Searches for Electric Dipole Moments - EDMs

• Why are they important (even after LHC)?
• Which EDMs are important?
• What is the future of EDMs and how do we get there?
EDMs violate Time Reversal & Parity Symmetry

Quantum Picture - Discrete Symmetries

Assume \( \tilde{\mu} = \mu \frac{\vec{J}}{J} \) and \( \tilde{d} = d \frac{\vec{J}}{J} \)

no spin \( \rightarrow \) no EDM

Then non-relativistic Hamiltonian is

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

P-even \hspace{1cm} T-even
P-odd \hspace{1cm} T-odd

Non-zero EDM violates both T and P
& assuming CPT invariance it also violates CP
Note: Nucleon EDM also appears in Electron Scattering

- **Nucleon EM current:**

\[
\langle n \mid J_{\mu}^{EM} \mid n \rangle = \bar{u}_N \left[ F_1(q^2)\gamma_\mu + \frac{F_2(q^2)}{2M_N} \sigma_{\mu\nu} q_\nu + F_A(q^2)(iq^2 \gamma_\mu \gamma_5 - 2M_N q_\mu \gamma_5) + \frac{F_3(q^2)}{2M_N} \gamma_5 \sigma_{\mu\nu} q_\nu \right] u_N
\]

- **F\textsubscript{3}** related to nucleon EDM: 
  \[ d_n = \lim_{q^2 \to 0} \frac{F_3(q^2)}{2M_N} \]

- **Also related to Transversity!**

\[
\delta q = \int_0^1 dx \left[ h_1(x) - \bar{h}_1(x) \right]
\]

\[ d_n = \sum_q d_q \delta q \]

Tensor Charge

Relates neutron EDM to quark EDM \( d_q \)
New CP Violation May Help Resolve Matter/Antimatter Asymmetry of the Universe

• **Sakharov Criteria**
  - Particle Physics can produce matter/antimatter asymmetry in the early universe *IF* there is:
    - Baryon Number Violation (need only very small amount)
    - CP & C violation (need much bigger CP violation than in Standard Model)
    - Departure from Thermal Equilibrium
How big is the are EDMs?

*e.g. neutron:*

\[ +\frac{2}{3}e \quad \text{u-quark} \]

\[ -2\left(\frac{1}{3}e\right) \quad \text{d-quarks} \]

If \( l \sim 0.1 \, r_n \)

\[ d_n \sim 5 \times 10^{-14} \, \text{e-cm} \]

But Experiment says

\[ d_n < 3 \times 10^{-26} \, \text{e-cm} \]
Origin of elementary EDMs

• Standard Model EDMs are due to CP violation in the quark weak mixing matrix CKM (e.g. the $K^0/B^0$-system) but...
  - $e^-$ and quark EDM’s are zero at 1 and 2 loops
  - Need at least three loops to get EDM’s (electron actually requires 4 loops!)
    • Thus EDM’s are VERY small in standard model

\[ \text{e.g. neutron EDM in Standard Model is } \sim 10^{-32} \text{ e-cm} \left( \sim 10^{-19} \text{ e-fm} \right) \]

Experimental neutron limit: $< 3 \times 10^{-26} \text{ e-cm}$
Is there a “natural” source for new CP violation & EDMs?

• New physics (e.g. SUSY/other) often has additional CP violating phases in added couplings
  - New phases: ($\phi_{CP}$) should be ~ 1 (why not?)

• Contribution to EDMs depends on masses of new particles

  \[ d_n \sim 10^{-24} \text{ e-cm} \times \sin\phi_{CP}(1 \text{ TeV}/M_{SUSY})^2 \]

Note: experimental limit: \[ d_n < 0.03 \times 10^{-24} \text{ e-cm} \]
Impact of non-zero EDM

- Must be new Physics
- Sharply constrains models beyond the Standard Model (especially with LHC data)

Example for Chromo-EDMs

McKeen, Pospelov & Ritz
hep-ph 1303.1172

Heavy sfermions >50 TeV
1 TeV gauginos
Present EDM Limits
Particle EDM Zoo (where to look)

- Paramagnetic atoms and polar molecules are very sensitive to $d_e$

- Diamagnetic atoms are sensitive to quark “chromo-“EDM \( (\text{gluon}+\text{photon}) = \tilde{d}_q \) and $\Theta_{QCD}$

- Neutron and proton sensitive to $d_q$, $\tilde{d}_q$ & $\Theta_{QCD}$

Observation or lack thereof in one system does not predict results for other systems
Note: $d_e$ and storage ring EDMs discussed earlier ...

