Fundamental Symmetries

Lecture 2:
Test of fundamental symmetries with nuclei, atoms, and molecules

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MIT

Toy problem: Two-level system

Without P-violation

With P-violation

$|-\rangle$

$|-\rangle$ + f(H_{PV} , ΔE)$|+\rangle$

$|+\rangle$

ΔE= $E_- - E_+$ -> ***Energy separation***

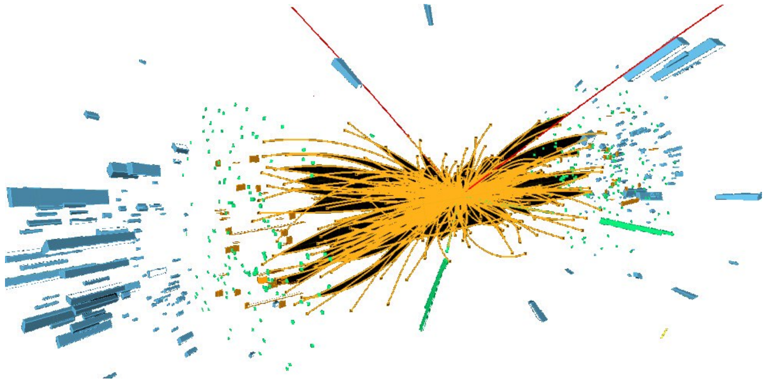
H_{PV} -> ***Weak interaction***

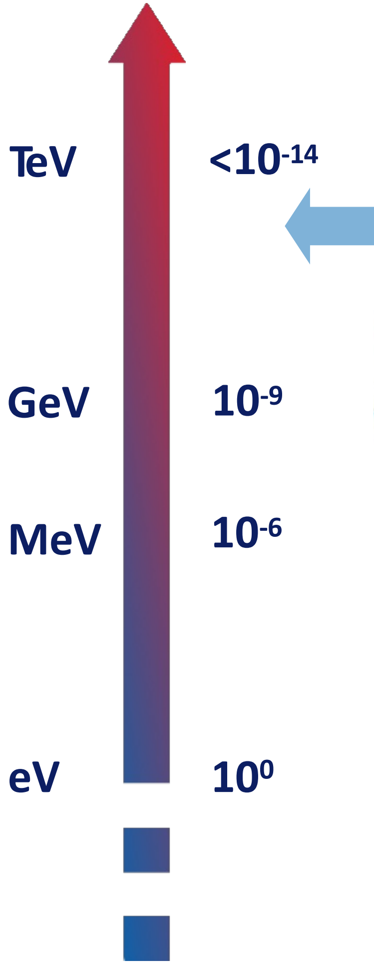
f(H_{PV} , ΔE)=?

Problem: Express the mixing coefficient in terms of H_{PV} , ΔE

What are the fundamental particles and forces of nature?

Energy frontier



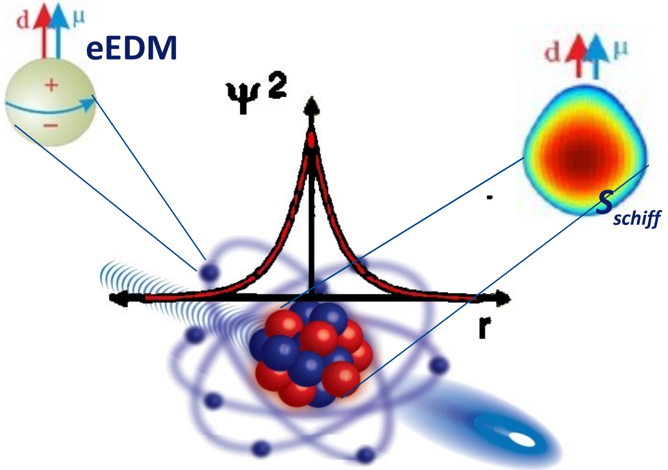

TeV $<10^{-14}$

GeV 10^{-9}

MeV 10^{-6}

eV 10^{0}

Precision frontier



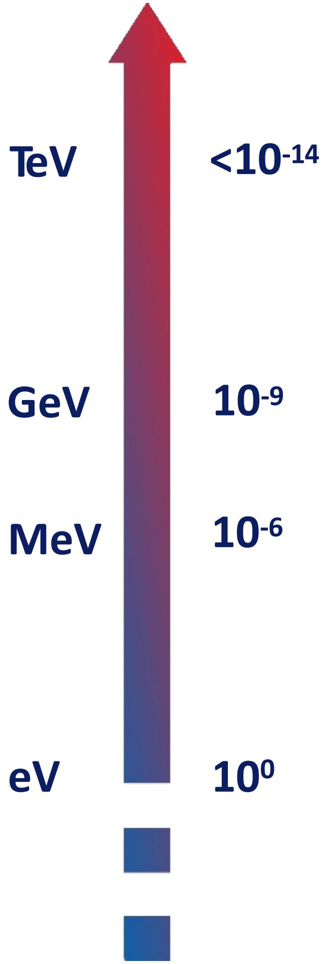
How do complex nuclear phenomena emerge?


Ocu
Box


e-

Precision Measurements in Atoms and Molecules

Energy frontier



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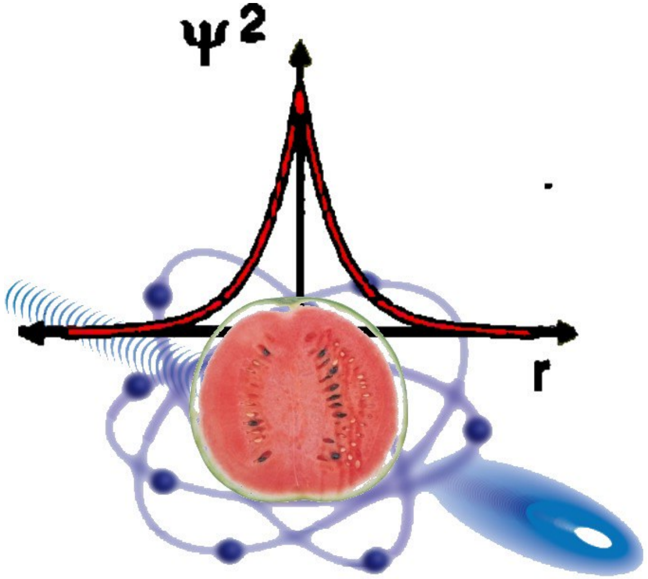
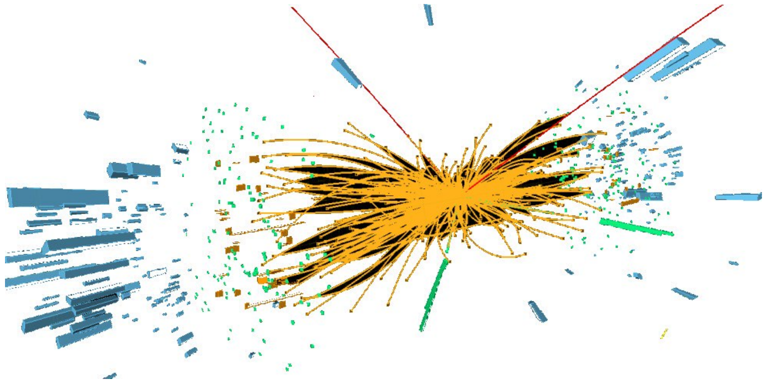
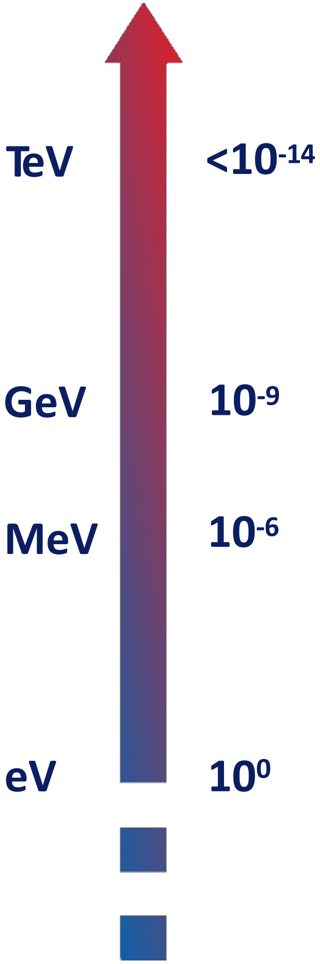


Precision Measurements in Atoms and Molecules

Energy frontier

Precision frontier





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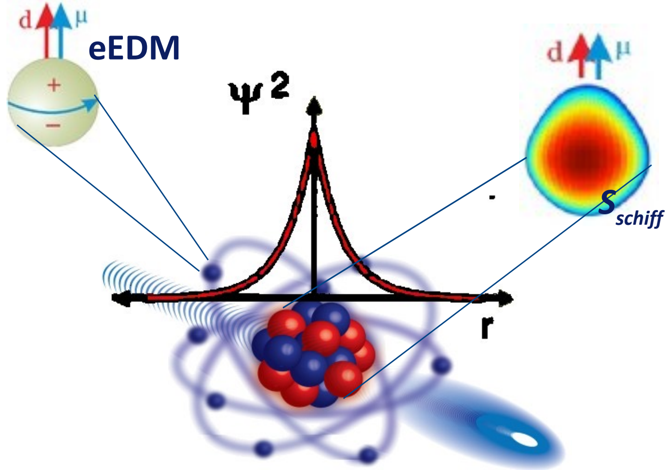
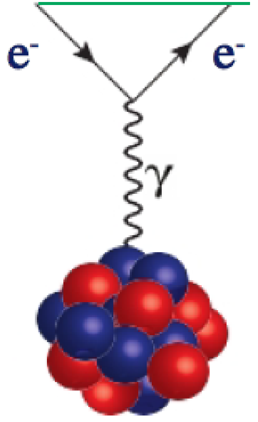
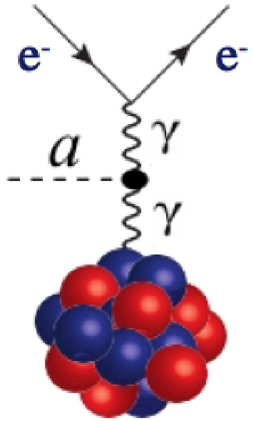


