Limits on CP Violation from Searches for Electric Dipole Moments

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EDM Searches

Nuclear Physics  Atomic Physics  Molecular Physics

- Neutron
- Diamagnetic Atoms Hg, Xe, Rn
- Paramagnetic Atoms Tl, Cs, Fr
- Molecules PbO, YbF, TlF

- Atomic Theory
- Nuclear Theory
- QCD
- Quark EDM
- Quark Chromo-EDM
- Electron EDM
- Fundamental Theory – SUSY, Strings

$10^{-24}$ eV
1 eV
1 MeV
1 GeV
1 TeV
T and CP violation by a permanent EDM

- Time Reversal:
  \[ t \rightarrow -t \]
  \[ \vec{I} \rightarrow -\vec{I} \]
  \[ \vec{d} \rightarrow \vec{d} \]

- Vector:
  \[ \vec{d} = d \frac{\vec{I}}{I} \]
  \[ d \rightarrow -d \rightarrow 0 \]
  \[ d \neq 0 \rightarrow \text{violation of time reversal symmetry} \]

- CPT theorem also implies violation of CP symmetry
  \[ \text{EDM} \rightarrow \text{T violation} \leftrightarrow \text{CP violation} \]

- Interaction with electric and magnetic fields:
  \[ H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \]
Experimental Detection of an EDM

\[ H = - \vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \]

\[ \omega_1 = \frac{2 \mu B + 2dE}{\hbar} \]

\[ \omega_2 = \frac{2 \mu B - 2dE}{\hbar} \]

\[ \omega_1 - \omega_2 = \frac{4dE}{\hbar} \]

• Statistical Sensitivity: Single atom with coherence time \( \tau \):

\[ \delta \omega = \frac{1}{\tau} \]

N uncorrelated atoms measured for time \( T >> \tau \):

\[ \delta d = \frac{\hbar}{2E} \frac{1}{\sqrt{2\pi TN}} \]
Search for EDM of the neutron

Historically, neutron EDM limits eliminated many proposed theories of CP violation in \( K^0 \).
Neutron EDM Experiments

- Ramsey separated field technique (in time)
- N = 13,000 neutrons
- Storage time T = 130 sec
- E = 4.5 kV/cm

ILL, Grenoble
Neutron EDM experiments (continued)

- **ILL, Grenoble**
  - Limited by statistics
  - $^{199}$Hg co-magnetometer cancels magnetic field noise and fields from leakage currents $\sim 1$ nA

- **PNPI, Gatchina**
  - Use two regions with opposite electric fields
  - No co-magnetometer

**ILL:** $d_n = (1.9\pm 5.4) \times 10^{-26}$ e cm
  

**PNPI:** $d_n = (2.6\pm 4.0 \pm 1.6) \times 10^{-26}$ e cm
  

$|d_n| < 6 \times 10^{-26}$ e cm

90% C.L.
Search for an electron EDM

- Electron has a finite charge, cannot be at rest in an electric field
  ⇒ For purely electrostatic interactions
  \[
  \langle \vec{E} \rangle = 0 \quad \text{— Schiff shielding}
  \]

- Can be circumvented by magnetic, relativistic interactions, extended nucleus

- Enhanced in heavy atoms as
  \[
  d_a \propto d_e \alpha^2 Z^3
  \]
  ⇒ Spin-orbit interaction
  ⇒ Nuclear Coulomb field
  ⇒ Relativistic electrons near the nucleus

  \[
  d_{\text{Tl}} = -(585 \pm 50) \ d_e
  \]

Cs: 114, Fr: 1150
Berkeley Tl EDM Experiment

- Classic Ramsey separated field atomic beam apparatus
  - Flux = $10^{17}$ atoms/sec
  - Transit time = 3 msec
  - $E = 120 \text{ kV/cm}$
  - Up and down beams
  - Left and right beams
  - 4 Na co-magnetometer beams
Berkeley Tl EDM Experiment (cont.)

