EDMs of stable atoms and molecules

outline

- Introduction
- EDM sensitivity
- Recent progress in

 EDMs paramagnetic atoms/molecules
 EDMs diamagnetic atoms
- Conclusion and outlook

Solvay workshop "Beyond the Standard model with Neutrinos and Nuclear Physics" Brussels, Nov. 29th – Dec. 1st, 2017

Our world is composed of matter

... and not antimatter





SM prediction based on observed flavor-changing CP-violation (CKM-matrix)

$$\eta = \frac{n_b - n_{\overline{b}}}{n_{\gamma}} \approx 10^{-18}$$

SM CP-odd phases

$$\delta_{\scriptscriptstyle CKM} \sim O(1)$$

explains QP in K and B meson mixing and decays

$$\overline{\theta}_{QCD} < 10^{-10}$$

constrained experimentally (d_n, d_{Hg}) (strong CP problem)



Atomic EDM

 \Rightarrow

complete shielding:

$$\vec{E}_{eff} = \vec{E}_{ext} + \vec{E}_{int} = \varepsilon \cdot \vec{E}_{ext} = 0$$
$$\Rightarrow \Delta E_{EDM} = -\vec{d}_{EDM} \cdot \vec{E}_{eff} = -\vec{d}_{EDM} \cdot \varepsilon \cdot \vec{E}_{ext} = 0$$

L.I.Schiff (*PR* 132 2194,1963):

EDM of a system of non-relativistic charged point particles that interact electrostatically can not be measured : $\varepsilon = 0$

Relativistic violation of Schiff screening

(requires the use of relativistic electron radial wavefunctions)

Paramagnetic EDMs – "Schiff enhancement"

Finite size violation of Schiff screening

Diamagnetic EDMs – "Schiff suppression"

For a finite nucleus, the charge and EDM have different spatial distributions

S-Schiff moment:
$$\vec{S} = S\frac{\vec{I}}{I} = \frac{1}{10} \left[\int e\rho(\vec{r})\vec{r}r^2d^3r - \frac{5}{3Z}\vec{d}\int\rho(\vec{r})r^2d^3r \right]$$

Schiff moment is dominant CP-odd N-N interaction for large atoms

$$d_A = k_A \cdot 10^{-17} \cdot \left[\frac{S}{e \, fm^3}\right] e \, cm \qquad (k_{\rm Hg} \sim -3)$$

 $S = S(\bar{g}_{\pi NN}^{(i)}, d_N, ...)$ (low energy parameters)

•
$$d_A \sim 10 Z^2 (R_N / R_A)^2 d_{nuc} \sim O(10^{-3}) d_{nuc}$$

• Nuclear deformation can enhance heavy atom EDMs (e.g., 225Ra, 223Rn)

> Heavy atoms (relativistic treatment) + finite size: $\varepsilon \neq 0$

$$-d_e \neq 0 \rightarrow d_{atom} \neq 0$$
 $\sim Z^3 \alpha^2 d_e$

- P,T-odd eN interaction
 Tensor-Pseudotensor ~Z²G_FC_T
 Scalar- Pseudoscalar ~Z³G_FC_S
- Nuclear EDM finite size
 Schiff moment induced by P,T-odd N-N interaction ~10⁻²⁵ η [ecm]
- General finding:

 $\eta(d_n, d_p, \bar{g}_0, \bar{g}_1, \bar{g}_2)$ $\smile \overline{\Theta}_{QCD}$

Paramagnetic EDMs: "Schiff enhancement" (ε >> 1) Diamagnetic EDMs: "Schiff suppression" (ε << 1)

Diamagnetic atoms:

Phys. Rep. 397 (04) 63; Phys. Rev. A 66 (02) 012111.