Precision studies in atoms and molecules

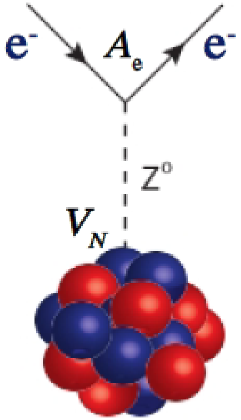
Nuclear structure



$\mu <r^2> I \quad Q$

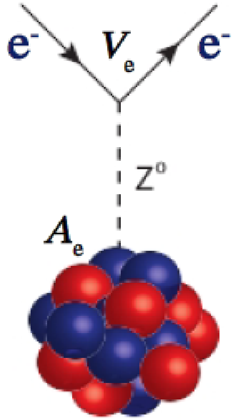


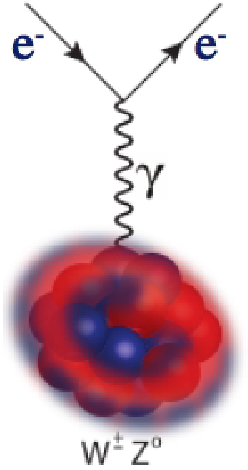
P- violation



$\sim Z^3$

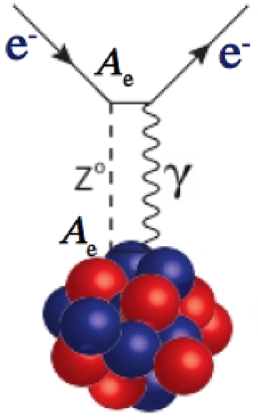
x 10^N





$\sim Z^2 A^{2/3} R(Z)$

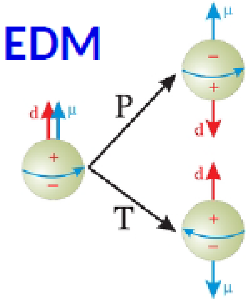
x 10^5



Atoms
Molecules

P,T- violation

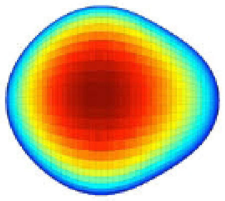
EDM



$\sim Z^2 R(Z)$

$> 10^3$

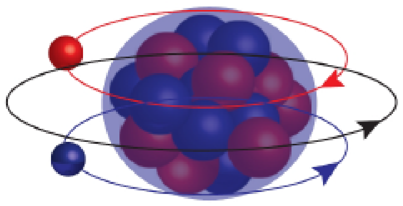
S_{schiff}



$S \sim Q_2 Q_3 Z A^{2/3} /(E_+ - E_-)$

$(> 10^5$ Octupole)

MQM

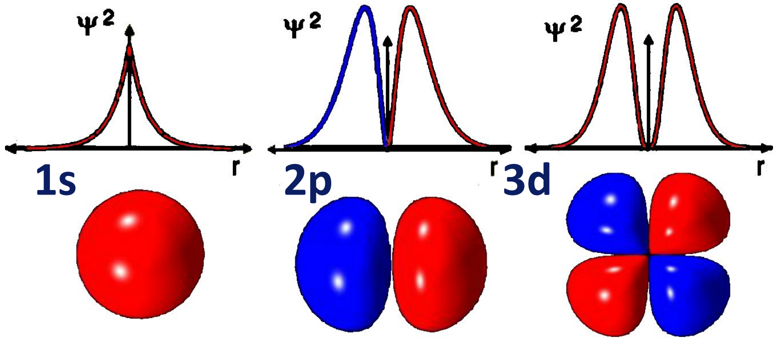


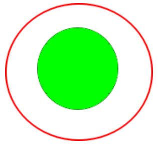
Atoms

Molecules

AMO for Nuclear Science

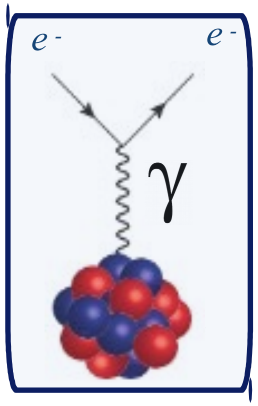
Atoms





Ra⁺

Long range (> 1 fm)

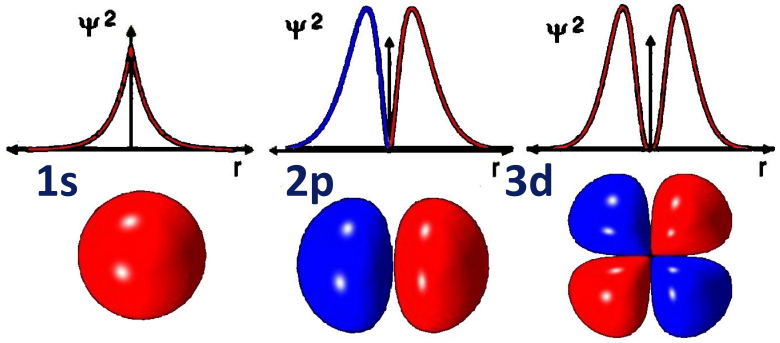


➡ Electromagnetic nuclear properties

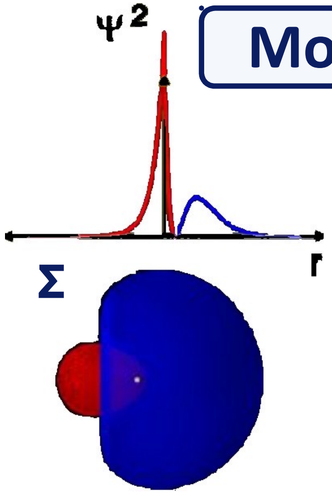
$$<r^2>, I, \mu, Q, \ldots$$

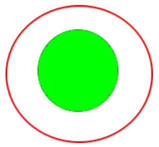
AMO for Nuclear Science

Atoms



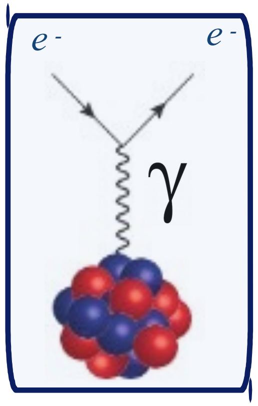
Molecules

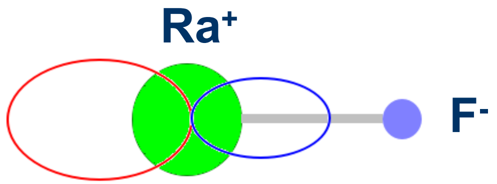




Ra$^+$

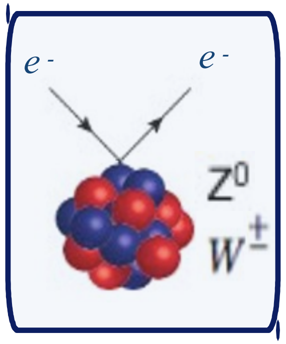
Long range (> 1 fm)





RaF

Short range (< 0.1 fm)

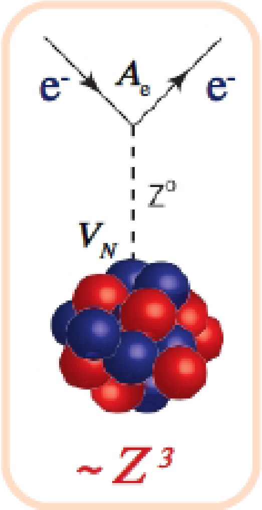


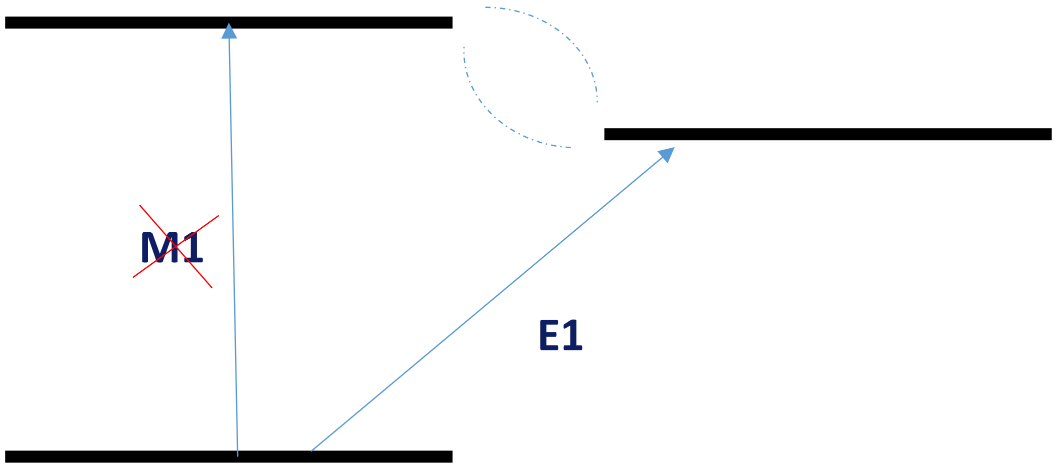
➡ **Electromagnetic nuclear properties**

