Improving the search for the electron’s electric dipole moment in ThO

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Advanced Cold Molecule Electron EDM (ACME) collaboration
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Outline

• Background
• Using ThO to measure the eEDM
• The ACME apparatus
• Data analysis
• Outlook
Outline

• Background
  – What is an EDM?
  – Why is the electron’s EDM small?
  – Why are we trying to measure it anyway?
  – How are we trying to do that?
• Using ThO to measure the eEDM
• The ACME apparatus
• Data analysis
• Outlook
Electromagnetic moments of the electron

- The electron has spin $S = 1/2$.
- Can specify one axis (plus overall phase)
  - Bloch sphere representation
- Allows for only monopole, dipole moments
  - E.g., quadrupole has two axes
- Dipole parallel to spin axis: $\vec{d} \propto \vec{S}$
Known and forbidden moments

- **Electric monopole** (charge):
  \[ H_q = \frac{1}{2m} (\vec{p} - q\vec{A})^2 + q\phi \]

- **Magnetic dipole** (spin):
  \[ H_\mu = -\vec{\mu} \cdot \vec{B} \]

Forbidden:
- Magnetic monopole
- Toroidal moments (e.g., “anapole moment”)
- All higher-order moments (quadrupole, octupole, etc.)
Why is the electric dipole moment small*?

\[ H_d = -2d\hat{S} \cdot \hat{E} \]

Symmetry transformations:

- \( T: \hat{S} \rightarrow -\hat{S} \)
- \( T: \hat{E} \rightarrow \hat{E} \)
- \( P: \hat{S} \rightarrow \hat{S} \)
- \( P: \hat{E} \rightarrow -\hat{E} \)

So:

\[ T: H_d \rightarrow -H_d \]
\[ P: H_d \rightarrow -H_d \]

*I will say “small compared to what” shortly
eEDM in the Standard Model

- Non-zero, non-cancelling effects only appear at four-loop diagrams
- Resulting EDM:

  \[ |d_e| \sim 10^{-38} \text{ e cm.} \]

...What does this mean? A few perspectives:
- Precession in 100 kV/cm field would take 10 ages of the universe
- 10 orders of magnitude smaller than experimental limit
- 24 orders of magnitude smaller than \((g - 2)\mu_B/c\)
Answer, Jan. 2014:
Too round!

$$|d_e| < 10^{-28} \text{ e cm}$$
Sakharov’s conditions

- Matter/antimatter imbalance requires both $C$ and $CP$ violation
- SM doesn’t contain enough $CP$ violation to account for observed imbalance
- Physics beyond the SM expected to have extra $CP$ violation
- $CP = T$
- This means bigger EDMs!
With a new particle $X$ and CP-violating phase $\phi$, a $(g - 2)$-type Feynman diagram (above) gives:

$$d_e \sim \left[ \left( \frac{f}{e} \right)^2 \sin \phi \left( \frac{m_e}{m_X} \right)^2 \right] \left( \frac{\alpha}{2\pi} \right) \mu_B \sim 10^{-3} \left( \frac{m_e}{m_X} \right)^2 \mu_B$$

(assuming natural units with $f \sim e$ and $\phi \sim 1$)

With $m_X \sim 10$ TeV, obtain $d_e \sim 5 \times 10^{-29} \, e \, \text{cm}$. 
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• Background
• **Using ThO to measure the eEDM**
  – Relativistic enhancement
  – Benefits of the $\Omega$ doublet and $^3\Delta_1$ structure
  – Other benefits of ThO
• The ACME apparatus
• Data analysis
• Outlook
EDM measurement scheme

\[ H = -\mu \cdot B - d \cdot E \]

Figure of merit:

\[ \frac{1}{\Delta d} \propto E\tau \sqrt{\dot{N}T} \]

\[ \phi_+ = \mu B \tau + d E \tau \]

\[ \phi_- = \mu B \tau - d E \tau \]

\( \Delta d = \text{electric field} \)  
\( \tau = \text{precession time} \)  
\( \dot{N} = \text{experiment repetition rate} \)  
\( T = \text{integration time} \)
Choosing a system

