Searches for the electric dipole moments of the neutron

Philipp Schmidt-Wellenburg, Paul Scherrer Institute Switzerland
Outline

- Complementarity to other EDM searches
- Ultracold neutrons and Ramsey’s technique
- Worldwide competition
- Searches for static and oscillating nEDM at PSI
nEDM searches

Supersymmetry predictions

Standard model calculations

Neutron EDM Upper Limit [e cm]

Year of Publication


ORNL, Harvard
MIT, BNL
LNPI
Sussex, RAL, ILL

First

Smith, Purcell, Ramsey

\[ d_n < 5 \times 10^{-20} \text{ e cm} \]

PR 108 (1957) 120

~ 50 years

Last

RAL-Sussex-ILL

\[ d_n < 3 \times 10^{-26} \text{ e cm} \] (90% C.L.)

C. Baker et al., PRL(2006) 131801
J.M. Pendlebury et al., PRD 92 (2015) 092003

Baryon asymmetry of the Universe
Arises "naturally" in beyond SM theories
Sensitive to QCD CP-violation
neutron EDM: complementary to other searches

\[ L_{\text{eff}} = L_{\text{QCD}} + \theta \frac{\alpha_s}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \]

QCD theta term “natural” in neutron, proton

From lattice calculations**

\[ \frac{d_n}{\theta} = -3.8(2)(9) \times 10^{-16} \text{ ecm} \quad \frac{d_p}{\theta} = +1.1(1.1) \times 10^{-16} \text{ ecm} \]

but

\[ d_n^{\text{ex}} < 3 \times 10^{-26} \text{ ecm}^* \]

\[ \theta < 1 \times 10^{-10} \text{ ecm} \]

Strongly suppressed in electron

*J.M. Pendlebury et al., PRD 92 (2015) 092003
**Guo et al., PRL (2015) 062001
**Higgs Portal CPV** (would also lead to strong first order phase transition)

![Diagram](image)

**Present**

**Future:**
- $d_n \times 0.1$
- $d_A(Hg) \times 0.1$
- $d_{ThO} \times 0.1$
- $d_A(Ra)$

**Farther future:**
- $d_n \times 0.01$
- $d_A(Hg) \times 0.1$
- $d_{ThO} \times 0.1$
- $d_A(Ra)$
Modified Larmor Frequency

\[ V_{\text{mag}} = -\mu_n \vec{\sigma} \cdot \vec{B} \]

\[ \Delta E_{\text{mag}} = \hbar \omega_L = 2\mu_n B \quad \text{with: } \mu_n = \frac{1}{2} \hbar \gamma_n \]

\[ V_{\text{edm}} = -d_n \vec{\sigma} \cdot \vec{E} \]

\[ \Delta E_{\text{edm}} = \hbar \omega_{edm} = 2d_n E \]

For parallel electric and magnetic fields the precession frequencies add up and for anti-parallel fields the frequencies have to be subtracted. The precession frequency difference of the two cases can be measured:

\[ \hbar \omega_{\uparrow\uparrow} = \hbar (\omega_L + \omega_{edm}) = 2(\mu_n B + d_n E) \]

\[ \hbar \omega_{\downarrow\downarrow} = \hbar (\omega_L - \omega_{edm}) = 2(\mu_n B - d_n E) \]

\[ \hbar (\omega_{\uparrow\uparrow} - \omega_{\downarrow\downarrow}) = 4 \, d_n E \]
The Ramsey technique

Spin “down” neutron...