$$< r^2 >, I, \mu, Q, \dots$$

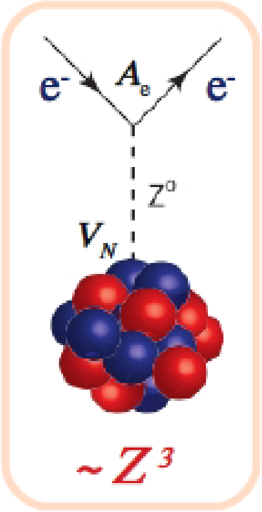
➡ **Electroweak nuclear properties**

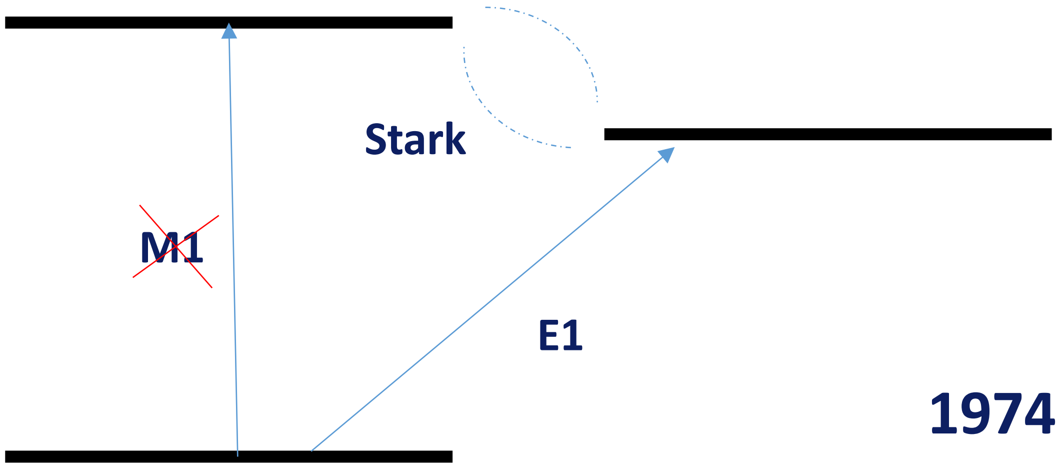
APV Experiments





APV Experiments





1974: Bouchiat

$$A_{\pm} = | \pm A_{Startk} + A_{PV} |^2$$

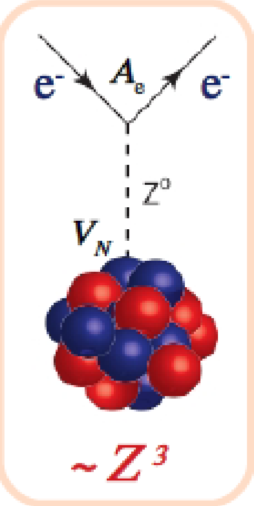
$$\sim \underbrace{A_{Startk}^2}_{PC} \pm \underbrace{2\, A_{Startk} + A_{PV}^2}_{PV}$$

$$\boxed{A_+ - A_- = E_{PV}}$$

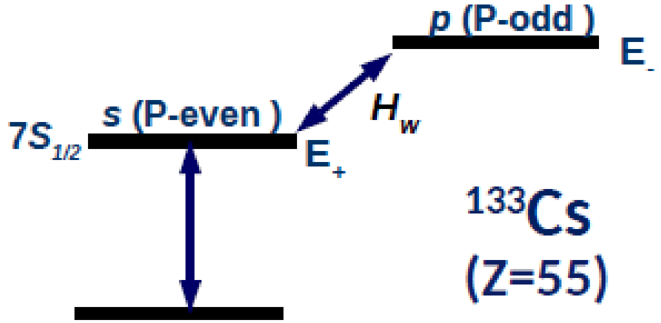
APV Experiments

$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \, \rho(r)$$

Atoms



PV → Mix states of different parity



^{133}Cs
(Z=55)

$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_w|\text{P-even}\rangle}{E_- - E_+}$$

$$E1_{APV} = \langle 7\widetilde{S}_{1/2} | D | 6\widetilde{S}_{1/2} \rangle = k\, Q_W \leftarrow$$

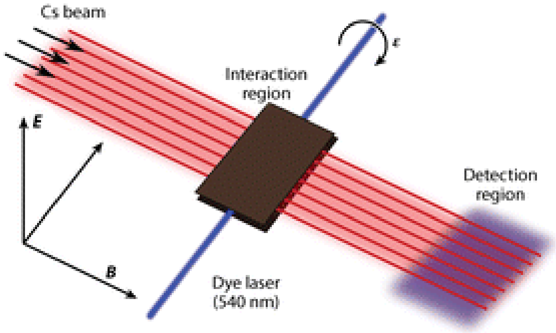
measure

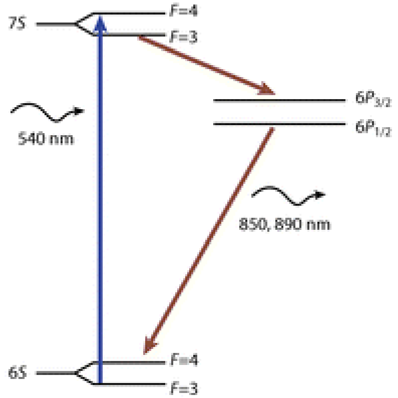
atomic calculation

Expt: $Q_W(^{133}\text{Cs}) = -72.06(28)_{\text{exp}}(34)_{\text{th}}$

$$Q_W = -N + (1 - 4\sin^2\theta_W)Z$$

[Wood et al. Science 275, 1759 (1997)]
[Porsev et al. PRL 102, 181601 (2009)]

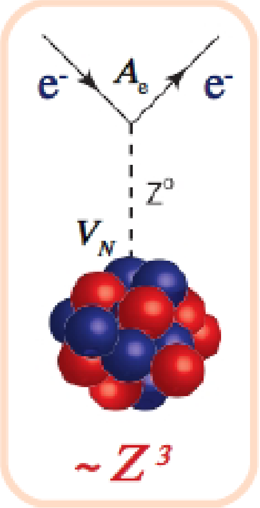




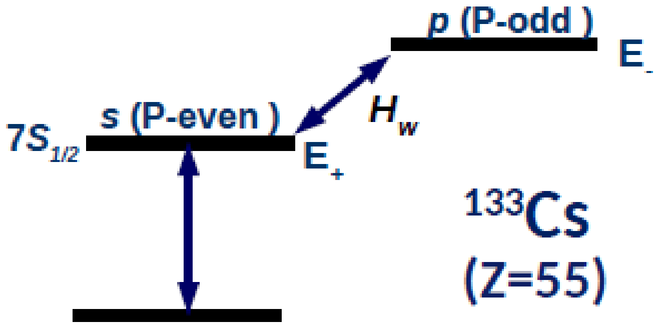
Annu. Rev. Nucl. Part. Sci. 65:63–86 2015.

Parity violation

Atoms



PV → Mix states of different parity



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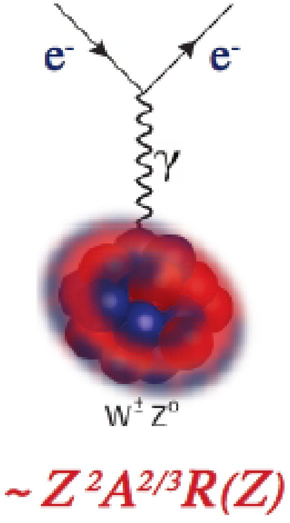


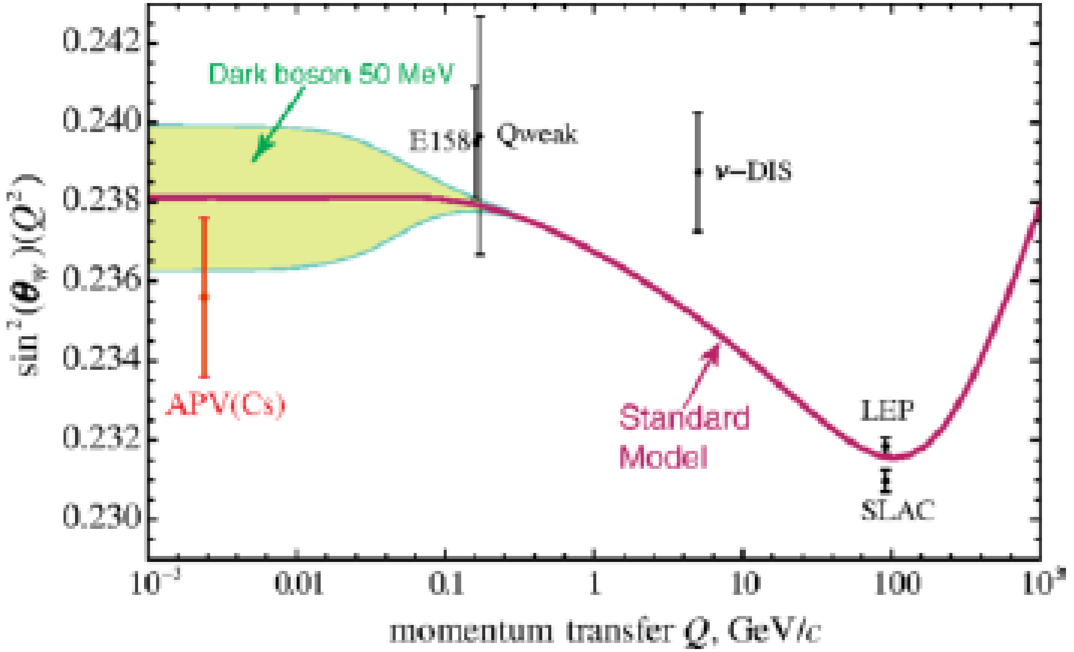
$$|s'\rangle = |s\rangle + \frac{\langle s| V_{PV} |p\rangle}{E_- - E_+} |p\rangle$$

