Measuring the electron edm using Cs and Rb atoms in optical lattices

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Supported by the NSF (and previously NIST and the Packard Foundation)
Atom and Molecule EDM Experiments

T-violating quark-quark interaction

Nuclear edm

Electron edm

T-violating quark-electron interaction

Hg cell (U. Washington)

TI Beam (Berkeley)
# Ongoing e⁻ EDM experiments

<table>
<thead>
<tr>
<th>Particle</th>
<th>Rb</th>
<th>Cs</th>
<th>Th</th>
<th>Fr</th>
<th>PbO</th>
<th>YbF</th>
</tr>
</thead>
<tbody>
<tr>
<td>enhancement</td>
<td>24</td>
<td>125</td>
<td>585</td>
<td>1150</td>
<td>60000</td>
<td>1.6×10⁶</td>
</tr>
</tbody>
</table>

1. **Paramagnetic atoms**: Trapped or launched Cs, Rb
   - Long coherence time
   - Penn State, Texas, LBNL

2. **Molecules and molecular ions**: PbO cell, YbF beam,
   - trapped PbF, trapped HBr⁺
   - ThO in a cryogenic beam
   - Large enhancement factor
   - Yale, Imperial, Oklahoma, JILA.
   - Harvard/Yale

3. **Solid state**: Large signal to noise ratio
   - Yale, Amherst
**Features of this atomic electron EDM experiment**

Cold Cs and Rb atoms in 1D optical lattice traps ➔
large trap volume; uniform polarization (the trap light shifts are like the quadratic dc Stark shift);
long measurement times, >2 s;
negligible \( \mathbf{v} \times \mathbf{E} \) systematic error;
only a tiny magnetic bias field needed

**Cs (and Rb) edm enhancement accurately known** ➔
120.5 ± 0.9, ultimately a precision measurement

**Cs and Rb** ➔ similar trap dynamics, but the edm enhancement factor differs by 4.69

We project a 4\( \times 10^{-30} \) e-cm sensitivity  (400x more precise)

Regan, Commins, Schmidt and DeMille, PRL 88, 071805 (2002)
Outline

- Spectroscopy of the measurement
- Atom trapping and processing
- Important experimental components
- Noise and possible systematic errors
The EDM Measurement

\[ \psi = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \]

Coherent "rf" transfer

\[ \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \]

evolve in E

\[ \exp \left( \frac{3(pE + \mu B)}{4\hbar} t \right) \]

Coherent transfer back

\[ \cos(\theta)\psi_A + \sin(\theta)\psi_{NA} \]

\[ \theta = \frac{3}{4\hbar}(pE + \mu B) t \]

Final \( m_F=0 \) pop.
Multi-photon “rf” pulses

With three frequency components we expect to achieve >99% fidelity in a few cycle long pulse.
Optical Lattices

Calculable, versatile atom traps

Far from resonance, no light scattering

1D systems model many-body system

1D: precision measurement

2D:

electron electric dipole moment search

3D:

Neutral atom quantum computing device
Processing the Atoms

Capture and cool atoms in 1.064 μm optical lattices

Each ~1mm length of pancakes yields its own fringe

Oven →10^{10} atoms/s Zeeman slower

MOT collect and precool

Launch ~20x to fill up the lattices
EDM Chamber

Magnetic Shields
Two parallel resonator enhanced 1D optical lattice traps

\[ F = \frac{FSR}{\text{Linewidth}} = \frac{23.35 \text{ ms}}{0.086 \text{ ms}} = 271 \]

\[ Q = \frac{\text{Cavity power}}{\text{Input power}} = 53.5 \]

\[ w_0 = 0.63 \text{ mm}, U \sim 250 \mu \text{K} \]
Guided Launch of atoms

Stop and trap atoms in the lattice

- **Guiding efficiency**
  - Graph showing the relationship between trap potential (µK) and guiding efficiency.

- **Center and Width**
  - Graph showing pixels over trapping time (ms).

- **Width (pixels)**
  - Graph showing width (pixels) over cooling steps.

