Searching for electric dipole moments

Peter Fierlinger
Motivation

Different systems to search for electric dipole moments (EDMs)

Status and problems for future experiments, with focus on ultra-cold neutrons
Neutron electric dipole moment

Magnetic moment

\[ H = -\mu B \cdot \frac{S}{S} - dE \cdot \frac{S}{S} \]

- EDM = time reversal symmetry violation
  Purcell and Ramsey, PR78(1950)807
- CPT conservation \(\Rightarrow\)
  CP violation = T violation
- Many systems can be used for EDM searches
- EDM limits are among the most precisely measured quantities
- EDM limits have ’killed‘ many theories

P. Fierlinger – Thessaloniki 2016
Neutron EDM and the SM

**CP violation from CKM**

Neutron EDM  $d_n \sim 10^{-32}$ ecm

More complex calculations may be required:

Side note: $d_{\text{electron}} < 10^{-38}$ ecm...

**Strong Interaction**

CP-odd term in Lagrangian:

$$L_\theta = \bar{\theta} \frac{\alpha_s}{8\pi} G \tilde{G}$$

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

Very small!

Strong CP problem
Physics behind EDMs

Fundamental theory
CKM, $\theta$, SUSY, Multi Higgs, LR-symmetry

Wilson coefficients
$\theta$, $C_{ggg}$, $C_{qqq}(1,8)$, $C_{qH}$, $d_{ud}$, $d_{ud}$, semileptonic, $d_e$

Low energy parameters
$g_0$, $g_1$, $g^2_0$, $d_{np}$, $d_p$

Nucleus level
$d, t, ^3$He, Schiff moment

Atom/molecule level
Diamagnetic, Paramagnetic

Solid state

... New review paper by T.Chupp et al., to be published soon

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

**Schiff moment:**
(Non-perfect) *cancellation* of $E_{\text{ext}}$ in atomic shell + Enhancements

Paramagnetic atoms ~ electron EDM: $d_a \propto d_e Z^3$
Relativistic effects

Diamagnetic atoms ~ nuclear EDM: $d_a \propto d_{\text{nucl}} Z^2$
Finite size of nucleus

**Strong enhancements:**

Large enhancements also with deformed nuclei (Ra, Rn, also Fr, Ac, Pa)
Large enhancement‘ factors in polar molecules: strong electric fields: (e.g. THO, PbO, YbF)
Very promising route for discovery: molecular ions (HfF+,...): Storage rings?
Different systems and effective parameters

- Paramagnetic atoms
  \[ d_{\text{para}} = \eta d_e d_e + k_{CS} \tilde{C}_S \]

- Polar molecules
  \[ \Delta \omega_{\text{para}}^{PT} = -\frac{d_e E_{\text{eff}}}{\hbar} + k_{CS} \tilde{C}_S \]

- Diamagnetic atoms
  \[ d_{\text{dia}} = \kappa S S(\tilde{g}_\pi^{0,1}) + k_{C_T} C_T + \ldots \]

- Nucleons
  \[ d_{n,p} = d_{n,p}^{\text{lr}}(\tilde{g}_\pi^{0,1}) + d_{n,p}^{\text{sr}}(\tilde{d}_{u,d}, d_{u,d}) \]

- Fundamental fermions
  \[ d_e, d_\mu, (d_\tau) \]

...Higher orders (199-Hg!):

\[ d_A = (k_{C_T} + k_{S} C_S) + \eta d_e + \kappa S + \text{h.o.} \quad (MQM) \]
Limits from different measurements

Measured limits
(note: ‘sole-source‘ analysis)