$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \, \rho(r)$$

Weinberg angle

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix} \quad m_Z = \frac{m_W}{\cos\theta_W}$$

Parity-violation



[Rev. Mod. Phys. 90, 025008 (2018)]

$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \, \rho(r)$$

$$\boxed{E_{PV} = k_{PV} Q_W}$$

$$Q_W \equiv 2Z\, C_p^{(1)} + 2N\, C_n^{(1)}$$

$$|s'\rangle = |s\rangle + \frac{\langle s|\, V_{PV}\, |p\rangle}{E_- - E_+} |p\rangle$$

$$C_p^{(1)} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

$$C_n^{(1)} = -\frac{1}{2},$$

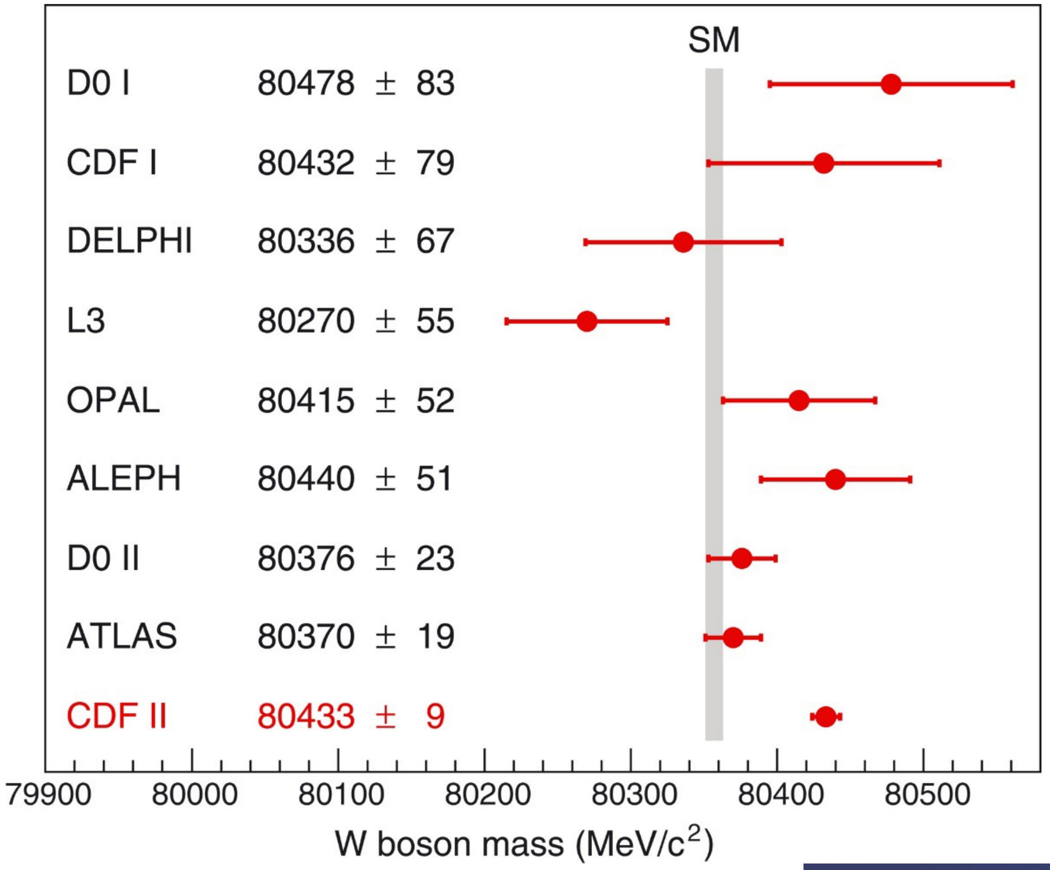
$$C_p^{(2)} = -C_n^{(2)} = g_A C_p^{(1)}$$

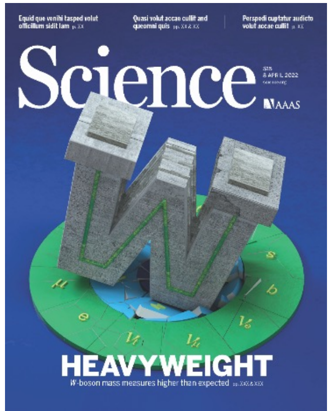
$H_{PV} \sim F(Z^c)\,/(E_+{}^e - E_-{}^e)$

Atoms: (E_+- E_-) ~ 1 eV
Molecules: (E_+- E_-) ~ 10^{-5} eV

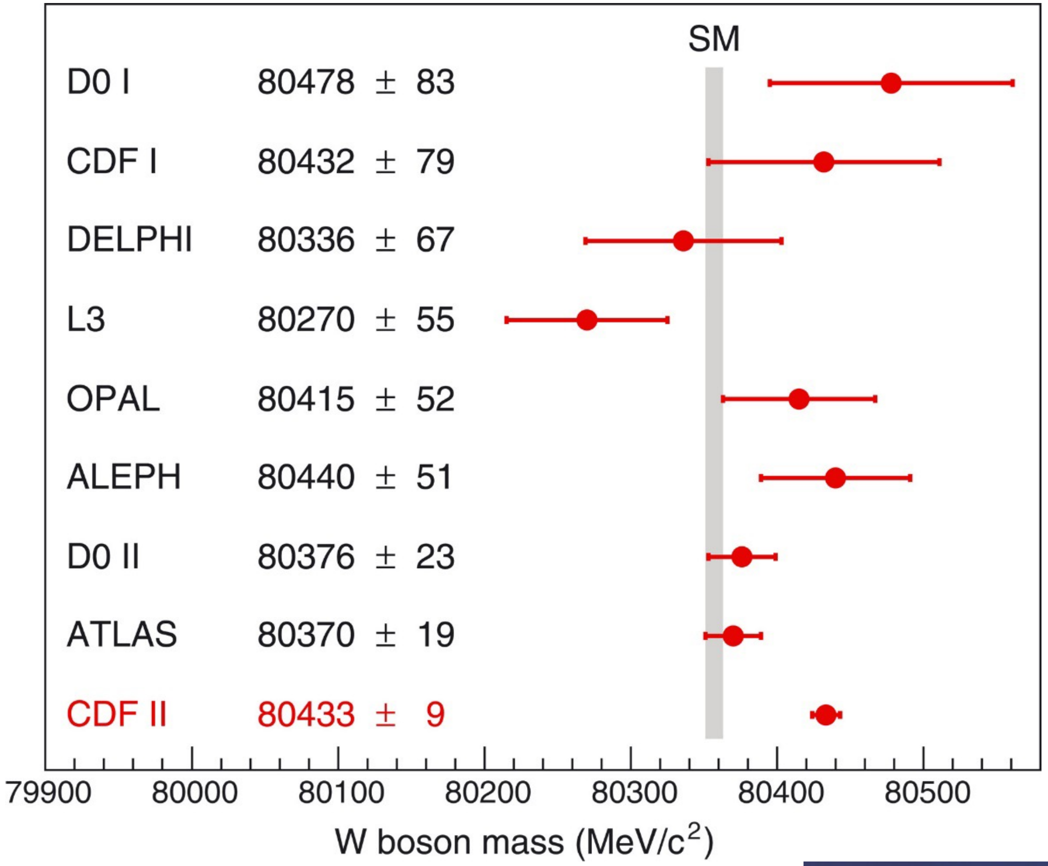
[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]