- D. Kawall
  - Recent Results and Progress on Leptonic and Storage Ring EDM Searches
- A. Lehrach
  - Storage Ring Based EDM Search
- A. Saleev
  - Studies of Systematic Limitations in EDM Searches in Storage Rings

- Here we will focus on hadronic EDMs
Origin of Hadronic EDMs

- Hadronic (strongly interacting particles) EDMs are from
  - $\theta_{\text{QCD}}$ (an allowed term in QCD)
  - or from the quarks and gluons themselves
## Relative EDM Sensitivities

<table>
<thead>
<tr>
<th>System</th>
<th>Dependence (simple quark model)</th>
<th>Present Limit (e-cm)</th>
<th>Future (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>[d_n \sim (3 \times 10^{-16}) \theta_{QCD} + 0.7(d_d - \frac{1}{4} d_u) + 0.6(\tilde{d}_d + \frac{1}{2} \tilde{d}_u)]</td>
<td>(&lt;3 \times 10^{-26})</td>
<td>(10^{-28})</td>
</tr>
<tr>
<td>(^{199}\text{Hg})</td>
<td>[d_{\text{Hg}} \sim (0.001 \times 10^{-16}) \theta_{QCD} - 0.006(\tilde{d}_d - \tilde{d}_u)]</td>
<td>(&lt;3 \times 10^{-29})</td>
<td>(10^{-30})</td>
</tr>
</tbody>
</table>
What is the precision for an EDM measurement?

\[ \mathcal{E} = \hbar \omega = \vec{d} \cdot \vec{E} \]

Uncertainty in \( d \):

\[ \sigma_d \sim \frac{\Delta \mathcal{E}}{|\vec{E}|} \]

\[ \Delta \mathcal{E} \Delta t \sim \hbar \]

Precise energy measurement requires long individual measurement time, giving

\[ \sigma_d^1 \sim \frac{\Delta \mathcal{E}}{|\vec{E}|} \sim \frac{\hbar}{|\vec{E}|T_m} \]

Can improve with counting statistics

\[ \propto \frac{1}{\sqrt{N}} \]
Simplified Measurement of EDM

1. Inject polarized particle
2. Rotate spin by \( \pi/2 \)
3. Flip E-field direction
4. Measure frequency shift

\[ \nu = \frac{2\mu \cdot \vec{B} \pm 2\vec{d} \cdot \vec{E}}{h} \]

must know \( B \) very well
Hadronic EDM experiments & plans

• Heavy Atoms increase sensitivity to EDM
  - Atomic electrons shield external E-field
  - Need to compensate for this via finite size

• $^{199}\text{Hg}$ – lowest measured EDM limit

• Deformed heavy-nuclei
  - Deformation can enhance further
  - several radioactive species appear best

• Improvements in Neutron technology
  - Vigorous world-wide effort underway
Electric Dipole Moment of $^{199}$Hg
University of Washington

2009: Last reported result
\[ d(^{199}\text{Hg}) = (0.49 \pm 1.29 \pm 0.76) \times 10^{-29} \text{ e-cm}; \]
PRL 102, 101601 (2009)

\[ | d(^{199}\text{Hg}) | \ < 3.1 \times 10^{-29} \text{ e-cm} \]

2014: EDM data-taking is underway.

