Nuclear structure relevant to fundamental symmetry studies with atoms and molecules

Outline

- Atoms & Molecules
- BSM searches
- P and T-violating nuclear properties
- Current and planned experiments
- **Nuclear structure** input

R. F. Garcia Ruiz

MIT

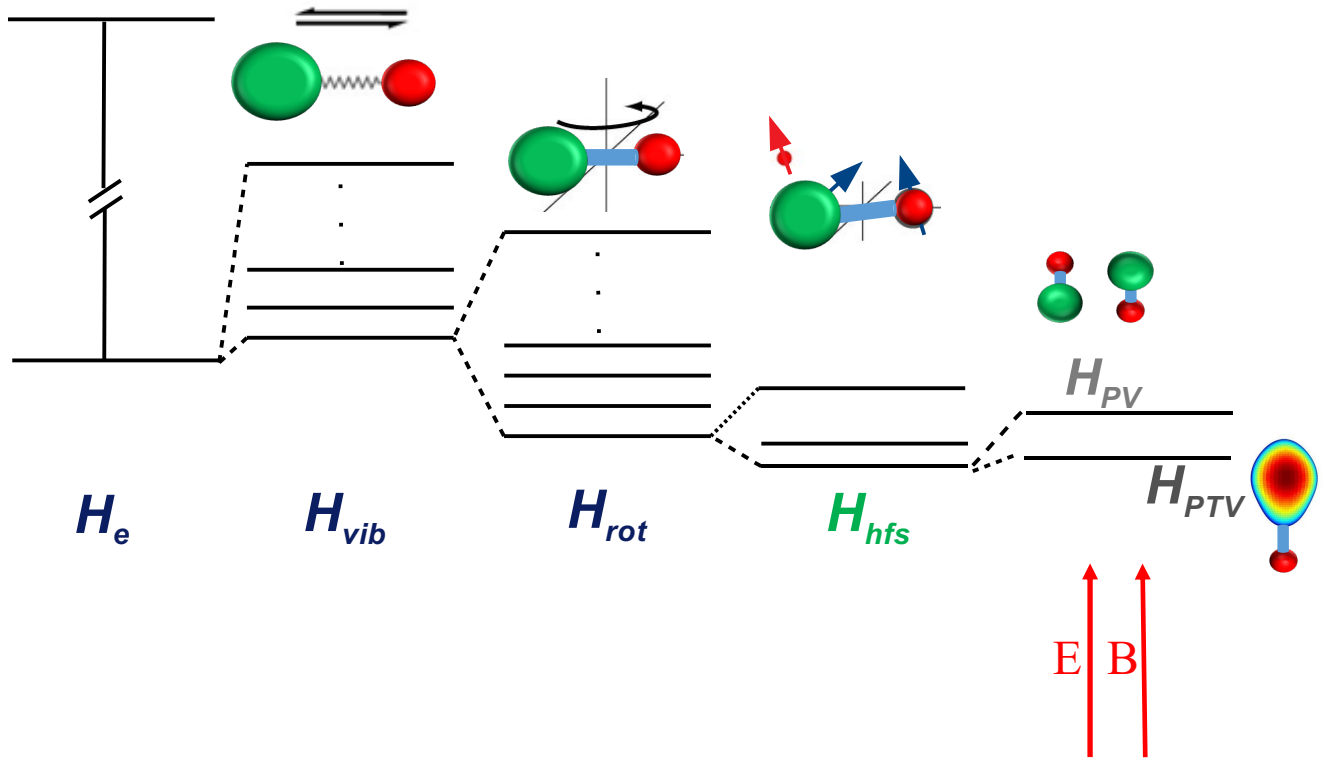
2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics

AMO techniques for Fundamental Symmetries

Nuclear → ~ O_{Nucl} F_{mol} ← Atom/molecule

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

eV	~ 2	10^{-2}	10^{-5}		10^{-8}	$<10^{-12}$	$<10^{-18}$	$<10^{-12}$



AMO techniques for Fundamental Symmetries

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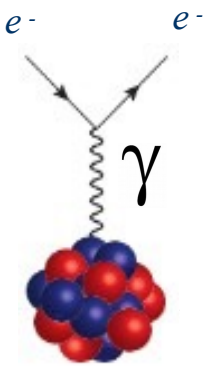
H_{hfs}



P,T-even

- Nuclear structure
- Nuclear matter

Nature 607, 260 (2022)
arXiv:2209.15228 (2022)

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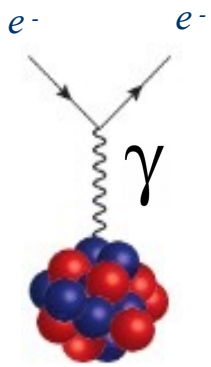
H_{hfs}



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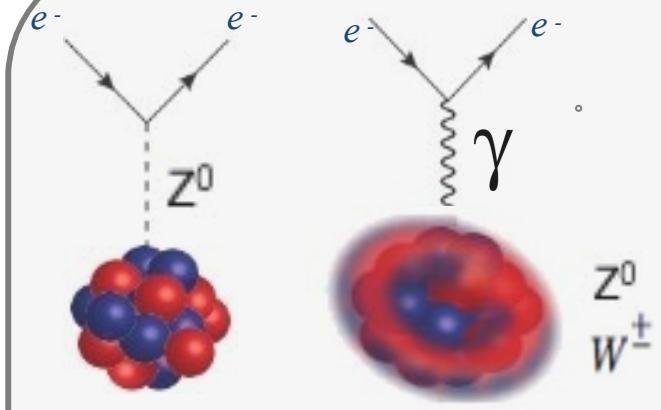
H_{PV}



P-violation

- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties
- New forces

RMP 90, 025008 (2018)
PRL 120, 142501 (2018)

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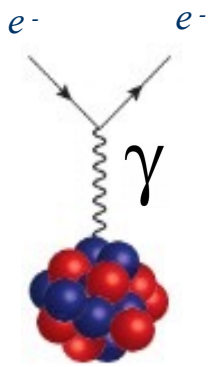
H_{hfs}



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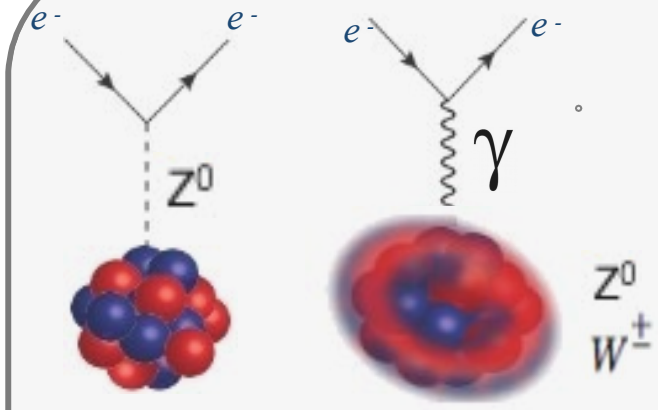

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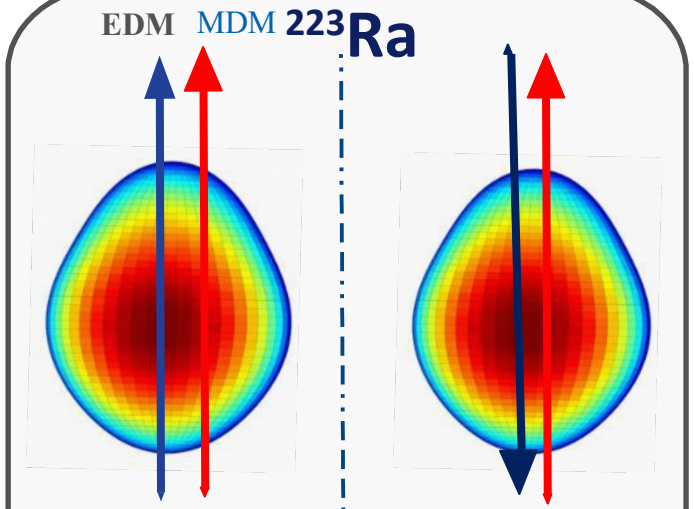
H_{PTV}



