Electric dipole moment searches

Peter Fierlinger
Outline

Motivation

Different systems to search for electric dipole moments (EDMs)

Examples
A non-zero particle EDM violates T (time reversal symmetry)

Purcell and Ramsey, PR78(1950)807

... assuming CPT conservation, also CP is violated

\[ H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \]
History

- SM neutron
- MSSM
- L-R symmetric
- Multi-Higgs
- Nucleon
- Electron

EDM limit [e·cm]

- $\phi \sim 1$
- $\phi \sim \alpha / \pi$

Ramsey & Purcell (1950)
Neutron EDM and the SM

**CP violation from CKM**

Neutron EDM \( d_n \approx 10^{-32} \text{ ecm} \)

More complex calculations may be required:


Side note: \( d_{\text{electron}} < 10^{-38} \text{ ecm} \)

**Strong Interaction**

CP-odd term in Lagrangian:

\[
L_\theta = \bar{\theta} \frac{\alpha_s}{8\pi} G \bar{G}
\]

\[
d_n(\bar{\theta}) \sim \bar{\theta} \frac{e}{m_n} \frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17} \bar{\theta}e \cdot \text{cm}
\]

\[
\bar{\theta} < 10^{-10}
\]

Strong CP problem
Baryon asymmetry

Observed: $n_B / n_\gamma \sim 6 \times 10^{-10}$

Expected: $n_B / n_\gamma \sim$ MUCH smaller

(BBN, CMB)

e.g. astro-ph/0603451

Ingredients‘ to model baryogenesis:

Sakharov criteria

Remarks:

- Beyond-SM physics usually requires large EDMs
- EDMs and Baryogenesis via Leptogenesis?
- Also other options w/o new CP violation possible (Kostelecky, CPT)
- SUSY: small CPV phases, heavy masses, cancellations?
- What do we learn from an EDM?
  Different measurements are needed!
Physics behind EDMs

See also e.g. Pospelov, Ritz, Ann. Phys. 318(2005)119

(adapted from Jordy de Vries, Jülich, March 14, 2013)
Atom EDM

**Schiff moment:**
Non-perfect cancellation of $E_{ext}$ in atomic shell

Paramagnetic atoms $\sim$ electron EDM
Relativistic effects
$$d_a \propto d_e Z^3$$ Sandars, 1968

Diamagnetic atoms $\sim$ nuclear EDM
Finite size of nucleus violates Schiff’s theorem
$$d_a \propto d_{nucl} Z^2$$ Schiff 1963; Sandars, 1968; Feinberg 1977; ... - 2010

Large enhancements also with deformed nuclei (Ra, Rn, also Fr, Ac, Pa)
Atomic effects

Contributions to atomic EDMs:

\[ d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{h.o.} \ (\text{MQM}) \]

- 13 (model-dependent) parameters
  - TeV-scale CP odd physics, nucleon level, nucleus-level
- Only 8 types of experiments

Illustration: T. Chupp et al., to be published

<table>
<thead>
<tr>
<th></th>
<th>( \theta_{QCD} )</th>
<th>( d_n^0 )</th>
<th>( d_n^1 )</th>
<th>( C_T )</th>
<th>( g_{\pi}^0 )</th>
<th>( g_{\pi}^1 )</th>
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</table>

\[ S = g_{\pi NN} (a_0 \tilde{g}_{CP}^0 + a_1 \tilde{g}_{CP}^1 + a_2 \tilde{g}_{CP}^2) \]

\[ d_n \approx \tilde{d}_n + \left( 1.44 \times 10^{-14} g_{\pi}^{(0)} - 8.3 \times 10^{-16} g_{\pi}^{(1)} \right) \text{ e - cm} \]

\[ \tilde{g}_{CP}^0 \approx 0.027 \ \theta_{QCD} \]
Measuring the neutron EDM

Ultra-cold neutrons (UCN) trapped at 300 K in vacuum

\[ E_{\text{kin}} < 250 \text{ neV} \]
\[ \lambda > 50 \text{ nm} \]
\[ T \sim \text{mK} \]
\[ \text{Storage} \sim 10^2 \text{ s} \]