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

Sensitivity:

$$\sigma(d_n) = \frac{\hbar}{2\alpha TE \sqrt{N}}$$
How to increase the statistical sensitivity

\[ \sigma(d_n) = \frac{\hbar}{2ET\alpha\sqrt{N}} \]
\[ = \frac{\hbar}{2ET\alpha_0 e^{-T/T_2} \sqrt{N_0 e^{-T/\tau_n}}} \]

- Make \( T_2, \alpha \) large \( \rightarrow \) large high performance magnetically shielded rooms
- Make \( \sqrt{N_0} \) large \( \rightarrow \) improve UCN sources
  - better extraction of UCN from converter
  - higher UCN production rates
  - adaptation / improvement of UCN transport
- Make \( ET\sqrt{N} \) large \( \rightarrow \) cryogenic UCN storage experiment

\( E \leq 20\text{kV/cm} : \) Limited by insulator
\( \alpha \rightarrow 1 : \) Polarization of neutrons
\( T \rightarrow \tau_n : \) Minimize losses
\( \sqrt{N_0} : \) Limited by transport losses
\( T_2 \rightarrow \infty : \) Magnetic field inhomogeneity

Talk : Dieter Ries
Ultracold neutrons (UCN)

\[
\sigma(d_n) \propto \frac{1}{\sqrt{NT^{3/2}}}
\]


Storage properties are material dependent

\[V_F \propto Nb \leq 350\text{ neV}\]

\[350\text{ neV} \leftrightarrow 8\text{ m/s} \leftrightarrow 500\text{ Å} \leftrightarrow 3\text{ mK}\]

Storable neutrons (UCN)

Gravity 102 neV/m

Strong \(V_F\)

Magnetic \(\sim 60\) neV/T
The measurement technique

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

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

Statistical accuracy of a magnetometer correcting for a change in B should be better than the neutron sensitivity per cycle:

\[ \delta f_n = \frac{1}{2\pi\alpha T \sqrt{N}} \approx 11\mu\text{Hz} \quad \frac{B_0=1\mu\text{T}}{\delta B \leq 100\text{fT}} \]
Magnetic fields

\[ \delta B < 100 \text{fT} \]

optical pumped magnetometers (CsM/HgM/XeM...)
\[ d_n = \frac{\hbar \Delta \omega - 2 \mu_n (B^{\uparrow\uparrow} - B^{\downarrow\downarrow})}{2(E^{\uparrow\uparrow} - E^{\downarrow\downarrow})} \approx \frac{\hbar \Delta \omega}{4|E|} \]

---

**Measured simultaneously (n2EDM)**

**Measured as sequence (nEDM)**

<table>
<thead>
<tr>
<th>Co-magnetometer (mercury, xenon,³He)</th>
<th>Corrections for differences of mean magnetic-field gradient</th>
<th>Corrections for changes of the mean magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic shield (active, passive)</td>
<td>Minimal residual fields + Stability: higher order gradients</td>
<td>Small residual fields + Stability paramount !!</td>
</tr>
<tr>
<td>Efforts</td>
<td>TUM/ILL, TRIUMF, PNPI, PSI(2), SNS, LANL(2)</td>
<td>LANL, PSI(1) finished, TRIUMF(1)</td>
</tr>
<tr>
<td>Non-UCN searches</td>
<td>Crystal EDM (ILL&amp;PNPI), beam EDM (F. Piegsa, ESS)</td>
<td></td>
</tr>
</tbody>
</table>
nEDM Experiment at LANL UCN Source

- Room temperature Ramsey experiment
- Initial goal is to demonstrate a stored UCN density sufficient for a several x 10^{-27} e-cm nEDM experiment
- UCN upgrade concluded
- First measurements with Ramsey cell

LANL collaboration:
LANL, Indiana Univ., Univ of Kentucky, Univ. of Michigan, Yale Univ., JINR

courtesy: Ito Takeyasu
ILL/TUM effort:
Berkley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM, UIUC, Yale

New UCN source based on He-II at ILL
Phase 1 (from 2019) \(1.9 \times 10^{-27} \text{ ecm}\)
Phase 2 (later) \(4.2 \times 10^{-28} \text{ ecm}\)
Current: $d_n < 5.5 \times 10^{-26} \text{ecm}$
Improvement by factor 3
at new position and with new precession cell

