Search for a Neutron Electric Dipole Moment at the SNS

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Executive Summary

• **Goal:** To develop a new experimental technique to search for the neutron electric dipole moment (EDM) that offers a factor of at least 100 increase in sensitivity over existing measurements.

• **Motivation:** The search for this moment has the potential to reveal new sources of time reversal ($T$) and charge conjugation and parity ($CP$) violation and to challenge calculations that propose extensions to the Standard Model.
Collaborating Institutions (nEDM)
Definition of an EDM

• A permanent neutron EDM $d$: a separation of the charged constituents of the neutron along the direction of the spin.

\[ \vec{d} \cdot \vec{E} \quad \vec{s} = 1/2 \quad \vec{d} = 2d_n \vec{s} \]

• An edm for a non-degenerate system is evidence of P and T symmetry breaking (W.E theorem $d \sim s$, but $d$ is T-even, whereas $s$ is T-odd; v.v for parity).
How large might an edm be?

- $d_n \sim e \times \text{nucleon size} \times \text{weak interaction} \times \text{CP violation}$
  
  
  $10^{-13}$ $10^{-7}$ $10^{-3}$

  
  $\sim 10^{-23}$ e-cm

- The current experimental limit is a factor of hundred smaller: $d_n < 3 \times 10^{-26}$ e·cm (Institut Laue Langevin).

- Standard model prediction $\sim 10^{-32}$ e-cm, but extensions predict effects at $10^{-28}$ e·cm level.
Mission Impossible 4?

• We hope to obtain $d_n < 10^{-28}$ e·cm at the SNS

• Like looking for a 0.01 micron bump at the North Pole.

• What’s new? Use ultracold neutrons stored in liquid helium, with polarized 3-He as a co-magnetometer (Golub and Lamoreaux- Phys. Reports)
**CP-Violation in the Standard Model**

- Occurs in two places:
  - As a complex phase in the CKM matrix
  - In the $\theta$ term in the QCD Lagrangian

- CP-violation observed in the kaon and B meson system is consistent with the presence of the phase

- Present bounds on the QCD-$\theta$ term from primarily EDM measurements give values for $\theta$ that are very small ($10^{-9}$). This small value has led to the search for axions.

- A new source of CP-violation is required to explain the observed matter-antimatter asymmetry in the Universe.
Uncertainty principle limit to edm measurement

Measure energies for $\pm$ spins in fields $\pm E$ for time $T$:

Uncertainty in each energy is $\delta W_\pm \sim \hbar / T$

Energy difference is $W_+ - W_- = 4 d_n E$

For $N$ neutrons: $\delta d_n \sim \hbar / (2 E T \sqrt{N})$

Need:
- large $E \sim 10^6$ V/m
- large $N$ ($\sim 10^8$ for ILL)
- long $T$ ($\sim 100$s for UCN’s)

ILL experiment got within a factor of two!
Basic Technique

Look for a precession frequency $\omega_n = 2\mu_n B \pm 2d_n E$

A moment of $10^{-25}$ e•cm in a 10 kV/cm electric field corresponds to a shift in frequency of 0.5 μHz!
Ramsey two coil method

- Phase angle $\Phi = (\omega_B + \omega_E - \omega_{rf}) \, T$
- Intensity at detector $\sim \sin^2 (\Phi/2)$
- Look for change in neutron intensity when E is reversed
ILL Neutron EDM Experiment

- Provides the current best limit: $d_n < 3 \times 10^{-26}$ e·cm
- Employs a $^{199}$Hg Co-magnetometer
- Characteristics:
  - 1 UCN/cc
  - 10 kV/cm
  - 100 s neutron storage time
- A new systematic “geometric phase” effect was found in this work (controllable to the $< 10^{-28}$ e·cm level for our experiment).
ILL EDM Experiment
Importance of a co-magnetometer

• ILL experiment (Baker et al PRL 2006) uses a Hg vapor co-magnetometer–removes B field jump ~ $10^{-10}$ T

• Conclusion: need to monitor B where the neutrons are!