<table>
<thead>
<tr>
<th>System</th>
<th>Result</th>
<th>95% u.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Paramagnetic systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe$m$</td>
<td>$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ e-cm</td>
<td>$1.4 \times 10^{-23}$</td>
</tr>
<tr>
<td></td>
<td>$d_e = (-1.5 \pm 5.6) \times 10^{-26}$ e-cm</td>
<td>$1.2 \times 10^{-25}$</td>
</tr>
<tr>
<td>Cs</td>
<td>$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ e-cm</td>
<td>$1.1 \times 10^{-24}$</td>
</tr>
<tr>
<td></td>
<td>$d_e = (-6.9 \pm 7.4) \times 10^{-28}$ e-cm</td>
<td>$1.9 \times 10^{-27}$</td>
</tr>
<tr>
<td>Tl</td>
<td>$d_A = (-2.4 \pm 5.9) \times 10^{-28}$ e-cm</td>
<td>$1.2 \times 10^{-27}$</td>
</tr>
<tr>
<td>ThO</td>
<td>$\omega^{NE} = 2.6 \pm 5.8 , \text{mrad/s}$</td>
<td>$9.7 \times 10^{-29}$</td>
</tr>
<tr>
<td></td>
<td>$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e-cm</td>
<td>$6.4 \times 10^{-30}$</td>
</tr>
<tr>
<td></td>
<td>$C_S = (-1.3 \pm 3.0) \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td><strong>Diamagnetic systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$d_A = (2.2 \pm 3.1) \times 10^{-30}$ e-cm</td>
<td>$7.4 \times 10^{-30}$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$d_A = (0.7 \pm 3) \times 10^{-27}$ e-cm</td>
<td>$6.6 \times 10^{-27}$</td>
</tr>
<tr>
<td>$^{225}$Ra</td>
<td>$d_A = (-0.5 \pm 2.5) \times 10^{-22}$ e-cm</td>
<td>$5.0 \times 10^{-22}$</td>
</tr>
<tr>
<td>TlF</td>
<td>$d = (-1.7 \pm 2.9) \times 10^{-23}$ e-cm</td>
<td>$6.5 \times 10^{-23}$</td>
</tr>
<tr>
<td></td>
<td>$d_n = (-0.21 \pm 1.82) \times 10^{-26}$ e-cm</td>
<td>$3.6 \times 10^{-26}$</td>
</tr>
<tr>
<td><strong>Particle systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$ e-cm</td>
<td>$1.8 \times 10^{-19}$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$d_A = (-3.0 \pm 7.4) \times 10^{-17}$ e-cm</td>
<td>$7.9 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

Parameters are not independent: e.g. $d_e$ as function of $C_S$

More measurements needed with different systems!

T. Chupp et al.

P. Fierlinger – Thessaloniki 2016
Measuring EDMs: Ramsey’s method

(Particle beam or trapped particles)

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

\[ \hbar L \sim B + dE \]
Ultra-cold neutrons (UCN) trapped at 300 K in vacuum.

\[ E_{\text{kin}} < 250 \text{ neV} \]

\[ \lambda > 50 \text{ nm} \]

Storage time: \( 10^2 \) s \(~0.5 \text{ m} \)

Mike Pendlebury
December 1, 1936 – September 1, 2015

(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
- PMT for Hg light
- Mercury prepolarizing cell
- Upper electrode
- High voltage lead

Approx scale: 1 m
Spin-clock comparison

- Neutrons +$^{199}$Hg vapor measured simultaneously
- UCN center of mass is affected by gravity

Illustration (2008 data)

Best limit:
$$d_n < 3 \times 10^{-26} \text{ e cm}^*$$

Energy resolution:
$$\Delta E \sim 10^{-22} \text{ eV}$$
Neutron EDM – improved Sussex experiment at PSI

- improved RAL/Sussex/ILL apparatus
- $\sigma_d = 10^{-25} \text{e cm/day}$
- Goal by 2017: $\sigma_d < 10^{-26} \text{e cm}$
- next generation experiment n2EDM: 5x better

Goal: $< 1 \cdot 10^{-26}$

Taken from R. Picker, 2016
Next generation neutron experiments: $\sim 10^{-27} - 10^{-28}$ ecm

**UCN, room temperature:** 1000 UCN / cm$^3$
- Sites: (sD2) FRM, LANL, PSI; (lHe-II) ILL, PNPI, TRIUMF, KEK
- Ramsey, (double chamber)
- Magnetometers: SQUIDs, Cs, $^3$He, $^{199}$Hg, $^{129}$Xe, $^{129}$Xe
- (co-)magnetometers

**UCN, Cryogenic:** 500 UCN/cm$^3$
- Site: SNS
- UCN source = EDM chamber, double chamber
- Co-magnetometer: spin dependent $^3$He absorption and scintillation

**Other ideas:** 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 2014)
- Large-scale space-like (not time-like) interferometer?
Systematic effects & the next-generation

Most critical: ‘geometric phase’:

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

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

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

• \( \sim < 0.3 \) nT/m average gradient at \( \sim 1 \) µT ...
  \( d_f \sim 4 \cdot 10^{-27} \) ecm (\(^{199}\)Hg geom. phase)
  \( d_n \sim 1 - 2 \cdot 10^{-28} \) ecm (UCN geom. phase)

• Dipoles on trap surface (dirt or \textbf{sparks}): max 1 dipole with 5 pT in 2 cm distance

• \( \sim 10 \) fT gradient drift measurement precision required

• \( \sim 1 \) fT to also measure ‘correlated’ changes
The 'old' problems

False EDM in $^{199}$Hg due to geometric phase:

SQUID measurements of Sussex- EDM electrodes @ PTB Berlin

demagnetized: 20 pT pp in 3 cm distance
Larger than error budget!

