Neutron Electric Dipole Moment (EDM)

• Why is it interesting? (recall S. Gardner)
• How do we measure it?
• What is the present limit?
• How can we significantly improve the sensitivity (& discover neutron EDM!!)?
What is an EDM?

\[ d = e \ell \]

How big is the neutron EDM?

\[ d_n \sim 4 \times 10^{-14} \text{ e-cm} \]

Experiment says \( d_n < 3 \times 10^{-26} \text{ e-cm} \)
Why Look for EDMs?

- Existence of EDM implies violation of Time Reversal Invariance

\[ J^+ - J^- \]

- Time Reversal Violation seen in \( K^0 - \bar{K}^0 \) system
- May also be seen in early Universe
  - Matter-Antimatter asymmetry

Cartoon

\[ \begin{align*}
\text{+} & \quad \text{t} \Leftrightarrow -t \\
\text{-} & \quad \bar{J} \Leftrightarrow -\bar{J} \\
\text{+} & \quad \bar{d} \Leftrightarrow \bar{d} \\
\text{-} & \quad -\bar{J}
\end{align*} \]

but the Standard Model effect is too small!
Quantum Picture - Discrete Symmetries
(08 Nobel Prize)

Charge Conjugation: \( \hat{C} \psi_n \Rightarrow \psi_{\bar{n}} \)
Parity: \( \hat{P} \psi(x,y,z) \Rightarrow \psi(-x,-y,-z) \)
Time Reversal: \( \hat{T} \psi(t) \Rightarrow \psi(-t) \)

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

Non-Relativistic Hamiltonian

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

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>P</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>( d )</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>( \vec{E} )</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>( \vec{B} )</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>( J )</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Non-zero \( d \) violates \( T \) and \( CP \)
(Field Theories generally preserve CPT)

\( \text{TPC} \)
\( \text{EdBH} \)
But some molecules have HUGE EDMs!

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

Note: n-EDM < 3 \times 10^{-26} \text{ e-cm}

But NH\textsubscript{3} EDM is not T-odd or CP-odd since

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

\[
\begin{align*}
\text{both } \bar{d} &= +d \frac{\vec{J}}{J} \quad \text{and} \quad \bar{d} = -d \frac{\vec{J}}{J} \text{ exist!}
\end{align*}
\]

If Neutron had degenerate state

\[
\vec{J}
\]

\[
\begin{align*}
u & \quad \text{dd} \\
dd & \quad \text{u}
\end{align*}
\]

it would not violate T or CP

Ground state is actually a superposition
Role of CP Violation in the 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
    • CP & C violation
    • Departure from Thermal Equilibrium
Baryogenesis

• **Plausibility Argument**
  - Consider heavy boson - $X$
    - Baryon number violation:
      $\Gamma_{X \rightarrow qq} = (1 + \Delta_q)\Gamma_q$; $\Gamma_{X \rightarrow q\ell} = (1 - \Delta_\ell)\Gamma_\ell$
      $\Gamma_{\bar{X} \rightarrow \bar{q}\bar{q}} = (1 - \Delta_q)\Gamma_q$; $\Gamma_{\bar{X} \rightarrow \bar{q}\bar{\ell}} = (1 + \Delta_\ell)\Gamma_\ell$
    - **C-Violation & CP-Violation**
      \[
      \Gamma_X^{\text{Tot}} = \Gamma_{\bar{X}}^{\text{Tot}} \quad \text{(CPT conservation!!)} \quad \text{if} \quad \Delta_q\Gamma_q = \Delta_\ell\Gamma_\ell
      \]
  - **Out of Thermal Equilibrium**
    Otherwise, in Equilibrium the reverse reactions:
    (e.g. $qq \rightarrow X$, $\bar{q}\bar{q} \rightarrow \bar{X}$) will smooth out any matter/antimatter excess
Electroweak Baryogenesis

Possible source of Matter-Antimatter Asymmetry

Before Electroweak Phase Transition

After EW Phase Transition

Today

$A_{BB} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 0$

$A_{BB} \approx 10^{-10}$

$A_{BB} \approx 1$

$N_{\gamma}$

$N_B \approx \frac{1}{2}$

$\approx 10^{-10}$
But Standard Model CP violation (CKM matrix) is Insufficient

- Must search for new sources of CP
  - B-factories, Neutrinos, EDMs
- Quarks/Gluons
  - Allows production of matter-antimatter asymmetry via “Baryogenesis”
- Neutrino mixing suggests possibility of new CP violation in leptons
  - Allows production of matter anti-matter asymmetry via “Leptogenesis”
What is the possible origin of new CP-violation?

