How symmetric is the electron? Looking for out-of-roundness of $10^{-14}$ femtometers

Eric Cornell
JILA -- NIST/CU  Boulder, CO
Meet Mr. Electron.

charge = -q
mass = m_e
Meet Mr. Electron.

charge = -q
mass = \( m_e \)
spin = \( \hbar/2 \)
Meet Mr. Electron.

charge = $-q$

mass = $m_e$

spin = $\hbar/2$

magnetic moment

= $\mu_B$
Meet Mr. Electron.

charge = \(-q\)
mass = \(m_e\)
spin = \(\hbar/2\)
magnetic moment
\[= \mu_B\]

and that's pretty much it.

Or is it?
Meet Mr. Electron.
Meet Mr. Electron.
Meet Mr. Electron.

electron
Electric
Dipole
Moment
(eEDM)?
Meet Mr. Electron.

eEDM looks like offset between center of mass and center of charge!

eEDM looks like offset between center of mass and center of charge!
Experimental Limit: $e\text{EDM} < 10^{-27}$ e-cm

$< 10^{-27}$ cm

$(< 10^{-14}$ fm)$
If the electron were the size of the earth, its asymmetry (scaled up) has been measured to be less than the diameter of a virus.
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: Why?
New particle physics from precision dipole moments ---- long tradition

Electron’s magnetic moment: $\mu_e = g\mu_b$
New particle physics from precision dipole moments ---- long tradition

   Electron’s magnetic moment: $\mu_e = g \mu_B$

1. $g = 2$ (2, not 1! The Dirac equation)
New particle physics from precision dipole moments ---- long tradition

Electron’s magnetic moment: $\mu_e = g \mu_b$

1. $g = 2$ (2, not 1! The Dirac equation)

2. $g = 2 - \alpha/2$ (early test of one-loop QED)
New particle physics from precision dipole moments ---- long tradition

Electron’s magnetic moment: $\mu_e = g \mu_b$

1. $g = 2$  
   (2, not 1! The Dirac equation)

2. $g = 2 - \alpha/2$  
   (early test of one-loop QED)

3. $g = 2 + a_1\alpha + a_2\alpha^2 + a_3\alpha^3 + a_4\alpha^4 + ...$
   (best test of many-loop field theory)
Q: Can we get still more particle physics, beyond SM, from electron $\mu_{\text{mag}}$?
Q: Can we get still more particle physics, beyond SM, from electron $\mu_{\text{mag}}$?

A: Probably not. $m_e$ is too small.
Q: How about new particle physics from muon $\mu_{mag}$?
Q: How about new particle physics from muon $\mu_{\text{mag}}$?

A: Probably not (although there has been a big effort) due to uncertainties in QCD “theory background”.

\[
\begin{array}{c}
\text{New physics}
\end{array}
\]

\[
\begin{array}{c}
\text{QCD}
\end{array}
\]
New particle physics from precision dipole moments

Advantage of electric dipole moments, with respect to magnetic dipole moments:

\[ d_e, d_n, d_\mu, d_{\text{Hg}} \ldots \]

have very small SM theory background

\[ |d_e| < 1.6 \times 10^{-27} \text{ e*cm} \]

E.D. Commins TI Exp. Limit [PRL 88, 071805 (2002)]
New physics against zero background – and (maybe) not too far away?

Sociology comment.

nEDM, nuclear Schiff moments, $\mu$EDM
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: Why?
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: How?
Cornell, Eric A.
Arrest date: 6/2/08
Arrest complaint: Symmetry violation in a public space
Charge: Symmetry violation in a public space

CONVICTED
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: How?
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: How?

A: With a lot of help.
JILA eEDM project

Cornell [Aaron Leanhardt] Russell Stutz
Laura Sinclair, Huanqian Loh, Herbert Looser
John Bohn Ed Meyer

Q: “Who are your influences?”