Thermally induced currents in metals:
More critical than Johnson noise

Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006), also:
What does *really* happen in next-generation experiments?
- Tsallis-distributions!
- Many sources of non-gaussian behavior
- Higher moments (skewness??) cause frequency shift
Impact on other measurements?

Non-gaussianity build-up with time:

M. Bales et al., arxiv:1602.01082
Small magnetic fields

- Highest damping ever obtained: \(\sim 6 \times 10^6\) (mHz)
- Highest stability ever obtained (<5 fT in 1000 s) (AIP Highlight 5/2015)
- Smallest gradient ever realized (\(\sim 10^{-10}\) T/m over 1 m³)
- Different low-drift magnetometer systems developed (in-house), capable of measuring these numbers!

One consequence: maybe no comagnetometer at all?

Typical SQUID Allan deviation

\[
\begin{array}{c|c|c|c|c}
\text{t [s]} & 2 & 5 & 10 & 20 \\
\text{B [fT]} & 10 & 30 & 100 & 1000 \\
\end{array}
\]

\(1.5 \text{ m}

\mu\text{T Ramsey field coils}

Field homogeneity maps [pT]:

(Measurement dominated by sensor cables!)
Our EDM apparatus

- Berkeley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM (FRM, Cluster), UIUC, Yale
- Ramsey experiment with UCN trapped at room temperature, ultimately cryogenic
- Double chamber with co-magnetometer as option (if really needed)
- Long-term stable $^{199}$Hg, Cs, $^{129}$Xe, $^3$He, SQUID magnetometers available
- Portable: first measurements with UCN at ILL in 1.5 years from now
R&D measurements at TUM & the HeXe-experiment

Recent upgrade: 1 cm warm-cold distance for SQUID (by PTB)

Illustration: simultaneous precession of $^{129}$Xe and $^3$He amplitude in cylindrical cell with 5 kV/cm applied

SQUID

3He/129Xe cell

Ongoing: 129-Xe EDM, Cs, SQUID, 199-Hg, 3-He, 129-Xe comparisons, current source tests etc.

P. Fierlinger – Thessaloniki 2016
Statistical improvements without more UCN density?

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

A factor 5 improvement seems feasible:

- Fast magnetic equilibration: \(M \times 2\)
  

- Deuterated polyethylene coatings: \(T \times 2, N \times 3\)
  

- Visibility: \(\alpha \times 1.25\)
  
  T. Zechlau, PhD thesis

- To understand systematics, many more measurements are needed.

- Only reasonable step: A strong UCN source will be needed!
He-based UCN source at ILL

‘Prototype’* source SUN-II:

- **Fixed number of UCN**
  - Dilution of density in the chambers and guide system

- **Build-up of UCN inside source**
  - Finally: magnetic confinement = polarized UCN in the source

- **Very low energy spectrum**
  - Extremely long storage times
  - In some cases large losses

- **Small systematics**
  - Geometric phase depends on UCN velocity

... Consequences for our experiment: Rebuild all neutron optics ...
The upgrade for EDM: Super-SUN (under construction at ILL)

For calculations of UCN storage see:

- Single-user facility
- Converter volume: $10^5$ /s ($E < 230$ neV)
- UCN production rate: $4 \times 10^6$ (2018)
- UCN saturation number: $2 \times 10^7$ (2019)

### SuperSun stage I
- UCN density: $333$ /cm$^3$
- Diluted density: $80$ /cm$^3$
- Transfer loss factor: $3$
- Source saturation loss factor: $2$
- Polarization loss factor: $2$
- Density in cells: $6.7$ /cm$^3$
- 2 EDM chamber volume: $33.2$ l
- Neutrons per chamber: $110556$