T-violation

- Matter-antimatter asymmetry
- New particles

PRL 114, 233002 (2015)
Nature 581, 396 (2020)

AMO techniques for Fundamental Symmetries

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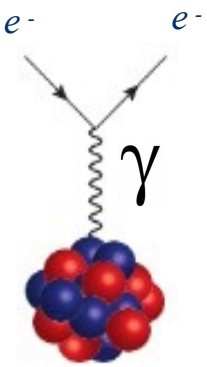
H_{hfs}



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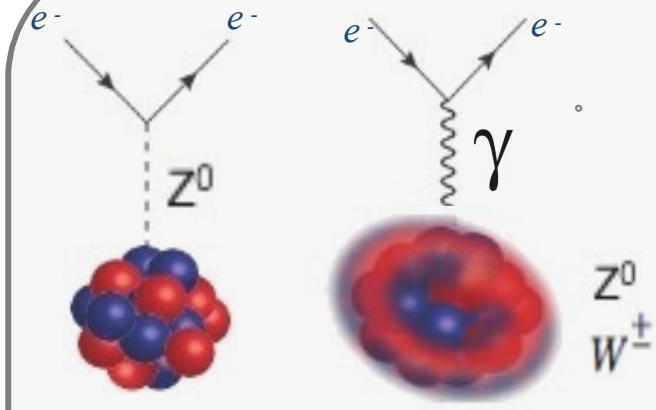

P-violation

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RMP 90, 025008 (2018)
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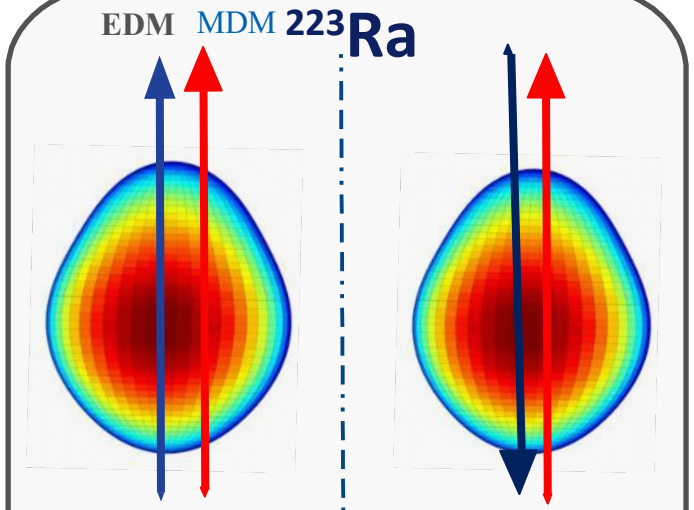
H_{PTV}



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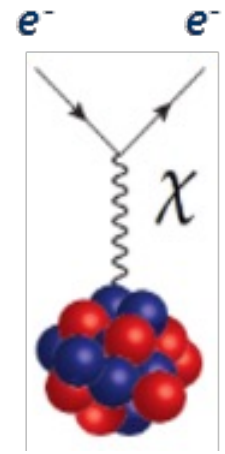
H_{BSM}



Fifth forces

- New electron-nucleon forces?
- Dark matter

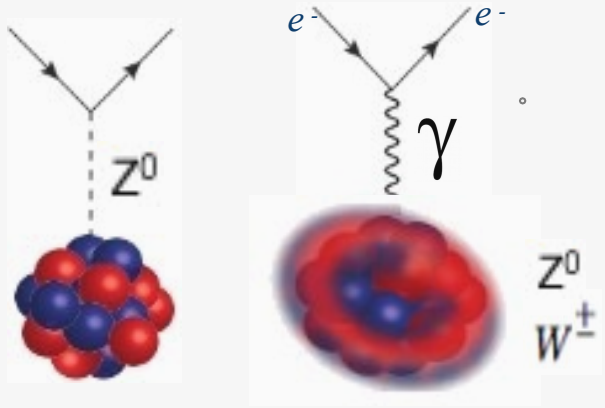
PRL 128, 073001 (2022)
PRL 125, 123003 (2021)

AMO techniques for Fundamental Symmetries

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

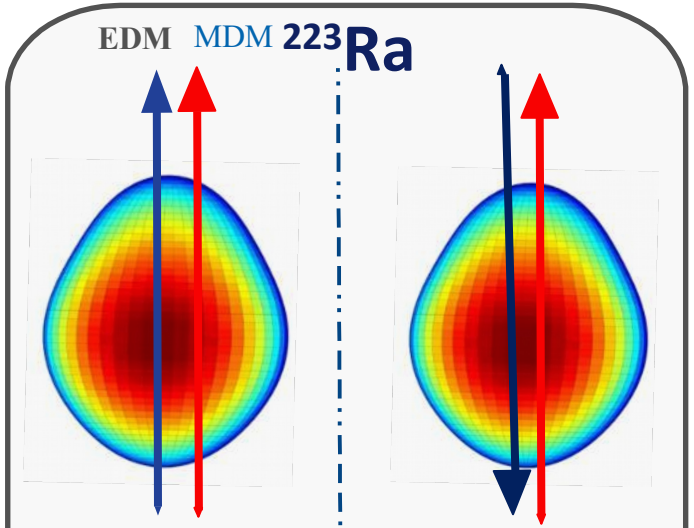
H_{PV} H_{PTV} H_{BSM}

Nuclear structure experiment & theory provide critical input



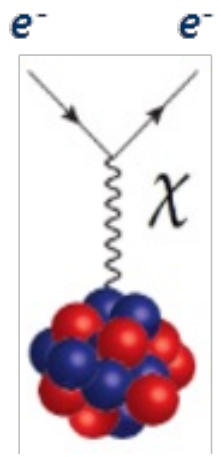
P-violation

- P-odd nuclear moments: e.g. Anapole moments
- Quark couplings: $C_{2u,d}$, P-odd nucleon- nucleon forces
- Weak quadrupole moments, neutron distribution



T-violation

- T-odd moments, EDMs, e.g. Schiff moments, magnetic quadrupole moment, T-odd nucleon-nucleon forces



Fifth forces

- Higher order EM moments: $\langle\delta r^2\rangle$, $\langle\delta r^4\rangle$, β_2,…
- Nuclear dipole polarizability

Current and planned experiments:

^{29}Si, ^{18,19}F, ^{133}Cs, ^{137}Br, ^{171}Yb, ^{205}Tl, ^{209,210}Fr, ^{223,225}Ra

^{129}Xe, ^{199}Hg, ^{171,173}Yb, ^{205}Tl , ^{181}Ta ^{223}Fr, ^{223}Rn, ^{223,225}Ra, ^{229}Th, ^{229}Pa