• New physics (e.g. SuperSymmetry=SUSY)
What's in SUSY?

• Great Names:
  - Squarks, sleptons, gauginos, winos, binos, neutralinos,…

• In MSSM
  - 124 parameters - 19 from Standard Model & 105 new parameters (from SUSY and also from SUSY breaking)
    - 36 mixing angles for squarks & sleptons
    - 40 CP-violating phases for squarks & sleptons
    - 21 squark & slepton masses
    - 5 couplings and 3 phases from gauginos/higgsinos
SUSY, CP-Violation and EDMs

- New physics (e.g. SuperSymmetry = SUSY) has additional CP violating phases in added couplings
  - New phases: ($\phi_{CP}$) should be $\sim 1$ (why not?)
- Contribution to EDMs depends on masses of new particles
  \[ d_n \sim 10^{-24} \text{ e-cm x sin} \phi_{CP} (200 \text{ GeV}/M_{SUSY})^2 \]

Note: experimental limit: \[ d_n < 0.03 \times 10^{-24} \text{ e-cm} \]
Standard Model Prediction: \[ d_n < 10^{-31} \text{ e-cm} \]
Origin of 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 in 1$^{\text{st}}$ & 2$^{\text{nd}}$ order
  - Need at least three Feynman diagram “loops” to get EDM’s (electron actually requires 4 loops!)
- Thus EDM’s are VERY small in standard model

Neutron EDM in Standard Model is
$\sim 10^{-32}$ e-cm ($=10^{-19}$ e-fm)
Experimental neutron limit: $< 3 \times 10^{-26}$ e-cm

Electron EDM in Standard Model is
$< 10^{-40}$ e-cm
Origin of Hadronic EDMs

• Hadronic (strongly interacting particles) EDMs are from
  - $\theta_{QCD}$ (a special parameter in Quantum Chromodynamics - QCD)
  - or from the quarks themselves

\[
L_{eff} = \frac{g_s^2}{32\pi^2} \bar{\theta} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + \frac{1}{3} \omega f^{abc} G^a_{\mu\nu} \tilde{G}^{\nu\beta,b} G^c_{\mu,c} \\
- \frac{i}{2} \sum_{i=e,u,d,s} d_i \bar{\psi}_i (F\gamma_5) \gamma_5 \psi - \frac{i}{2} \sum_{i=u,d,s} \tilde{d}_i \bar{\psi}_i g_s (G\gamma_5) \gamma_5 \psi + \cdots
\]

- $\theta_{QCD}$
- Weinberg 3-gluon term
- $e^-, \text{quark EDM}$
- quark color EDM (chromo-EDM)
EDM from $\theta_{\text{QCD}}$

- This is the strong-CP problem in QCD

\[ L_{\text{QCD}} = -\theta \left( \frac{\alpha_s}{8\pi} \right) \tilde{G}_a^{\mu\nu} G_a^{\mu\nu} \]

- $\theta_{\text{QCD}}$ should be naturally about $\sim 1$

- This gives a neutron EDM of

\[ d_n = \frac{g_{\pi NN}}{4\pi^2} \left( \frac{e}{m_p f_\pi} \right) \ln \left( \frac{m_\rho}{m_\pi} \right) \left( \frac{m_u m_d}{m_u + m_d} \right) \theta \approx (-10^{-15}) \theta \text{ e - cm} \]

but $d_n^{\text{exp}} < 10^{-25} \text{ e - cm}$

\[ \therefore \theta < 10^{-10} \text{ Why so small??} \]
EDM from $\theta_{QCD}$

- Small $\theta_{QCD}$ does not provide any new symmetry for $\mathcal{L}_{QCD}$
  - Popular solution is “axions” (Peccei-Quinn symmetry) - new term in $\mathcal{L}_{QCD}$
    - No Axions observed yet
  - Extra dimensions might suppress $\theta_{QCD}$
  - Remains an unsolved theoretical “problem”
Hadronic EDM from Quarks