- Free electrons impractical (small $\tau$)
- Schiff’s theorem: electrostatically bound electrons have no observable EDM:
  \[ \langle H_d \rangle = -\langle 2d \, S \cdot E \rangle = -2d \, S \cdot \langle E(r) \rangle = 0 \]
  (otherwise, electron would accelerate away)
- Loophole: relativistic electron has length-contracted spin.
  \[ \langle H_d \rangle = -\langle 2d \, S \cdot E \rangle = -2d \, \langle S(r) \cdot E(r) \rangle \neq -2d \langle S \rangle \cdot \langle E \rangle \]
- Therefore, want relativistic bound electrons
  - Will use a molecule with a heavy atom: ThO ($Z_{Th} = 90$)
Ω doublets in molecules

- Molecules have large internal electric fields
- Easily polarized due to nearby opposite-parity states
  - Rotational levels: $\sim 10^{-5}$ eV $\rightarrow$ $\sim 100$ kV/cm
  - $\Omega$ doublets: $\sim 10^{-9}$ eV $\rightarrow$ $\sim 10$ V/cm
**Ω doublet structure**

Takeaway: can reverse effective electric field spectroscopically!
\[ \Delta_1 \] structure

Choose a state with:

1. \(|S_z| = 1\)
2. \(|L_z| = 2\)
3. \(\hat{S} = -\hat{L}\)

\[ |\mu_{tot}| = |g_sS_z + g_L L_z| \mu_B \]
\[ \approx |2 \times 1 + 1 \times (-2)| \mu_B \]
\[ = 0. \]

(Actually, \(g_{tot} \approx 10^{-2}\).)
Criteria favorable to ThO

• Large effective electric field (relativistic; heavy nucleus)
• Polarizable (omega doublet)
• Orientations in applied field spectroscopically resolvable
• Diatomic (simple spectra)
• Transitions accessible by lasers
• Spectroscopy worked out before our experiment
• Magnetically insensitive (systematic error rejection)
• “Long” lifetime (precession time) in science state: \(~1\) ms
• Efficiently produced in a beam
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• Background
• Using ThO to measure the eEDM
• The ACME apparatus
  – Beam source
  – Rotational cooling
  – State preparation
  – State readout
  – Parameter switches
• Data analysis
• Outlook
Doing the measurement

1. Create a molecular beam
2. Consolidate to a single quantum state
3. Transfer to the $^3\Delta_1$ science state
4. Polarize the molecule
5. Orient the spin
6. Wait for precession
7. Read out the spin precession
Doing the measurement

\[ X(J = 0,1,2,3) \rightarrow X(J = 0) \]

\[ X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle) \]

\[ \cos(\omega \tau) \propto S_y - S_x \]
...and actually doing the measurement
**Closer look: beam source**

\[
X(J = 0,1,2,3) \rightarrow X(J = 0)
\]

\[
X(J = 0) \rightarrow H(J = 1)(|+\rangle + |--\rangle)
\]

\[
\cos(\omega \tau) \propto S_y - S_x
\]
Beam source: laser ablation

- ThO$_2$ ablated by pulsed Nd:YAG laser
- Some of the ablation plume is ThO
- The plume is entrained in a flow of cold neon buffer gas
Buffer-gas beam source

- Slow (180 m/s)
- Cold (\(~\)all ThO molecules in vibronic ground state, \(T_{rot} \approx 4\) K)
- Relatively high flux. ThO ablation source: \(5 \times 10^{12}\) mol/sec
Thermochemical source

