Electron EDM Searches

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INT Workshop
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Outline

• Theoretical Motivation
• General detection method
• Past and current eEDM searches
• Molecular eEDM searches and the PbO* experiment
  – Advantages of molecules
  – Apparatus
  – Results
  – Conclusions
An EDM Violates Parity and Time Reversal Symmetries

CPT theorem $\Rightarrow$ T-violation = CP-violation

Standard Model generates through radiative corrections $|d_e| < 10^{-40} \text{ e}\cdot\text{cm}$

Any observation of $d_e \neq 0$ is definitive evidence of new physics

CP violation in SM too small to account for matter-antimatter asymmetry

A window to NEW physics
Standard model extensions often include new source of T-violation
How does an electron EDM arise?

Standard Model
Supersymmetry
Beyond the SM Electron EDM estimation

- The analogous diagram for first-order correction to electron $g$ factor gives $g-2 \approx \alpha / \pi$
- Since $m_e$ is the only energy scale we expect the EDM to scale as
  \[ \frac{d_e}{(g - 2) \mu_B} \propto \left( \frac{m_e}{m_x} \right)^2 \]
- Which gives an estimate of
  \[ d_e \approx \sin \phi \left( \frac{f}{e} \right)^2 \left( \frac{m_e}{m_x} \right)^2 \left( \frac{\alpha}{\pi} \right) \mu_B \]
  or
  \[ d_e \approx 10^{-24} e \cdot cm \left( \frac{100 \text{ GeV}}{m_X} \right)^2 \]
eEDM Theoretical Predictions
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General method to detect an EDM

Energy level picture:

Figure of merit:

\[
\frac{\text{shift}}{\text{resolution}} = \frac{dE}{\left(\frac{1}{\tau_{coh}}\right)(S/N)^{-1}} \propto E \cdot \tau_{coh} \cdot \sqrt{N \cdot T_{int}}
\]

\[\eta \omega = 2\mu B + 2dE\]
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Na detectors

Na reservoir (~350 °C)

590 nm laser beams

RF 1

RF 2

State of the art electron EDM search: the Berkeley Tl beam experiment

- Thermal beam of atomic Tl (Z=81)
- Efficient laser/rf spin polarization & detection

Thermal beam of atomic Tl (Z=81)

Efficient laser/rf spin polarization & detection

Electron EDM limit:
B. Regan, E. Commins, C. Schmidt, D. DeMille
\[ |d_e| < 1.6 \times 10^{-27} \text{ e}\cdot\text{cm} (90\% \text{ c.l.}) \]

\[ B_{\text{motional}} = E \times v/c \]

(but: complex procedure to null residuals)
A new generation of electron EDM searches

<table>
<thead>
<tr>
<th>Group</th>
<th>System</th>
<th>Advantages</th>
<th>Projected gain</th>
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<tbody>
<tr>
<td>D. Weiss (Penn St.)</td>
<td>Trapped Cs</td>
<td>Long coherence</td>
<td>~100</td>
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<tr>
<td>D. Heinzen (Texas)</td>
<td>Trapped Cs</td>
<td>Long coherence</td>
<td>~100</td>
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<td>H. Gould (LBL)</td>
<td>Cs fountain</td>
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<td>GdIG solid</td>
<td>Huge S/N</td>
<td>100?, limited by systematic</td>
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<td>S. Lamoreaux (Yale)</td>
<td>GdIG solid</td>
<td>Huge S/N</td>
<td>100?-100,000?</td>
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<td>E. Hinds (Imperial)</td>
<td>YbF beam</td>
<td>Internal E</td>
<td>10?</td>
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<tr>
<td>D. DeMille (Yale)</td>
<td>PbO* cell ThO beam</td>
<td>Int.E+good S/N</td>
<td>2-10? 1000+?</td>
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<td>J. Doyle G. Gabrielse (Harvard)</td>
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Electron EDM with cold trapped atoms

David Weiss et al. (& similar D. Heinzen et al.)

Cs (Z=55) EDM
plus Rb(Z=37) comagnetometer

\[
E \sim 1.5 \times 10^5 \frac{V}{cm} \times 100 \text{ for Cs } E_{int}
\]

Coherence time: \( T \sim 2 - 5 \text{ s} \)

Atom number: \( N_{Cs} \sim 2 \times 10^8 \quad N_{Rb} \sim 8 \times 10^9 \)

\[ \delta d_e \sim 10^{-29} \text{ e.cm for both Cs and Rb in } \sim 1 \text{ day} \]
Solid state electron EDM searches

1: B from E

Sample magnetization
\[ M \propto d_e E/T \]

magnetometer coil

Expt: Lamoreaux (Yale)

2: E from B

Sample voltage
\[ V \propto d_e \]