Ca, Sr, Cd, Yb, Ra, …

AMO techniques for Fundamental Symmetries

Nuclear → $\sim O_{Nucl} F_{mol}$ ← Atom/molecule

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

Nuclear

$\sim Z^a A^b \beta_2\beta_3 / (E_+^N - E_-^N)$

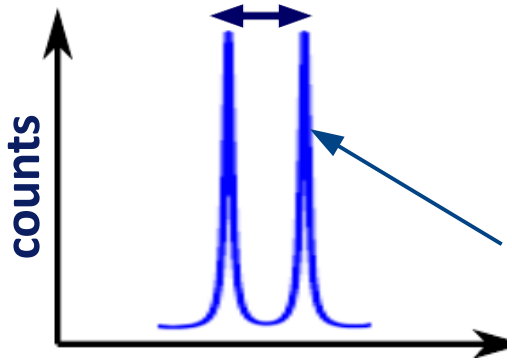
Atom/molecule

$\sim Z^c / (E_+^e - E_-^e)$

$\sim O_{Nucl} F_{mol}$

molecule

$E_+^N - E_-^N \sim 10^{-5}$ eV



$$\sim \frac{1}{\tau\sqrt{N}}$$

Experiment

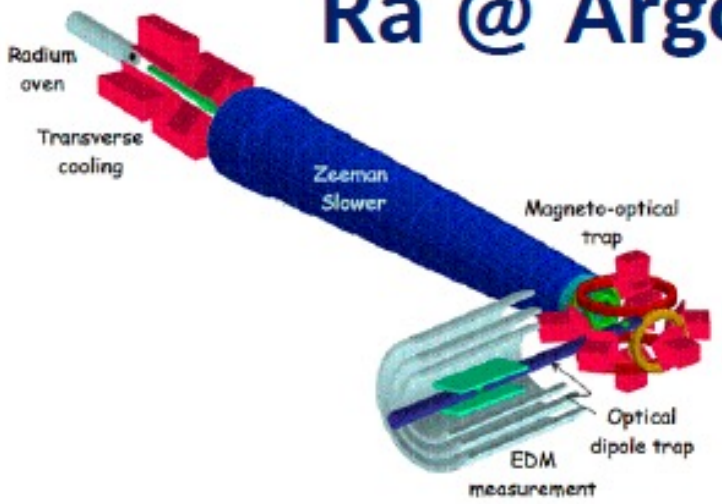
Nuclear *x* Molecule

Molecule	$> 10^3$
Nuclear amplification	$> 10^3$

Parker et al. PRL 114, 233002 (2015)
Safronova et al. RMP 90, 025008 (2018)
Garcia Ruiz et al. Nature 607, 260 (2022)

P, T violation searches with radioactive atoms

Ra @ Argonne

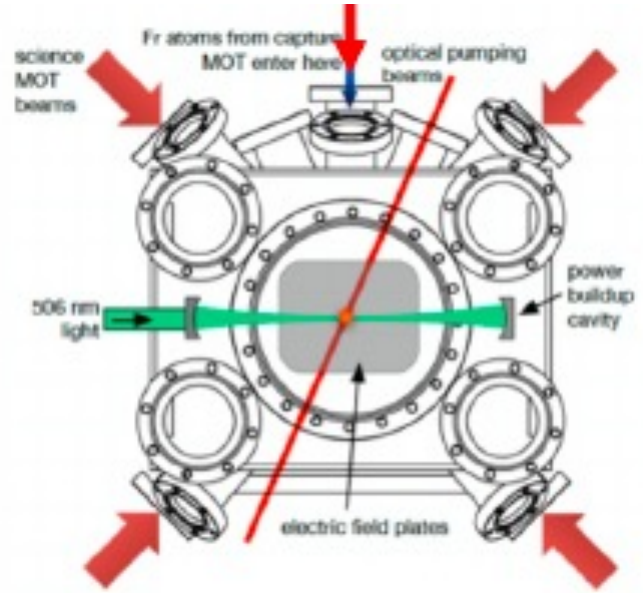


$$|d(^{225}\mathrm{Ra})| < 5.0 \times 10^{-22}\ e\,\mathrm{cm}$$

Phys. Rev. Lett. 114, 233002 (2015)

Argonne NATIONAL LABORATORY

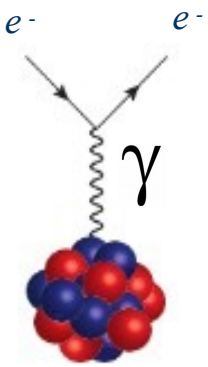
Fr (Z=87) @ TRIUMF



[Zang et al. Phys. Rev. Lett. 115, 042501 (2015)]
[Kalita et al. Phys. Rev. A 97, 042507 (2018)]

Nuclear Electromagnetic Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$



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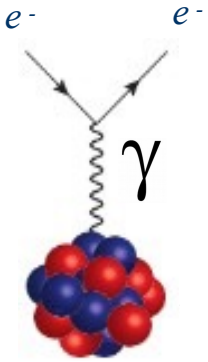
Atom/molecule
Nuclear



P,T-even

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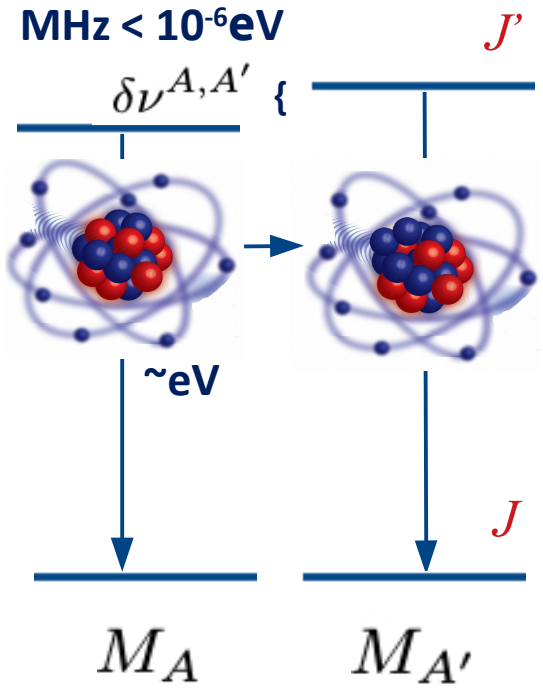
$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Isotope shift
MHz < 10^{-6}eV