(RAL/SUSSEX/ILL experiment)

- Four-layer \( \mu \)-metal shield
- Quartz insulating cylinder
- Storage cell
- Hg u.v. lamp
- Vacuum wall
- RF coil to flip spins
- Magnet
- UCN polarizing foil
- UCN detector
- Approx scale 1 m

\[ B_0 \]

Material box

\[ \sim 0.5 \text{ m} \]
Ramsey's method

Particle beam or trapped particles

\( B_0 \uparrow \)

External clock

\( \omega_1 \sim \omega_L \)

Polarization

\( \omega_1 - \omega_L \) ("detuning")

\[ \sigma_{dn} = \frac{h}{2\alpha ET \sqrt{N}} \]

EDM changes frequency:

\( \hbar \omega_L \sim \mu B + dE \)
Clock-comparison experiment

- Neutrons and $^{199}$Hg stored in the same chamber

- Gravity changes center of mass!

$B = 1 \mu T$ ( + small vertical gradient)

Analysis using the gradient:

$$d_n < 2.9 \times 10^{-26} \text{ e cm}$$

Requirement: $^{199}$Hg-EDM must be small:

(btw., this also limits other parameters, e.g. $C_S, C_T$...):

$$d_{\text{Hg}} < 3.1 \times 10^{-29} \text{ e cm}$$

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## Neutron and proton experiments

<table>
<thead>
<tr>
<th>Method</th>
<th>Goal (x10^{-28} ecm)</th>
<th>Comments</th>
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<tbody>
<tr>
<td><strong>nEDM</strong></td>
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<tr>
<td>Cryo EDM</td>
<td>4He</td>
<td>1. ~ 50; 2. &lt; 5</td>
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<td>ILL Crystal EDM</td>
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<td>FRM-II EDM</td>
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<td>&lt; 5</td>
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<td>JPARC</td>
<td>sD2</td>
<td>&lt; 10</td>
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<td>NIST Crystal</td>
<td>Cold beam</td>
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<tr>
<td>PNPI/ILL</td>
<td>Turbine</td>
<td>1. ~ 100; 2. &lt; 10</td>
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<td>TRIUMF/RNPC</td>
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<td><strong>pEDM</strong></td>
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<td>Jülich</td>
<td>B and E field ring</td>
<td>1. R&amp;D; 2. 10^{-24}; 3. 10^{-29}</td>
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<td>BNL</td>
<td>Electrostatic ring</td>
<td>10^{-29}</td>
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</table>

**Comments**:  
- **CANCELED in 2014**  
- Diffraction in crystal: large E  
- Adjustable UCN velocity  
- Special UCN handling  
- R&D  
- E = 0 reference cell  
- Phase 1 takes data  
- Sophisticated technology  
- Phase II at TRIUMF  
- Stepwise improvements  
- Completely novel technology
Current generation improvements

PSI (adapted from B. Lauss, K. Kirch, 2013)

UCN density measured in a 25l volume extrapolated to t=0 at PSI area West-1

- 2010 ~0.15 UCN/cm³
- 2011 ~18 UCN/cm³
- 2012 ~23 UCN/cm³

⇒ correct for detector foil transmission status (4/2013) >33 UCN/cm³ in storage experiment (↔ this is an extrapolation)

< 2 UCN/cm³ in EDM experiment

PNPI/ILL (adapted from A. Serebrov, 2013):

UCN density 3-4 ucn/cm³ (MAM position)

Electric field 10 kV/cm

\[ T(\text{cycle}) = 65 \, \text{s} \]

\[ \delta D_{\text{edm}} \sim 5 \cdot 10^{-25} \, \text{e}\cdot\text{cm/day} \]

...new electric field 20 kV/cm

\[ \delta D_{\text{edm}} \sim 2.5 \cdot 10^{-25} \, \text{e}\cdot\text{cm/day} \]