Main limitation- Systematic effects

• Motional Fields \( B_m = E \times v/c \)
  \( \Rightarrow \) Need to be suppressed by a factor of \( 10^8 \)!
  * Suppressed for \( v \perp B, E \)
  * Cancel between up and down beams
  * Problems due to misalignment coupled with field gradients

• Geometric Phase
  \( \Rightarrow \) Generated by complicated gradients as atoms pass in and out of electric field region
  \( \Rightarrow \) Na beams could be used for diagnostic
  * But have additional non-adiabatic effects

\[
d_e = (6.9 \pm 7.4) \times 10^{-28} \, \text{e} \cdot \text{cm}
\]

\[
|d_e| < 1.6 \times 10^{-27} \, \text{e} \cdot \text{cm} \, (90\% \, \text{C.L.})
\]

B. Regan, E. Commins, C. Schmidt, D. DeMille

\( \times 2.5 \) improvement
$^{199}\text{Hg EDM Experiment}$

**Synchronous Optical Pumping**

$\omega_{\text{chop}} = \omega_{\text{Larmor}}$

**Monitoring Spin Precession**

$\alpha_{\text{rot}} \propto k \cdot S$

- **Si Photodiodes**
- **Hg Laser**
- **Hg Cells**
- **BBO Lin. Pol.**
- **Ultra-low noise current source**
- **Magnetic Shields**
- **Pneumatic Actuators**
- **Synch. Chopper**
- **Norm.**
$^{199}$Hg Cells

- UV curing
- Norland glue
- SnO$_2$ conductive coating
- US penny
- Paraffin
- Synthetic quartz

$\text{N}_2 + \text{CO buffer gas (500 torr), saturated } ^{199}\text{Hg vapor}$

- Number of $^{199}$Hg atoms: $2 \times 10^{14}$
- Optical depth on resonance: 2.5
- Spin relaxation time: 100 – 200 sec
- Leakage currents at 10 kV: 0.5 – 1 pA
Leakage Currents

Only helical leakage currents contribute to first order:

One complete loop around the cell with $I = 0.6$ pA:

$$d_{\text{leak}} < 0.25 \times 10^{-28} \, \text{e cm}$$

Correlation Slope

$$[-0.4 \pm 2.0] \times 10^{-29} \, \text{e cm/pA}$$

From correlation:

$$d_{\text{leak}} < 0.14 \times 10^{-28} \, \text{e cm}$$
$^{199}\text{Hg EDM Data}$

- 50,000 electric field reversals
- Regular reversals of
  - Magnetic Field
  - Acquisition Channels
  - EDM cells
- Other changes
- Over 30 correlations examined

$\chi^2/\text{n.d.f.} = 0.95$

$d_{\text{Hg}} = -[1.06\pm0.49 \pm0.40] \times 10^{-28} \text{ e cm}$

$|d_{\text{Hg}}| < 2.1 \times 10^{-28} \text{ e cm at 95\% C.L.}$


$\times 4$ improvement
Interpretation of $^{199}$Hg EDM Limit

- $^{199}$Hg atomic EDM is induced by the nuclear Schiff moment $S$
  - Electric field inside the nucleus mixes atomic $S$ and $P$ states
    \[ d_a = R_A S \]

- Schiff moment is induced by CP-odd nuclear force
  - Interaction between valence neutron and core protons
    \[ S = R_N \bar{g}_{\pi NN} \]

- CP-odd pion exchange dominated by chromo-EDMs of quarks
  - Isospin-triplet coupling dominates
    \[ \bar{g}^{(1)}_{\pi NN} = R_{QCD} (\tilde{d}_u - \tilde{d}_d) \]
**Recent Calculations for EDM interpretation**