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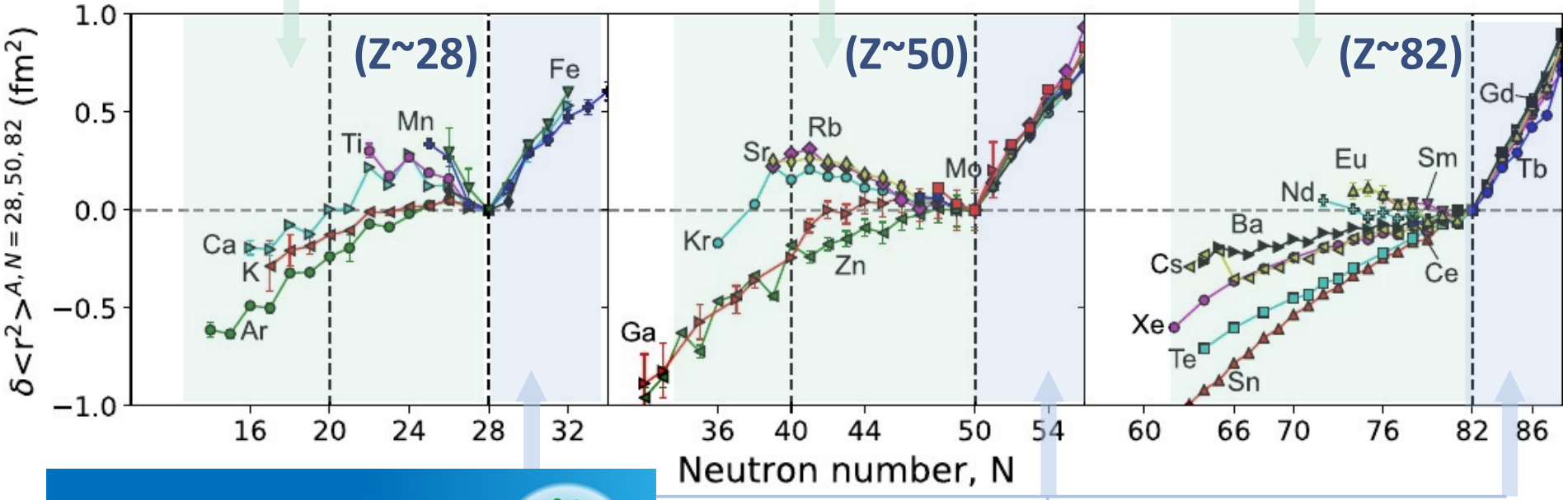
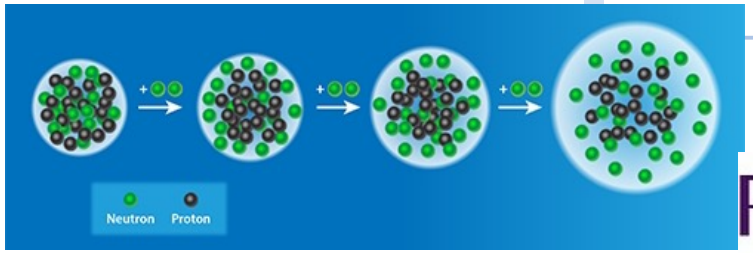
[Koszorus et al. Nature Phys. (2021)]
[Degroote et al. Nature Phys. 16, 620 (2020)]
[Kaufmann Phys. Rev. Lett. 124, 132502 (2020)]
[Garcia Ruiz & Vernon EPJ A 56, 136 (2020)]
[Gorges et al. Phys. Rev. Lett. 122, 192502 (2019)]
[Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

Strong Z dependence



Similar trends for neutron-rich



Physics

New Particles and Forces

$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$

Atom/molecule
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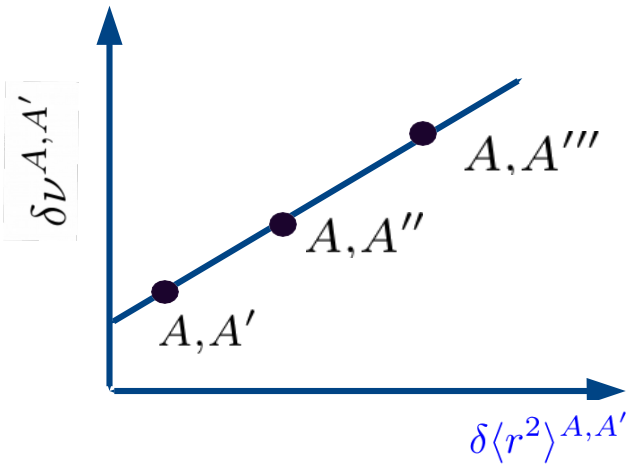

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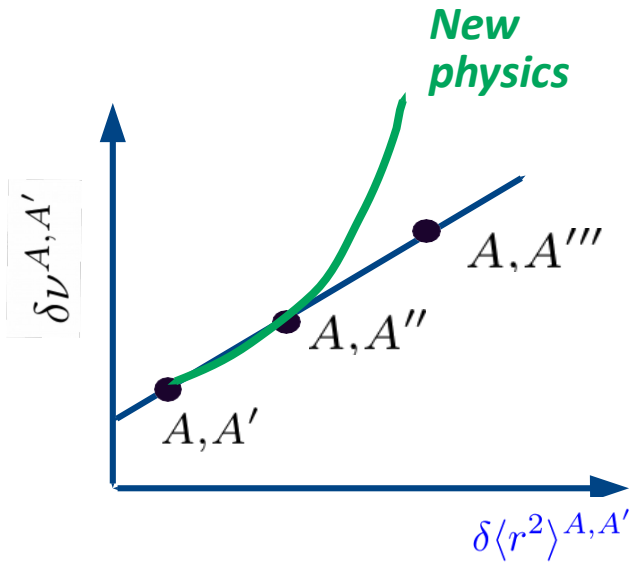
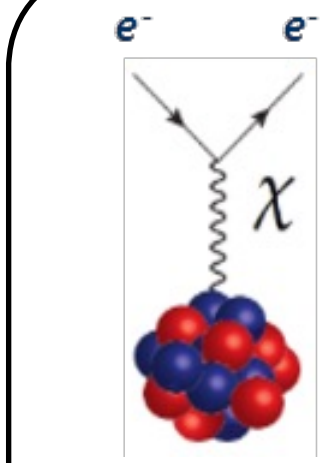


H_{BSM}



Fifth forces

- New electron-nucleon forces?
- Dark matter

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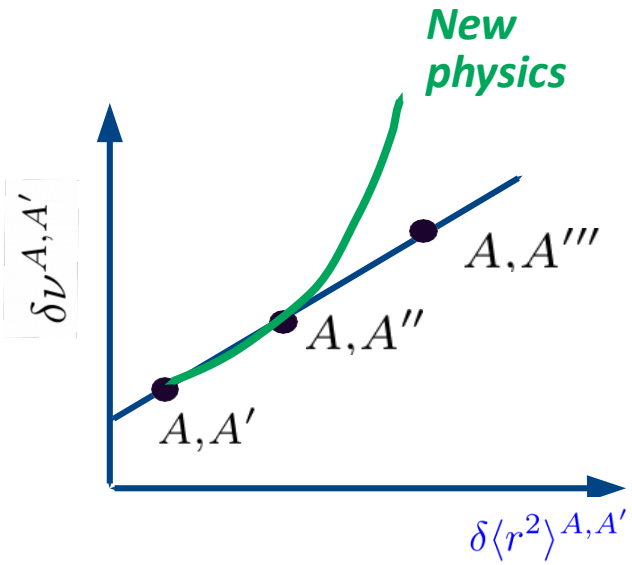
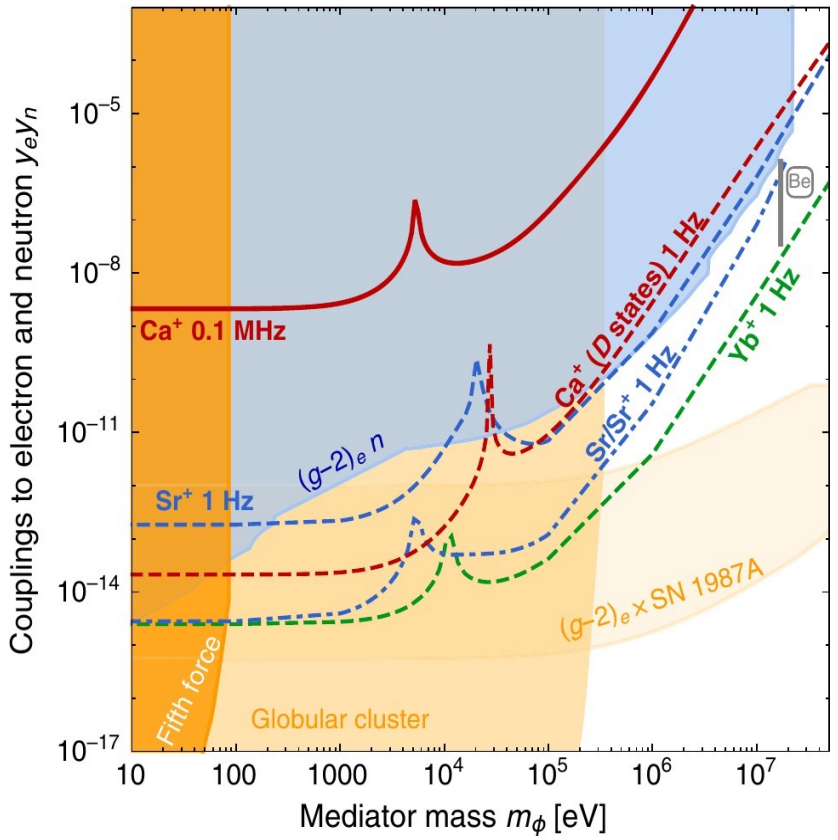
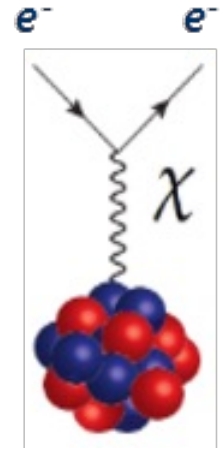