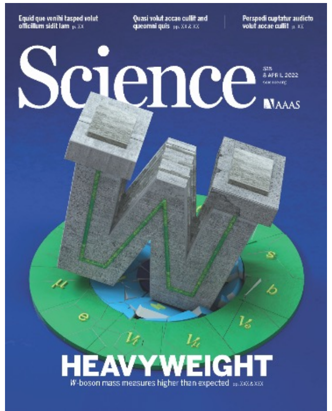
APV and W-mass





APV and W-mass



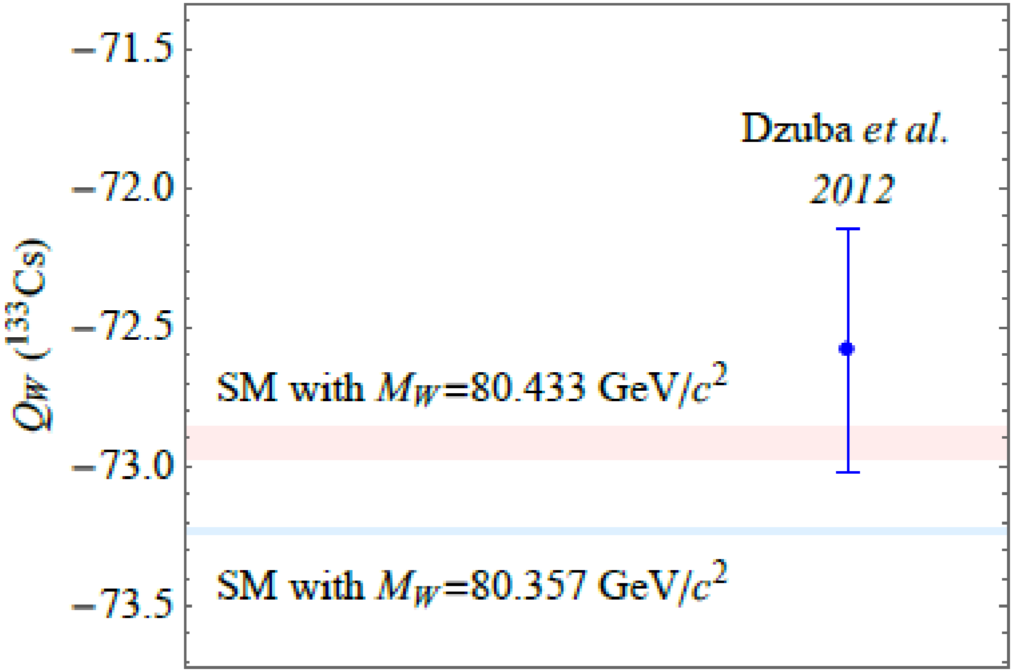


$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \, \rho(r)$$

$$Q_W = Z\left(1 - 4\sin^2\theta_W(0)\right) - N$$

$$\sin^2\hat{\theta}_W(Q^2) \approx \frac{\kappa(Q^2)A^2}{M_W^2}$$

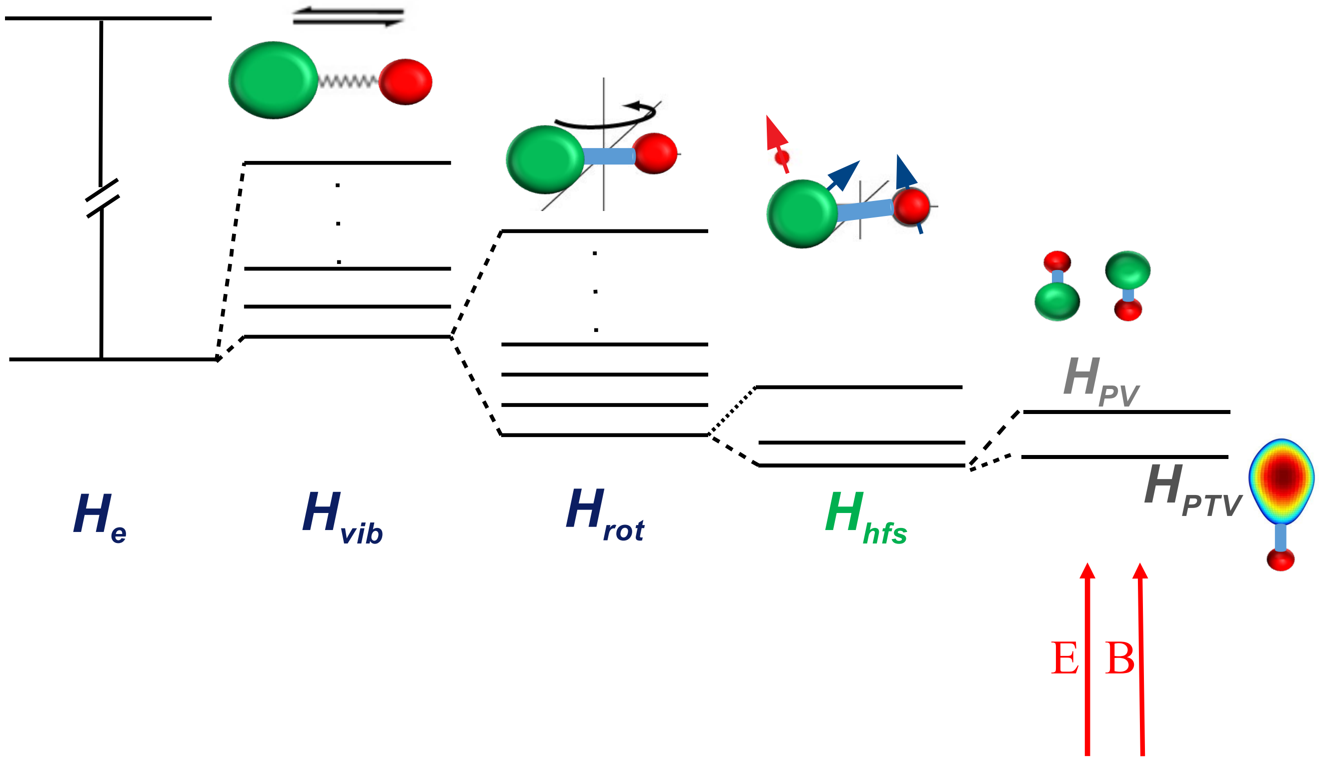
arXiv:2204.11991



Why (radioactive) molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots \ + \overbrace{H_{hfs} + H_{PV} + H_{PTV}}^{\sim O_{Nucl}\, F_{mol}}$$

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



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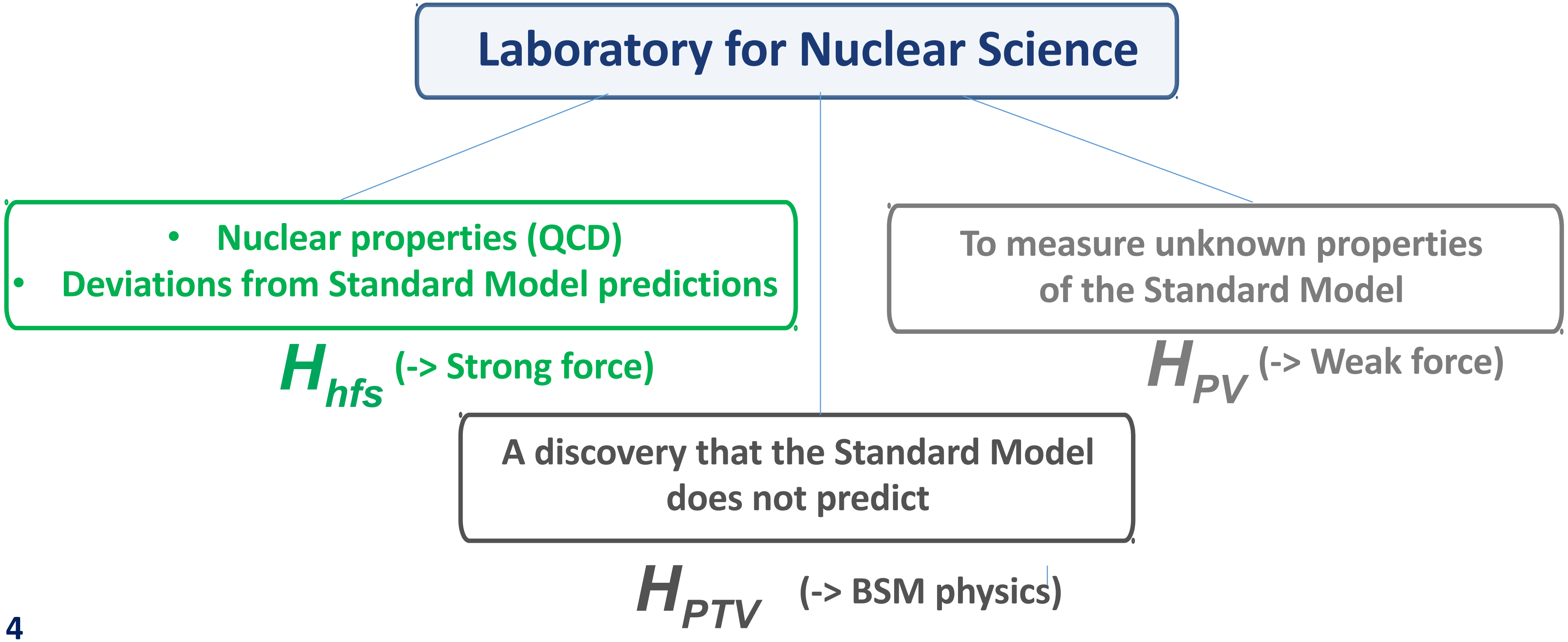


Laboratory for Nuclear Science

- Nuclear properties (QCD)
- Deviations from Standard Model predictions

H_{hfs} (-> Strong force)

To measure unknown properties of the Standard Model

H_{PV} (-> Weak force)

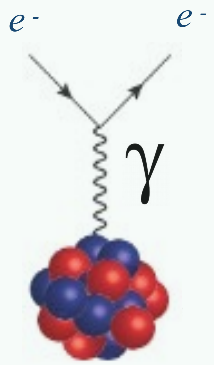
A discovery that the Standard Model does not predict

H_{PTV} (-> BSM physics)

Precision Measurements in Atoms and Molecules

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

H_{hfs}



P,T-even

- Nuclear matter
- Nuclear structure
- BSM searches

- **How do nuclear phenomena emerge?**
- **Can we connect the description of nuclei with QCD?**

Electromagnetic structure

Rms charge radii: $<r^2>$
Nuclear spin: I
Magnetic moment: μ
Quadrupole moment : Q

COLLAPS CRIS

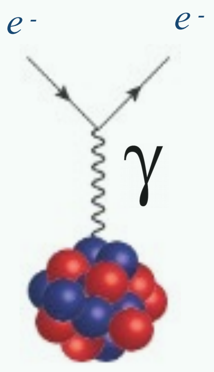
Some recent highlights:

- Physical Review Letters 127, 033001 (2021)
- Nature Physics 17, 439 (2021)
- Nature 581, 396 (2020)
- Nature Physics 16, 620 (2020)
- Nature Communications 11, 3824 (2020)
- Physical Review Letters 124, 132502 (2020)

Why (radioactive) molecules?