Jun Ye
Konrad Lehnert
Carl Lineberger
David Nesbitt

remote help: Peter Bernath and St. Pete’s bunch:
Titov, Petrov
NSF, NIST, Marsico Chair
JILA eEDM project

Cornell [Aaron Leanhardt] Russell Stutz
Laura Sinclair, Huanqian Loh, Herbert Looser
John Bohn Ed Meyer

Q: “Who are your influences?”
--- The Commitments (1991)

Jun Ye
Konrad Lehnert
Carl Lineberger
David Nesbitt


remote help: Peter Bernath and St. Pete’s bunch:
Titov, Petrov

NSF, NIST, Marsico Chair
JILA eEDM project

Cornell [Aaron Leanhardt] Russell Stutz
Laura Sinclair, Huanqian Loh, Herbert Looser
John Bohn Ed Meyer

Q: “Who are your influences?”

--- The Commitments (1991)

Jun Ye
Konrad Lehnert
Carl Lineberger
David Nesbitt

…Norman Ramsey. Pat Saunders.
Carl Wieman. Commins/Budker/Demille

remote help: Peter Bernath and St. Pete’s bunch:
Titov, Petrov

NSF, NIST, Marsico Chair
Asymmetry less than $10^{-27}$ cm. Commins, 2002. Pretty good!

At JILA we are planning to do one hundred times better yet.

Q: How?
How to measure eEDM? First, how do we measure eMDM?
How to measure eEDM?
How to measure eEDM?
Figure-of-merit:
What makes a good EDM experiment?
Figure-of-merit: What makes a good EDM experiment?

Big Electric Field!

$E_{eff}$

$\tau$

Combined Figure-of-merit: $B \times E$

$2d_e E$
Figure-of-merit: What makes a good EDM experiment?

- Big Electric Field!
- Big Coherence Time (narrow resonances)!

Combined Figure-of-merit: $B_E$
Figure-of-merit: What makes a good EDM experiment?

Big Electric Field!

Big Coherence Time (narrow resonances)!

Large count rate (split resonance by $\sqrt{N_{\text{eff}}}$)

Combined Figure-of-merit: $E_{\text{eff}} \tau \sqrt{N_{\text{eff}}}$
When quantization axis B traces out a closed loop that encloses solid angle $\Omega$, then a quantum spin* with angular momentum projection $m$ on the quantization axis picks up a phase $m\Omega$ with each cycle (in the limit of really slow change.)

*Note, true for composite objects, like molecules, too. What matters is total $m$. 
Who’s Our Daddy?
Neutron EDM experiment

<table>
<thead>
<tr>
<th>Ez</th>
<th>Bz</th>
<th>E(m=1/2)-E(m=-1/2)</th>
<th>Chop</th>
</tr>
</thead>
<tbody>
<tr>
<td>E₀+δE</td>
<td>B₀+δB</td>
<td>d(E₀+δE) +μ(B₀+δB)</td>
<td>+1</td>
</tr>
<tr>
<td>E₀+δE</td>
<td>-B₀+δB</td>
<td>d(E₀+δE) +μ(-B₀+δB)</td>
<td>+1</td>
</tr>
</tbody>
</table>

Total: \( 4d(E₀+δE) + 2μδB \)
Who’s Our Granddaddy?
Neutron EDM experiment

\[
\begin{align*}
E_z & \quad B_z & \quad E(m=1/2) - E(m=-1/2) & \quad \text{Chop} \\
E_0 + \delta E & \quad B_0 + \delta B & \quad d( E_0 + \delta E) + \mu( B_0 + \delta B) & \quad +1 \\
E_0 + \delta E & \quad -B_0 + \delta B & \quad d( E_0 + \delta E) + \mu(-B_0 + \delta B) & \quad +1 \\
\end{align*}
\]

Total: \[4d(E_0 + \delta E) + 2\mu\delta B\]
Who’s Our Great Granddaddy? Neutron EDM experiment

\[
\begin{align*}
E_z & \quad B_z & \quad E(m=1/2) - E(m=-1/2) & \quad \text{Chop} \\
E_0 + \delta E & \quad B_0 + \delta B & \quad d(E_0 + \delta E) + \mu(B_0 + \delta B) & +1 \\
E_0 + \delta E & \quad -B_0 + \delta B & \quad d(E_0 + \delta E) + \mu(-B_0 + \delta B) & +1 \\
\text{Total:} & \quad 4d(E_0 + \delta E) + 2\mu\delta B
\end{align*}
\]
Neutron EDM experiment

\[ \begin{align*} \]
Neutron-in-a-box (literally)

E

B

Many cm
B_0, E_0, point up out of the screen

Neutron motion partially transforms strong electric field into B-field.