We anticipate a reportable result by the end of 2014 with a statistical uncertainty of \( \sim 3.5 \times 10^{-30} \text{ e-cm}. \)

2017: They believe another factor of 3 increase in sensitivity is achievable

• With a larger electric field, longer spin coherence times, and better control of the uv beam paths, the current apparatus could reach a statistical sensitivity of \( \sim 1 \times 10^{-30} \text{ e-cm}. \)

Thanks to B. Heckel (UW)
EDM of $^{225}$Ra is Significantly Enhanced

- Closely spaced parity doublet - Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation - Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure ($^{225}$Ra / $^{199}$Hg ~ 3) - Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet

$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$

$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$

55 keV

Schiff moment

$$\text{Schiff \hspace{1mm} moment} = \sum_{i\neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$  

Enhancement Factor: EDM ($^{225}$Ra) / EDM ($^{199}$Hg)

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIII</td>
<td>300</td>
<td>4000</td>
</tr>
<tr>
<td>SkM*</td>
<td>300</td>
<td>2000</td>
</tr>
<tr>
<td>SLy4</td>
<td>700</td>
<td>8000</td>
</tr>
</tbody>
</table>

Schiff moment of $^{225}$Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of $^{199}$Hg, Dobaczewski, Engel et al., PRC (2010)

- Near goal: $10^{-26}$ e cm
- 5-10 years: $10^{-28}$ e cm
- $10^{-30}$ e cm may be ultimate limit

Thanks to Z-T Lu (ANL)

$\rightarrow$ Deformation enhanced $^{223}$Rn experiment also under development at TRIUMF
History of nEDM Sensitivity

Theoretical Prediction:

- Electromagnetic
- Milliweak
- Weinberg Multi-Higgs
- Supersymmetry
- Cosmology
- Superweak
- Standard Model

Neutron EDM Experimental Limit (e cm)

Best Existing Neutron Limit: ILL-Grenoble neutron EDM Experiment

- Trapped Ultra-Cold Neutrons (UCN)
- $N_{UCN} = 0.5$ UCN/cc
- $|E| = 5 - 10$ kV/cm
- 100 sec storage time

$\sigma_d < 3 \times 10^{-26}$ e-cm

Harris et al. Phys. Rev. Lett. 82, 904 (1999)
Technologies for new neutron EDM

• UCN (or beam for crystal exps)
  - $SD_2$, Superfluid $^4$He
• HV - the bigger the better
  - Vacuum, LHe, Crystal
• Magnetic Shielding
  - Room temperature and Cryogenic Shields
• Magnetometers
  - Atomic & others: $^{199}$Hg, $^3$He, $^{129}$Xe, $^{133}$Cs, SQUIDs, neutrons
  - Co-magnetometers most effective
Worldwide neutron EDM Searches

- SNS
- J-PARC
- PSI
- FRMII
- ILL
- TRIUMF
- LANL
- RCNP
- PNPI
<table>
<thead>
<tr>
<th>Experiment</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>$\sigma_d$ Goal (10^{-28} e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL-PNPI</td>
<td>ILL turbine PNPI/Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey technique for $\omega$ E=0 cell for magnetometer</td>
<td>Phase1 &lt; 100</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILL Crystal</td>
<td>Cold n Beam</td>
<td>solid</td>
<td>Crystal Diffraction Non-Centrosymmetric crystal</td>
<td>&lt; 100</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PSI EDM</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey for $\omega$, external Cs &amp; $^3$He, Hg co-magnetom. Xe or Hg comagnetometer</td>
<td>Phase1 ~ 50</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Munich FRMII</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Room Temp., Hg Co-mag., also external Cs mag.</td>
<td>&lt; 5</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>RCNP/TRIUMF</td>
<td>Superfluid $^4$He</td>
<td>Vac.</td>
<td>Small vol., Xe co-mag. @ RCNP Then move to TRIUMF</td>
<td>&lt; 50</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>SNS nEDM</td>
<td>Superfluid $^4$He</td>
<td>$^4$He</td>
<td>Cryo-HV, $^3$He capture for $\omega$, $^3$He co-mag. with SQUIDS &amp; dressed spins, supercond.</td>
<td>&lt; 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Solid</td>
<td>Crystal Diffraction Non-Centrosymmetric crystal</td>
<td>&lt; 10?</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LANL</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>R &amp; D</td>
<td>~ 30</td>
</tr>
</tbody>
</table>

= sensitivity < 5 x 10^{-28} e-cm
Comparison of Capabilities for High Sensitivity experiments

