Search for the Electric Dipole Moment of the Neutron

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Our goal is to measure the neutron electric dipole moment with a sensitivity of $d_n < 5 \times 10^{-28} \text{e} \cdot \text{cm}$ (90%).

- The current experimental limit is $d_n < 3 \times 10^{-26} \text{e} \cdot \text{cm}$ (Institut Laue Langevin).

Collaborative effort based at Oak Ridge National Laboratory (ORNL), that includes 21 institutions and more than 67 individuals.
Physics Motivation

**Significant discovery potential in search for EDMs**

- If particle EDMs are observed in the next round of experiments, a new source of CP violation will have been discovered.

- Such CP violation could play a role in explaining the observed excess of matter over anti-matter in the Universe.

- The neutron is a key component of understanding new CP violation should it be observed in any EDM.

- EDM searches continue to be compelling even as the LHC produces new physics results.
FNPB Facility

Fundamental Neutron Physics Facility at the SNS. Beamline 13

Cold Polarized neutron experimental area on main beamline

UCN experimental area in external building. 8.9 Å beamline extracted via double-crystal monochromator
Unique Features of Our Experiment

- Production of ultracold neutrons (UCN) within the apparatus
  - higher UCN density and longer storage times

- Use of liquid as a high voltage insulator
  - higher electric fields

- Use of a $^3$He co-magnetometer and superconducting shield
  - better control of magnetic field systematics

- Employ two different measurement techniques
  - oscillation of scintillation rate and dressed spin techniques

Tackling unknown systematic effects requires unique handles in the experiment that can be varied.
Figure of Merit for EDM Experiments

$$E \sqrt{N \tau}$$

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:

$$\tau \rightarrow 4 \tau$$
$$N \rightarrow 100 N$$
$$E \rightarrow 5E$$

× ~100 when operated at the SNS
Basic Experimental Technique
Basic Experimental Technique
Basic Experimental Technique

Look for a precession frequency $f_n = \gamma_n B \pm 2d_n E$
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Key Experimental Concepts

- Ultracold Neutrons/Superthermal Production
- $^3$He Co-Magnetometry
- Charge Particle Detection in Liquid Helium
Ultracold Neutrons

- **Strong Interaction**

  \[
  \sin \theta \leq \sin \theta_c = \left( \frac{V}{E} \right)^{1/2}
  \]

  \[
  V = \frac{2 \pi \hbar^2}{m} \text{ Na}
  \]

  \[V \sim 10^{-7} \text{eV}\]

- **Gravitational Interaction**

  \[V_g = mg \text{h} \]

  \[10^{-7} \text{eV/m}\]

- **Magnetic Interaction**

  \[V_m = -\mu \cdot B \]

  \[10^{-7} \text{eV/T}\]
Superthermal Production of UCN

- 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)
  \[ \sim \text{Population of 12 K phonons} \sim e^{-12 K/T_{\text{bath}}} \]
Co-Magnetometry

- Look for a difference in precession frequency
  \[ f_n - f_3 = (\gamma_n - \gamma_3) B \pm 2 d_n E = (0.1 \gamma_n) B \pm 2 d_n E \]

- Detect precession of \( ^3\text{He} \) magnetization by SQUIDS which serves as a direct magnetometer (\( d_{^3\text{He}} \ll d_n \))
$^{199}$Hg Co-Magnetometer (ILL Experiment)

\[ \Delta B = 10^{-10} \text{ T} \]
$^{199}$Hg Co-Magnetometer (ILL Experiment)

- Raw neutron frequency
- Corrected frequency

$\Delta B = 10^{-10} \text{T}$
$^3$He Transport - Heat Flush Technique

- Used to move $^3$He around in the apparatus
- Source of our isotopically pure $^4$He
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Recoiling charged particle creates an ionization track in the helium.

Helium ions form excited He2* molecules (ns time scale) in both singlet and triplet states.

He2* 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).

\( n + {^3}\text{He} \rightarrow p + T \)

\( \sigma(\text{parallel}) < 10^2 \text{ b} \)

\( \sigma(\text{opposite}) \sim 10^4 \text{ b} \)
Measurement Overview

- Two measurement techniques
  - Oscillation of the scintillation rate (baseline)
  - Spin Dressing

- Capabilities for performing both techniques are being built into the apparatus.