### Mercury

<table>
<thead>
<tr>
<th>Result</th>
<th>Change</th>
<th>Accuracy</th>
<th>Notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_A$</td>
<td>$-2.8 \times 10^{-4}$</td>
<td>30%</td>
<td>Includes finite nucleus, relativistic electron corrections</td>
<td>Dzuba, Flambaum, Ginges, Kozlov, hep-ph/0203202</td>
</tr>
<tr>
<td>$R_{QCD}$</td>
<td>20 Factor of 3</td>
<td>Factor of 2</td>
<td>QCD sum rules</td>
<td>Pospelov, Phys. Lett. B530, 123 (2002))</td>
</tr>
</tbody>
</table>

### Neutron

QCD Sum Rules

$$d_n = (1 \pm 0.5)[0.7d_d - 0.2d_u + 0.6e\tilde{d}_d + 0.3e\tilde{d}_u]$$

Factor of 2 different from SU(6) and NDA models
## Limits from neutron and $^{199}$Hg EDMs

<table>
<thead>
<tr>
<th></th>
<th>Neutron</th>
<th>$^{199}$Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QCD $\bar{\theta}$</strong></td>
<td>$\bar{\theta} = (1.9 \pm 2.8) \times 10^{-10}$</td>
<td>$\bar{\theta} = (1.2 \pm 0.7) \times 10^{-10}$</td>
</tr>
</tbody>
</table>
| **Quark EDMs and Chromo-EDMs** | $1.3d_d - 0.3d_u + e(\tilde{d}_d + 0.5\tilde{d}_u)$  
$= (4.2 \pm 6.2) \times 10^{-26}$ ecm | $e(\tilde{d}_d - \tilde{d}_u)$  
$= -(1.6 \pm 0.9) \times 10^{-26}$ e cm |

Assuming Peccei-Quinn mechanism for removing $\bar{\theta}$ term

- $^{199}$Hg EDM has higher sensitivity
- Constrains a different combination of quark EDMs
Limits on CP violation in Supersymmetry

- For “natural” CP violation in SUSY, EDMs should have been found a long time ago

Based on:
S. Abel, S. Khalil, O. Lebedev

Includes latest limits and calculations

\[ \tan \beta = 3, \ m_{1/2} = A = 200 \text{ GeV}, \ \phi_\mu = \phi_A = \pi/2 \]

Large masses
4–10 TeV

Small phases
10^{-2} – 10^{-3}

Cancellations
SUSY CP Problem

- Large Superpartner Masses
  \[ \Rightarrow \text{Higgs-mediated contribution still large for } \tan \beta > 10 \]
  \[ \Rightarrow \text{Two-loop chargino contribution to EDMs further limits possibility of electroweak baryogenesis} \]

- Small SUSY phases
  \[ \Rightarrow \text{Difficult to reconcile with large } \delta_{\text{CKM}} \text{ in string models} \]

- Cancelations
  \[ \Rightarrow \text{Further constrained by addition of } ^{199}\text{Hg EDM} \]

Lebedev and Pospelov
hep-ph/0204359

Chang, Chang, Keung
hep-ph/0205084

Abel, Khalil, Lebedev
hep-ph/0112260

Falk, Olive, Pospelov, Roiban,

Abel, Khalil, Lebedev

Barger, Falk, Han, Jiang, Li,
Plehn, Phys. Rev. D 64, 056007 (2001)
Further Improvements in $^{199}$Hg Experiment

- 4 Cells
  - Magnetic Gradient Noise Cancellation
    \[ S = (\omega_2 - \omega_3) - \frac{1}{3} (\omega_1 - \omega_4) \]
  - Leakage Current Diagnostic
    \[ L = (\omega_2 + \omega_3) - (\omega_1 + \omega_4) \]

- Longer lifetimes, better signals

Clark Griffith et al, C4.001,
Wednesday 2:00 PM, Rm 102, Tyler Hall
Search for EDM in liquid $^{129}\text{Xe}$

\[ \delta d = \frac{\hbar}{2E} \frac{1}{\sqrt{2} \tau TN} \]