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

H_{hfs}



P,T-even

- Nuclear matter
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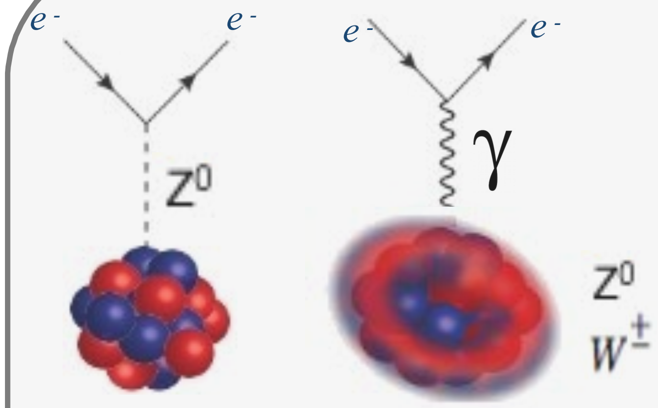
H_{PV}



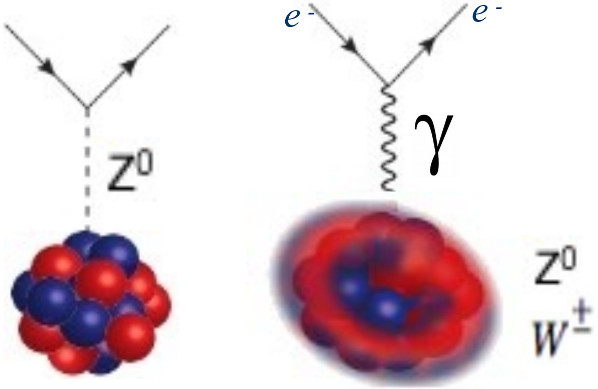
P-violation

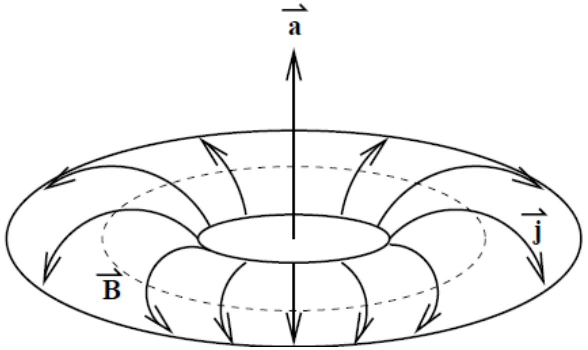
- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties?
- New forces?

Nuclear Anapole moment

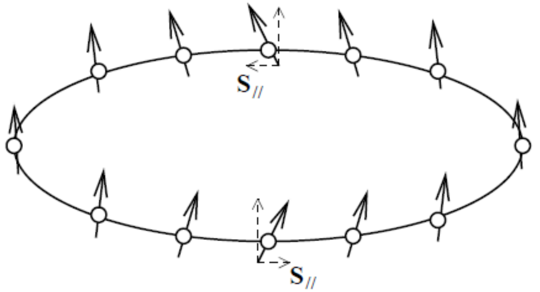
Only one measurement (1997): ^{137}Cs

Science 275, 1759 (1997)





$$\boldsymbol{a} = -\pi \int d^3r\, r^2\, \boldsymbol{j}(\boldsymbol{r})$$



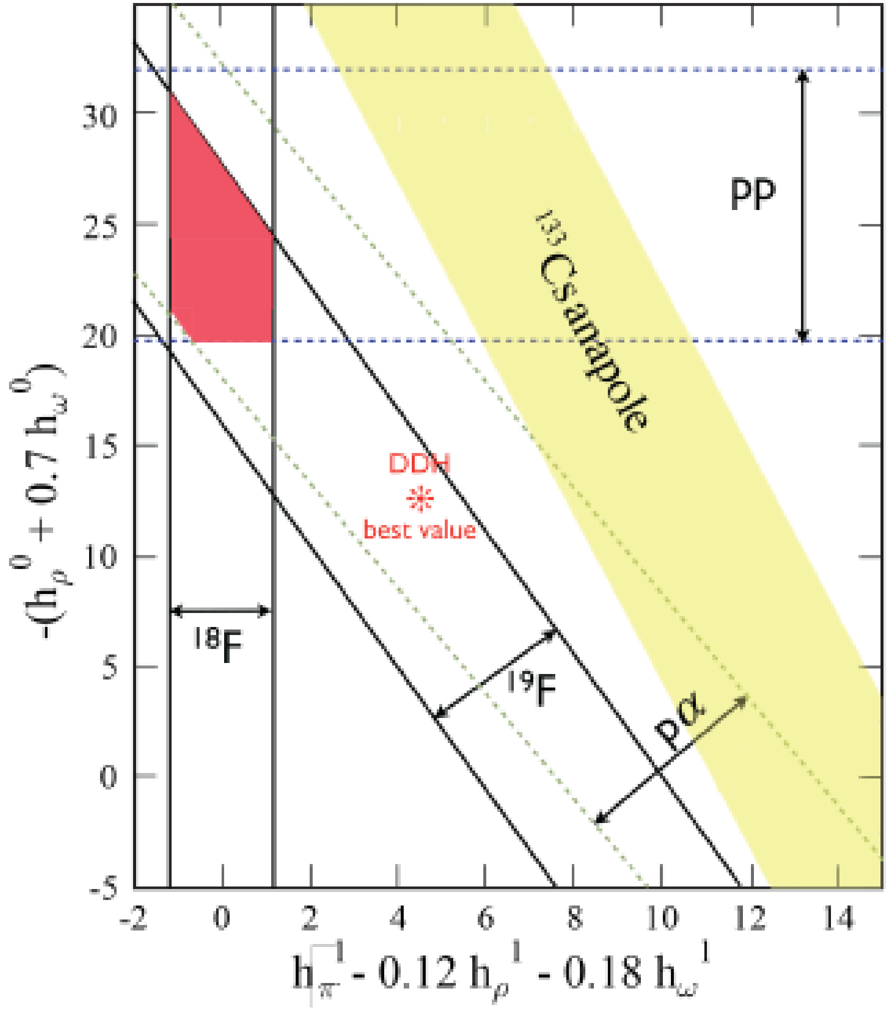
$$H^{(1)} = \sum_{i=1}^{A} \frac{g_S + g_V \tau_3(i)}{2M} \vec{\sigma}(i) \cdot \vec{p}(i)$$

Phys. Rev. C 65, 045502 (2002)

Nuclear Anapole moment

- **Hadronic parity violation**

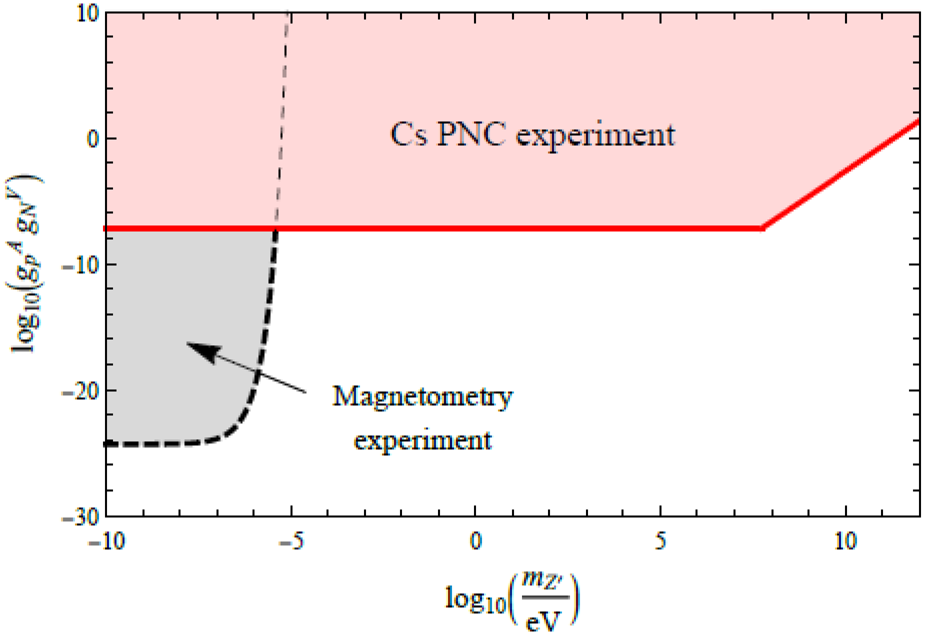
Only one measurement (1997): ^{137}Cs



Rev. Mod. Phys. 90, 025008 (2018)

- **A possible new vector boson**

$$V_{12}(r) = \frac{g_1^A g_2^V}{4\pi} \frac{e^{-m_{Z'} r}}{r} \gamma_5$$

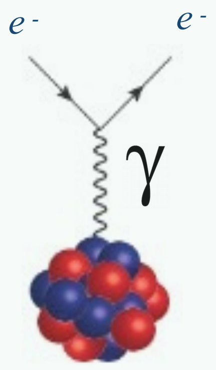


Phys. Rev. Lett. 119, 223201 (2017)

Why (radioactive) molecules?