- Oscillation of scintillation rate
  - Look for a difference in precession frequency
    \[ f_n - f_3 = (\gamma_n - \gamma_3) B \pm 2 d_n E = (0.1 \gamma_n) B \pm 2 d_n E \]
  - Detect precession of \(^3\)He magnetization by SQUIDS which serves as a direct magnetometer

- Spin Dressing
  - seeks to make the magnetic moments equal to minimize sensitivity to background fields
## Systematics

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Systematic error (e-cm)</th>
<th>Comments</th>
<th>Key parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric phase (linear E×v)</td>
<td>&lt; 1 x 10^{-28}</td>
<td>Uniformity of B0 field</td>
<td>B field gradient, temperature</td>
</tr>
<tr>
<td>Quadratic E×v</td>
<td>&lt; 0.5 x 10^{-28}</td>
<td>E-field reversal to &lt;1%</td>
<td></td>
</tr>
<tr>
<td>Pseudomagnetic Field Effects</td>
<td>&lt; 1 x 10^{-28}</td>
<td>π/2 pulse, comparing 2 cells</td>
<td>^3He density, π/2 pulse</td>
</tr>
<tr>
<td>Gravitational offset</td>
<td>&lt; 0.2 x 10^{-28}</td>
<td>With 1 nA leakage currents</td>
<td></td>
</tr>
<tr>
<td>Heat from leakage currents</td>
<td>&lt; 1.5 x 10^{-28}</td>
<td>&lt; 1 pA</td>
<td>temperature</td>
</tr>
<tr>
<td>E×v rotational n flow</td>
<td>&lt; 1 x 10^{-28}</td>
<td>E-field uniformity &lt; 0.5%</td>
<td></td>
</tr>
<tr>
<td>E-field stability</td>
<td>&lt; 1 x 10^{-28}</td>
<td>ΔE/E &lt; 0.1%</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>&lt; 1 x 10^{-28}</td>
<td>Other E×v, wall losses</td>
<td></td>
</tr>
</tbody>
</table>
Measurement Cells

7 x 10 x 40 cm³
Measurement Cells

7 x 10 x 40 cm$^3$

Electric Field
HV Capacitor

\[ q = CV \]

\[
\begin{align*}
d &= 0.5 \\
HV &= 50 \\
5 &= 500 \\
cm &= kV
\end{align*}
\]
Magnets and Cryogenic Magnetic Shields
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- Spin Dressing Coils
- $B_0$ Coil
- Ferromagnetic Shield
- Superconducting Lead Shield
Cryovessel
Cryovessel

4K Shield

77K Shield

Cryovessel
Cryogenics

- Cryovessel
- 77K Shield
- 4K Shield
- Dilution Refrigerator
- Helium Liquefier and Gas Handling System (not shown)
- $T \sim 450 \text{ mK}$
External Magnetic Shielding

4-layer Magnetic Shields and Support System

Trim Coils

Scale: ~5.5 m tall, ~7.5 m long
Measurement Cycle

- Load collection volume with polarized $^3$He atoms
- Transfer polarized $^3$He atoms into the measurement cell
- Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
- Apply a $\pi/2$ pulse to rotate spins perpendicular to $B_0$
- Measure precession frequency
- Remove reduced polarization $^3$He atoms from measurement cell
- Repeat (periodically reversing $B$ and/or $E$)
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- Transfer polarized $^3\text{He}$ atoms into the measurement cell
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Signal Detection

- Light Guides
- 4K PMT’s
- SQUIDS
Global View
Summary

- The neutron EDM remains an important parameter in understanding the origin of the universe and testing for physics beyond the Standard Model.

- Both the free precession and dressed spin techniques give an ultimate sensitivity of $d_n < 3–5 \times 10^{-28} \text{ e.cm} \ (90\%)$ using the cold beamline at the FnPB.

- The experimental design has many features that will allow us to explore possible unknown systematic effects.

- We expect to begin putting neutrons into the apparatus in approximately 6-7 years.