Limiting neutron, $^{199}\text{Hg}$ experiments

<table>
<thead>
<tr>
<th></th>
<th>Liquid $^{129}\text{Xe}$ (ideal)</th>
<th>Improv. Rel. $^{199}\text{Hg}$</th>
<th>Liquid $^{129}\text{Xe}$ (easy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$10^{22}$ cm$^{-3}$</td>
<td>$\times10^8$</td>
<td>$10^{20}$</td>
</tr>
<tr>
<td>Spin lifetime</td>
<td>$&gt;1300$ sec</td>
<td>$\times10$</td>
<td>$10$ sec</td>
</tr>
<tr>
<td>E field</td>
<td>$400$ kV/cm</td>
<td>$\times50$</td>
<td>$60$ kV/cm</td>
</tr>
<tr>
<td>$\delta d$ (stat.)/1 day</td>
<td>$10^{-36}$ e cm</td>
<td></td>
<td>$10^{-33}$ e cm</td>
</tr>
</tbody>
</table>

+ SQUIDs can be used for detection and as a near-magnetometer

— Smaller sensitivity to CP-odd interactions by a factor of 6 compared with Hg.

\[ d_{\text{Xe}} \sim 10^{-30} - 10^{-31} \text{ e cm with LN}_2 \text{ SQUIDs} \]

\[ d_{\text{Xe}} \sim 10^{-33} \text{ e cm with LHe SQUIDs} \]
Measurement of $^{129}$Xe EDM

- Find non-linear evolution in response to magnetic field gradients
  - Positive feedback due to Xe self-interaction field
  - Allows “exponential” amplification of potential EDM signal
  - In good agreement with simple model

$\phi \sim \sinh \left( \frac{t}{\tau} \right)$

$\tau \sim 1 \text{ sec}$

Micah Ledbetter, C4.004

Wednesday 2:00 PM, Rm 102, Tyler Hall
Search for electron EDM using a laser trap

- Dipole traps give long coherence time $\tau=10$ sec for paramagnetic atoms (3 msec for Tl beam)
- No $E \times v/c$ effects
- Laser confinement minimizes motion of atoms in gradients
- Cs is the element of choice (Fr ?)
- Rb co-magnetometer
- Apparatus being built

$\epsilon_e \sim 10^{-28} - 10^{-29}$ e cm
Search for electron EDM using PbO

- PbO has a metastable paramagnetic state a(1)
  \[ \Rightarrow \text{Can be populated with a laser, no chemistry} \]
- a(1) has a very small splitting of opposite parity \( \Omega^\pm \) states
  \[ \Rightarrow \text{Strongly mixed even by a 20V/cm field} \]
  \[ \Rightarrow \text{Can operate in a cell with density } 10^{14} \text{ cm}^{-3} \]
- Heavy element, strong molecular field – \( 10^3 \) larger enhancement than Tl
- Sign of EDM effect opposite for two RF transitions

\[ m = -1 \quad 0 \quad 1 \]

\[ d_e \approx 10^{-29} - 10^{-31} \text{ e cm} \]
Search for neutron EDM in superfluid He

- Superthermal production in $^4$He
  $\Rightarrow$ N increased by 100 - 10000
- Good isolator, low temperature
  $\Rightarrow$ E increased by 5
- Dopped with a small amount of polarized $^3$He
  $\Rightarrow$ UCN polarizer
  $\Rightarrow$ UCN analyzer
- SQUID magnetometers
  $d_n \sim 10^{-27} - 10^{-28} \, \text{e cm}$

Steve Lamoreaux,
Martin Cooper
LANL
Conclusions

- Despite over 40 years of experiments a permanent EDM still has not been observed.

- This fact gives stringent constraints on how CP symmetry is violated (or not violated) in the Universe.

- Combination of different types of measurements is particularly valuable for eliminating possible scenarios of CP violation.

- While current techniques approach their limits, a new set of experiments promise to improve the sensitivity further by up to 4 orders of magnitude.