Berengut et al. PRL 120, 091801 (2018)



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Figueroa et al. PRL 128, 073001 (2022)
Hur et al. PRL 128, 163201 (2022)

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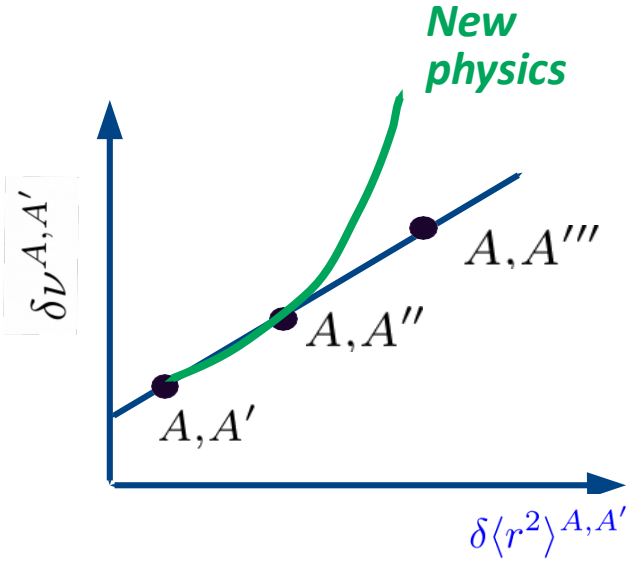
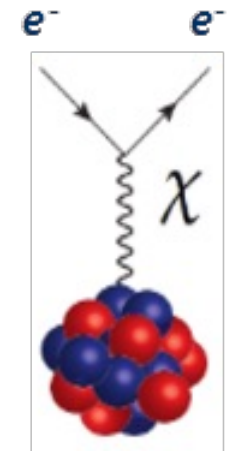
H_{BSM}



Nuclear structure input

- Higher order EM moments: $\langle\delta r^2\rangle$, $\langle\delta r^4\rangle$, β_2,…
- Nuclear dipole polarizability

Current & planned experiments:
Ca, Sr, Cd, Yb, Ra,…



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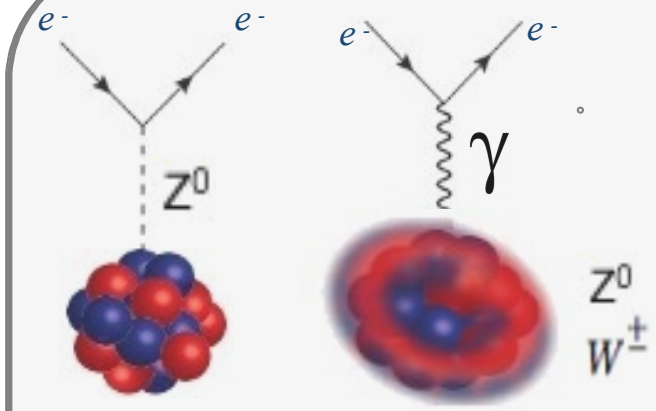
Parity-Violating Nuclear Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PV}



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Safronova et al. RMP 90, 025008 (2018)
Altunas et al. PRL 120, 142501 (2018)

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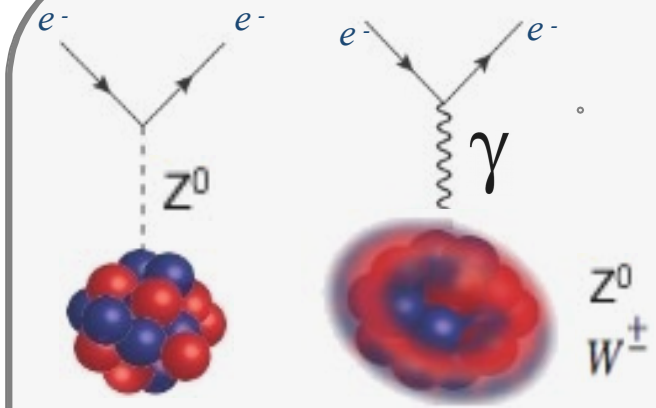

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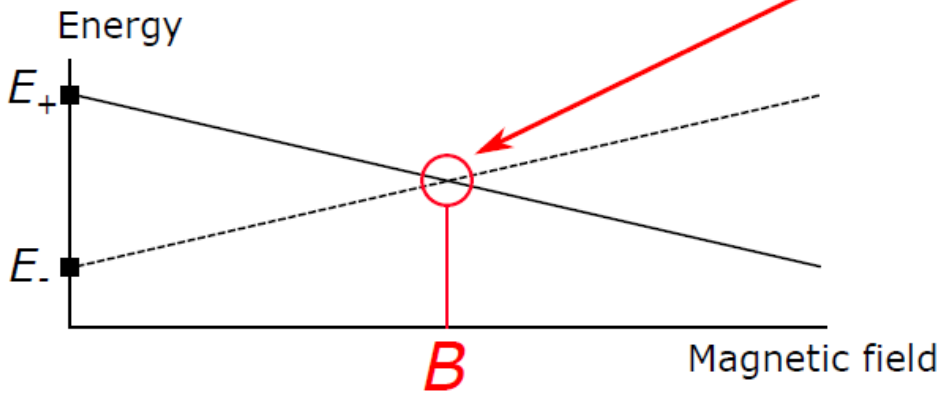
$$E_{PV} \sim \frac{\langle \psi_{\uparrow}^{+} | H_{\pm} | \psi_{\downarrow}^{-} \rangle}{E_{-} - E_{+}}$$

$>10^{11}$ molecular enhancement



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Parity-Violating Nuclear Properties

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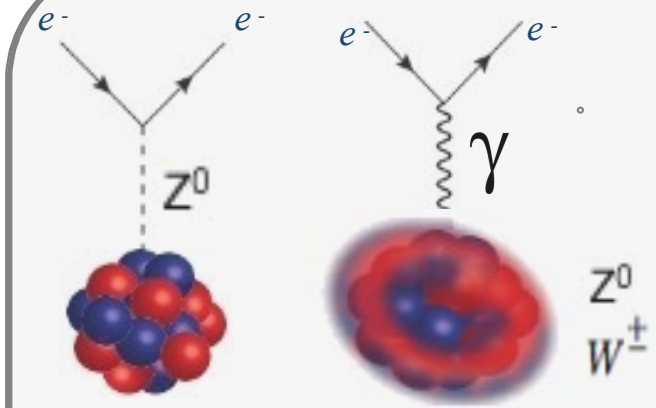
H_{PV}



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$$H_{\rm PV} \sim \frac{G_F}{\sqrt{2}} [Q_W \gamma_5/2 + (\eta_{\rm axial} + \eta_{\rm AM} + \eta_{\rm hf})(\boldsymbol{\alpha} \cdot \boldsymbol{I})\ ] \rho(r)$$