 $d(^{129}Xe) = 10^{-3}d_e + 5.2x10^{-21}C_T + 5.6x10^{-23}C_S + 6.7x10^{-26}\eta \approx 6.7x10^{-26}\eta$

EDM precision experiments (upper limits)

EDM search: Ramsey type phase measurements

$$\frac{shift}{resolution} = \frac{\phi_E \cdot (dS / d\phi)}{noise} = 2 \cdot d \cdot (\varepsilon \cdot E) \cdot \tau \cdot \sqrt{N} / \hbar$$
$$\delta d \propto \frac{1}{(\varepsilon \cdot E_{ext}) \cdot \tau \cdot SNR}$$

$$\begin{vmatrix} \widehat{\mathbf{x}} \rangle \quad \phi = \phi_B + \phi_E = -(2\mu B + 2d\varepsilon E) \cdot \tau / \hbar$$

noise
$$d \widehat{d} \phi \approx N$$

Precession phase
bias phase (\phi_B) \qquad \text{EDM phase}

EDMs of paramagnetic atoms and molecules (**Tl, YbF, ThO, ...**) Interaction energy

 $(E_{lab} \approx 100 \text{ V/cm})$

2. advantage of YbF, ThO:

No coupling $\mu \bullet \mathbf{v} \times \mathbf{E}$ to motional magnetic field

electron spin is coupled to internuclear axis

and internuclear axis is coupled to \mathbf{E}

Experimental setup: general scheme

ThO: metastable state $|H; J = 1\rangle$ (ground rotational level; J=1), lifetime ~ 2ms

$$M = -1 \qquad M = 0 \qquad M = +1$$

$$|\Psi(\hat{x},\tau),\mathcal{N}\rangle = \left(e^{-i\phi}|M = +1,\mathcal{N}\rangle + e^{+i\phi}|M = -1,\mathcal{N}\rangle\right)/\sqrt{2}$$
$$\phi = -\left(\mu_B g \cdot B + \mathcal{N}d_e E_{eff}\right)\cdot \tau/\hbar$$

Results

Science 343 (2014) 269

$$(2.6 \pm 4.8_{stat} \pm 3.2_{sys}) \cdot 10^{-3} [rad / s] = (-d_e \cdot E_{eff}) / W_S \cdot C_S) / \hbar$$

using $E_{eff} = 84 \text{ GV/cm}$, W_{S} (molecule-specific constant) Phys.Rev. A **84**, 052108 (2011)

$$C_{\rm S} = 0$$

$$d_e = \left(-2.1 \pm 3.7_{stat} \pm 2.5_{sys}\right) \cdot 10^{-29} ecm \quad \rightarrow \quad |d_e| < 8.7 \times 10^{-29} ecm \ (90\% CL)$$

$$d_e = 0$$

$$|C_s| < 5.9 \times 10^{-9}$$
 (90% CL)

¹⁹⁹Hg EDM experiment

Effective data taking: 252 days

Results: Hg-EDM

$$d_{\rm Hg} = (-2.20 \pm 2.75_{\rm stat} \pm 1.48_{\rm syst}) \times 10^{-30} \ e \,{\rm cm},$$

$$\left| d_{Hg} \right| < 7.4 \times 10^{-30} \, ecm \quad (95\% \, \text{CL})$$

Limits on CP-violating observables from ^{199}Hg EDM limit $\mathbf{d}_{\text{Hg}} = -2.4 \times 10^{-4} \mathbf{S}_{\text{Hg}}/\text{fm}^2.$

Quantity	Expression	Limit	Ref.
\mathbf{d}_n	$S_{Hg}/(1.9 \text{ fm}^2)$	$1.6 \times 10^{-26} \ e {\rm cm}$	[21]
\mathbf{d}_p	$1.3 \times S_{Hg}/(0.2 \text{ fm}^2)$	$2.0 \times 10^{-25} e \mathrm{cm}$	[21]
\bar{g}_0	$S_{Hg}/(0.135 \ e \ fm^3)$	2.3×10^{-12}	[5]
\bar{g}_1	$S_{Hg}/(0.27 \ e \ fm^3)$	1.1×10^{-12}	[5]
\bar{g}_2	$S_{Hg}/(0.27 \ e \ fm^3)$	1.1×10^{-12}	[5]
$\bar{ heta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22,23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14} \text{ cm}^{-1})$	5.7×10^{-27} cm	[25]
C_{S}	$d_{\rm Hg}/(5.9 \times 10^{-22} \ e {\rm cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{\rm Hg}/(6.0 \times 10^{-23} \ e {\rm cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{\rm Hg}/(4.89 \times 10^{-20} \ e {\rm cm})$	1.5×10^{-10}	see text

Towards the Xe EDM

Courtes

Towards long spin-coherence times (T₂*)

A magnetic moment *M* is associated with the atomic spin.

