The Search for Neutron Electric Dipole Moment, present experiment at ILL, Grenoble, and future prospects

nEDM experiment - Rutherford Appleton Laboratory - University of Sussex - ILL

CryoEDM experiment - Rutherford Appleton Laboratory - University of Sussex – ILL – University of Kure – University of Oxford

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RAL - M.A.H Tucker, S.N. Balashov, V. Francis
University of Sussex - M. Hardiman, P. Smith, J. Grozier, K. Zuber
University of Oxford H. Kraus, B. Majorovits, N. Jelley, U. Divaker
**nEDM experiment**

1. Why we need to measure neutron EDM
2. Measurement principle
3. nEDM apparatus
4. Magnetometry – Hg comagnetometer
5. Statistical and systematical errors

**CryoEDM experiment**

1. Why superfluid Helium
2. UCN source at H53 beam at ILL
3. CryoEDM apparatus
4. Present status and future prospects
The Neutron Electric Dipole Moment: $d_n$

$d_n \neq 0 \Rightarrow P$ and $T$ violation
Why we need to measure nEDM

- The validity of the parity assumption must rest on experimental evidence...
- CP violation is observed in K and B meson systems.
- CP violation outside of SM is needed to explain observed particle-antiparticle asymmetry in the Universe
- Theoretical predictions beyond the SM

The neutron is not as simple as it looks…
Measurement principle

\[ H = -\mu_n \vec{B} - d_n \vec{E} \]

\[ \nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = \Delta \nu = -4 \frac{dE}{h} \]

\( B_0 \) has to be unchanged when \( E \) is reversed.
1. "Spin up" neutron...

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

3. Free precession...

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

Statistical uncertainty

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

$$\sigma(d_n) = 2 \times 10^{-25} \text{ e.cm/day}$$
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nEDM apparatus
Experimental setup
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The ILL Reactor

- Neutron turbine
- Vertical guide tube
- Cold source
- Reactor core
Grenoble
Institut Laue
Langevin (Alpes)

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The Search for Neutron Electric Dipole Moment at ILL
Measuring the mercury Larmor precession frequency:

Turn polarised $^{199}$Hg by $\frac{\pi}{2}$ rf pulse
Hg precesses in same volume as neutrons
PMT measures signal of reading bulb
Fit signal to decaying sine curve

$d(^{199}$Hg$) < 2.1 \times 10^{-28} \text{ e cm}$
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Hg co-magnetometer

Top view:

Polarised Hg atoms

PMT output:

Digitised voltage (bits)

ADC reading no.
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nEDM measurement

Hg co-magnetometer now compensates B drift

Run duration (hours)

ΔB = 10^{-10} T
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The graph shows the neutron EDM measurements over time, with data points indicating a fluctuating pattern around zero. The y-axis represents the neutron EDM in $10^{-25}$ e cm, while the x-axis represents the run number ranging from 1300 to 1900. The graph also includes a zoomed-in section showing a more detailed view of the data points, along with a note indicating post-publication data.
False effects

from Special Relativity, extra motion-induced field

$$\vec{B}_v = \frac{\vec{v} \times \vec{E}}{c^2}$$

If $B_0$ field has vertical gradient, then

$$B_{0r}(\vec{r}) = -\frac{\partial B_{0z}}{\partial z} \frac{\vec{r}}{r^2}$$
Geometric phase

... so particle sees additional rotating field

Frequency shift $\propto E$

Looks like an EDM
Systematics

- Consider

\[ R = \frac{\nu_n}{\nu_{Hg}} \cdot \frac{\gamma_{Hg}}{\gamma_n} \]

- Should have value 1
- R is shifted by magnetic field gradients
- Plot EDM vs measured R-1:

\[ \Delta h = 2.73 \pm 0.39 \text{ mm} \]
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B field Down

B field Up
Statistical and systematical errors

\[ d_n = -0.31 \pm 1.54 \times 10^{-26} \text{ e.cm} \quad \text{preliminary} \]

**Systematical errors**

<table>
<thead>
<tr>
<th>Error Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole &amp; quadrupole shifts</td>
</tr>
<tr>
<td>Enhanced GP dipole shifts</td>
</tr>
<tr>
<td>((E \times v)/c^2) from translation</td>
</tr>
<tr>
<td>((E \times v)/c^2) from rotation</td>
</tr>
<tr>
<td>Light shift: direct</td>
</tr>
<tr>
<td>B fluctuations</td>
</tr>
<tr>
<td>Light shift: GP effects</td>
</tr>
<tr>
<td>E forces – distortion of bottle</td>
</tr>
<tr>
<td>Tangential leakage currents</td>
</tr>
<tr>
<td>AC B fields from HV ripple</td>
</tr>
<tr>
<td>Others …….</td>
</tr>
</tbody>
</table>
CryoEDM experiment