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

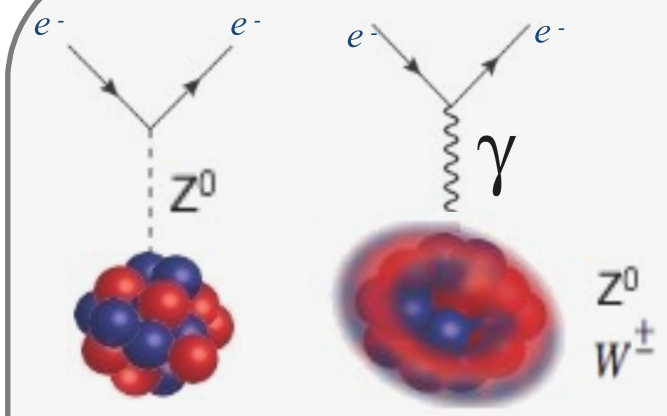
H_{hfs}



P,T-even

- Nuclear matter
- Nuclear structure
- BSM searches

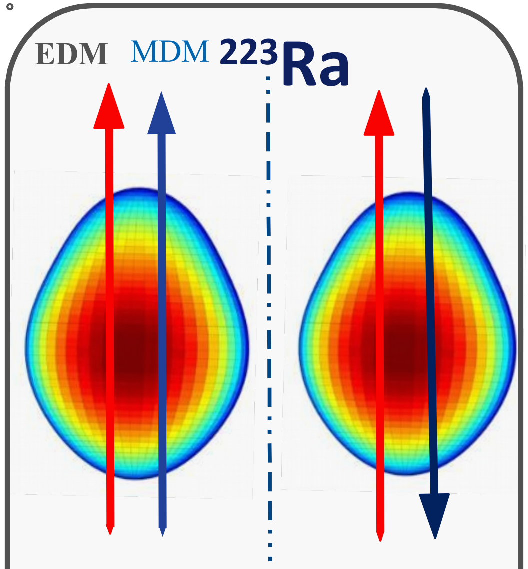
H_{PV}



P-violation

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

H_{PTV}



T-violation

- Matter-antimatter asymmetry
- New particles?

Why (radioactive) molecules?

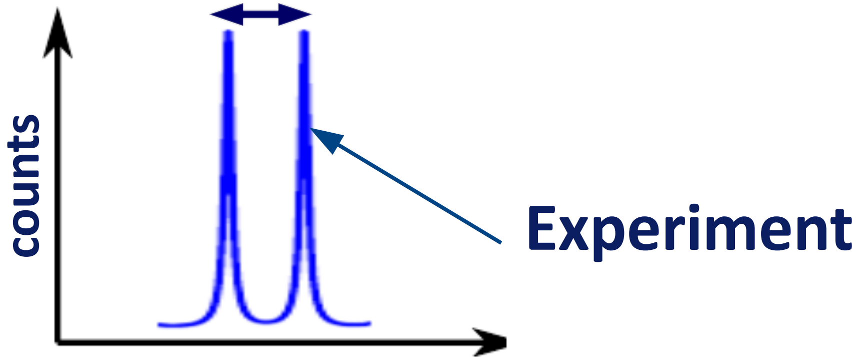
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots \ + \overbrace{H_{hfs} + H_{PV} + H_{PTV}}^{\sim O_{Nucl}\,F_{mol}}$$

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

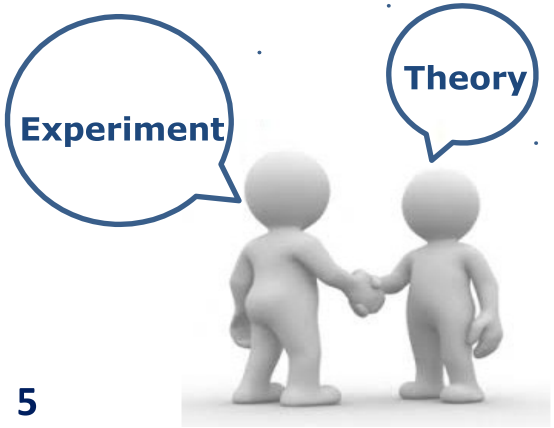
Nuclear

molecule

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



Nuclear & Atomic & Molecular



Radioactive Molecules

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ \ldots + \overbrace{H_{hfs} + H_{PV} + H_{PTV}}^{\sim O_{Nucl}\, F_{mol}}$$

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

Nuclear

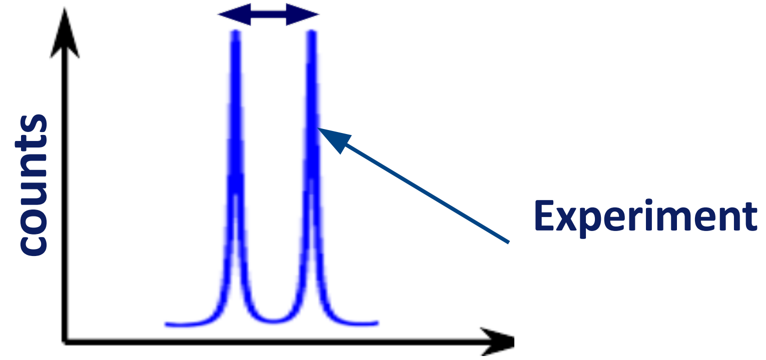
$S \sim Z^a A^b \beta_2 \beta_3 / (E_+^N - E_-^N)$

Atom/molecule

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

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

$E_+^N - E_-^N \sim 10^{-5}$ smaller in molecules

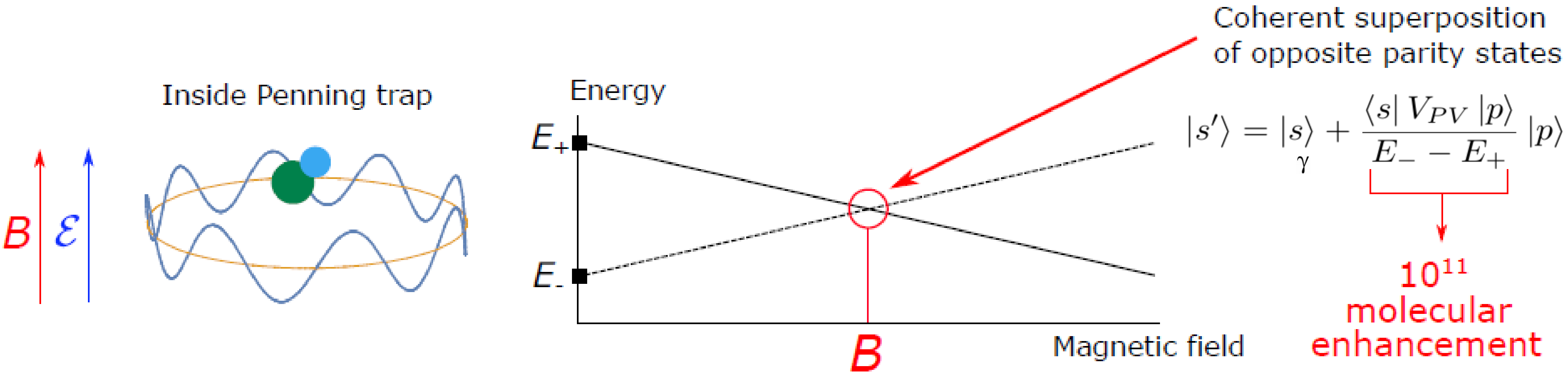


Nuclear x Molecule

Molecule	> 10^3

A single molecule in a Penning trap

$H_{PV} \sim F(Z^c)\,/(E_+{}^e - E_-{}^e)$



Coherent superposition of opposite parity states

$$|s'\rangle = \underset{\gamma}{|s\rangle} + \frac{\langle s|\, V_{PV}\, |p\rangle}{\underbrace{E_- - E_+}_{10^{11}\ \text{molecular enhancement}}}\, |p\rangle$$

10^{11} molecular enhancement

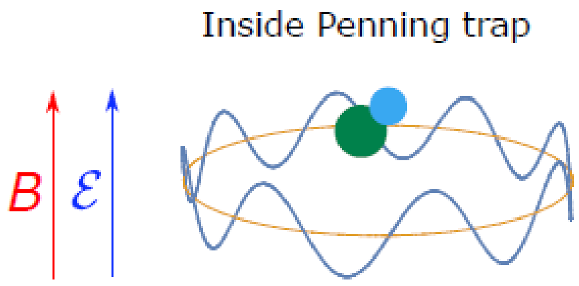
[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]
Demille's group

- Parity and Time reversal violation $> 10^3$
- **Nuclear amplification** $> 10^3$
- **Parity violation** $> 10^{11}$