- Quark EDM contributes via

\[ d_q \]
Quark EDM

\[ \tilde{d}_q \]
Quark ChromoEDM
## Relative EDM Sensitivities

<table>
<thead>
<tr>
<th>System</th>
<th>Dependence</th>
<th>Present Limit (e-cm)</th>
<th>Future (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>$d_n \sim (3 \times 10^{-16}) \theta_{QCD} + 0.7(d_d - \frac{1}{4} d_u) + 0.6e(\tilde{d}_d + \frac{1}{2} \tilde{d}_u)$</td>
<td>$&lt;3 \times 10^{-26}$</td>
<td>$10^{-28}$</td>
</tr>
<tr>
<td>d</td>
<td>$d_d \sim (-1 \times 10^{-16}) \theta_{QCD} + 6e(\tilde{d}_d - \tilde{d}_u)$</td>
<td>?</td>
<td>$10^{-27}(?)$</td>
</tr>
<tr>
<td>$^{199}\text{Hg}$</td>
<td>$d_{Hg} \sim (0.007 \times 10^{-16}) \theta_{QCD} - 0.007e(\tilde{d}_d - \tilde{d}_u)$</td>
<td>$&lt;7 \times 10^{-29}$</td>
<td>$10^{-29}(?)$</td>
</tr>
</tbody>
</table>
Possible impacts of non-zero EDM

- **Must be new Physics**
- **Sharply constrains models beyond the Standard Model** (especially *with* LHC data)
- **May account for matter-antimatter asymmetry of the universe**

![Graph showing the relationship between Higgs superpartner mass and EDM](image)

---


Large Hadron Collider
First result for neutron EDM

  - Neutron Scattering
  - Searching for Parity Violation
  - Pioneered Neutron Beam Magnetic Resonance
n-EDM vs Time

Theoretical Prediction:
- Electromagnetic
- Milliweak
- Weinberg
- Multi-Higgs
- Supersymmetry
- Cosmology
- Superweak
- Standard Model
How to measure an EDM?

Recall magnetic moment in B field:

\[ \hat{H} = \vec{\mu} \cdot \vec{B}; \quad \vec{\mu} = 2 \left( \frac{\mu_N}{\hbar} \right) \vec{S} \quad \text{for spin} \quad \frac{1}{2} \]

\[ \vec{\tau} = \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} \Rightarrow 2 \left( \frac{\mu_N}{\hbar} \right) |\vec{S}| |\vec{B}| \quad \text{if} \quad \vec{S} \perp \vec{B} \]

Classical Picture:

- If the spin is not aligned with B there will be a precession due to the torque.
- Precession frequency \( \omega \) given by

\[ \omega = \frac{d\phi}{dt} = \frac{1}{S} \frac{dS}{dt} \]

\[ \frac{d\vec{S}}{dt} = \frac{2\mu_N B}{\hbar} \quad \text{or} \quad \frac{2d_N E}{\hbar} \quad \text{for a} \quad \vec{d}_N \text{ in} \quad \vec{E} \]
1. Inject polarized particle
2. Rotate spin by $\pi/2$
3. Flip E-field direction
4. Measure frequency shift

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

Must know B very well
What is the precision in EDM measurement?

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

Using Uncertainty Principle:

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

Precise energy measurement requires long measurement time, giving

\[ \sigma_d \sim \frac{\hbar}{|\mathbf{E}| T_m} \]

But must include counting statistics

\[ \propto \frac{1}{\sqrt{N}} \]

Sensitivity:

\[ \sigma_d \approx \frac{\hbar}{|\mathbf{E}| T_m \sqrt{mN}} \]

**Symbols:**
- \( \mathcal{E} \) – Electric Field
- \( T_m \) – Time for measurement
- \( m \) – total # of measurements
- \( N \) – Total # of counts/meas.
What particles can be measured?

• Charged particle is difficult
  - Electric field accelerates
  - May work for storage ring

• Neutral particle is easier
  - Atoms (for electron EDM)
    • Also can work for quark EDM
  - Free Neutrons (for quark EDM)
Atomic EDMs

• Schiff Theorem
  - Neutral atomic system of point particles in Electric field readjusts itself to give zero E field at all charges
But ...

- Magnetic effects and finite size of nucleus can break the symmetry (relativistic effects can also enhance)
  - Enhancement for $d_e$ in paramagnetic atoms (unpaired electrons)
    (magnetic effect with mixing of opposite parity atomic states)
  - Suppression for hadronic EDMs in Diamagnetic atoms (paired electrons) - but Schiff Moment is non-zero
    (due to finite size of nucleus and nuclear force)
  
  Thus $d_{\text{Tl}} \sim -585 \, d_e$ & $|d_e| < 1.5 \times 10^{-27}$ e-cm

Naively expect $d_A \sim \left( \frac{R_{\text{Nucleus}}}{r_{\text{Atom}}} \right)^2 d_{n,p} \sim \left( \frac{A^{1/3} R_0}{a / Z} \right)^2 d_{n,p} \sim 10^{-4} d_{n,p}$

for $^{199}\text{Hg}$
But, but, ...

