199</sup>Hg

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nuclear Schiff momen	ts of 12	<sup>9</sup> Xe an	d <sup>199</sup> Hg
ummary			
Nuclei	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>
JHJ and Engel = PR Dmitriev et al. = PR	C <b>72</b> , 045 C <b>71</b> , 035	503 (200 501 (2005	5) 5)
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The	e nuclear Schiff momer	nts of <sup>12</sup>	<sup>9</sup> Xe an	d <sup>199</sup> Hg		
S	Gummary					
	Nuclei	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>		
	<sup>199</sup> Hg (JHJ and Engel)	0.010	0.074	0.018		
	<sup>199</sup> Hg (Dmitriev <i>et al.</i> )	0.0004	0.055	0.009		
	<sup>129</sup> Xe (to be published)	-0.002	-0.034	-0.007		
	<sup>129</sup> Xe (Dmitriev <i>et al.</i> )	-0.008	-0.006	-0.009		
	JHJ and Engel = PI Dmitriev et al. = PF	RC <b>72</b> , 045 RC <b>71</b> , 035	503 (2005 501 (2005	5) 5)		
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Ma A

#### Enhancement 225 Ra

### Octupole enhancement

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



 Asymmetric shape of octupole-deformed nuclei implies parity doubling.

• In spherical nuclei,  $(E_0 - E_i) \sim \text{MeV}$ .

 In octupole-deformed nuclei, very low-energy state above the ground state, with opposite parity.

### ln <sup>225</sup>Ra, $(E_0 - E_1) = 55.3$ keV

#### An enhancement factor of up to 100 is expected! More, in fact...

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225 Ra

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225 Ra

### Octupole enhancement

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



 Asymmetric shape of octupole-deformed nuclei implies parity doubling.

• In spherical nuclei,  $(E_0 - E_i) \sim \text{MeV}$ .

 In octupole-deformed nuclei, very low-energy state above the ground state, with opposite parity.

 $\ln {}^{225}\text{Ra}, (E_0 - E_1) = 55.3 \text{ keV}$ 

#### An enhancement factor of up to 100 is expected! More, in fact...

225 Ra

#### Octupole enhancement





- Asymmetric shape of octupole-deformed nuclei implies parity doubling.
- $|\Psi_0\rangle$  and  $|\Psi_1\rangle$  are projections onto good parity and angular momentum of the same "intrinsic state".

• One can write  $S \sim \langle S_z \rangle_{intr} \langle W_{PT} \rangle_{intr} / \Delta E$ .

The intrinsic-state expectation value  $\langle S_z \rangle_{intr}$  is **larger** than a typical matrix element in a spherical nucleus.

The expected enhancement factor is larger than 100

225 Ra

#### Octupole enhancement

$$S\simeq \frac{\langle \Psi_0|S_z|\Psi_1\rangle \langle \Psi_1|W_{\rm PT}|\Psi_0\rangle}{({\cal E}_0-{\cal E}_1)}+{\rm c.c.}$$



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225 Ra

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### Outline

# 1 Introduction

### 2 Spherical nuclei

- Nuclear physics input
- Schiff-related observables in <sup>208</sup>Pb
- The nuclear Schiff moments of <sup>129</sup>Xe and <sup>199</sup>Hg
- Octupole-deformed nuclei
  - Octupole enhancement
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# ConclusionsOverview

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### $S_{^{225}Ra} \sim \langle S_z \rangle_{intr} \langle \textit{W}_{PT} \rangle_{intr} / (55.3 \text{ keV})$

- Error in  $\langle S_z \rangle_{intr}$  is < 2.
- A first calculation was made [Engel, Bender, Dobaczewski, JHJ and Olbratowski, PRC 68, 025501 (2003)] assuming a delta W<sub>PT</sub> and direct terms only.
- Finite range is more realistic. Exchange terms and short range correlations contribute ~ 10%.
- \$\langle W\_{PT} \rangle\_{intr}\$ is harder to estimate because it is sensitive to the nuclear spin distribution (complicated to describe near the Fermi surface).

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Enhancement 225Ra

# The nuclear Schiff moment of <sup>225</sup>Ra

Nuclei	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>
<sup>225</sup> Ra (zero range only <sup>[1]</sup> )	-5.06	10.4	-10.1
<sup>[1]</sup> Engel <i>et al.</i> , PRC 6 <sup>[2]</sup> Dobaczewski and Engel, <sup>[3]</sup> Dmitriev et al., PRC	<b>58</b> , 02550 PRL <b>94</b> , 1 <b>71</b> , 0355	1 (2003) 232502 (2 01 (2005)	2005)

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<sup>225</sup> Ra (no deformation <sup>[3]</sup> )	-0.033	0.037	-0.046

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- 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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$ S_{225_{Ra}}/S_{199_{Hg}} $							
	Skyrme interaction	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>			
	SIII	100	123	177			
	SkM*	522	307	500			
	SLy4	1000	188	677			
	SkO′	150	81	222			

João H. de Jesus Nuclear Schiff Moment Calculations

# ... THE END!

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