- **Cooling steps**
  - x-axis ranges from 0 to 6.
Multiple loading atoms

Electric field plates, top view

The trap laser polarization can be made parallel to $E$ ➔ minimal trap systematic errors
Electric Field Plates

Friction-mounted; handle baking
Plate mounting to vacuum chamber
Measurement Sequence

Load Cs
  optically pump
  +HV on
  Ramsey spectroscopy
  +HV off, detect with large $B_z$
  sequentially detect $F=3$ sublevels
  (spatially resolved, normalized)

Load Cs : repeat with  -HV
Load Rb; +HV
Load Rb;  -HV
Repeat, while scanning the small $B_z$
during Ramsey spectroscopy
Uniformity of microwave pulses

With the appropriate choice of polarization, homogeneity at the atoms ~10%. Use adiabatic rapid passage for >99.9% transition efficiency.
Magnetic Shields

4 shielding layers, from 23 cm to 43 cm radii. Realistic (pessimistic) shielding factor estimate ~ $6 \times 10^4$
Cancelling B-field Gradients

dB_z/dz

measure it directly

dB_z/dx = dB_x/dz

We can map out the B-field in detail, and cancel it.

B-field gradient stability is critical

State College has no BART, no Blue Line, no IRT
Calculated surface currents to generate bias and gradient cancellation fields.

Designed for just inside the inner shield.
Implementation of 3 bias and 5 gradient cancellation coils

Use 8 homemade current sources, \(\sim 20\ \mu A\) output, with 200 nV/Hz\(^{1/2}\) noise, and 30 \(\mu V\) step size
The Shot Noise Limit

Electric Field: \( E \sim 1.5 \times 10^5 \frac{V}{cm} \)

Coherence time: \( T \sim 2 \, s \)

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

Integration time: \( \tau \sim 24 \, hr \)

\[
\delta p_e = \frac{4\hbar}{6R_{Cs}E\sqrt{NT\tau}} = 4 \times 10^{-30} \, e \cdot cm \quad \text{For Cs, } F=3
\]

\[
\delta p_e = \frac{\hbar}{R_{Rb}E\sqrt{NT\tau}} = 4 \times 10^{-30} \, e \cdot cm \quad \text{For Rb, } F=1
\]
Noise Considerations

Resonance shifts: must be $<\sim 5$ Hz

E-field magnitude fluctuation: $10^{-3}$
B$_z$-field magnitude: $<\sim 2\ \mu G$
B$_z$-field gradient: $<\sim 2\ \mu G/cm$
Trap linear polarization quality: $10^{-4}$
Trap intensity: insensitive

Common-mode (for parallel traps) noise: must be $<\sim 100$ mHz

Readout fluorescence frequency: insensitive
B-field fluctuations: preferably $<\sim 50$ nG shot to shot
More Noise Considerations

Uncorrelated noise: between parallel traps
~15 \( \mu \text{Hz} \) at shot noise limit

Uncorrelated noise: between trapped groups
~150 \( \mu \text{Hz} \) at the shot noise limit

Eg.: B-fields from Johnson noise in conductors:
- ITO coating; all good conductors >10 cm away

Magnetic field gradient fluctuations:
\(<~10 \text{ pG/cm shot to shot}\)

Trap position noise + B-field gradient
For \( \nabla B_z \sim 40 \text{ nG/cm} \) the trap center must be stable to \(<~0.7 \mu \text{m}\)

Collision shifts:
Populations of each magnetic sublevel measured each shot.
Potential Systematic Errors

Murthy, Krause, Li, and Hunter, PRL 63, 965 (1989)
Regan, Commins, Schmidt and DeMille, PRL 88, 071805 (2002)

leakage currents:
if they're near the spacers, <~50 pA is okay;
we connect to the plates from both ends

B-field gradient + imperfect plate geometry +
imperfect E-reversal: with $\nabla B_z \sim 50$ nG/cm, need 1 μm
plate parallelism and $1 \times 10^{-4}$ E-field reversal precision

B-field gradient + patch field: $r^2_{\text{patch}} V_{\text{patch}} < 100 \mu m^2 V$

third order corrections:
beam alignment (parallel to plates): $10^{-5}$
trap retroreflection balance: $10^{-3}$
linear polarization purity: $10^{-4}$
Summary

We continue to build an experiment to measure the edm of Cs and Rb. We hope to be taking preliminary edm data this year.

Sensitivity at the shot noise limit: $4 \times 10^{-30}$ e-cm of electron edm (400 times improvement in sensitivity)

There are many handles on systematic errors, including:
- two sets of \textit{spatially resolved} atoms in opposite E-fields;
- two alkali species

If an alkali EDM can be measured, the atomic theory allows for the underlying physics to be extracted precisely.