ILL 2020: $d_n < 2 \times 10^{-26} \text{ecm}$

future source at PNPI: $d_n < 1 \times 10^{-27} \text{ecm}$

new electrode scheme
• Overview:
  – Japan-Canada collaboration
  – Spallation-driven He-II
    UCN source connected to RT nEDM experiment.
  – First UCN Nov 2017!
    Congratulations
  – Goal sensitivity (statistics):
    $\delta d_n \sim 10^{-27}$ e-cm (2020-2023)

• Features:
  - Unique UCN source technology with world-leading potential.
  - $^{129}$Xe/$^{199}$Hg dual-species comagnetometer to cancel false EDM’s.

courtesy: Rüdiger Picker
nEDM @ SNS

Redesign to reduce costs (7/17)

- Sensitivity: $\sim 2 \times 10^{-28}$ e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- Polarized $^3$He co-magnetometer
  - Also functions as neutron spin precession monitor via spin-dependent $n-^3$He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via “dressed spins”
    - Extra RF field allows synching of $n$ & $^3$He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary $^3$He diffusion (mfp)- big change in geometric phase effect on $^3$He

Smaller shield house
Non-modular $^3$He system
& smaller building

courtesy: Brad Filippone

Full-scale operation in 2022
<table>
<thead>
<tr>
<th>Project</th>
<th>Status</th>
<th>Sensitivity goal (E-27 ecm)</th>
<th>Schedule (start data-taking)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANL</td>
<td>2017: UCN source upgrade finished</td>
<td>UCN density sufficient for O(1)</td>
<td>2019</td>
</tr>
<tr>
<td>TUM-ILL</td>
<td>TUM apparatus moves to ILL</td>
<td>O(0.1)</td>
<td>2019</td>
</tr>
<tr>
<td>PNPI</td>
<td>At PNPI 2020</td>
<td>PNPI: 0.5</td>
<td>PNPI later</td>
</tr>
<tr>
<td>SNS</td>
<td>Critical component demonstration concluded</td>
<td>0.2</td>
<td>2022</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>2017: first UCN 2-3 years for experiment</td>
<td>O(1)</td>
<td>2020</td>
</tr>
<tr>
<td>PSI</td>
<td>Phase(1) data-taking concluded</td>
<td>Phase 1: O(10)</td>
<td>Phase(2): 2020</td>
</tr>
<tr>
<td></td>
<td>Phase(2) construction</td>
<td>Phase 2: O(1)</td>
<td></td>
</tr>
<tr>
<td>ESS</td>
<td>Demonstration phase at ILL</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>CrystalEDM</td>
<td>Demonstration at ILL successful in 2010</td>
<td>O(1) (at ESS)</td>
<td>?</td>
</tr>
</tbody>
</table>
Ultracold neutrons

$V_F \propto N_b \leq 350 \text{ neV}$

Solid deuterium

$D_2O$ thermal moderator

~ 8 m

~ 4 m

5 tesla magnet

Switch

Spin analyzers & neutron detectors
The nEDM spectrometer

624'364'314 neutrons

$$\sigma = 0.94 \times 10^{-26} \text{ecm}$$

Analysis ongoing:
Blinded data
Two groups
Result planned for 2018
Dark matter limit from the nEDM - search

First experimental limits on gluonic coupling

\[ d_n(t) = A \sin(2\pi f t) + B \cos(2\pi f t) + C \]
A new spectrometer 6-layer Mu

\[ \sigma(d_n) \approx 1 \times 10^{-27} \]
The collaboration

- 15 Institutions
- 7 Countries
- 48 Members
- 14 PhD students
• The search for an nEDM is an attractive complementary path for discover of new physics
• Many groups worldwide compete for the next most sensitive nEDM experiment
• The nEDM@PSI collaboration has taken sufficient data for a new result
• Possible un-blinding of the blind analysis still in 2018
• The same data was used for search for an oscillating nEDM, setting first limits on a coupling of the neutron to axions.
Thank you for your attention.
We show that Big Bang Nucleosynthesis (BBN) significantly constrains axion-like dark matter. The axion acts like an oscillating QCD $\theta$ angle that redshifts in the early Universe, increasing the neutron–proton mass difference at neutron freeze-out. An axion-like particle that couples too strongly to QCD results in the underproduction of $^4$He during BBN and is thus excluded. The BBN bound overlaps with much of the parameter space that would be covered by proposed searches for a time-varying neutron EDM. The QCD axion does not couple strongly enough to affect BBN.