- Drive reaction by heating:
  \[ \text{ThO}_2 \, (s) + \text{Th}(s) \rightarrow 2\text{ThO}(g) \]
- Use 10 W fiber laser
- 10x higher flux!
- Radioactive dust high
- Target lifetimes low
Closer look: Optical pumping

\[ X(J = 0,1,2,3) \rightarrow X(J = 0) \]

\[ X(J = 0) \rightarrow H(J = 1)(|+\rangle + |->) \]

\[ \cos(\omega \tau) \propto S_y - S_x \]
Rotational cooling

- Rotational temperature $\sim 4$ K
- Drive population to $J = 0$
- Increase population by $\sim 4 \times$
- No gain relative to Gen. I
Closer look: STIRAP

\[ X(J = 0, 1, 2, 3) \rightarrow X(J = 0) \]

\[ X(J = 0) \rightarrow H(J = 1)(|+\rangle + |\rangle) \]

\[ \cos(\omega \tau) \propto S_y - S_x \]
State preparation: STIRAP

• Gen. I state preparation via optical pumping
  – ~5% efficiency
• Gen. II: counter-intuitive pulse sequence coherently transfers 80-100% of population to target state
• Demonstrated 40%; improvements ongoing
Closer look: state readout

\[ X(J = 0, 1, 2, 3) \rightarrow X(J = 0) \]

\[ X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle) \]

\[ \cos(\omega \tau) \propto S_y - S_x \]
Projective measurement

- Alternately project spin along \( \hat{x} \) and \( \hat{y} \)
- Detect fluorescence signals \( S_x \) and \( S_y \)
- Phase given by \( \cos(\phi) \propto A = \frac{S_y - S_x}{S_y + S_x} \)
- Dither readout basis to measure “contrast,” sensitivity to \( \Delta \phi \)
Fluorescence collection

- Collect 512 nm fluorescence using lenses and light pipes
  - 10-20% photon collection efficiency
- Quantum efficiency with photomultiplier tubes: 20-25%
  - Overall efficiency: 2-5%
- Very preliminary: switch to silicon photomultipliers? (QE ~40%)
Repeat under different conditions

- 1 min: A “block” of data contains all switches for an independent “EDM experiment”
- 30 mins: A “superblock” contains auxiliary switches for systematic checks
- 1 hr: The magnetic field magnitude is varied across superblocks
- 5 hrs: Some superblocks are performed with parameters intentionally varied (IPV)
- 1 day: The electric field magnitude is changed between “runs”
- 1 wk: The propagation direction of lasers for state preparation and readout is reversed
- 2 wks: All data for the Jan. 2014 result

Before this: 1 year of systematic checks!
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  – Extracting the eEDM
  – Checking for systematic errors
• Outlook
Extracting the eEDM

Decompose phase according to parity under experimental switches:

\[ \phi = \phi^0 + \phi^N + \phi^E + \phi^B + \phi^{NE} + \phi^{NB} + \phi^{EB} + \phi^{NEB} \]

\[ N = \hat{E}_{mol} \cdot \hat{E}_{lab} \]
\[ E = \hat{E}_{lab} \cdot \hat{z} \]
\[ B = \hat{B}_{lab} \cdot \hat{z} \]

EDM here! (Or not.)
- Reverses with \( N \) and \( E \)
- Doesn’t reverse with \( B \)

\[ \phi^{NE} = 2(dE_{mol})\tau + \phi_{syst} \]

Many other terms in the Hamiltonian...

<table>
<thead>
<tr>
<th>( NIB ) parity</th>
<th>( \phi^p(N, I, B) )</th>
</tr>
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<tbody>
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<td>++ +</td>
<td>( \Theta_{nr} + \mu gB_{nr} \tau + \alpha \Delta_0 + \beta \Delta_0^2 B_{nr} + \ldots )</td>
</tr>
<tr>
<td>++ -</td>
<td>( \mu g\delta B_0 \tau + \beta \Delta_0^2 B_0 + \ldots )</td>
</tr>
<tr>
<td>+- +</td>
<td>( \mu g B_{\varepsilon} \tau + \beta \Delta_0^2 B_{\varepsilon} + \ldots )</td>
</tr>
<tr>
<td>- + +</td>
<td>( \beta \Delta_0 B_0 D_H \varepsilon_{nr} + \ldots )</td>
</tr>
<tr>
<td>- - +</td>
<td>( \mu \Delta g B_{nr} \tau + \alpha \Delta_N + \beta \Delta_0 \Delta_N B_{nr} + \ldots )</td>
</tr>
<tr>
<td>- + -</td>
<td>( \mu \Delta g B_0 \tau + \beta \Delta \Delta_N B_0 + \ldots )</td>
</tr>
<tr>
<td>- - +</td>
<td>( [d_{e} E_{mol}] + \alpha D_H \varepsilon_{nr} + \mu \Delta g B_{\varepsilon} \tau + \ldots )</td>
</tr>
<tr>
<td>- - -</td>
<td>( \beta \Delta D_H \varepsilon_{nr} B_0 + \ldots )</td>
</tr>
</tbody>
</table>