Comagnetometry to get rid of magnetic field drifts

Subtraction of deterministic phase shifts

Measurement sensitivity: ¹²⁹Xe electric dipole moment $\begin{array}{c|c} & & & \\ & &$

Observable: weighted frequency difference

$$\Delta \upsilon_{\uparrow\uparrow} = \Delta \upsilon_{\uparrow\uparrow}^{He,EDM} - (\gamma_{He} / \gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\uparrow}^{Xe,EDM} \approx -(\gamma_{He} / \gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\uparrow}^{Xe,EDM}$$

$$\Delta \upsilon_{\uparrow\downarrow} = \Delta \upsilon_{\uparrow\downarrow}^{He,EDM} - (\gamma_{He} / \gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\downarrow}^{Xe,EDM} \approx -(\gamma_{He} / \gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\downarrow}^{Xe,EDM}$$

sensitivity limit:

$$\left. \delta d_{Xe} \right| < \frac{h \cdot \delta \upsilon}{4E \cdot \left(\gamma_{He} / \gamma_{Xe} \right)}$$

Experimental EDM sensitivity estimation

- d_{Xe} sensitivity per day estimation from previous run on LV search
- (SNR \approx 3000, $T \approx 3 \cdot T_2^* \approx 24 h$)

Experimental Setup: Overview

Experimental Setup: EDM-Cell

10 cm

Comparison: Hg-EDM vs Xe-EDM sensitivity

Hg-EDM:

SNR~ 30000 @ $f_{BW} = 1 Hz$ <E > = 8 kV/cm $\delta d_{Hg} = 4.1 x 10^{-29} ecm/day$

SNR~ 10000 @ $f_{BW} = 1$ Hz <E> = 0.8 kV/cm $T_{2,Xe}$ *~ 3 h $\delta d_{Xe} = 4 \times 10^{-28}$ ecm/day Improvements:

- <*E*>
- $T_{2,Xe}^*$
- $SNR \rightarrow magnetic \ shield$

Conclusion and outlook

- > Tremendous advance in complexity and sensitivity for polar molecules
- Steady progress in EDMs of diamagnetic atoms (Hg,Xe,...)
- ➢ EDM measurement FOM

$$\delta d \propto \left(\varepsilon \cdot E_{ext} \cdot \tau \cdot SNR \right)^{-1}$$

- > Further improvements to be expected:
- magnetic shielded rooms
- laser sources
- yield of atomic and molecular beam sources
- comagnetometry techniques
- spin coherence times O (h)
- ...
- Connecting experiment and theory
- theory efforts in particular nuclear theory to sharpen EDM results.

Thank you for your attention.

Mixed Measurement and Investigation of the Xenon-129 electric dipole moment

EDM5

3He/129Xe clock-comparison experiments

3He/129Xe clock-comparison experiments

The detection of the free precession of co-located ³He/¹²⁹Xe sample spins can be used as ultra-sensitive probe for

non-magnetic spin interactions of type:

Search for a Lorentz violating sidereal modulation of the Larmor frequency Phys. Rev. Lett. 112, 110801 (2014)

Search for EDM of Xenon

$$V(r)/\hbar = \left\langle \widetilde{\mathbf{b}} \right\rangle \hat{\varepsilon} \cdot \vec{\sigma}/\hbar$$

$$V(r)/\hbar = -|\mathbf{d}_{\mathrm{Xe}}| \,\vec{\sigma} \cdot \vec{E}/\hbar$$

Current limits on EDMs

Experimental Setup: Magnetic Field

- simulated ~pT/cm
- measured (T2*) ~ 10 pT/cm (position of EDM-cell)

x,y,z – gradient colls

 $\mathsf{B}_{\text{solenoid}}$

, E

COS

Ζ

Minimizing magnetic field gradients

(arXiv:1608.01830v1)