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!
$B_0, E_0$, point up out of the screen

Neutron motion partially strong electric field into B-field.

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between $m=1/2$ and $m=-1/2$ levels!

Thermal distribution of trajectories means this effect as no net sign.
Not an important source of dephasing (decoherence) in the nEDM experiments. But, with the addition of a stray gradient, can cause systematic error.

Stray gradient due to permanently magnetized piece of schmutz
Top view, $B_0$ out of the page.

You can now get enclosed B-field trajectory over time even when neutron’s coordinate-space trajectory enclose no area.
Neutron EDM experiment

<table>
<thead>
<tr>
<th>Ez</th>
<th>Bz</th>
<th>$E(m=1/2)-E(m=-1/2)$</th>
<th>Chop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0 + \delta E$</td>
<td>$B_0 + \delta B$</td>
<td>$d( E_0 + \delta E) + \mu(B_0 + \delta B)$</td>
<td>$+1$</td>
</tr>
<tr>
<td>$E_0 + \delta E$</td>
<td>$-B_0 + \delta B$</td>
<td>$d( E_0 + \delta E) + \mu(-B_0 + \delta B)$</td>
<td>$+1$</td>
</tr>
<tr>
<td>$-E_0 + \delta E$</td>
<td>$B_0 + \delta B$</td>
<td>$d(-E_0 + \delta E) + \mu(B_0 + \delta B)$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$-E_0 + \delta E$</td>
<td>$-B_0 + \delta B$</td>
<td>$d(-E_0 + \delta E) + \mu(-B_0 + \delta B)$</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

Total: $4E_0$
Neutron EDM experiment

Total: \[4dE_0 + 4 \text{ cw phase units. Ouch.}\]

Gets worse for big \(E_0\) and long free paths. Leakage currents.
B₀, E₀, point up out of the screen

Neutron motion partially transforms strong electric field into B-field.

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!

Go back to this case: No dirt (no spatial gradient in B) means no systematic. But, what about dephasing?
$B_0, E_0$, point up out of the screen

Neutron motion partially strong electric field into $B$-field.

Go back to this case: No dirt (no spatial gradient in $B$) means no systematic. But, what about dephasing?

Thermal distribution of trajectories means this effect as no net sign.

Enclosed area of neutron trajectory means enclosed area of $B$-vector in time. A shift in phase between $m=1/2$ and $m=-1/2$ levels!
$B_0, E_0$, point up out of the screen

Neutron motion partially strong electric field into B-field.

Thermal distribution of trajectories means this effect as no net sign.

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between $m=1/2$ and $m=-1/2$ levels!

OK for a box. What about trapped particles!?
Aside: the granddaddy
Problem:
Big E, long $\tau$. Electron accelerates quickly, and is gone???

$E$
Problem: Big $E$, long $\tau$. Electron accelerates quickly, and is gone????

Solution: Attach electron spin to a big atomic nucleus!

$$E_{\text{eff}} = a E_{\text{lab}} Z^3$$
The Lessons of History: eEDM

Limit on eEDM (e-cm)

- Gould, Sandars, Cs beams
- Hunter, Cs vapor cell
- Commings Ti beam

[Graph showing improvements in limit on eEDM from 1965 to 2009]
The Lessons of History: eEDM

The smooth march of progress into the future.... or....
The Lessons of History: eEDM

...or “Impulse Progress”?
Current limit, beam of atomic Thallium:


$|d_e| < 1.6 \times 10^{-27} \text{ e*cm (90\% c.l.)}$

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{eff}}$</th>
<th>$\tau$</th>
<th>$\sqrt{N_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commins Tl beam</td>
<td>$6 \times 10^7 \text{ V/cm}$</td>
<td>2 msec</td>
<td>$10^9 \text{ s}^{-1}$</td>
</tr>
</tbody>
</table>
Our approach. 1. Use molecule for big $E_{\text{eff}}$

(we follow Hinds and Demille in this)

$E_{\text{lab}} = 10 \text{ V/cm}$  $E_{\text{eff}} > 10^{10} \text{ V/cm}$
Our approach. 2. Use trapped ion for long $\tau$

(atomic spectroscopy in ion traps sees many seconds)

We will work in a linear Paul trap.
Current limit, beam of atomic Thallium:


\[ |d_e| < 1.6 \times 10^{-27} \text{ e}\text{*cm (90\% c.l.)} \]

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{eff}}$</th>
<th>$\tau$</th>
<th>$\sqrt{N_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commins Tl beam</td>
<td>$6 \times 10^7$ V/cm</td>
<td>2 msec</td>
<td>$10^9$ s$^{-1}$</td>
</tr>
<tr>
<td>Hinds YbF beam</td>
<td>&gt;</td>
<td>&lt;</td>
<td></td>
</tr>
<tr>
<td>DeMille PbO vapor cell</td>
<td>&gt;</td>
<td>&lt;</td>
<td></td>
</tr>
<tr>
<td>Weiss trapped Cs</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&lt;</td>
</tr>
<tr>
<td>Heinzen trapped Cs</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&lt;</td>
</tr>
<tr>
<td>Gould Cs fountain</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&lt;</td>
</tr>
<tr>
<td>Shafer-Ray PbF beam</td>
<td>&gt;</td>
<td>&lt;</td>
<td></td>
</tr>
<tr>
<td>Cornell trapped HfF+ or ThF+</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&lt;&lt;</td>
</tr>
</tbody>
</table>

Solid State
The Lessons of History: eEDM

...or “Impulse Progress”?
The Lessons of History: eEDM

...or "Impulse Progress"?
Candidate Molecular Ions

HfF$^+$ and ThF$^+$
- $^3\Delta$ ground states $\rightarrow$ 1 V/cm to fully polarize
- strong atomic 6s character $\rightarrow$ large $E_{\text{eff}}$

Meyer and Bohn “jiffycalc” points in blue. PRA 73, 062108 (2006)
Full-on “one-calculation-equals-one-publication”, various authors, in black, arXiv:physics/0506038 and refs. therein
Why Use $^3\Delta_1$ state of molecule?

\[ \vec{L} \cdot \hat{z} = 2, \quad \vec{s} \cdot \hat{z} = -1 \]

\[ g \approx 0 \quad (= 0.03 \mu_B) \]

Thallium: \[ E_{\text{lab}} = 10^5 \text{V/cm} \quad E_{\text{eff}} = 6 \times 10^7 \text{ V/cm} \quad \mu_{\text{mag}} = 1.0 \mu_B \]

HfF$^+$ or ThF$^+$: \[ E_{\text{lab}} = 10^1 \quad E_{\text{eff}} = 1.5 \times 10^{10} \quad \mu_{\text{mag}} = 0.03 \]

E-field-systematic Figure-of-merit: \[ \frac{E_{\text{eff}}}{(E_{\text{lab}} \mu_{\text{mag}})} \]

Our experiment is $>10^7$ to the good. Probably will not even need mu-metal shielding.
Why Use $^3\Delta_1$ state of molecule?

\[ \vec{L} \cdot \vec{z} = 2, \quad \vec{s} \cdot \vec{z} = -1 \]
\[ g \approx 0 \quad (= 0.03 \mu_B) \]

Thallium: \quad E_{lab} = 10^5 V/cm \quad E_{eff} = 6 \times 10^7 V/cm \quad \mu_{mag} = 1.0 \mu_B

HfF$^+$ or ThF$^+$: \quad E_{lab} = 10^1 \quad E_{eff} = 1.5 \times 10^{10} \quad \mu_{mag} = 0.03

Figure-of-merit: \quad \frac{E_{eff}}{E_{lab} \mu_{mag}}

Our experiment is $>10^7$ to the good.