The supernova bound arises, as too strong coupling would result in lots of axions produced in supernovae which, in turn, would cause it to cool faster than observed.

The "Galaxies" bound is dashed. If axions make up all of the dark matter, they need to be heavier than this so that they can reproduce observed distribution of dark matter (rotational curves). If they are only a part of dark matter, they can be lighter.
Overview of the data

2.5% Issues which do not allow to use all data
(no HV reversal, too short runs, ...)

- 83.1% blinded
- 13.8% unblinded
- 3.0% can’t be used

A total of 54333 cycles to analyze
Crossing point analysis

\[ d_x = (14.96 \pm 1.12) \times 10^{-26} e \text{ cm} \]

\[ R_0 = 3.8424521(28) \]

\[ \chi^2 / \text{NDF} = 109/86 \]
Least square spectral analysis

$d_n$, from each run corrected with crossing lines

$A \sin (2\pi ft) + B \cos (2\pi ft) + C$

Power

$\frac{N}{4} (A^2 + B^2)$
Highest peaks

Three “data sets”:
- $E = 0$
- $E \uparrow \uparrow B$
- $E \perp B$

(parallel but pointing in different directions)

Requirements for signal:
- Five sigma in both $E \neq 0$
- and phase shift of $\pi$ between both set
- No signal in $E = 0$
Ramsey fit procedure

- Split sequence in sub-sequence:
  E-field (+ - - +) pattern

- Split data in two dataset: SF state (↑/↓) discrimination

Ramsey fit with the asymmetry:

\[
A = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

\[
\tilde{R} = \frac{f_{\text{RF}}}{f_{\text{Hg}}}
\]

\[
A^\uparrow(\tilde{R}) = \bar{A}^\uparrow + \bar{\alpha} \cos(\Omega(\tilde{R} - R_0))
\]

\[
A^\downarrow(\tilde{R}) = \bar{A}^\downarrow + \bar{\alpha} \cos(\Omega(\tilde{R} - R_0))
\]
Mercury co-magnetometer

- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100 \text{ fT}$ (CR-limit)
- $\tau > 100 \text{ s}$ wo HV (with 90s)
- $s/n > 1000$
Hg co-magnetometer

Extract B field from Larmor frequency and correct UCN frequency

1.6 pT

100 pT

3.5 days
EDM and R-calculation

\[ f^{i,1(2)}_n = f^{i}_{RF} \pm \frac{f_{Hg}^i}{\Omega} \arccos \left( \frac{\bar{A}_{1(2)} - A^i}{\bar{A}} \right) \]

\[ d_n = \frac{h(f^+_n - f^-_n)}{2E} \]

\[ R = \frac{f^n_i}{f^i_{Hg}} \]

Earth rotation frequency correction:

\[ R^{corr} = R(1 \pm \delta_{earth}) = R \cdot (1 + \delta_{gz}) \]

\[ (R_a - 1)^{corr} = \frac{R}{<R>} - 1 \pm \delta_{earth} = \delta_{gz} \]

B-gradient fluctuation correction:

\[ R^i_{Gz}^{corr} = R^i \left( 1 \pm (G_z^i - <G_z>) \frac{h}{B_0} \right) \]
Three Periodograms

Agreement of the EB parallel dataset with the null hypothesis

\[ E \uparrow \uparrow B \]