Can enhance heavy atom EDMs via nuclear deformation

Octupole deformations

\[ S_{\text{intr}} \sim eZA\beta_2\beta_3 \]
\[ S_{\text{lab}} \sim eZA^{2/3}\beta_2\beta_3^2/\Delta E \]
\[ \beta_2, \beta_3 \sim 0.1 \]

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel

<table>
<thead>
<tr>
<th>(223\text{Rn} )</th>
<th>(223\text{Ra} )</th>
<th>(225\text{Ra} )</th>
<th>(223\text{Fr} )</th>
<th>(225\text{Ac} )</th>
<th>(229\text{Pa} )</th>
<th>(199\text{Hg} )</th>
<th>(129\text{Xe} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{1/2} )</td>
<td>23.2 m</td>
<td>11.4 d</td>
<td>14.9 d</td>
<td>22 m</td>
<td>10.0 d</td>
<td>1.5 d</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>7/2</td>
<td>3/2</td>
<td>1/2</td>
<td>3/2</td>
<td>3/2</td>
<td>5/2</td>
<td>1/2</td>
</tr>
<tr>
<td>( \Delta e_m ) (keV)</td>
<td>37</td>
<td>170</td>
<td>47</td>
<td>75</td>
<td>49</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>( \Delta E_{\text{exp}} ) (keV)</td>
<td>--</td>
<td>50.2</td>
<td>55.2</td>
<td>160.5</td>
<td>40.1</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>(10^3 S ) (efm(^3))</td>
<td>1000</td>
<td>400</td>
<td>300</td>
<td>500</td>
<td>900</td>
<td>12000</td>
<td>-1.4</td>
</tr>
<tr>
<td>(10^{28} d_A ) (e cm)</td>
<td>2000</td>
<td>2700</td>
<td>2100</td>
<td>2800</td>
<td></td>
<td></td>
<td>-5.6</td>
</tr>
</tbody>
</table>
Experimental EDMs

• Present best limits come from atomic systems and the free neutron
  - Paramagnetic like $^{205}$Tl are primarily sensitive to $d_e$
  - Diamagnetic atoms (e.g. $^{199}$Hg) and the free neutron are primarily sensitive to $\theta_{\text{QCD}}, d_q, \bar{d}_q$

• Future best limits may come from
  - Molecules (ThO, YbF)
  - Liquids ($^{129}$Xe)
  - Solid State systems (high density)
  - Storage Rings (Muons, Deuteron)
  - Radioactive Atoms ($^{225}$Ra, $^{223}$Rn)
  - New Technology for Free Neutrons (PSI, ILL, SNS)
## Present and Future EDMs

<table>
<thead>
<tr>
<th>particle</th>
<th>Present Limit (90% CL) (e-cm)</th>
<th>Laboratory</th>
<th>Possible Sensitivity (e-cm)</th>
<th>Standard Model (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻ (TI)</td>
<td>$1.6 \times 10^{-27}$</td>
<td>Berkeley</td>
<td>$10^{-29}$</td>
<td>&lt; $10^{-40}$</td>
</tr>
<tr>
<td>e⁻ (PbO)</td>
<td></td>
<td>Yale</td>
<td>$10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>e⁻ (YbF)</td>
<td></td>
<td>Sussex</td>
<td>$10^{-30}$</td>
<td></td>
</tr>
<tr>
<td>e⁻ (GGG)</td>
<td></td>
<td>Yale/Indiana</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>$9.3 \times 10^{-19}$</td>
<td>CERN</td>
<td>&lt; $10^{-24}$</td>
<td>&lt; $10^{-36}$</td>
</tr>
<tr>
<td>μ</td>
<td></td>
<td>BNL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>$3 \times 10^{-26}$</td>
<td>ILL</td>
<td>$1.5 \times 10^{-26}$</td>
<td>~ $10^{-32}$</td>
</tr>
<tr>
<td>n</td>
<td></td>
<td>ILL</td>
<td>~ $2 \times 10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td></td>
<td>PSI</td>
<td>~ $7 \times 10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td></td>
<td>SNS</td>
<td>&lt; $1 \times 10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$3 \times 10^{-29}$</td>
<td>Seattle</td>
<td>$1 \times 10^{-29}$</td>
<td>~ $10^{-33}$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>(if interpreted as $d_n &lt; 6 \times 10^{-26}$)</td>
<td>Princeton</td>
<td>$10^{-31}$</td>
<td></td>
</tr>
<tr>
<td>$^{225}$Ra</td>
<td></td>
<td>Argonne</td>
<td>$10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>$^{223}$Rn</td>
<td></td>
<td>TRIUMF</td>
<td>$1 \times 10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td></td>
<td>BNL/JPARC?</td>
<td>&lt; $10^{-27}$</td>
<td></td>
</tr>
</tbody>
</table>
Non-neutron EDMs