• Do better with $^3$He?
Evolution of Neutron EDM Experiments
Figure of Merit for EDM Experiments

\[ E \tau \sqrt{N} \]

By performing the experiment directly in superfluid helium-4 (dielectric properties + superthermal neutron production) that is doped with polarized helium-3 that serves as a co-magnetometer and spin precession analyzer:

\[ \tau \rightarrow 5 \tau \]
\[ N \rightarrow 100 \ N \]
\[ E \rightarrow 5E \]

potentially \( \times 250 \) when operated at the SNS.
Lifetime $\tau$ in a Storage  

- Goal: 500 seconds storage time
- Production rate at SNS implies $P = 0.3-1 \text{ /(cc sec)}$
  production

\[ \rho = P \tau \]

\[
\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_w} + \frac{1}{\tau_3} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{hole}}
\]

where $\tau_n$ is the neutron lifetime,
$\tau_w$ is the wall lifetime,
$\tau_3$ is the absorption lifetime,
$\tau_{up}$ is the upscattering lifetime,
$\tau_{hole}$ is lifetime due to loss through holes.
High Voltage Capacitor System (E → 5 E)

- Employs a capacitive amplification technique

\[ q = CV \]

- Distance: 0.5 cm
- High Voltage: 500 kV
Superthermal Production of UCN (N → 100 N)

- 8.9 Å (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering (by 12 K phonon absorption)

- ~ Population of 12 K phonons ~ $e^{-12 \frac{K}{T_{bath}}}$
\[ \omega_n = 2\mu_n B \pm 2d_n E \]

\[ \omega_3 = 2\mu_3 B \]

\[ \mu_3 = 1.1 \mu_n \]

- Look for a difference in precession frequency

\[ \omega_n - \omega_3 = 2(\mu_n - \mu_3)B \pm 2d_n E \]
$^3$He Co-Magnetometer

$^3$He + n → t + p

$\sigma$(parallel) < $10^2$ b

$\sigma$(opposite) $\sim 10^4$ b

- $1 - \vec{p}_3 \cdot \vec{p}_n = 1 - p_3 p_n \cos[2(\mu_n - \mu_3)B_0 + 2dE] t$
- Detect $^3$He precession rate with SQUIDS.
- $|\mu_n - \mu_3| = |\mu_3|/10$ – Sensitivity to magnetic fields is reduced by an order of magnitude!
- $^3$He concentration must be adjusted to keep the lifetime $\tau$ reasonable for a given value of the $^3$He polarization.
- The proper value for the fractional concentration $x = ^3$He/$^4$He $\sim 10^{-10}$. 
\[ \gamma_3 = 1.1 \gamma_n \]

\[ \gamma' = \gamma J_0 (\gamma B_{rf} / \omega_{rf}) \]

\[ \gamma_n' = \gamma_3' \quad \text{when} \quad \gamma_n B_{rf} / \omega_{rf} \approx 1.1 \]

- \( B_{rf} >> B_0 \) (1-10 mG) so \( B_{rf} \approx 1 \) G, \( \omega_{rf} / 2\pi \approx 3 \) kHz.
- RF field must be homogeneous at the 0.1–1% level.
- Heating and gradients due to eddy currents present design challenges.
- Eliminates need for SQUID magnetometers and may increase the sensitivity of the experiment.
The Experimental Apparatus
Overall Size

- Overall size: 5.5 m (height) x 1.7 m (base diameter) x 7.6 m (length)
- 2.2 m segment visible on the right side
Measurement Cells

- 2 acrylic cells with inner dimensions of 7.62 cm (width) × 10.16 cm (height) × 50 cm (length)
Four-Layer Conventional Magnetic Shield

- Entire experimental apparatus enclosed within 4-layer conventional magnetic shield (µ-metal) designed to shield experiment from Earth’s magnetic field and other ambient background fields.
Major Internal Components

- Cryogenic System
- 3He Polarized Source
- 3He Injection Volume
- Central Detector (300mK)
- Re-entrant Insert for Neutron Beam Guide
- 4 Layer μ-metal Shield
- Magnetic coil and shielding package
Internal Cryogenic System

Dilution refrigerator

Intermediate shield

LHe reservoir

4 K shield

Cryovessel

Helium insulation volume
Processes sensitive to operating temperature

- $^3$He transport by diffusion, $T < 310$ mK
- $^3$He evaporation $370$ mK < $T < 420$ mK
- Geometric phase $T > 370$ mK, $\frac{\partial B_z}{\partial z} < 10^{-7}$ gauss/cm
- $^3$He depolarization (T2) $T < 420$ mK, $\frac{\partial B_z}{\partial y} < 10^{-7}$ gauss/cm
Magnets and Cryogenic Magnetic Shields

- Inner-Dressing & Spin-Flip Coil
- Outer Dressing Coil
- $B_0 \cos \theta$ Magnet
- Ferromagnetic Shield
- Superconducting Lead Shield
Main Static Field Prototype Coil

- open-ended “saddle-shaped” \( \cos \theta \) coil
- Field strength of \( B_0 = 10 \) mGauss
- Temporal stability of \( 10^{-7} \)
- Uniformity of \( 5 \times 10^{-4} \)
- \( \left< \partial B_x / \partial x \right> \) of \( 0.01 \) µGauss/cm
Central Detector and High Voltage System