~ 2014: EDM position at PF2

1 \cdot 10^{-26} \, \text{e}\cdot\text{cm/100 days}
Most critical systematic effect for next generation experiments:

\[ \Delta \omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)} \]

\[ \omega_{xy}^2 = \left( \frac{\partial B_0}{\partial z} \alpha \right)^2 + \left( \frac{E \times v}{c^2} \right)^2 + 2 \frac{\partial B_0}{\partial z} \alpha \cdot \frac{E \times v}{c^2} \]

Magnetic field requirements for 10^{-28} ecm – level accuracy:

~ fT field drift error,
~ < 0.3 nT/m avg. gradients
\[ d_f \sim 4 \times 10^{-27} \text{ ecm} \quad (^{199}\text{Hg geom. phase}) \]
\[ d_n \sim 1-2 \times 10^{-28} \text{ ecm} \quad (\text{UCN geom. phase}) \]

Example:
Dipole fields in EDM chambers

SQUID measurements of Sussex EDM electrodes @ PTB Berlin

\[ \sim 20 \text{ pT pp} \quad \text{demagnetized:} \quad 2 \text{ pT pp} \]

20 pT in 3 cm ~ 5 x error budget!

Statistics: \( 10^3 \text{ UCN/cm}^3 \sim 1 \text{ year} \)

Magnetic fields

The smallest extended size field and gradient on earth

- < 100 pT/m gradient in 0.5 m³
- At FRM-II EDM setup: fields designed and measured - this technology is ready and available!

\[
\begin{align*}
x [\text{m}] & \quad y [-0.5 \text{ m} – 0.5 \text{ m}] & \quad z = 0.5 \text{ m} \\
z = 0 \text{ m (center)} & \quad z = -0.5 \text{ m} \\
\end{align*}
\]

SQUID offset in z not corrected

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New sources of UCN

Superthermal solid $D_2$ or superfluid $^4$He-II

$sD_2$: Molceular excitations used to cool neutrons to zero energy - similar: ILL, LANL, Mainz, NCSU, PNPI, PSI, TUM ...

$^4$He: ILL, KEK, SNS, TRIUMF, ...

Goal of most sources: $10^3$ UCN/cm$^3$ in experiment
Next generation experiments

E.g. at FRM-II (reactor):
- 'Conventional', double chamber
- UCN velocity tuning
- SQUIDs, Cs, $^3$He, $^{199}$Hg, $^{129}$Xe (co)magnetometers
- Measurements at FRM and ILL

E.g. at SNS (spallation):
- Cryogenic, double chamber
- Neutron detection via spin dependent $^3$He absorption and scintillation
- $^3$He co-magnetometry

In the future... again nEDM with a cold beam?

Pulse structure and strong peak flux:
- Cold-beam-EDM at long-pulse-neutron source (ESS) could be competitive? (Piegsa, PRC)
- Re-accelerated polarized UCN with pulse-structure?
- Large-scale neutron interferometer?

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Work at FRM-II:
- Ongoing noble gas EDM measurement
- Magnetometry: geometric phases controlled to $1.1 \times 10^{-27}$ ecm

Work at ILL starting end of 2014:
- Commissioning and optimization of inner apparatus with UCN (initially 1-10 UCN/cc)
- $< 10^{-26}$ ecm sensitivity in 2015/16;
- $< 10^{-27}$ ecm sensitivity in 2017

Future: possible cryogenic inner module
Next generation nucleon EDMs

Proton, deuteron, ... EDM

• Charged particle EDM searches require the development of a new class of high-precision storage rings

• Projected sensitivity $\sim 10^{-29}$ ecm: ... tests $\theta$ to $\sim 10^{-13}$!