• Atomic EDMs for electron EDM

• Atomic EDMs for quark chromo-EDM

• Possible storage ring experiments:
  - In particle rest frame see an electric field
    \[ \vec{E} = \frac{\vec{v} \times \vec{B}}{c} \]  
    (Can be large if $\beta \sim 1$)

  Rotates a longitudinally polarized particle into the vertical direction
$^{205}$TI EDM

B. C. Regan, E. D. Commins, C. J. Schmidt, & D. DeMille
Phys. Rev. Lett. 102, 101601 (2009)
W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, and E. N. Fortson
Advantages of an EDM measurement on $^{225}$Ra atoms in a trap

- In $^{225}$Ra the EDM effect is enhanced by two orders of magnitude due to nuclear quadrupole and octupole deformation.
- Trap allows a long coherence time (~ 300 s).
- Cold atoms result in a negligible “v x E” systematic effect.
- Trap allows the efficient use of the rare and radioactive $^{225}$Ra atoms.
- Small sample in an UHV allows a high electric field (> 100 kV/cm).

$^{225}$Ra
Nuclear Spin = $\frac{1}{2}$
Electronic Spin = 0
$t_{1/2} = 15$ days
**EDM in Rn**

Spokesmen: Timothy Chupp\(^2\) and Carl Svensson\(^1\)
Sarah Nuss-Warren\(^2\), Eric Tardiff\(^2\), Kevin Coulter\(^2\), Wolfgang Lorenzon\(^2\), Timothy Chupp\(^2\)
John Behr\(^4\), Matt Pearson\(^4\), Peter Jackson\(^4\), Mike Hayden\(^3\), Carl Svensson\(^1\)

*University of Guelph\(^1\), University of Michigan\(^2\), Simon Fraser University\(^3\), TRIUMF\(^4\)*

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**Diagram:**

1. **TRIUMF** → **Rn**
2. **Neutralize and cool down** → **N\(_2\) pushes Rn into cell** → **Rn + Rb**
3. **Rn** + **B ± E fields** → **Rn + Rb exchange**
4. **Analyze**:
   - \(\gamma\) ray anisotropy
   - Laser probing

---

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>(^{211})Rn ((I=1/2); 15h)</th>
<th>(^{223})Rn ((I=7/2); 23 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>(2\times10^9)</td>
<td>(1\times10^7)</td>
</tr>
<tr>
<td>(\sigma_d (\sqrt{\text{day}}))</td>
<td>(6\times10^{-29})</td>
<td>(2\times10^{-27})</td>
</tr>
<tr>
<td><strong>TRIUMF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RIA</strong></td>
<td>(1\times10^{10})</td>
<td>(5\times10^8)</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(1\times10^{-28})</td>
</tr>
</tbody>
</table>

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*Note: The diagram and table provide a simplified overview of the EDM in Rn process.*
Deuteron (and Muon) EDM in Storage Ring
BNL, BU, Cornell, Illinois, Indiana, Massachusetts, Oklahoma & Foreign Institutions

Possible ring layout

Injection dipoles and quads

3 spin precession solenoids 3.9 T-m

RFQ 3 MeV

Linac 11 MeV

Strip-inject accumulator and synchrotron

RF cavity

Atomic beam proton/deuteron polarized ion source

Polarimeter (4)

Ring Properties:
- \( E = 3.5 \text{ MV/m} \)
- \( B = 2.1 \text{ kG} \)
- \( T(d) = 126 \text{ MeV} \)
- \( p = 0.7 \text{ GeV/c} \)
- \( \beta = 0.35 \)
- \( \gamma = 1.07 \)
- Dipole radius = 13.3 m

Example for ring:
1. polarized ion source
2. pre-accelerator
3. accumulator
4. accelerator
5. spin preparation
6. injection
7. EDM ring

Deuteron (and Muon) EDM in Storage Ring
BNL, BU, Cornell, Illinois, Indiana, Massachusetts, Oklahoma & Foreign Institutions
Neutron EDM Experiments

• Most recent published result
  - (from ILL)
  - Experiment limited by new systematic effect “discovered” during measurement

• Future experiments
  - 3xILL, PSI, SNS, TRIUMF(?), NIST(?)

