Status of the PSI nEDM Experiment

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On behalf of the nEDM Collaboration
PSI in Villigen Switzerland
nEDM Collaboration

About 50 members from 14 institutions in 8 countries.
Overview

Background

The Experiment
- Method
- Apparatus
- Magnetometry

Sensitivity
- Statistical Sensitivity
- Systematic Effects

Status
- Current Successes
- Future Plans
Electric Dipole Moment

\[ \mathbf{P} \]

\[ \mathbf{E} \]

\[ \mathbf{T} \]
Motivation

The Baryon Asymmetry of the Universe

SM Expectation:

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18} \]

Oberved:

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10} \]

Sakharov criteria

1. Baryon number violation
2. C and CP violation
3. Thermal non-equilibrium
History of nEDM Searches

Ramsey's Neutron Beamline at Oak Ridge

First Limit
Smith, Purcell, Ramsey
\[ d_n < 5 \times 10^{-20} \text{ e cm} \]
PR 108 (1957) 120

~ 50 years

Present Limit
RAL-Sussex-ILL
\[ d_n < 2.9 \times 10^{-26} \text{ e cm (90% C.L.)} \]
C.A.Baker et al., PRL 97 (2006) 131801
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Measurement Technique

Measure the difference of precession frequencies in parallel/anti-parallel fields:

\[ \hbar \Delta \omega = 2d_n \left( E_{\uparrow\uparrow} + E_{\uparrow\downarrow} \right) + 2\mu_n \left( B_{\uparrow\uparrow} - B_{\uparrow\downarrow} \right) \]

for \( d_n < 10^{-26} \) & \( E = 10 \, \text{kV/cm} \)

\( B = 1 \, \mu\text{T} \) \( \rightarrow \) \( \omega_L \approx 30 \, \text{Hz} \)

\( \Delta \omega < 60 \, \text{nHz} \)
Separated Oscillatory Fields

Spin “down” neutron...

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

Free precession at $\omega_L$

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

\[ B_{0\uparrow} + B_{rf} \]

\[ \omega_{nRF} \]

\[ t = 2s \]

\[ T \gg t \]

\[ t = 2s \]
Ramsey Resonance Curve

Spin-Up Neutron Counts vs. Applied Frequency (Hz)

- x = working points
- Resonant freq.
UCN Source

- UCN storage vessel
- Solid D$_2$
- UCN-converter
- Spallation target
- UCN guides
- 7 m
The nEDM Spectrometer

Precession Chamber (UCN & Hg)

Passive Magnetic Shielding (4 layers)

HV Electrode

5 T Magnet

Vacuum Tank

UCN Switch

Analyzer(s) & Detector(s)

~ 2 m
Hg Co-Magnetometer

- Precession Chamber
- PM
- Polarization Cell
- $B_0 \approx 1 \mu T$

- Corrects UCN frequency
- Average magnetic field
- $\sigma_B \sim 400 \text{ fT}$
Hg Co-Magnetometer

16 h

1.5 pT
Cs Atomic Magnetometers

- Six HV CsM and ten ground CsM
- Monitors vertical magnetic gradients
- Comparable sensitivity to Hg Co-Magnetometer
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Statistical Sensitivity

\[
\sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}}
\]

- \(\alpha\): Visibility of resonance
- \(T\): Time of free precession
- \(E\): Electric field strength
- \(N\): Number of neutrons
Statistical Sensitivity

\[ \sigma(f) = \frac{\hbar}{2 \alpha T_E \sqrt{N}} \]

- Product of polarizer and analyzer efficiency
- \( \sim 20\% \) increase in sensitivity with USSA

\( \alpha \) Visibility of resonance
\( T \) Time of free precession
\( E \) Electric field strength
\( N \) Number of neutrons
Statistical Sensitivity

\[ \sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}} \]

- Currently limited by the Hg depolarization time
- “Opera House” Effect

\( \alpha \)  Visibility of resonance

\( T \)  Time of free precession

\( E \)  Electric field strength

\( N \)  Number of neutrons
Statistical Sensitivity

\[ \sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}} \]

- \( \alpha \): Visibility of resonance
- \( T \): Time of free precession
- \( E \): Electric field strength
- \( N \): Number of neutrons

- Best HV performance 144 kV \( \rightarrow \) 12.0 kV/cm
- Average E-Field while data taking: 10.3 kV/cm
Statistical Sensitivity

\[
\sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}}
\]

- \(\alpha\) Visibility of resonance
- \(T\) Time of free precession
- \(E\) Electric field strength
- \(N\) Number of neutrons

• Expect \(~11000\) neutron per cycle in 2015
• Storage filling time determined by optimization of \(\alpha \sqrt{N}\)
Systematic Effects

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \rangle_{\perp}}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right) \]
Geometric Phase Shift

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \rangle_\perp}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right) \]

Vertical gradients are monitored by Cs magnetometers

\[ \Delta G = 8 \text{ pT/cm} \]
Transverse Fields

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \perp \rangle}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right) \]

- Field mapped with fluxgate
- Monitored by Cs magnetometers
- Soon vector Cs magnetometers will be installed
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The neutron gyromagnetic ratio was measured relative to the $^{199}$Hg gyromagnetic ratio as a test of magnetic field control.