- Contains the high-voltage capacitor and electrodes, the measurement cells and light collection system.
$^3$He System

- $^3$He atomic beam source
- $^3$He injection volume
- Helium purifiers
- Collection system cos(θ) coil
$^3$He Atomic Beam Polarizer

- Device commissioned
- Flux $1 \times 10^{14}$ atoms/s with good emittance
- Average velocity $\sim 150$ m/s
- Polarization measurements ($99.6 \pm 0.25$)%
- Loading time 300 s
Operation of the Experiment

• Cell filled with superfluid helium, doped with polarized $^3$He in a weak B field, strong E field.

• Accumulate UCN for about 1000 s (superthermal production).

• Flip neutron and $^3$He spins 90° with respect to $B_0$ by RF pulses.

• Observe the scintillation and SQUID signals as a function of time for 1000 s.

• Drain cell of spent/unpolarized $^3$He.

• Repeat after reversing E.
R & D Program

• A vigorous research and development program is underway.

• The program is spread across multiple institutions, with the intent of addressing high-risk areas in the proposed experiment.

• A conceptual model has been developed.

• Programs include:
  – Studies of systematic effects
  – Light detection and background suppression
  – High voltage tests
  – Magnetic shielding and magnetic coils
  – SQUIDS
  – $^3$He injection, storage, and removal
Geometric Phase Effect (Berry phase)

Berry phase (1984) \( \Phi = m \Omega \)

Net phase \( \sim \frac{1}{2} (\Phi_c - \Phi_{cc}) \sim B_r B_v / B_0^2 \sim E \)
RBS shift for circular orbits $r=R$

$B_0$ and $E$ up

$B_r = a \, r$

$B_v = \pm (v/c) \cdot E$

More generally, with $\omega_0 = \gamma \, B_0$ and $\omega_r = v/R$:

**UCN’s:** $\omega_0 \gg \omega_r$

$\Delta \omega = a \, v^2 \, E/c B_0^2$

**3He:** $\omega_0 \ll \omega_r$

$\Delta \omega = \gamma^2 \, a \, R^2 \, E/c$
Monte Carlo Simulation of the Effect

Tune temp to take advantage of the zero crossing?

“Stop the World” - false ILL edm due to $\Omega_{\text{earth}}$?

- Earth rotates $\Omega/2\pi = 11.6 \, \mu\text{Hz}$
- $\omega_n = \gamma_n B_0 - \Omega \sin \theta_L$
- $\omega_{\text{Hg}} = \gamma_{\text{Hg}} B_0 - \Omega \sin \theta_L$
- False edm $d_{\text{earth}} \sim k \Omega \sin \theta_L / (\gamma' B_0) \sim 3 \times 10^{-26} \, \text{e}\cdot\text{cm}$
- $k$ is slope of $d_{\text{meas}}$ vs $R_a = (\omega_n / \gamma_n) / (\omega_{\text{Hg}} / \gamma_{\text{Hg}})$, with $(\gamma')^{-1} = |\gamma_n|^{-1} + |\gamma_{\text{Hg}}|^{-1}$

- See PRL 98 (2007) comment (SL and RG) and response (Baker et al)

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

- Recoiling charged particle creates an ionization track in the helium.

- Helium ions form excited $\text{He}_2^*$ molecules (ns time scale) in both singlet and triplet states.

- $\text{He}_2^*$ singlet molecules decay, producing a large prompt (< 20 ns) emission of extreme ultraviolet (EUV) light.

- EUV light (80 nm) converted to blue using the deuterated organic fluor dTPB (tetraphenyl butadiene).

\[ n + ^3\text{He} \rightarrow p + T \]
Sample Event

Scintillation event with afterpulses
Background Discrimination

- **Gammas (no $^3$He in cell)**
- **Neutrons ($^3$He in cell)**

- Afterpulses in 0.5 - 45 μs interval

- Pulse Area (nV s)

- Signal Pulse Height [mV]

- # of after-pulses
Spallation Neutron Source
First SNS Beam on Target—April 28, 2006
Beamline 13 Allocated for Nuclear Physics