Statistical uncertainty

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

\[ \sigma(d_n) = 2 \times 10^{-25} \text{ e.cm/day} \]

for “room temperature”

nEDM experiment

New UCN source

Superthermal UCN source:

a) a medium has a very small neutron absorption;
b) the medium has a critical energy for total reflection which is much smaller than that of vessel’s walls
c) the medium behaves as if there were only one excited state with excitation energy \( E \gg T \gg E_u \)

T-temperature of the medium, \( E_u \) – the UCN energy


Isotopically pure HeII

a) \( \sigma_{\text{absorption}}=0 \)
b) \( V_{\text{crit}}=21 \text{ neV} \)
c) Pure coherent scattering \( E_{\text{phonon}}=11K, \)

\( T_{\text{He}}=0.5K, E_{\text{UCN}}=1 \text{ mK} \)
Production rate one-phonon interaction:

\[ R_I = 4.1 \times 10^8 \frac{d\Phi}{d\lambda} \left|_{\lambda} \right. \text{cm}^{-3}\text{s}^{-1} \]

main process: one phonon downscattering

cold neutron → phonon → ultra cold neutron

Energy momentum dispersion curve

free neutron

liquid He

12 K

0.7 Å⁻¹
Storing superthermal UCN

limited by:

- neutron lifetime
- $^{4}\text{He}$ purity
- storage volume wall absorption cross section
- upscattering

$\tau$ - storage time, one phonon scattering only

$$\frac{1}{\tau} = A \exp\left[-\frac{11.9}{T}\right] + \frac{1}{\tau_0}$$
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CryoEDM overview
Neutron detection

Ion-implanted Si with neutron to charged particles converter

\[ n + ^{10}B \rightarrow \alpha(1.78 \text{ MeV}) + ^{7}\text{Li}(1.01) \]

\[ n + ^{10}B \rightarrow \alpha(1.47 \text{ MeV}) + ^{7}\text{Li}(0.83 \text{ MeV}) + \gamma(0.48 \text{ MeV}) \]

\[ n + ^{6}\text{Li} \rightarrow \alpha (2.05 \text{ MeV}) + ^{3}\text{H} (2.74 \text{ MeV}) \]
Pulse Height Analysis of cryogenic UCN detectors
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![Graph showing neutron count against wavelength (Å) for different wavelengths including 4.5 Å, 5 Å, 5.5 Å, 6 Å, 6.5 Å, 7 Å, 7.5 Å, 8 Å, 8.5 Å, 9.0 Å, 9.5 Å, 10 Å, 10.5 Å, and 11.0 Å, with a line for no velocity selector.]
Neutron velocity selector

Daimler-Benz Aerospace
Dornier

Wavelength $\lambda$ 0.45 to 4.3 nm

$\alpha(\degree)$  $T(\%)$  $R(\%)$

60  79.4  11.4
UCN production rate vs $\lambda_n$

1.19±0.18 UCN cm$^{-3}$ s$^{-1}$ expected, 0.91±0.13 observed

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CryoEDM overview
Cryogenic Ramsey chamber
Magnetometry

• **SQUID Magnetometers**
  – Developed at Oxford for CRESST
  – Highly sensitive: adequate to monitor field fluctuations

• Also: Neutron Magnetometers...
Statistical limits

\[
\sigma_d = \frac{\hbar/2}{\alpha \, E \, T \, \sqrt{N}}
\]

<table>
<thead>
<tr>
<th>Factor</th>
<th>Current</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation+detection</td>
<td>(\alpha = 0.75)</td>
<td>x 1.5</td>
</tr>
<tr>
<td>Electric field:</td>
<td>(E = 10^6 \text{ V/m})</td>
<td>x 2.0</td>
</tr>
<tr>
<td>Precession period:</td>
<td>(T = 130 \text{ s})</td>
<td>x 1.8</td>
</tr>
<tr>
<td>Neutrons counted:</td>
<td>(N = 6 \times 10^6 \text{ /day})</td>
<td>x 14.9</td>
</tr>
<tr>
<td>(with new beamline)</td>
<td></td>
<td>x 2.6</td>
</tr>
</tbody>
</table>

Total increase = x 80 (x200 with new beamline)
CryoEDM to start running in summer 2006
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CryoEDM

10^{-27} \text{ e.cm  2006/8}

10^{-28} \text{ e.cm  2008/9}

nEDM

dn = -0.31 \pm 1.54 \times 10^{-26} \text{ e.cm}

preliminary