The rate of transverse depolarization in an applied field gradient is dependent of the UCN energy spectrum.
UCN Energy Spectrum

$\chi^2$/dof = 348/65
Center of mass offset: 4.9(1) mm

Preliminary
Laser Based Hg Magnetometer

- Improved Hg signal sensitivity
- Reduced Hg light shift effect
Current Status

- The UCN source is delivering sufficient neutrons to reach the statistical goal (when operational).
- Several improvements to increase the sensitivity over the current limit have been implemented.
- New physics results have been obtained such as the gyromagnetic ratio of the neutron and $^{199}$Hg and a spin-echo measurement of UCNs.
- We have a sensitivity of $1.6 \times 10^{-25}$ ecm per day and expect 300 data-days through 2016.

Goal sensitivity: $d_n < 5 \times 10^{-27}$ e cm (95% C.L.)
The Nest Phase: n2EMD

- Two precession chambers
- Improved magnetic shielding
- 3He magnetometers
Thank you for your attention.

Thanks go to Philipp Schmidt-Wellenburg, Bernhard Lauss, and Florian Piegsa for use of their slides and to Clark Griffith and Philip Harris for guidance.
Backup Slides
UCN Spin-Echo
Simultaneous Spin Detection

\[ \text{counts/s} \]

\[ \text{counting time [s]} \]

<table>
<thead>
<tr>
<th>Visibility $\alpha$ [%]</th>
<th>$N_{\text{tot}}$</th>
<th>$N_{\text{West-1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>USSA</td>
<td>63.4 ± 1.8</td>
<td>3791(14)</td>
</tr>
<tr>
<td>Sequential</td>
<td>59.7 ± 2.2</td>
<td>2692(15)</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.062(49)</td>
<td>1.238(10)</td>
</tr>
</tbody>
</table>

$\sim 20\%$ increase in sensitivity

Matthew Musgrave

ISINN-23

36
Systematic Effects

\[
\gamma_{\text{Hg}} \approx \frac{8 \text{ Hz/\mu T}}{2\pi}
\]

\[
\bar{v}_{\text{Hg}} \approx 160 \text{ m/s}
\]

\[
\bar{v}_{\text{UCN}} \approx 3 \text{ m/s}
\]

\[
R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B_0^2 \rangle}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg\text{-lightshift}}} \right)
\]
Transverse Fields

UCN: Adiabatic regime

\[ f_n \propto \langle |\vec{B}| \rangle = B_0 + \frac{\langle B_T^2 \rangle}{2B_0} \]

Mercury: Non-adiabatic regime

\[ f_{\text{Hg}} \propto |\langle \vec{B} \rangle| = B_0 \]

- Mapping with fluxgate and vector cesium magnetometer
- \(-20 < z < 20, -10 < r < 30, \Delta \phi = 5^\circ\)

\[ \delta R_{\text{Transverse}} = (3 \pm 1) \times 10^{-6} \]

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B_T^2 \rangle}{|B_0|^2} \mp \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right) \]
Vertical Field Gradients

- Field parameterized by 9 parameters
- Parameters are adjusted to 12 Cs magnetometers
- Residuals are about 30 pT
- Jackknife procedure used to estimate error of the total gradient $G$

$$\Delta G = 8 \text{ pT/cm}$$

$\Delta \rho = -0.235(5) \text{ cm}$

$R_0^\uparrow = 3.8424580(23)$

$R_0^\downarrow = 3.8424653(27)$

$$R = \frac{\langle f_{\text{UON}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{B^2_{\perp}}{|B_0|^2} \mp \delta_{\text{Earth}} + \delta_{\text{Hg–lightshift}} \right)$$
Earth Rotation Correction

\[ \delta_{\text{Earth}} = \pm \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( \frac{f_{\text{Earth}}}{f_n} + \frac{f_{\text{Earth}}}{f_{\text{Hg}}} \right) \sin(\lambda) \]

\[ = \pm 5.3 \times 10^{-6} \]
Hg Light Shift

Hg reading light can create an effective magnetic field that only alters the precession frequency of the Hg atoms.

Effective magnetic field depends on:

• Light intensity
• Light polarization
• Light frequency
• Light beam alignment

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} \approx \frac{\gamma n}{\gamma_{Hg}} \left( 1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \perp \rangle}{|B_0|^2} \mp \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right)$$

$$\delta_{\text{Light}}^\downarrow = (0.21 \pm 0.14) \times 10^{-6}$$

$$\delta_{\text{Light}}^\uparrow = (0.34 \pm 0.18) \times 10^{-6}$$
## Current Status

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-field (kV/cm)</td>
<td>11</td>
</tr>
<tr>
<td>Neutrons</td>
<td>11 200</td>
</tr>
<tr>
<td>$T_{\text{free}}$</td>
<td>194</td>
</tr>
<tr>
<td>$T_{\text{duty}}$</td>
<td>340</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.65</td>
</tr>
<tr>
<td>$\sigma/d^{-1/2}$ (10^{-25}ecm)</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Goal sensitivity:** $d_n < 5 \times 10^{-27}$ e cm (95% C.L.)