Spin independent — Spin dependent

The single particle limit

$$\eta_{\rm axial} \approx C_2 \frac{1/2 - K}{I(I+1)},$$

$$\eta_{\rm AM} \approx \frac{9}{10} \frac{\alpha \mu_i}{m_p r_0} g_i A^{2/3} \frac{K}{I(I+1)} \approx 1.15 \times 10^{-3} g_i \mu_i A^{2/3} \frac{K}{I(I+1)},$$

$$C_{2,p} = -C_{2,n} = g_A(1 - 4\sin^2\theta_W)/2 \approx 0.05$$

Flambaum et al. Phys. Lett. B 146, 367 (1984).
Phys. Rev. C 56, 1641 (1997)

Nuclear physics problem: $\eta_{\rm AM} = \frac{\sqrt{2}e}{G_F} \langle IM | a_{10} | IM \rangle$

- Precise wave function |IM>
- Operator a_{10}

Slide thanks to: T. Miyagi

Parity-Violating Nuclear Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PV}

$$H_{\rm PV} \sim \frac{G_F}{\sqrt{2}} \left[Q_W \gamma_5 / 2 + (\eta_{\rm axial} + \eta_{\rm AM} + \eta_{\rm hf})(\boldsymbol{\alpha} \cdot \boldsymbol{I}) \ \right] \rho(r)$$

Spin independent — Spin dependent

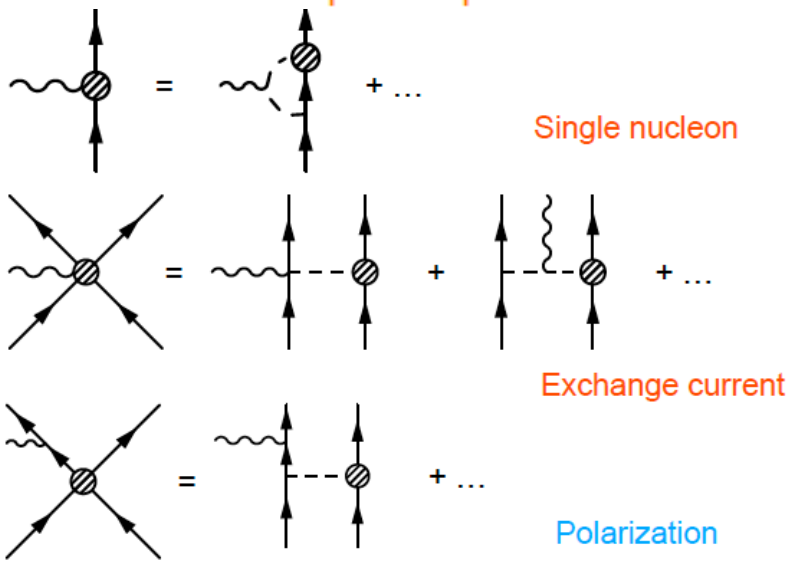
Operators: $a_{10} = a_{10}^{N} + a_{10}^{\rm ex} + a_{10}^{\rm pol}$

Single-nucleon and exchange-current terms

$$\langle IM | a_{10}^{N} + a_{10}^{\rm ex} | IM \rangle$$

Nuclear polarization term

- LO in perturbation



Nuclear physics problem: $\eta_{\rm AM} = \frac{\sqrt{2}e}{G_F} \langle IM | a_{10} | IM \rangle$

- Precise wave function |IM>
- Operator a_{10}

Slide thanks to: T. Miyagi

Parity-Violating Nuclear Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PV}

$$H_{\rm PV} \sim \frac{G_F}{\sqrt{2}} \left[Q_W \gamma_5 /2 + (\eta_{\rm axial} + \eta_{\rm AM} + \eta_{\rm hf})(\boldsymbol{\alpha} \cdot \boldsymbol{I}) \right] \rho(r)$$

Spin independent — Spin dependent

Operators: $a_{10} = a_{10}^N + a_{10}^e$

Single-nucleon and exchang

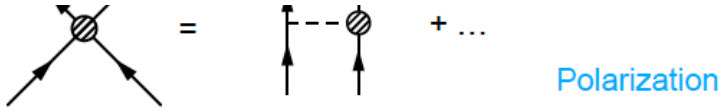
$\langle IM | a_{10}^N + a_{10}^{\rm ex} |_{^{205}\rm Tl}$

Nucleus	Source	f_π	h_ρ^0	h_ρ^1	h_ρ^2	h_ω^0	h_ω^1
^{133}Cs	nucleonic	0.59	0.87	0.90	0.36	0.28	0.29
	ex. cur.	8.58	0.02	0.11	0.06	−0.57	−0.57
	polariz.	51.57	−16.67	−4.88	−0.06	−9.79	−4.59
	total	60.74	−15.78	−3.87	0.36	−10.09	−4.87
	nucleonic	−0.63	−0.86	−0.96	−0.35	−0.29	−0.29
	ex. cur.	−3.54	−0.01	−0.06	−0.03	0.28	0.28
	polariz.	−13.86	4.63	1.34	0.08	2.77	1.27
	total	−18.03	3.76	0.33	−0.30	2.76	1.26

Haxton, Liu, & Ramsey-Musolf PRC 65, 045502 (2002).
Hao et al. PRA 102, 052828 (2020)

Nuclear polarization term

- LO in perturbation



Polarization

P-odd nucleon-nucleon interaction

Nuclear structure

$$\langle IM | a_{10}^{\rm pol} | IM \rangle \sim \sum_n \frac{\langle I^\pi || a_1 || I_n^{-\pi} \rangle \langle I_n^{-\pi} | V_{\rm PV} | I^\pi \rangle}{E_{\rm g.s.} - E_n} + \text{c.c.}$$

Energy splitting of opposite parity states

Nuclear physics problem: $\eta_{\rm AM} = \frac{\sqrt{2}e}{G_F} \langle IM | a_{10} | IM \rangle$

- Precise wave function |IM>
- Operator a_{10}

Slide thanks to: T. Miyagi

Parity-Violating Nuclear Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PV}

$$H_{\rm PV} \sim \frac{G_F}{\sqrt{2}} \left[Q_W \gamma_5 /2 + (\eta_{\rm axial} + \eta_{\rm AM} + \eta_{\rm hf})(\boldsymbol{\alpha} \cdot \boldsymbol{I}) \right] \rho(r)$$

Spin independent — Spin dependent

Nuclear structure input

- Anapole moments
- P-odd nucleon- nucleon forces
- Quark couplings: $C_{2u,d}$
- Weak quadrupole moments, neutron distribution

Nuclear structure — P-odd nucleon-nucleon interaction

$$\langle IM|a_{10}^{\rm pol}|IM\rangle \sim \sum_n \frac{\langle I^\pi||a_1||I_n^{-\pi}\rangle \langle I_n^{-\pi}|V_{\rm PV}|I^\pi\rangle}{E_{\rm g.s.} - E_n} + \text{c.c.}$$

Energy splitting of opposite parity states

Nuclear physics problem: $\eta_{\rm AM} = \frac{\sqrt{2}e}{G_F}\langle IM|a_{10}|IM\rangle$