11A - Powder Diffractometer
Commission 2007

12 - Single Crystal Diffractometer
Commission 2009

13 - Fundamental Physics Beamline
Commission 2007

14B - Hybrid Spectrometer
Commission 2011

15 - Spin Echo

17 - High Resolution Chopper Spectrometer
Commission 2008

18 - Wide Angle Chopper Spectrometer
Commission 2007

1B - Disordered Mat'l's
Commission 2010

2 - Backscattering Spectrometer
Commission 2006

3 - High Pressure Diffractometer
Commission 2008

4A - Magnetism Reflectometer
Commission 2006

5 - Cold Neutron Chopper Spectrometer
Commission 2007

6 - SANS
Commission 2007

7 - Engineering Diffractometer
IDT CFI Funded
Commission 2008

9 – VISION

14B - Liquids Reflectometer
Commission 2006

NC STATE UNIVERSITY
Fundamental Neutron Physics Beamline
Organizational Chart

Martin Cooper
(Project Manager, Co-spokesperson)
Steve Lamoreaux
(Co-spokesperson)
Jan Boisevain
(Chief Engineer)
Kim Selvage
(Project Controls Analyst)
Paul Huffman
(Technical Coordinator)
Vince Cianciolo
(ORNL Operations Manager/ES&H)
TBD
(Business Manager)

1.1 Research & Development
Martin Cooper (LANL)

1.2 Polarized Neutron Beam Line & Shielding
Wolfgang Korsch (Kentucky)

1.3 Cryostats, Refrigerators and Related Equipment
David Haase (NCSU)

1.4 3He Systems
Steve Williamson (Illinois)

1.5 Magnets and Magnetic Shielding
Brad Filippone (Cal Tech)

1.6 Central Detector Systems
Takeyasu Ito (LANL)

1.7 Electronics, Computers, Simulations, Data Analysis
(Chris Gould (NCSU))
Jim Miller (BU)

1.8 Infrastructure
Walt Sondheim (LANL)

1.9 Assembly & Commissioning
Paul Huffman (NCSU)

1.10 Project Management
Martin Cooper (LANL)
• CD-0 – (mission need) issued fall 2005
• CD-1 – spring 2007
• CD-4 – project ends mid 2014 ($21M @40% contingency)
• 2014 - 20?? – EDM data collection
EDM Experiments in Other Systems

- CP violating EDM’s are studied in particles, nuclei, atoms and molecules. Shielding comparison $R = \frac{E_{\text{eff}}}{E_{\text{applied}}}$
- Free neutrons $R = 1$
- Diamagnetic atoms ($^{199}\text{Hg}$) $R \sim 10 Z^2 \left( \frac{r_{\text{nuc}}}{r_{\text{atom}}} \right)^2 \sim 10^{-3}$
  \textit{Schiff shielding}
- Paramagnetic atoms (Tl) $R \sim Z (Z\alpha)^2 \sim 600$
- Polar molecules (YbF, PbO) $R \sim 10^7$
EDM’s elsewhere (BF, INT workshop spring 07)

<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^-) (Tl) (\mu) (\mu)</td>
<td>1.6 x 10^{-27} 9.3 x 10^{-19}</td>
<td>Berkeley Yale</td>
<td>10^{-29} 10^{-29}</td>
<td>&lt;10^{-40}</td>
</tr>
<tr>
<td>(e^-) (PbO) (\mu)</td>
<td></td>
<td>Sussex LANL/Indiana</td>
<td>10^{-29} 10^{-30}</td>
<td></td>
</tr>
<tr>
<td>(e^-) (YbF) (n)</td>
<td></td>
<td>CERN BNL</td>
<td>&lt;10^{-24}</td>
<td>&lt;10^{-36}</td>
</tr>
<tr>
<td>(e^-) (GGG) (n)</td>
<td></td>
<td>ILL ILL PSI SNS</td>
<td>2 x 10^{-28} 5 x 10^{-28} 2 x 10^{-28}</td>
<td>~10^{-32}</td>
</tr>
<tr>
<td>(^{199}\text{Hg}) (^{129}\text{Xe}) (^{225}\text{Ra}) (^{223}\text{Rn}) (d)</td>
<td>1.9 x 10^{-27}</td>
<td>Seattle Princeton Argonne TRIUMF COSY/JPARC?</td>
<td>2 x 10^{-28} 10^{-31} 10^{-28} 1 x 10^{-28} &lt;10^{-28}</td>
<td>~10^{-33} ~10^{-34}</td>
</tr>
</tbody>
</table>
Conclusions

• We are constructing apparatus to measure the neutron EDM at the SNS using UCN’s and polarized 3He atoms in a superfluid 4He bath.

• The construction project has obtained CD1 approval from DOE and is moving towards finalizing a design for CD2 approval.

• We expect to begin taking data in ~2014.

• Our goal is to measure the magnitude of the neutron EDM, or to lower the current experimental limit by two orders of magnitude.