A single molecule in a Penning trap

$H_{PV} \sim F(Z^c)/(E_+^{\ e} - E_-^{\ e})$

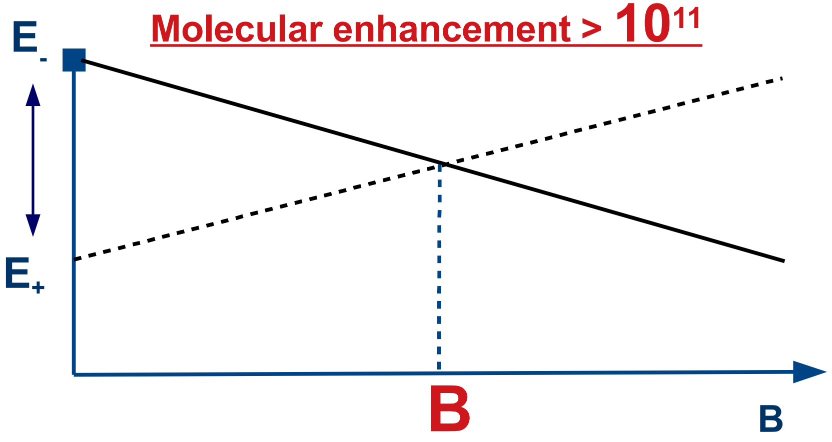
In collaboration with: D. Demille's group (U Chicago), J. Dilling (TRIUMF), N. Hutzler (Caltech), K. Blaum (MPIK)


Inside Penning trap


J. Karthein

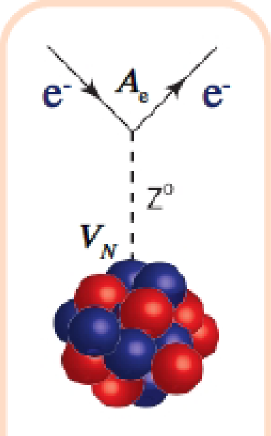

S. Udrescu


S. Moroch


Molecular enhancement > 10^{11}

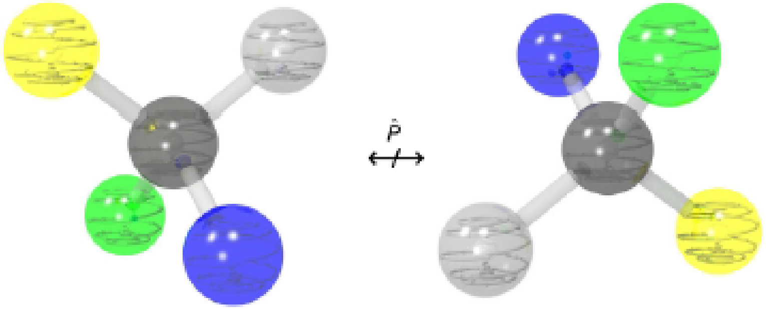
Parity and Time reversal violation	> 10^3
Nuclear amplification	**> 10^3**
Parity violation	**> 10^{11}**

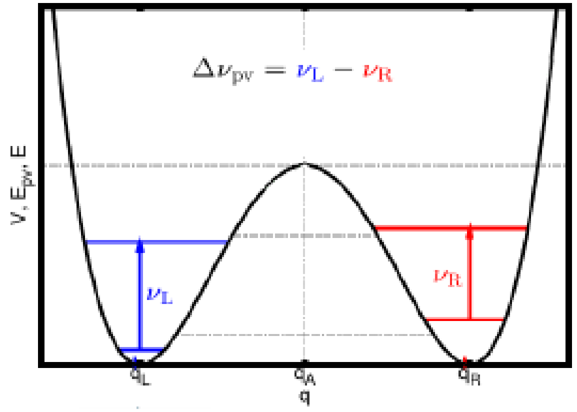
Parity violation in Chiral Molecules



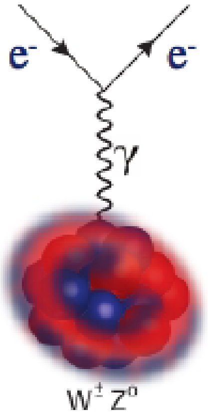
$\sim Z^5$

Chiral molecules





[Berger & Stohner. WIREs Comput. Mol. Sci. e1396, 1 (2018)]
[Laerdahl et al. Phys. Rev. Lett. 84, 3811 (2000)]



$\sim Z^2 A^{2/3} R(Z)$

$\Delta\nu_{\rm pv}/\nu$ (x 10^{-16})

Molecule	HF	B3LYP	B–LYP	LDA
CHBrClF	+0.72	+1.01	+0.93	+0.98
CHBrFI	+17.8	+22.9	+22.1	+24.1
CHClFI	+9.35	+8.96	+6.94	+7.38
CHAtFI	−1072	−1008	−850	−946

[Berger et al. Mol. Phys. 105, 41 (2007)]

$$H_{\rm W} = Q_{\rm W} \frac{G_{\rm F}}{\sqrt{8}} \gamma_5 \, \rho\,(r)$$

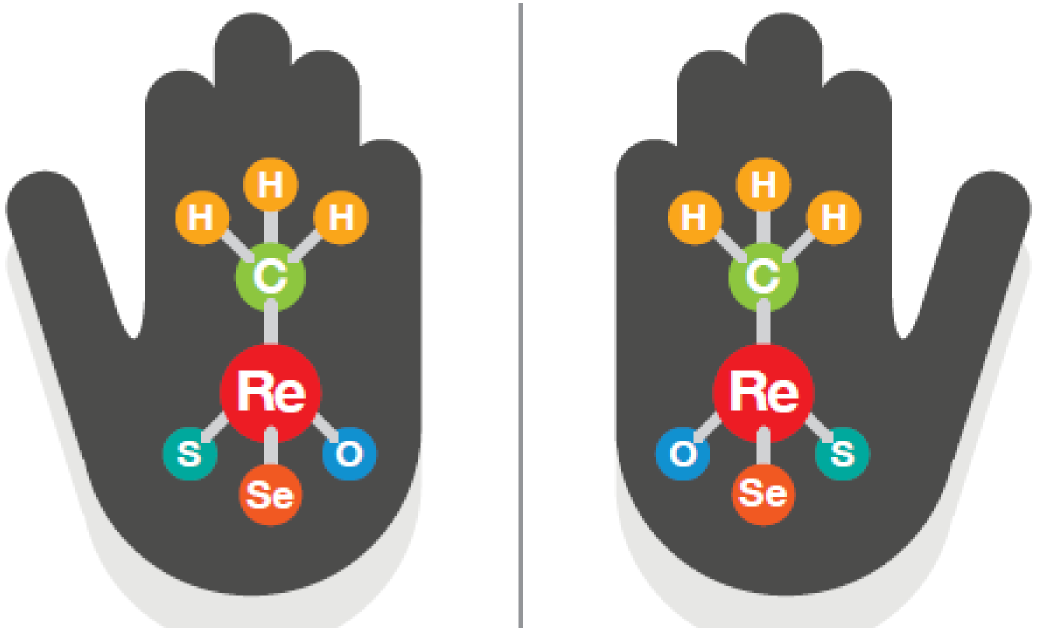
^{211}At (Z=85, $T_{1/2}$~7.2 h) → Freq. shift ~ 3-10 Hz

Tough science: five experiments as hard as finding the Higgs

Nature 481, 7379, (2012)

- *Higgs Boson*
- *Extraterrestrial life*
- *Role of the weak force in molecular chirality*
- *Finding Extra-dimension*
- *Gravitational waves*

- …

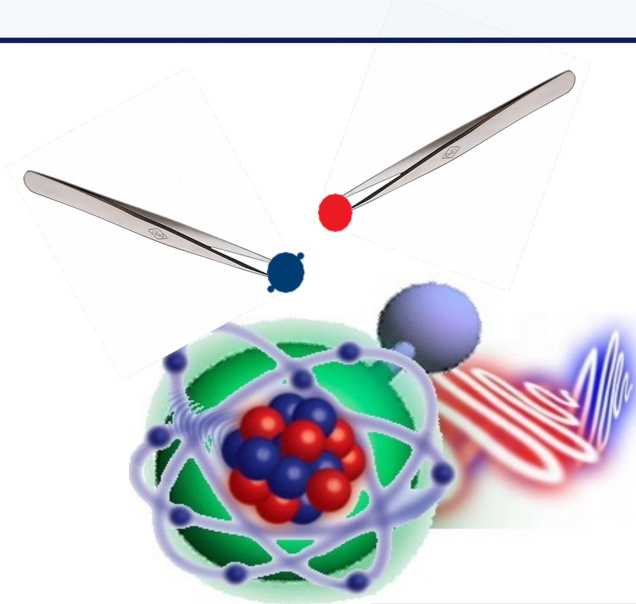


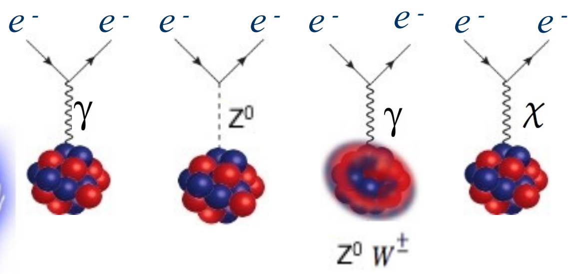
Summary

Precision measurements of atoms and molecules offer unique probes to understand fundamental interactions

Nuclear EM structure

Nuclear EW structure





Fundamental symmetries

Parity and Time reversal violation	> 10^3
Nuclear amplification	> 10^3
Parity violation	> 10^{11}