Non-EDM channels used to understand systematic errors
Checking for systematic errors

1. Exaggerate parameter variation
2. Check effect on $\phi^{NE}$
3. Measure normal parameter variation
4. Infer normal effect on $\phi^{NE}$

- Repeat for many parameters...
  - Laser detuning, power, pointing, polarization
  - Field plate voltage offset
  - Molecular beam shape (via clipping)
  - Magnetic field gradients
  - Non-reversing electric and magnetic field
  - Polarization switching rate

- In analysis, vary:
  - Data cut thresholds, time within molecular pulse profile, correlations with auxiliary parameters like vacuum pressure, time over dataset...
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• Gen. I:
  – good Gaussian statistics
  – Found $\Delta d_{syst} < \Delta d_{stat}$

• Gen. II statistical improvements (250-500x):
  – State preparation: 8x (16x?)
  – Fluorescence collection in light pipes: 2x
  – Detection at 512 nm: 2x
  – Beam solid angle: 8x

• Gen. III improvements (with above, $>10^4 x$):
  – Thermochemical beam source: 10x?
  – Detection with silicon photomultipliers: 2x?
  – Electrostatic lens: 3x?
  – Optical cycling: 6x??
Projected Gen. II improvements

10x Thermochemical beam source

8x Solid angle

8x-16x STIRAP state preparation

2x PMTs @512 nm

2x Fluorescence collection
What could go wrong?

Systematics not expected to be limiting... but needs to be thoroughly checked
Front: Elizabeth Petrik (J.D.), Jacob Baron (J.D.), Cris Panda (G.G.), Brendon O’Leary (D.D.), Zack Lasner (D.D.), Adam West (D.D.)
Middle (PIs): John Doyle, Gerald Gabrielse, David DeMille
Back: Daniel Ang (G.G.), Vitaly Andreev (G.G.), Grey Wilburn (J.D.), Christian Weber (D.D.)
...And many former members!
Questions?
Extra slides
How STIRAP works

• Foolproof method:
  1. Write down Hamiltonian.
  2. Diagonalize.
  3. Look at answer.

• More intuitive example:
  1. Imagine $\vert 1 \rangle$ and $\vert 2 \rangle$ have orthogonal spin projections; each couples to only one laser polarization, $\hat{x}$ or $\hat{y}$. Population initially in $\vert 1 \rangle$.
  2. Turn on laser driving $\vert 2 \rangle \leftrightarrow \vert 3 \rangle$.
  4. Once polarization is rotated, the “dark” state is $\vert 2 \rangle$.
  5. Ramp down laser.
STIRAP in the lab

Lasers propagate between field plates

- “Laser lounge” allows for vertical propagation

Technically challenging:

- Lasers must be narrow-linewidth (1 kHz)
- Efficiency depends on beam shaping, pointing, etc.
- Long path length

Demonstrated:

- 40% for $X \rightarrow C \rightarrow H$
- 80% for $X \rightarrow C \rightarrow X$ (won’t be used)

Improvements ongoing.
Forbidden electromagnetic moments

- **Magnetic monopole**: $\nabla \cdot \vec{B} = 0$
- **Toroidal monopole**: (Static limit) $\nabla \cdot \vec{J} = 0$
- **Toroidal dipole**: Not invariant under electroweak gauge transformations; not physically meaningful in SM.
- **Quadrupole, octupole, etc.**: $S = 1/2$ for the electron