The Search for the Neutron Electric Dipole Moment

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- Motivation
- The nEDM experiment on PF2:
  - Experiment vs Theory
  - Measurement principle
  - Experimental set-up
  - Data & Results
- Cryogenic nEDM R&D running at PF1
  - Superthermal UCN source
  - UCN production & detection in superfluid helium
  - Outlook
- Conclusions

Motivation

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The Neutron Electric Dipole Moment: $d_n$

$d_n \neq 0 \Rightarrow P$ and $T$ violation

$CP$ & $T$ violation observed in $K$ decay, Belle & BaBar $\Rightarrow d_n \neq 0$

CP violation

Electric dipole moment $d_n$

Spin $S$ transform.

$P$ & $T$ violation

CPT conservation $\Rightarrow$ CP violation

The neutron EDM: exp. vs theory

Progress at ~ order of magnitude per decade
Standard Model out of reach
strong constraints on e.g. Super Symmetry

$d_n = 1 \text{ e-cm}$

$d_n < 6.3 \times 10^{-26} \text{ e-cm} \ (90\% \ CL)$
\( d_N < 6.3 \times 10^{-26} \text{ ecm} \)

<table>
<thead>
<tr>
<th>Category</th>
<th>Formula</th>
<th>Condition</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>( d_n \approx 2 \times 10^{-16} \text{ ecm} )</td>
<td>( \bar{\theta} &lt; 10^9 )</td>
<td>CP problem</td>
</tr>
<tr>
<td>Electroweak</td>
<td>( d_n \approx \cdots c_0^2 c_2 s_4 c_2 s_4 \sin \delta_{\text{ew}} )</td>
<td>( d_n \approx 10^{-32} \text{ ecm} )</td>
<td>No problem but what about baryon asymmetry?</td>
</tr>
<tr>
<td>Supersymmetric</td>
<td>( d_n \approx \left( \frac{G e V^2}{\hbar} \right) \sin \Phi_{\alpha,B} 10^{-31} \text{ ecm} )</td>
<td>( \sin \Phi_{\alpha,B} \approx 10^{-2} )</td>
<td>Supersymmetric CP problem</td>
</tr>
</tbody>
</table>

Experiments:
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

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

- \( \alpha \): polarisation product
- \( E \): electric field
- \( T \): observation time
- \( N \): number of neutrons

The difference is proportional to \( d_n \) and \( E \):
\[
\hbar(\nu_{\parallel} - \nu_{\perp}) = 4E \cdot d_n
\]

Compare the precession frequency for parallel fields:
\[
\nu_{\parallel} = \Delta E_{\|} / \hbar = [-2B_0 \mu_n - 2Ed_n] / \hbar
\]

Compare the precession frequency for anti-parallel fields:
\[
\nu_{\perp} = \Delta E_{\perp} / \hbar = [-2B_0 \mu_n + 2Ed_n] / \hbar
\]
Measuring the neutron Larmor precession frequency:

Turn polarised neutron by π/2 rf pulse
Neutron and rf precess separately
Turn neutron again by a 2nd π/2 rf pulse

if in phase neutron ends up anti-parallel

Analyse spin

If there is a difference in ν_L and ν_RF a phase difference will accumulate and 2nd rf pulse will not take the neutron fully anti-parallel to B_0
Measuring the mercury Larmor precession frequency:

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

The ILL Reactor

- Neutron turbine
- Vertical guide tube
- Cold source
- Reactor core
- UCN (PF2)
- Cold neutrons (PF1)
Data Analysis

- Fit data to pair of cosine curves.
- Fitted curves “slide” sideways to match each data point in turn: each point then yields a unique resonant frequency.
- Plot freq. shift vs. applied E-field: slope of fitted line yields EDM
Further progress

A MUCH stronger UCN source is required
Superthermal UCN production


High UCN densities obtainable if medium in storage vessel:
1. has small neutron absorption
2. $V_F$ medium $<< V_F$ walls
3. one single state with excitation energy $E >> T >> E_U$


Isotopically pure $^4$He:
1. $\sigma_{abs} = 0$
2. $V_F, ^4$He $= 21$ meV
3. Pure coherent scattering

---

Production rate one-phonon interaction:

$R_1 = 4.1 \times 10^{-8} \frac{d\Phi}{d\lambda}$ cm$^{-3}$s$^{-1}$

Energy momentum dispersion curve

$\rho_{UCN} = 4 \times 10^7$ n/cm$^3$
(several litres of liquid He, T < 1K, inside a 20K cold source in a reactor)

$\rho_{UCN} = 3 \times 10^3$ n/cm$^3$
(end of neutron guide)

Production rate one-phonon interaction:

$R_1 = 4.1 \times 10^{-8} \frac{d\Phi}{d\lambda}$ cm$^{-3}$s$^{-1}$

single phonon, multiple phonon & roton interaction:

single phonon

multiple phonon & roton

8.9 Å $\lambda$
Storing superthermal UCN

limited by:
- neutron lifetime
- $^4$He purity
- storage volume wall absorption cross section
- upscattering

Storage lifetime (one-phonon upscattering only)

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

storage time vs helium temperature:

Cryogenic Neutron EDM Experiment
Experiments on superthermal UCN production in $^4\text{He}$

  transmission of $0.17 \pm ??$
  "we have not measured the transmission of this UCN transport system"
  transmission of windows $0.08 \pm ??$
  "the factor of 50 discrepancy between the production rate deduced from the present upscattering measurements and that from the UCN measurements is thought to be due to the losses in the UCN extraction system"
  attenuation aluminium windows $0.25 \pm ??$
  "the poor ratio of the detected UCN to the expected UCN in this experiment is not well understood. We are left with an unresolved attenuation factor of about 100 in order of magnitude"

UCN produced alright…

extraction uncertainties

absolute production rate?

Good basis for new nEDM exp???
Cold neutron beam through isotopically pure superfluid He
Contain ultracold neutrons within Be
Detect UCN *in situ*

- stainless steel Ø=67mm, L=326mm
- Ø=10mm escape aperture
- 2500 Å beryllium coating
- 0.25mm beryllium windows
- 1.2mm $^{6}$LiF plastic (67%)
Solid state UCN detectors:

- $^{10}$B & $^6$Li converters
- EDM UCN flux monitor
- UCN spectrum analysis

Record the number of neutrons as a function of time during filling/emptying.
Pulse Height Analysis of cryogenic UCN detectors

- Cold neutron beam open to liquid helium
- Cold neutron beam closed to liquid helium

- 2322 UCN/cycle to detection chamber
  \( \rho \sim 2 \text{ UCN/cc} \) \([\tau = 10 \text{ sec}]\)
storage time-temperature

- Experimental data
- Single phonon interaction only
- Single & multiple phonon & roton interaction

Temperature [K]:
- T=0.43 K
- T=1.00 K
- T=1.30 K
- T=1.44 K

Temperature vs. Storage Time [sec]

Neutron count vs. Wavelength [Å]

No velocity selector
$R = (0.91 \pm 0.13) \text{ cm}^3\text{sec}^{-1}$

Expected rate: $R_I = (1.19 \pm 0.18) \text{ UCN cm}^{-3}\text{s}^{-1}$

($\text{gold foil activation measurements}$

$\frac{d\Phi}{d\lambda} = (2.88 \pm 0.39) \times 10^7 \text{ neutrons cm}^{-2}\text{Å}^{-1}$)

~25% of UCN produced by multiple phonon/roton interaction

2001 - 2003

- Superthermal UCN created at ~ 50 UCN/cc
- Cryogenic UCN detectors have been developed and are operational within superfluid helium
- 80% efficient

- UCN production mechanism established
  - ~75% from 9Å neutrons
  - ~25% from 4Å - 7Å

- Separate filling/storing/emptying of production volume
- Cryogenic UCN valve system

2003 - 2004

- Polarisation of UCN in superthermal source
- Long depolarisation times

- UCN spectrum as produced by down-scattering

- Extracting UCN into room temp. apparatus
- Enlarge production volume
- Minimise dilution effect

- Superconducting magnetic shielding, $B_0$
- NMR with neutrons
In conclusion:

Room temperature:
• close to concluding data acquisition
• sensitivity $\sim 1.5 \times 10^{-26} \text{ ecm}$

cryoEDM:
• superthermal UCN production/detection R&D concluded
• viability of method demonstrated
• 3 years of capital construction phase
• sensitivity $\sim 10^{-27} - 10^{-28} \text{ ecm capital constr./exploitation}$

a very big effort for a very small number
The impact is HUGE