**EDM sensitivity**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SuperSun stage I</th>
<th>SuperSun stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (2018)</td>
<td>$2 \times 10^6$</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>alpha</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>$T$ (2018)</td>
<td>250 s</td>
<td>250 s</td>
</tr>
<tr>
<td>$N$ after time $T$ (1/e)</td>
<td>398000</td>
<td>794000</td>
</tr>
<tr>
<td>Number of EDM cells</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 1 cell)</td>
<td>3.9E-25 ecm</td>
<td>8.7E-26 ecm</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells)</td>
<td>2.7E-25 ecm</td>
<td>6.1E-26 ecm</td>
</tr>
<tr>
<td>Preparation time</td>
<td>150 s</td>
<td>150 s</td>
</tr>
<tr>
<td>Measurements per day</td>
<td>216 s</td>
<td>216 s</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells) per day</td>
<td>1.9E-26 ecm</td>
<td>4.2E-27 ecm</td>
</tr>
<tr>
<td><strong>Sensitivity 100 days</strong></td>
<td>1.9E-27 ecm</td>
<td>4.2E-28 ecm</td>
</tr>
<tr>
<td><strong>Limit 90% 100 days</strong></td>
<td>3.00E-27 ecm</td>
<td>7.00E-28 ecm</td>
</tr>
</tbody>
</table>

P. Fierlinger – Thessaloniki 2016
Proton EDM

- Projected goal for proton: up to $10^{-29}$ ecm, developed in stages (e.g. Jülich)
- Lots of progress, but a long way to go...

'Magic' (fully) electrostatic storage ring with frozen spin:
- $p \parallel s$
- EDM turns $s$ out of plane

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

$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$

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

• Different EDM experiments are needed to understand the physics behind

• Neutrons, current generation: PSI will have a result with an improvement of the state of the art - will be the leading result for the next years

• Apparatus for a next-generation experiment at TUM built (the only one so far…), measurements will start at ILL in 1.5 years with new source. TUM UCN source still interesting, but in the far future (> 2022?)

• Several major technical problems solved: different handling of systematics in future

• Proton EDM doesn’t need a reactor and is progressing quite well now at Jülich
# Neutron EDM projects

<table>
<thead>
<tr>
<th>RAL SUSSEX ILL (Grenoble, FR)</th>
<th>PSI (Villigen, CH)</th>
<th>TUM ILL (Grenoble, FR ⇒ Munich, DE)</th>
<th>LANCSE EDM (Los Alamos, US)</th>
<th>SNS EDM (Oakridge, US)</th>
<th>PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)</th>
<th>TRIUMF (Vancouver, CA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>temperature</strong></td>
<td>RT</td>
<td>RT</td>
<td>RT 0.7 K</td>
<td>RT 0.7 K</td>
<td>RT</td>
<td>RT</td>
</tr>
<tr>
<td><strong>comag</strong></td>
<td>Hg</td>
<td>Hg</td>
<td>Hg</td>
<td>$^3$He</td>
<td>none</td>
<td>Xe+Hg</td>
</tr>
<tr>
<td><strong>source</strong></td>
<td>reactor, turbine</td>
<td>spall., $sD_2$</td>
<td>reactor, cold neutrons, $^4$He</td>
<td>spall, internal $^4$He</td>
<td>reactor, turbine, $^4$He</td>
<td>spall, $^4$He</td>
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<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1, 2</td>
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<tr>
<td>[UCN/cc]</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>700</td>
</tr>
<tr>
<td><strong>goal [e·cm]$^2$</strong></td>
<td>$3·10^{-26}$</td>
<td>$1·10^{-26}$</td>
<td>$1·10^{-27}$</td>
<td>$2·10^{-28}$</td>
<td>$5·10^{-26}$</td>
<td>$5·10^{-28}$</td>
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<tr>
<td><strong>status</strong></td>
<td>done!</td>
<td>using left exp.</td>
<td>new modifications for Munich ⇒ ILL, $D_2 ⇒ He$</td>
<td>Critical Component Demonstration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>comment</td>
<td>Best limit so far!</td>
<td>Source delivery behind expectations</td>
<td>regulatory issues for UCN source in Munich ⇒ ILL for now</td>
<td>great new concept, high risk</td>
<td></td>
<td>Component development phase</td>
</tr>
</tbody>
</table>

Taken from R. Picker (2016)
Ultra-cold neutrons (UCN)

T \sim mK, \ E_{\text{kin}} < 200 \ \text{NANO-eV}, v < 7 \ \text{m/s}, \ \lambda > 50 \ \text{nm}

**Strong Interaction:**
'Fermi potential'

\[ U_F \mu N \times b_c \sim 100 \ \text{neV} \]

**Electromagnetism:**

Magnitude moment:
|B| = 60 \ \text{neV/T}

... magnetic traps

**Weak Interaction:**

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ \tau \sim 881 \ \text{s} \]

**Gravity:**

\[ V = m_n g h \]

100 \ \text{neV/m}