• Currently 2 approaches:
  - JEDI collab.: starting with COSY ring, development in stages E, B fields
  - BNL: completely electrostatic, new design all-electric ring

• Requirements:
  - Electric field gradients $17$ MV/m (possible)
  - Spin coherence times $>1000$ s (200s demonstrated at Jülich)
  - Continuous polarimetry $<1$ ppm error (demonstrated at Jülich)
  - Spin tracking simulations of $10^9$ particles over 1000 s
Proton EDM in ‘magic‘ ring

- Frozen horizontal spin precession: p || s
- EDM turns s out of plane

\[
\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}
\]

\[
\vec{\Omega} = \frac{e\hbar}{mc}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \vec{v} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v} \times \vec{B})\right]
\]

\[
\vec{d} = \eta \frac{e\hbar}{2mc} \vec{S}, \quad \vec{\mu} = 2(G + 1) \frac{e\hbar}{2m} \vec{S}, \quad G = \frac{g - 2}{2}
\]

Magic ring:
- Purely electric ring only for G > 0
- E and B ring for other isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>G = \frac{g - 2}{2}</th>
<th>p/GeV/c</th>
<th>E_R/MV/m</th>
<th>B_V/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1.79</td>
<td>0.701</td>
<td>10</td>
<td>0</td>
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<tr>
<td>deuteron</td>
<td>-0.14</td>
<td>1.0</td>
<td>-4</td>
<td>0.16</td>
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<tr>
<td>(^3\text{He})</td>
<td>-4.18</td>
<td>1.285</td>
<td>17</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Electrostatic ring proposal at BNL


Figures: H. Stroehrer

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Octupole deformations: $^{225}\text{Ra}$

Enhancement factors: EDM ($^{225}\text{Ra}$) / EDM ($^{199}\text{Hg}$) $\sim 10^3$

Why trap $^{225}\text{Ra}$ atoms:
- efficient use of the rare $^{225}\text{Ra}$ atoms
- high electric field (> 100 kV/cm)
- long coherence times $\sim 100$ s
- negligible “$v \times E$” effect

Goal $\sim 10^{-28}$ ecm

Main issue: statistics
(Project X, MSU?)

Schiff moment of $^{225}\text{Ra}$, Dobaczewski & Engel, PRL (2005)

Figures: Z.-T. Lu

Dipole trap: Trimble et al. (2010)
MOT: Guest et al., PRL (2007)
Lepton EDM measurements

Best limits:

Mainly paramagnetic systems and polar molecules
- Cs, Tl, YbF: $d_e < 1.05 \cdot 10^{-27}$ ecm (E. Hinds et al.)
- Soon: ThO – currently taking data
- Molecules, molecular ions, solids: PbO, PbF, HBr, BaF, HgF, GGG, Gd$_2$Ga$_5$O$_{12}$ etc.
- $d_{GGG} \sim < 10^{-24}$ ecm
- $d_\mu < 1.8 \cdot 10^{-19}$ (90%) ecm from $g$-2
- $d_\tau < 1.7 \cdot 10^{-17}$ (90%) ecm from $Z\tau\tau$

Diamagnetic atoms also contribute to such limits!

TI, YbF limits together, courtesy T. Chupp (2013)
The ACME experiment

- ThO molecules: 100 GV/cm internal electric field due to level structure, polarizable with very small lab-field
- Small magnetic moment, therefore less sensitive to B-field quality
- Ω-doublet: internal co-magnetometer
- High Z: enhancement
- Well understood system
- High statistics: strong cold beam

Status: $10^{-28}$ ecm/√day, limit $d_e < 8.7 \times 10^{-29}$ ecm

Figures: thesis Y. Gurevich
Summary

New EDM experiments are highly sensitive probes for new physics

Several experiments must be performed to understand the underlying physics.

Experimental techniques span from table top AMO - solid state - low temperature – accelerators - neutron physics

Next generation precision within next

2 years: nEDM ~ few $10^{-27}$ ecm
atoms ~ $< 1.10^{-29}$ ecm ($\text{ThO}$, $^{199}\text{Hg}$, $^{129}\text{Xe}$)

6 years: nEDM ~ few $10^{-28}$ ecm
atoms - hard to predict

... Note: my nEDM time estimate stayed constant since 2009