Agreement of the E=0 dataset with the null hypothesis

\[ E = 0 \]
Frequency ratio $R = \frac{f_n}{f_{\text{Hg}}}$

- Center of mass offset
- Non-adiabaticity

\[ \frac{\nu_{\text{Hg}}}{2\pi} \approx 8 \text{ Hz}/\mu\text{T} \]
\[ \frac{\nu_{\text{n}}}{2\pi} \approx 30 \text{ Hz}/\mu\text{T} \]
\[ \nu_{\text{Hg}} \approx 160 \text{ m/s vs. } \nu_{\text{UCN}} \approx 3 \text{ m/s} \]

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} = \frac{\nu_n}{\nu_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \rangle_{\perp}}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right) \]
• Motional magnetic field from $B_m = -\frac{v \times E}{c^2}$

• Naively no contribution as $\bar{v} = 0$ for UCN?

• In homogenous B-field and E-field:

  $\left|B\right| = B_0 + \ldots$
  
  $\frac{\theta v_x^2 E}{c^2}$
  
  $\frac{(xv_y + yv_x + \theta yv_z) \partial B_z E}{2B_0c^4}$
  
  $\frac{v_y^2 + (v_x - \theta v_z) E^2}{2B_0c^4}$

Result depends on how particle average the magnetic field:

  adiabatic (UCN)
  
  $\delta \omega = \frac{v_{xy}^2 E}{2B_0c^2} \frac{\partial B_z}{\partial z}$

  non - adiabatic (Hg)
  
  $\delta \omega = \frac{\gamma D^2}{16c^2} \frac{\partial B_z}{\partial z} E$
• Typical B-field gradients: \(\sim 10\ \text{pT/cm}\)
• Dominant effect from mercury transferred to neutron by correction

\[
\frac{d_{\text{false}}}{d_n} = \frac{\partial B_z}{\partial z} \cdot 1.5 \times 10^{-29} \text{ e cm cm/pT}
\]

\[
\frac{d_{\text{false}}}{d_{\text{Hg}}} = \frac{\partial B_z}{\partial z} \cdot 1.15 \times 10^{-27} \text{ e cm cm/pT}
\]

\[
\frac{d_{\text{false}}}{d_{\text{Hg} \rightarrow n}} = -\frac{\partial B_z}{\partial z} \cdot 4.4 \times 10^{-27} \text{ e cm cm/pT}
\]

Measurable nEDM as function of B-Field gradient

nEDM strategy
Blinding

How?

- Shift the central value by adding an unknown offset EDM of -1.5 to $1.5E-25$ ecm to the data

\[
\delta N_{\uparrow, \downarrow; i} = \pm \bar{N} \frac{\pi \alpha d \cdot E}{\Delta \nu h} \sin \phi_i
\]

with \( \phi_i = \frac{(\nu_i - \nu_0)}{\Delta \nu} \pi \)

- Keep un-blinded data in a safe place (encrypted)
Cesium gradiometer

Monitoring of vertical magnetic gradients

Cesium magnetometers on HV electrode

Current accuracy:

\[ \sigma(g_z) \approx 10\text{pT/cm} \]
Critical Component Demonstration (1/14-12/17) nearing completion

- > 75kV/cm achieved in mid-scale HV system
  - With Cu-coated composite electrodes
  - With closed measurement cell
- $^3$He transport (phonon heat-flush) demonstrated in large-scale
- Non-magnetic dilution fridge nearly complete
- B-field uniformity (3 ppm/cm in full-scale) achieved in 1/3-scale cryogenic prototype & dressed spin design advanced
- Noise levels sufficient in SQUID system prototype
  - 1800s UCN storage time measured in cryogenic cell
  - > 18 photo-electrons equivalent observed in cryogenic light collection system with LHe & TBP (need 6 PE at least)

Full-scale operation in 2022

courtesy: Brad Filippone
• UCN density $>1 \times 10^5 \text{ cm}^{-3}$
• All hardware exists
• Necessary cooling power test successful
• Unclear whether and when WWR-M will get permission to operate
Use neutron source’s intrinsic pulses
Fixed installation
Lenght: 50m
dN/dt > 100 MHz

courtesy: F. Piegsa