A new measurement of the electron edm

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How a point electron gets structure

polarisable vacuum with increasingly rich structure at shorter distances:

(anti)leptons, (anti)quarks, Higgs (standard model)
beyond that: supersymmetric particles ........?
If the electron has an EDM, nature has chosen one of these, breaking T symmetry... CP
The interesting region of sensitivity between the $eEDM$ ranges of $10^{-24}$ to $10^{-22}$ (e.cm) is highlighted in green. The theoretical estimates suggest that the $eEDM$ values are insufficient to make the universe of matter. The MSSM (Minimal Supersymmetric Standard Model) and Multi-Higgs models are within this region, indicating potential CP violation effects. The left-right symmetric model and other SUSY (Super-Symmetric) models are also considered, with the selectron contributing to the sensitivity region.
The magnetic moment problem

Suppose \( d_e = 5 \times 10^{-28} \text{ e.cm} \) (the region to explore)

\[ = 3 \times 10^{-19} \text{ Debye} \]

In a field of 10kV/cm

\[ d_e \sigma \cdot \vec{E} \approx 1 \text{ nHz} \]

When does \( \mu_B \cdot B \) equal this? \( B \approx 1 \text{ fG} \)

This is very small
A clever solution

For more details, see E. A. H. Physica Scripta T70, 34 (1997)

Electric field

Atom or molecule containing electron

Amplification

(Sandars 1964)

Interaction energy

\[-d_e \eta \vec{E} \cdot \vec{\sigma}\]

F P

Polarization factor

Structure-dependent relativistic factor

\( \propto Z^3 \)
Our experiment uses a molecule - YbF

- EDM interaction energy is a million times larger (mHz)
- needs nG stray B field control

16 GV/cm
The lowest two levels of YbF: $X^2\Sigma^+ (N = 0, v = 0)$

Goal: measure the splitting $2d_e\eta E$ to $\sim 1\text{mHz}$
How it is done

Ch 15 *Cold Molecules*, eds. Krems, Stwalley and Friedrich, (CRC Press 2009)

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Measuring the edm

Interferometer phase $\phi = 2(\mu B \pm d_e \eta E) \tau / \hbar$
Modulate everything

- Generalisation of phase-sensitive detection
- Switch periodically on short timescale
  but randomly on long timescale.
- Measure all 512 correlations.

9 switches:

512 possible correlations
** Don’t look at the mean edm **

• We don’t know what result to expect.

• Still, to avoid inadvertent bias we hide the mean edm.

• A random blind offset is added that only the computer knows.

• More important than you might think.
  - e.g. Jeng, Am. J. Phys. 74 (7), 2006.
Measuring the other 511 correlations

<table>
<thead>
<tr>
<th>correlation</th>
<th>mean</th>
<th>σ</th>
<th>mean/σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>fringe slope calibration</td>
<td>(-19.8038, 0.251037)</td>
<td>78.888</td>
<td></td>
</tr>
<tr>
<td>beam intensity</td>
<td>(150.576, 1.9145)</td>
<td>78.6502</td>
<td></td>
</tr>
<tr>
<td>ϕ-switch changes rf amplitude</td>
<td>(0.0781105, 0.00478208)</td>
<td>16.334</td>
<td></td>
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<tr>
<td>E drift</td>
<td>(0.0709938, 0.00481574)</td>
<td>14.742</td>
<td></td>
</tr>
<tr>
<td>E asymmetry</td>
<td>(E, RF2F)</td>
<td>(0.0282234, 0.00457979)</td>
<td>6.16259</td>
</tr>
<tr>
<td>E asymmetry</td>
<td>(E, RF1F)</td>
<td>(0.0239194, 0.00437301)</td>
<td>5.46978</td>
</tr>
<tr>
<td>inexact π pulse</td>
<td>(DB, RF1A)</td>
<td>(-0.0212292, 0.00407424)</td>
<td>5.21058</td>
</tr>
</tbody>
</table>

- Nearly all are zero (as they should be)!
The only systematic error correction

• rf detuning from resonance
  makes a (small) interferometer phase shift
  We measure this by the \{rf1f.B\} and \{rf2f.B\} correlations
  they are both \(\sim 100\ \text{nrad/Hz}\)

• Electric field “reversal”
  changes magnitude of E (slightly) causing a Stark shift
  We measure this by the \{rf1f.E\} and \{rf2f.E\} correlations

• Together \(\leftrightarrow\) false EDM
  We measure and correct: \((+5.5 \pm 1.1) \times 10^{-28}\ \text{e.cm.}\)
• Magnetic field noise
  B fluctuations have some component synchronous with E reversal:
  \[ (-0.3 \pm 1.7) \times 10^{-28} \text{ e.cm.} \]
6194 measurements (~6 min each) at 10 kV/cm.

EDM ($10^{-25}$ e.cm) includes blind offset

25 million beam shots

Distribution of $\frac{edm}{\sigma_{edm}}$ follows a Gaussian distribution

bootstrap method determines distribution

68% confidence level

?? $\pm$ 5.7 $\times 10^{-28}$ e.cm

includes blind offset
Current status

- Previous result - Tl atoms
  \[ d_e < 2.0 \times 10^{-27} \text{ e.cm with 90\% confidence} \]

- New result - YbF - Hudson et al. (Nature 2011)
  \[ d_e = (-2.4 \pm 5.7 \pm 1.5) \times 10^{-28} \text{ e.cm} \]
  68\% statistical
  \[ \text{systematic - limited by statistical noise} \]

\[ d_e < 1 \times 10^{-27} \text{ e.cm with 90\% confidence} \]

Regan et al. (PRL 2002)
Nataraj et al. (PRL 2011)
Dzuba/Flambaum (PRL 2009)
We are ready to explore this region (if funded)

New excluded region $d_e < 1 \times 10^{-27}$ e.cm

Standard Model

Multi Higgs

MSSM

Left - Right

other SUSY

18
New cryogenic buffer gas source of YbF

Yb+AlF$_3$ target

YbF beam

YAG ablation laser

3K He gas cell

15 $\times$ more molecules/pulse

3 $\times$ longer interaction time (slower beam)

$\Rightarrow$ 10 $\times$ better signal:noise ratio

$\Rightarrow$ access to mid $10^{-29}$ e.cm range
Current status of EDMs

\[ d(\text{muon}) \leq 7 \times 10^{-19} \]

\[ d(\text{proton}) \leq 5 \times 10^{-24} \]

\[ d(\text{neutron}) \leq 3 \times 10^{-26} \]

\[ d(\text{electron}) \leq 1 \times 10^{-27} \]
Summary

- EDM is a direct probe of physics beyond SM
  - specifically probes CP violation
    (how come we’re here?)

  absence of EDM suggests no
  min. supersymmetry

Atto-eV molecular spectroscopy
tells us about TeV particle physics!