But even 10 V/cm is enough to make an ion accelerate out of trap???
!!!!!Use rotating E-field bias!!!!!

-E-field defines quantization axis
-Excellent rejection of lab-frame residual B-field.

\[ \omega_{\text{rot}} \]\ is:
BIG enough that radius of "micromotion" circle is small compared to trap size.

SMALL enough so that \( d_{\text{mol}} E >> \omega_{\text{rot}} \) and the molecule axis stays aligned with E.

One does Zeeman-level spectroscopy then in the rotating frame.
Experimental Procedure

HfF$^+ \; ^3\Delta_1 \; J=1$ ground state

• $\Omega$-doublet splitting $\sim 1$ MHz

Energies not to scale.
Nuclear spin of $\frac{1}{2}$ excluded for clarity.
An aside about lambda, or omega doubling.
Experimental Procedure

HfF⁺ ³Δ₁ J=1 ground state

• Ω-doublet splitting ~ 1 MHz

Energies not to scale. Nuclear spin of ½ excluded for clarity.
Experimental Procedure

HfF$^+ \, ^3\Delta_1$ J=1 ground state

- Electric field 1 V/cm mixes states of opposite parity.

Energies not to scale.
Experimental Procedure

HfF$^+$ $^3\Delta_1$ J=1 ground state

- Magnetic field lifts degeneracy between $|m|=1$ levels.

Energies not to scale.
**Experimental Procedure**

$\text{ThF}^+ \ {}^3\Delta_1 \ J=1$ ground state

- Electron EDM shifts the $|m|=1$ levels in opposite directions in the two $\Omega$-doublet levels.

Energies not to scale.

Science signal = $4d_{\text{e}E_{\text{eff}}} < 90$ mHz, out of “Berry’s offset” of 250 kHz

Energies not to scale.
Experimental Procedure

HfH\(^{+} 3\Delta_1 \) J=1 ground state

- Perform electron spin resonance (ESR) frequency measurement via the Ramsey Method.
- Photodissociate one spin state and count HfH\(^{+} \) and Hf\(^{+} \) ions.

Energies not to scale.
Current Experimental Progress

Laser Ablation in a Supersonic Jet
- Creation of HfF+, ThF+
- Cooling of rotational, vibrational and translational motion

Fluorescence Spectroscopy
- Measure rotational temperature of neutral HfF molecular beam

Mass Spectrometry
- Trap Hf+, HfF+, HfF₂+, HfF₃+, Th+, ThF+, ThF₂+, ThF₃+

Ion Beam Imaging
- Measure translational temperature of ion beam

1064 nm ablation pulse
~ 50 psig Ne + 1% SF₆
Hf rod
pulse valve
skimmer
RF Paul Trap
microchannel plate
photomultiplier tube

Laser Ablation in a Supersonic Jet
Fluorescence Spectroscopy
Mass Spectrometry
Ion Beam Imaging

Not to Scale
Molecular Ion Production and Trapping

RF Paul Trap and Quadrupole Mass Filter

Ion signal [arb. units] vs. mass [amu]

- $\text{Hf}^+$
- $\text{HfF}^+$
- $\text{HfF}_2^+$
- $\text{HfF}_3^+$

- $\text{Th}^+$
- $\text{ThF}^+$
- $\text{ThF}_2^+$
- $\text{ThF}_3^+$
1 amu Mass Resolution for Time of Flight Mass Spectrometry

Data from 2-photon REMPI from HfF $X^2\Delta_{3/2}$
Characterizing Temperatures

• Only get to use molecules in one electronic, vibrational and rotational state for measurement