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{8R^4\gamma^2}{175D} \left(|\nabla B_z|^2 + a(\lambda) \cdot \left(|\nabla B_x|^2 + |\nabla B_y|^2 \right) \right)$$
$$0 < a(\lambda) < 0.5 \qquad \lambda = \frac{D^2}{\gamma^2 B_0^2 R^4} \propto \frac{1}{p^2}$$

Minimizing magnetic field gradients

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{8R^4\gamma^2}{175D} \left(|\nabla B_z|^2 + a(\lambda) \cdot \left(|\nabla B_x|^2 + |\nabla B_y|^2 \right) \right)$$
$$0 < a(\lambda) < 0.5 \qquad \lambda = \frac{D^2}{\gamma^2 B_0^2 R^4} \propto \frac{1}{p^2}$$

Example: EDM-cell filled with 30 mbar of polarized 3He T2* measurement time: 10 min Total measurement time: 4 h Downhill-simplex algorithm

Iteration	Ch A / mA	Ch B / mA	Ch C / mA	Ch D / mA	T ₂ * / s
start	0	0	0	0	7499
0	0	0.15	0	0	9758
1	0.11	0.11	-0.30	0.11	14750
3	0.30	0.30	-0.34	0.01	26590
5	0.33	0.30	-0.60	0.02	35120
13	0.30	0.40	-0.67	0.18	37686

Features of ³He/¹²⁹Xe spin-clocks

Accuracy of frequency estimation:

example: SNR = 10000:1,
$$f_{BW} = 1$$
 Hz, T= 1 day $\Rightarrow \sqrt{\sigma_f^2} \approx pHz$

Features of ³He/¹²⁹Xe spin-clocks

Co-Magnetometry

$$\varphi_{\mathrm{He}} \stackrel{\boldsymbol{\nabla}}{=} \frac{2}{h} \left(\mu_{\mathrm{He}} \mathbf{B} + \mathbf{d}_{\mathrm{He}} \mathbf{E} \right) t$$
$$\varphi_{\mathrm{Xe}} = \frac{2}{h} \left(\mu_{\mathrm{Xe}} \mathbf{B} + \mathbf{d}_{\mathrm{Xe}} \mathbf{E} \right) t$$
$$\Delta \varphi = \varphi_{\mathrm{He}} - \left(\gamma_{\mathrm{He}} / \gamma_{\mathrm{Xe}} \right) \varphi_{\mathrm{Xe}}$$

- ³He/¹²⁹Xe co-habituating same volume
- ³He to monitor magnetic field
- Zeeman term drops out
- measure with B|E↑↑ and B|E↑↓

$$\xrightarrow{\mathbf{d}_{\mathsf{He}} < <\mathbf{d}_{\mathsf{Xe}}} \sim \frac{4}{h} \left(\mathbf{d}_{\mathbf{Xe}} \mathbf{E} \right) t$$

.... systematics (cont.)

motional magnetic fields

$$\vec{B}_m = \frac{1}{c^2} \left(\vec{v} \times \vec{E} \right)$$

B₀

> parameter correlations

▶

Coil assembly

Non-magnetic ℓHe Dewar housing three low-T_c SQUID gradiometers

Magnetically shielded room (MSR) at Jülich Research Center

	Result	95% u	. . l.	ref.			
Paramagnetic systems							
Xe^m	$d_A = (0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e-cm	a			
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e-cm	b			
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e-cm				
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}					
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.7×10^{-7}	$\mu_N R_{\rm Cs}$				
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e-cm	c			
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e-cm				
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e-cm	d			
ThO	$\omega^{\mathcal{N}E} = 2.6 \pm 5.8 \text{ mrad/s}$			e			
	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	$9.7 imes 10^{-29}$	e-cm				
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}					
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6 \text{ mrad/s}$			f			
	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	16×10^{-29}	e-cm				
Diamagnetic systems							
¹⁹⁹ Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e-cm	\boldsymbol{g}			
¹²⁹ Xe	$d_A = (0.7 \pm 3) \times 10^{-27}$	6.6×10^{-27}	e-cm	h			
²²⁵ Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e-cm	i			
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e-cm	j			
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e-cm	k			
Particle systems							
μ	$d_{\mu} = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e-cm	l			
Λ	$d_{\Lambda} = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17}	e-cm	m			