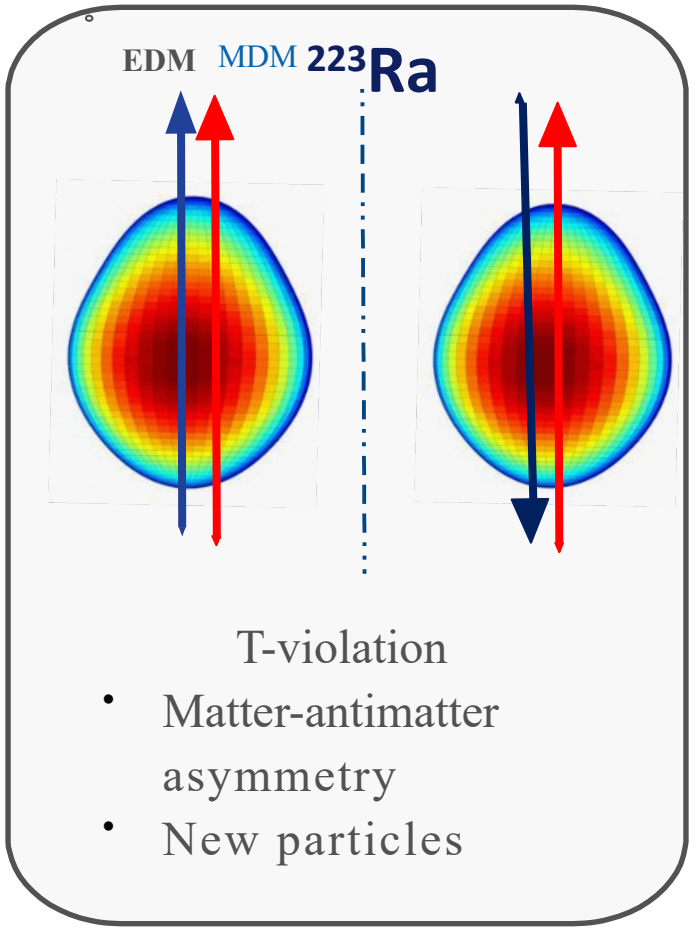
- Precise wave function |IM>
- Operator a_{10}

Slide thanks to: T. Miyagi

T-Violating Nuclear Properties

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PTV}



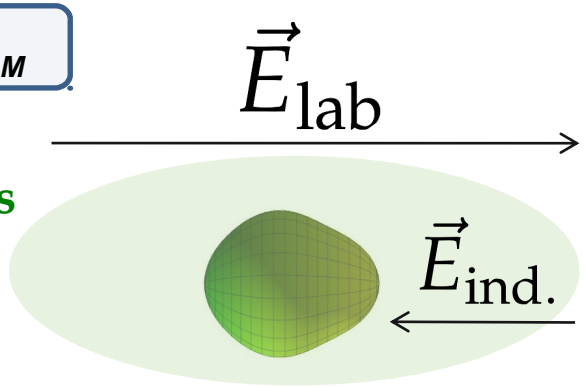
T-violation

- Matter-antimatter asymmetry
- New particles

Chupp et al. RMP 91, 01500 (2019)
Parker et al. PRL 114, 233002 (2015)

- **Shielding in Diamagnetic Atoms**

Schiff PR 132:2194 (1963)

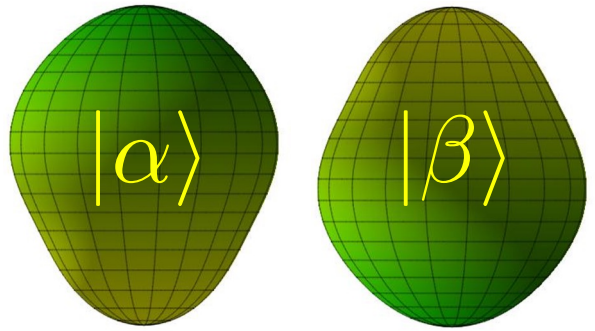


$$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$$

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

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

Parity Doublet



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

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

Slide thanks to: J. Singh

T-Violating Nuclear Properties

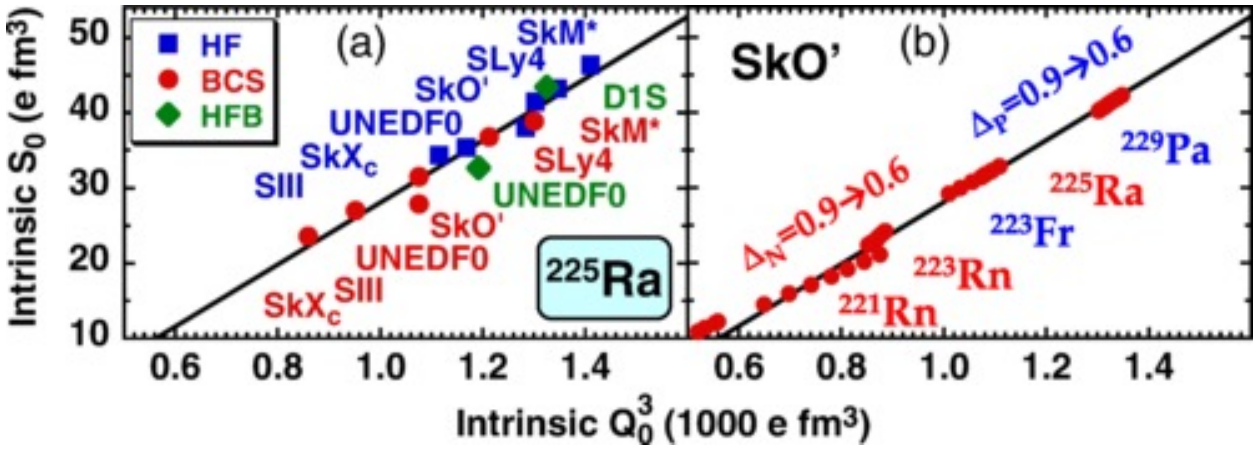
Schiff Moments

Nuclear structure

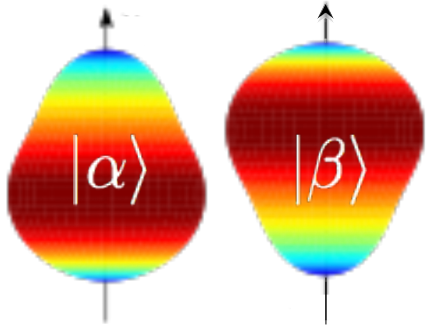
P,T-odd nucleon-nucleon interaction

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

Energy splitting of opposite parity states



Dobaczewski et al. Phys. Rev. Lett. **121**, 232501 (2018)
Chupp et al. Rev. Mod. Phys. **91**, 015001 (2019)



^{225}Ra

Δ E = 55 keV

[Gaffney et al. Nature 497, 199 (2013)]

T-Violating Nuclear Properties

Schiff Moments

Nuclear structure

P,T-odd nucleon-nucleon interaction

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

Energy splitting of opposite parity states

Nuclear structure input

- T-odd moments: Schiff moment, Magnetic quadrupole moment
- Sensitivity to CP-violating physics
- Energy splitting of opposite parity-state

Current & planned experiments:

^{129}Xe, ^{199}Hg, ^{171,173}Yb, ^{205}Tl , ^{181}Ta ^{223}Fr, ^{223}Rn, ^{223,225}Ra, ^{229}Th, ^{229}Pa