Expt: Hunter (Amherst)
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A new direction in EDM searches:
using molecules to search for $d_e$

$\uparrow$ \textit{Extremely} large effective E-field
with lab-size external field:
$\mathcal{P} \sim 1 \Rightarrow E_{\text{eff}} \sim 10^{11} \text{ V/cm}$
(For atoms, $\mathcal{P} \sim 10^{-3}$ @ $E_{\text{ext}} \sim 100\text{ kV/cm}$)

$\downarrow$ Smaller signals due to
thermal distribution over rotational levels ($\sim 10^{-4}$)

$\downarrow$ Molecules with unpaired electron spins are
thermodynamically disfavored
$\Rightarrow$ high temperature chemistry, even smaller signals
Addressing some problems with molecules:
the metastable $a(1)[^{3}\Sigma^{+}]$ state of PbO

- PbO is thermodynamically stable
  (routinely purchased and vaporized)
a(1) populated via laser excitation (replaces chemistry)

- a(1) has very small $\Omega$-doublet splitting
  $\Rightarrow$ complete polarization with very small fields (>10 V/cm),
equivalent to $E \sim 10^7$ V/cm on an atom!

$\Rightarrow$ can work in vapor cell
(MUCH larger density and volume than beam)

**PbO Cell:**
$N = nV \sim 10^{16}$

**Tl Beam:**
$N = nV \sim 10^{8}$
Amplifying the electric field \( E \) with a polar molecule

Inside molecule, electron feels internal field

\[
E_{\text{int}} \sim \alpha^2 Z^3 \frac{e}{a_0^2} \cong 2.1^{(b)} - 4.0^{(a)} \times 10^{10} \text{ V/cm in PbO*}
\]

(a) Semiempirical: M. Kozlov & D.D., PRL 89, 133001 (2002);

Complete polarization of PbO* achieved with \( E_{\text{ext}} \sim 10 \text{ V/cm} \)
PbO $\Omega$ doublet structure

- Electric field polarizes molecule
- Zeeman shift splits sublevels
- EDM shift depends on relative alignment of spin and internal electric field
- $\Omega$ doublet pairs have opposite sign for EDM shift but respond identically to magnetic fields -> internal co-magnetometer
The PbO EDM lab
Experimental apparatus

a) Magnetic shielding (up to 4 layers)
b) Vacuum chamber
c) Alumina fiber board insulation
d) Quartz oven w/ resistively heated Ta foils
e) Alumina vapor cell with YAG windows
f) Gold electrodes
g) Quartz light pipes
h) PMTs
i) Microwave horn
Detection Method

- Quantum beat spectroscopy: Fluorescence modulation frequency equals energy level splitting – Doppler free!
- Current detection method suffers from low contrast and large background due to blackbody radiation from the oven

\[
\frac{\text{shift}}{\text{resolution}} \propto \frac{E}{(1/T)(\text{SNR})^{-1}(1/c)} = E \cdot T \cdot \sqrt{N} \cdot c
\]
Data collection and analysis

Repeat 1440 times (~2 hr)

Avg 16 shots each, fit, repeat 32 times (~5s)
## Preliminary systematic checks

<table>
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<th>$N$</th>
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<th>$B$</th>
<th>Largest terms</th>
<th>Derived quantity</th>
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<td>$+ 8 \Delta g \mu B_{\text{leak}}$</td>
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</tbody>
</table>
Results

- $\Delta E$ systematic: Applied $\Delta E = 1.3$ V/cm, measured $1.34 \pm 0.32$ V/cm, limit during data taking <80 mV/cm
- $\Delta B$ systematic: Masked by field drift up to 400 $\mu$G ($\Delta B/B = 2.5 \times 10^{-3}$) over several hours
- EDM data:
  - 41 hours of data with no cuts
  - 66% duty cycle maintained over 36 hrs; with further automation >90% should be easily achievable

Best fit $e$EDM = $-1.9 \pm 2.0 \times 10^{-26}\ e\cdot\text{cm}$
The future of PbO

- Current limitations are now well understood and verified experimentally
- Improvements since May
  - Better heat shielding, lower blackbody
  - Excitation from ground vibrational level -> 3x increase in count rate
- Near term improvements (by end of year)
  - Optimize detection filters -> increase count rate by 2-4
  - Polarization sensitive detection -> reduce background by 2, increase contrast by up to 2
  - Seed dye laser to match Doppler profile -> increase contrast by up to 4, increase count rate by up to 5
- Total increase in sensitivity of 10-20
- Improving upon the Berkeley result is nearly at hand!
- Focus will shift to ThO beam experiment
Acknowledgements

- Current PbO group: David DeMille (PI), Hunter Smith

- Former members: Yong Jiang, Sarah Bickman, Amar Vutha