Trapped Ultra-Cold Neutrons (UCN) with $N_{\text{UCN}} = 0.5 \text{ UCN/cc}$

$|E| = 5 - 10 \text{ kV/cm}$

100 sec storage time

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

Harris et al. Phys. Rev. Lett. 82, 904 (1999)
Measurement of frequency difference

- ILL uses Ramsey separated-oscillatory field technique
  - Inject $n$
  - Rotate and precess for $\Delta t$
  - Spin rotates by $\Delta \omega \Delta t$ (assuming $<< 1$)
  - Measure how many $n\uparrow$ vs. $n\downarrow$
Careful magnetometry is essential!
Experiment limited by systematic effect “Geometric Phase”

• For slow particles:
  - Path-dependent phase
  - E.g. Parallel transport of vector on sphere
  - In Quantum Mechanics often called Berry’s phase
  - Actually a relativistic effect!
False EDM from Geometric phase

- Commins Am J Phys 59, 1077 (91)
- Pendlebury et al PRA 70 032102 (04)
- Lamoreaux and Golub PRA 71 032104 (05)

- Motional \((v \times E)\) B-fields can add to radial B fields perpendicular to \(B_0\) (These result e.g. from \(dB_0/dz\)) giving a false EDM
Geometric phase with $B_E = v \times E$ field

Radial B-field due to gradient

- Motion in $B$–field shifts the precession frequency $-\omega_0$:
  \[ \Delta \omega \cong \omega_\perp \frac{1 \pm (2\vec{v}_n \times \vec{E})/cB_\perp}{2(\omega_0 \mp v_n/R)} \]

- $\pm, \mp$ due to different trajectories
- Does NOT average to 0
- Is proportional to $\vec{E}$

- Gives:
  \[ v_\perp \frac{\partial B}{\partial z} \]
  \[ d_n \approx \frac{v_\perp^2}{B_0^2} \]
Observed in ILL Experiment

\[ \omega \text{ depends on E-field} \]
For neutrons and magnetometers

ILL exp. oriented vertically!!

FIG. 2: (Color online) Measured EDM as a function of the relative frequency shift of neutrons and mercury. For clarity, data are binned.
Related Relativistic Issue

PHYSICAL REVIEW A 78, 023401 (2008)

Motional spin relaxation in large electric fields

Ricardo Schmid, B. Plaster, and B. W. Filippone
California Institute of Technology, Pasadena, California 91125, USA
(Received 16 May 2008; published 1 August 2008)

For Polarized \(^3\)He
To further improve search for neutron EDM, need new techniques

- Enhance number of stored neutrons
- Increase Electric field
- Minimize key systematic effects
Active worldwide effort to improve neutron EDM sensitivity

- ILL – Grenoble
  - CryoEDM at ILL (superfluid $^4$He)
  - Multiple cell
  - Crystal diffraction of neutron beam
- Paul-Scherrer Institute (PSI) – Switzerland
  - Large Solid $D_2$ UCN source
- TRIUMF (possible continuation at JPARC)
  - Superfluid $^4$He source
- Spallation Neutron Source (SNS)
  @ Oak Ridge National Lab
  - Superfluid $^4$He
## Example of future Neutron EDM Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>EDM @ ILL</th>
<th>EDM @ SNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{UCN} )</td>
<td>1.3 \times 10^4</td>
<td>4 \times 10^5</td>
</tr>
<tr>
<td>(</td>
<td>\mathbf{E}</td>
<td>)</td>
</tr>
<tr>
<td>( T_m )</td>
<td>130 s</td>
<td>500 s</td>
</tr>
<tr>
<td>( m ) (cycles/day)</td>
<td>270</td>
<td>30</td>
</tr>
<tr>
<td>( \sigma_d ) (e-cm)/day</td>
<td>3 \times 10^{-25}</td>
<td>8 \times 10^{-27}</td>
</tr>
</tbody>
</table>

\[
\sigma_d \approx \frac{\hbar}{|\mathbf{E}| T_m \sqrt{mN_{UCN}}}
\]
Scheme of PNPI-ILL multi-chamber EDM spectrometer

System of 16 Cs-magnetometers

Could move experiment to Solid D₂ UCN source at PNPI
whole experiment in superfluid He at 0.5 K
- production of UCN
- storage & Larmor precession of UCN
- SQUID magnetometry
- detection of UCN
CryoEDM

- Completed constructed, beginning commissioning/start of exploitation
- still requires tuning to deliver a competitive EDM measurement
- apparatus in a position to make an EDM measurement first half 2009 and deliver improved limits

On H53 beam: sensitivity $\sim 10^{-27} \, e \, cm$
On new beam: sensitivity $\sim 10^{-28} \, e \, cm$
Neutron EDM at PSI