T-Violating Nuclear Properties

Schiff Moments

Nuclear structure

P,T-odd nucleon-nucleon interaction

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

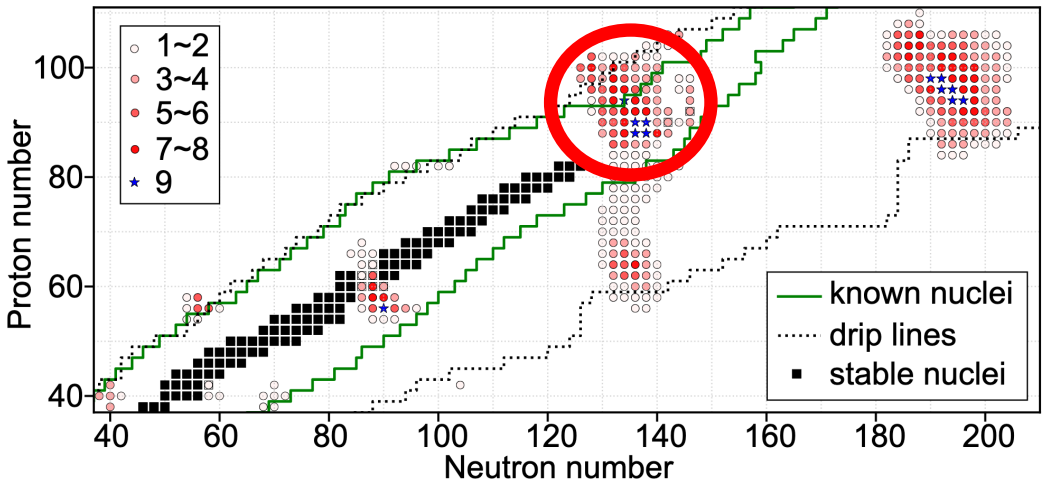
Energy splitting of opposite parity states

Pa-229: Haxton & Henley PRL 51:1937 (1983)
I. Ahmad et al Phys. Rev. C 92:024313 (2015)
Dobaczewski et al PRL 121, 232501 (2018)

Isotope	ΔE (keV)	$\tau_{1/2}$ (sec)	sensitivity
Hg-199	1800	stable	1
Rn-223	~10^2?	10^3	10^2
Ra-225	55	10^6	10^3
Pa-229	**(0.06 +/- 0.05)?**	**10^5**	**10^6**

FRIB will make lots of Pa-229!

FRIB



Cao et al. Phys. Rev. C, 102:024311 (2020)

Slide thanks to: J. Singh

Nuclear Schiff Moment (NSM) and Magnetic Quadrupole Moment (MQM)

$$S = \underbrace{\kappa_p d_p + \kappa_n d_n}_{\text{short range single nucleon EDMs}} + \underbrace{a_1 g_1 + a_2 g_2}_{\text{long range CPV pion-nucleon couplings}}$$

$$\kappa_p, \kappa_n, a_1, a_2 = \text{from nuclear structure}$$

$$\texttt{MQM} = \underbrace{\kappa'_p d_p + \kappa'_n d_n}_{\text{short range single nucleon EDMs}} + \underbrace{a'_1 g_1 + a'_2 g_2}_{\text{long range CPV pion-nucleon couplings}}$$

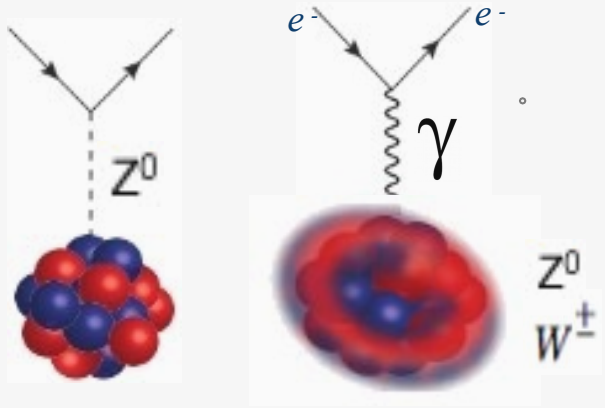
Slide thanks to: J. Singh

Summary

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

Nuclear structure experiment & theory provide critical input

H_{PV}



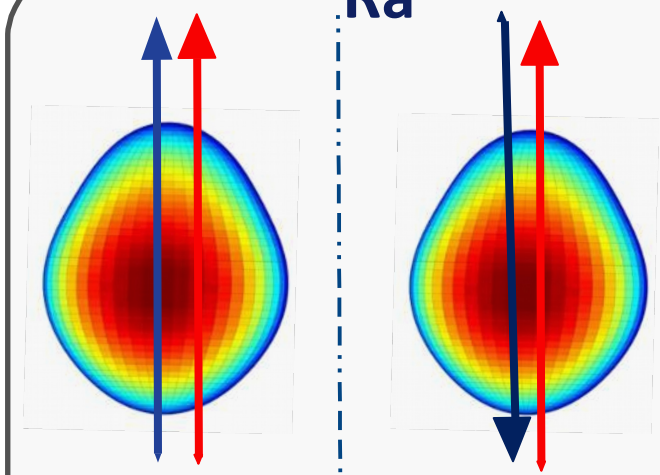
P-violation

- P-odd nuclear moments: e.g. Anapole moments
- Quark couplings: $C_{2u,d}$, P-odd nucleon- nucleon forces
- Weak quadrupole moments, neutron distribution

Current and planned experiments:

^{29}Si, ^{18,19}F, ^{133}Cs, ^{137}Br, ^{171}Yb, ^{205}Tl, ^{209,210}Fr, ^{223,225}Ra

H_{PTV}

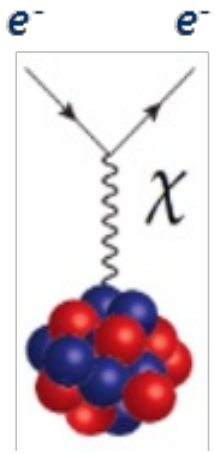


T-violation

- T-odd moments, EDMs, e.g. Schiff moments, magnetic quadrupole moment, T-odd nucleon-nucleon forces

^{129}Xe, ^{199}Hg, ^{171,173}Yb, ^{205}Tl , ^{181}Ta ^{223}Fr, ^{223}Rn, ^{223,225}Ra, ^{229}Th, ^{229}Pa

H_{BSM}



Fifth forces

- Higher order EM moments: $\langle\delta r^2\rangle$, $\langle\delta r^4\rangle$, β_2,…
- Nuclear dipole polarizability

Ca, Sr, Cd, Yb, Ra, …

Summary

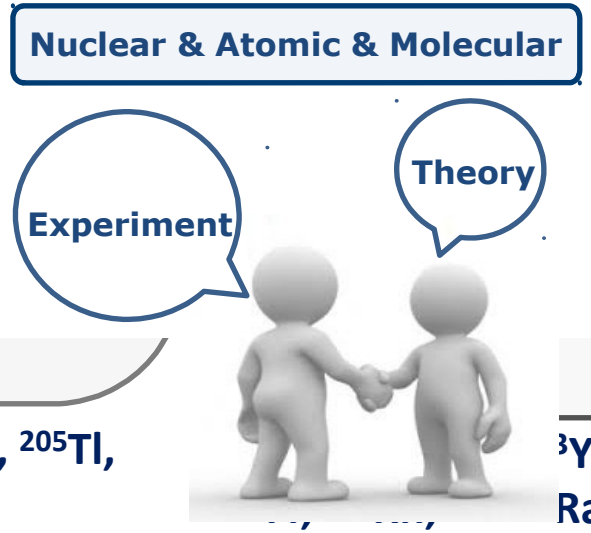
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + H_{BSM}$$

H_{PV} H_{PTV} H_{BSM}

Once-in-a-lifetime opportunity!

- **New Facilities (FRIB, TRIUMF, ISOLDE, FAIR,….)**
- **New Era of Precision (Atomic, Molecular, Nuclear) Physics**

Nuclear structure experiment & theory provide critical input



neutron distribution

Current and planned experiments:

^{29}Si, ^{18,19}F, ^{133}Cs, ^{137}Br, ^{171}Yb, ^{205}Tl, ^{209,210}Fr, ^{223,225}Ra

^{3}Yb, ^{205}Tl , ^{181}Ta Ra, ^{229}Th, ^{229}Pa

Ca, Sr, Cd, Yb, Ra, …