<table>
<thead>
<tr>
<th>Capability</th>
<th>Cryo</th>
<th>FRM</th>
<th>PSI1</th>
<th>PSI2</th>
<th>SNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δω via accumulated phase in n polarization</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Δω via light oscillation in $^3$He capture</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Horizontal B-field</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>*Comagnetometer</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>*Superconducting B-shield</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>*Dressed Spin Technique</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>*Multiple EDM cells</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>*Temperature Dependence of Geometric phase effect</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>

Last five items (marked with *) denote a systematics advantage

- SNS is arguably the most ambitious of the new experiments
- Will probe for systematic effects < $1 \times 10^{-28}$ e-cm
US nEDM Experiment at Oak Ridge Lab-SNS


• Production of ultracold neutrons (UCN) within the apparatus
  - high UCN density and long storage times

• Liquid He as a high voltage insulator
  - high electric fields

• Use of a $^3\text{He}$ co-magnetometer and superconducting shield
  - Control of magnetic field systematics

• Use $\vec{n} - ^3\text{He}$ capture $\rightarrow$ Scintillation light variation allows neutron precession frequency measurement via two techniques:
  • free precession
  • dressed spin techniques

• Sensitivity estimate: $d_n \sim 3-5 \times 10^{-28} \text{ e\cdotcm} \ (90\% \text{ CL after 3 yrs)}$
SNS-nEDM Experiment

Neutron beam is into page
1. Load collection volume with polarized $^3$He atoms
2. Transfer polarized $^3$He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to $B_0$
5. Measure precession frequency
6. Remove reduced polarization $^3$He atoms from measurement cell
7. Flip E-field & Go to 1.

$^3$He functions as “co-magnetometer”

Since $d_{^3\text{He}} \ll d_n$ due to e- screening
Two ways to measure nEDM via direct frequency measurement

e.g. via spin-dependent neutron capture on polarized $^3$He

Signal oscillates at n-$^3$He beat frequency

N (counts/0.03 sec)
Can also take advantage of “Dressed” Spins

Add a non-resonant AC B-Field

Use of two measurement techniques provides critical cross-check of EDM result with different systematics

Can match effective precession frequency of n & $^3$He about $B_0$

Video from Pinghan Chu (Duke)
SNS nEDM Construction

• Four year “Critical Component Demonstration” construction underway
  - Construction of the most challenging components 2014-2017
  - Build from the inside to the outside
• Followed by two year Conventional Construction
  - Begin data taking by 2020
Future nEDM Sensitivity

Theoretical Prediction:
- Electromagnetic
- Milliweak
- Weinberg Multi-Higgs
- Supersymmetry
- Cosmology
- Superweak
- Standard Model

Future neutron EDM
Summary

- Greatly improved EDM sensitivity can probe Beyond-Standard-Model physics at very high mass scales

- A number of exciting technologies are being developed to extend the EDM sensitivity by more than two orders-of-magnitudes

- We look forward to the discovery of an EDM in the next decade
Extra Slides
nEDM @ SNS COLLABORATION

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**Valparaiso University**  
S. Baeßler  
**University of Virginia**  
S. Lamoreaux  
**Yale University**
Note: Some molecules have HUGE EDMs!

\[ H_2O: \quad d = 0.4 \times 10^{-8} \text{ e-cm} \]
\[ NaCl: \quad d = 1.8 \times 10^{-8} \text{ e-cm} \]
\[ NH_3: \quad d = 0.3 \times 10^{-8} \text{ e-cm} \]

But \( NH_3 \) EDM is not \( T \)-odd or \( CP \)-odd since

\[ \vec{d} \neq d \frac{\vec{J}}{J} \]

\( \left( \text{both} \quad \vec{d} = +d \frac{\vec{J}}{J} \quad \text{and} \quad \vec{d} = -d \frac{\vec{J}}{J} \quad \text{exist!} \right) \]

If Neutron had degenerate state it would not violate \( T \) or \( CP \)

Ground state is actually a superposition
How to Measure an EDM
Ramsey Separated Oscillatory Field Technique

1. “Spin up” neutron...

2. Apply $\pi/2$ spin flip pulse...

3. Free precession...

4. Second $\pi/2$ spin flip pulse.

If small angle (phase) is added after ~ 1000s of oscillations (e.g. from EDM) then final spin doesn’t point exactly down.