Paul Scherrer Institut

Using new PSI UCN Facility using Solid D$_2$

(Based on Los Alamos-et al Concept for UCNA)
Neutron EDM at PSI

- Initial data will use original apparatus from ILL with magnetic upgrades
- New apparatus being designed for higher sensitivity
Crystal-diffraction neutron EDM project @ ILL

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>( \sigma^{-1} \sim E\tau \sqrt{N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max for UCN method</strong></td>
<td>( E \sim 10^3 \text{V/cm} )</td>
</tr>
<tr>
<td>( \tau \sim 1000\text{s (time of life)} )</td>
<td>( E\tau \sim 10^7 (\text{V} \cdot \text{s})/\text{cm} )</td>
</tr>
<tr>
<td><strong>Max for Crystal-diffraction</strong></td>
<td>( E \sim 10^9 \text{V/cm} )</td>
</tr>
<tr>
<td>( \tau \sim 10^{-2}\text{s (time of absorption)} )</td>
<td>( E\tau \sim 10^7 (\text{V} \cdot \text{s})/\text{cm} )</td>
</tr>
</tbody>
</table>

In the non-centrosymmetric crystal

neutron is moving under strong electric field if the electric planes deviate from the nuclear ones spatially, because of the neutron concentration on (or between) the nuclear planes.

\[
V^E(\mathbf{r}) = 2V_g^E \cos(\mathbf{g} \cdot \mathbf{r} + \Delta \phi_g)
\]

\[
V^N(\mathbf{r}) = 2V_g^N \cos(\mathbf{g} \cdot \mathbf{r})
\]
Test experiment (2006)

$T = T_0 + \Delta$

(110) plane

PG (002) (R~50%)

$T = T_0$

(110) plane

Meissner cavity

$H_L \approx 0$

3He cell

nPSD

Beamstop

$T = T_0$ ± $\Delta$

(110) plane

$\text{ddnn} = (2.4 \pm 6.5) \times 10^{10}$

Crystal size 90 cm$^3$

Full scale setup with quartz

$H_L \approx 0$

En < E_0

$V_n$

En > E_0

$+E$

$-E$
New Technique for n-EDM

1. Inject polarized neutron & polarized $^3$He
2. Rotate both spins by 90°
3. Measure $n^+^3$He capture vs. time
   (note: $\sigma_{\downarrow\uparrow} \gg \sigma_{\uparrow\uparrow}$)
4. Flip E-field direction

$^3$He functions as "co-magnetometer"
New Technique for n-EDM:

- Use Superthermal (non-equilibrium) system to produce UCN
  - Superfluid $^4$He can yield $\sim 1000$ more UCN than conventional UCN source

- Higher Electric fields in $^4$He
  - Breakdown voltage may be 10x vacuum breakdown

- $^3$He comagnetometer measures B-field at same location as neutrons
  - Very small amount of $^3$He in $^4$He
  - Use SQUIDs to measure $^3$He precession - calibrates B-field since $\omega_3 \propto |B|$

  $\vec{n} + ^3\text{He} \Rightarrow t + p$ has $\sigma_{\uparrow\downarrow} \gg \sigma_{\uparrow\uparrow}$

  - Detect capture via scintillation of $^4$He
    - UV photons converted to visible in tetraphenyl butadiene - TPB
    - Measures difference of $\omega_n$ and $\omega_3$

- “Dressed” spin technique suppresses sensitivity to fluctuations in B-field
  - Additional RF field can match $^3$He and neutron precession frequency
“Dressed Spins”

- By applying a strong non-resonant RF field, the effective precession frequencies can be modified or “dressed”
Classical spin in AC B-field

Consider

\[ \vec{B} = B_{rf} \sin(\omega_{rf} t) \hat{x} \]

Solution:

\[ S_z = \cos \left[ \left( \frac{\gamma B_{rf}}{\omega_{rf}} \right) \sin(\omega_{rf} t) \right] \]

; & averaging over time :

\[ \langle S_z \rangle = \frac{\omega_{rf}}{2\pi} \int_0^T S_z \, dt \equiv \frac{1}{2\pi} \int_0^{2\pi} \cos \left[ \frac{\gamma B_{rf}}{\omega_{rf}} \sin(\theta) \right] d\theta \equiv J_0 \left( \frac{\gamma B_{rf}}{\omega_{rf}} \right) = J_0(\mathbf{x}) \]
Classical spin in AC B-field

- Now apply a very small B-field along \( z = B_0 \)

\[
\langle \hat{S}_z \rangle = J_0(x) \text{ begins to precess about } z\text{-axis with reduced frequency } \sim \gamma B_0 J_0(x)
\]
Classical spin in AC B-field