• Ions not in the right state can still collide leading to decoherence

• Decoherence depends on temperature
  • Too hot → Ions see inhomogeneous fields
  • As temperature decreases Ion-Ion collision rate increases
Supersonic Expansion and Translational Cooling

N = 600 ions/shot

T = 2 K
Neutral HfF states observed via 2 photon ionization show low rotational temperatures.

\[ \Omega'' = \frac{3}{2} \rightarrow \Omega' = \frac{3}{2} \]

\[ T = 8 \text{ cm}^{-1}, \quad B'' = 0.284 \text{ cm}^{-1}, \quad B' = 0.264 \text{ cm}^{-1} \]
Rethinking Ion Trap Loading

Create pre-polarized sample of ions via 2 photon process

- 1064 nm ablation pulse
- skimmer
- deflection plate
- 2 photon ionization
- ~100 psig He + 1% SF$_6$
- Hf rod
- Total length ~1.5 m

Not to Scale
Current Experiment Status

- Created and Trapped HfF+ and ThF+
- Mass resolution to distinguish 1 amu differences
- Characterized supersonic expansion and beam
- Internal and External temperatures in the right range for final experiment
- Theoretical considerations of Berry’s phase and decoherence effects
  - Ongoing survey spectroscopy of HfF+ and ThF+
  - Ongoing development of methods for loading trap with ions pre-polarized
  - Spin level readout and characterization of coherence times
  - On to measurement of the electron EDM...
The decohering effects of ion-ion collisions:

Ion picks up a little random Berry's phase with each near miss.

\[ \tau_{\text{cohere}} \propto n_{\text{ion}}^{-1} \]

Sensitivity to EDM fairly flat with \( N_{\text{ion}} \), but \( N_{\text{usable}} / N_{\text{ion}} \) is critical. (And rather uncertain).
Sensitivity Estimate

\[ |d_e| < \frac{h}{2E_{\text{eff}} \tau \sqrt{N}} \]

- \( N = 10 \text{ ions/shot (10}^7 \text{ ions/day)} \)
- \( E_{\text{eff}} = 9 \times 10^{10} \text{ V/cm} \)
- \( \tau = 0.1 \text{ second} \)

proj. sensitivity: \( |d_e| < \text{few x 10}^{-29} \text{ e*cm} \) with 1 day of data
## Systematic Error Rejection. Key Chops.

<table>
<thead>
<tr>
<th>Chop:</th>
<th>B</th>
<th>E</th>
<th>E/E_{eff}</th>
<th>v</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl beam</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>YbF beam</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>PbO vapor cell</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>trapped Cs</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Trap</td>
<td></td>
</tr>
<tr>
<td>Cs fountain</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>PbF beam</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>Trapped MF+</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td></td>
<td>Rotation sense</td>
</tr>
</tbody>
</table>
Systematic Error Rejection. Key Chops.

We’ve got the chops, and:

Key fact: $\nu_{\text{science}}$ is independent of magnitude of $E$, $B$, and $\omega_{\text{rot}}$. Also should be independent of strength of ion trap confinement, $T$, and $n_{\text{ion}}$. 

<table>
<thead>
<tr>
<th>Trapped MF+</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>Y*</th>
<th>Rotation sense</th>
</tr>
</thead>
</table>
Systematics bottom line:
We haven’t thought of a killer systematic at the $10^{-28}$ level yet. We will have a number of powerful techniques for smoking out unforeseen ones.

In the end, we’ve got to try it.
Test of Physics Beyond the Standard Model

|d_e| < 1.6 x 10^{-27} e*cm [~10^{-18} Debye]
E.D. Commins TI Exp. Limit [PRL 88, 071805 (2002)]

|d_e| < 10^{-29} e*cm / day^{1/2}

Projected sensitivity: |d_e| < few x 10^{-29} e*cm / day^{1/2}
- Theoretical calculations: E_{eff} ~ 9 x 10^{10} V/cm
- Expected spin coherence time: \( \tau \sim 100 \text{ ms} \)
- Expected counting statistics: \( N \sim 9 \times 10^6 \text{ ions / day} \)