- For particular values of the dressing field, the neutron and $^3$He precession frequencies are equal

\[ \gamma_3 J_0 \left( \frac{\gamma_3 B_{rf}}{\omega_{rf}} \right) = \gamma_n J_0 \left( \frac{\gamma_n B_{rf}}{\omega_{rf}} \right) \]

- Can modulate the dressing field around a relative precession of zero.
  - Reducing effect of external B-fields
  - Measure this parameter vs. direction of E-field

- Challenging technical issues must be overcome
  - Uniformity of the RF field must be better than 0.1%
  - Eddy currents will heat conductors
The SNS nEDM Collaboration

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Expertise:
Nuclear
Atomic
Condensed Matter
Low Temperature
Polarized $^3$He
UCN
SNS nEDM Measurement cycle

1. Load collection volume with polarized $^3$He atoms
2. Transfer polarized $^3$He atoms into the 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. Go to 1.
Systematic Effects in EDM

• Variation of B-field
  - Comagnetometer cancels B-field variations

• Leakage currents from Electric Field
  - These produce B-fields that change with E-field (must be less than picoAmps)

• Gravitational offset of n and $^3$He ($\sim 10^{-29}$ e-cm)

• $\vec{\nu} \times \vec{E}$ effects are the largest sources of systematic error in present ILL exp.
  - $\vec{B}_E = \vec{\nu} \times \vec{E} \rightarrow$ changes $\vec{\mu}$ precession frequency
  - Geometric phase due to $\vec{B}$ gradients
Systematic Controls in new EDM experiment

• Highly uniform E and B fields
  – $\cos \theta$ coil in Ferromagnetic shield
  – Kerr effect measurement of E-field
• Two cells with opposite E-field
• Ability to vary influence of $B_0$ field
  – via “dressed spins” (atomic physics trick)
• Control of central temperature
  – Can vary $^3$He diffusion
Measurement Cell

Neutrons come from Oak Ridge National Laboratory

Inner Dressing Coil
Outer Dressing Coil
50K Shield
4K Shield
Superconducting Lead Shield
Ferromagnetic Shield

$B_0 \cos \theta$ Magnet
Spallation Neutron Source (SNS) at ORNL
1 GeV proton beam with 1.4 MW on spallation target
SNS Status

- SNS completed: 2006
- Beam line completed: 2007
- Full design flux: 2009
- SNS Total Project Cost: 1.411B$
SNS Target Hall

P beam

18 neutron beam ports with 1 for Nuclear Physics
Fundamental Neutron Physics
Beamline

Double monochromometer selects 8.9 Å neutrons

UCN experimental area in external building. 8.9 Å beamline extracted via double-crystal monochromator

Cold Polarized neutron experimental area on main beamline

Fundamental Neutron Physics Facility at the SNS. Beamline 13
EDM Experiment at SNS

- He Liquifier
- Isolated floor
## Summary of future neutron EDM experiments

<table>
<thead>
<tr>
<th>Exp</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>$\sigma_d$ (10^{-28} \text{ e- cm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL CryoEDM</td>
<td>Superfluid $^4$He</td>
<td>$^4$He</td>
<td>Ramsey technique for $\omega$ External SQUID magnetometers</td>
<td>$\sim 50$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>PNPI – I LL – SD$_2$</td>
<td>ILL turbine</td>
<td>Vac.</td>
<td>Ramsey technique for $\omega$ E=0 cell for magnetometer</td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td></td>
<td>PNPI/Solid D$_2$</td>
<td></td>
<td></td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>ILL Crystal</td>
<td>Cold n Beam</td>
<td></td>
<td></td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td>PSI EDM</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey technique for $\omega$ External Cs &amp; $^3$He magnetom.</td>
<td>$\sim 50$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>SNS EDM</td>
<td>Superfluid $^4$He</td>
<td>$^4$He</td>
<td>$^3$He capture for $\omega$ $^3$He comagnetometer SQUIDS &amp; Dressed spins</td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>TRIUMF/JPARC</td>
<td>Superfluid $^4$He</td>
<td>Vac.</td>
<td>Under Development</td>
<td>?</td>
</tr>
</tbody>
</table>
New n-EDM Sensitivity

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

Future neutron EDM
Summary

• Physics reach of EDM measurements is significant (even after Large Hadron Collider)
  - New sources of CP violation likely in SUSY

• A new neutron EDM experiment with two orders of magnitude improvement
  - Allows possible discovery of new sources of CP violation