Searching for a neutron electric dipole moment -

European efforts

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Dec. 7, 2018
Outline

• neutron electric dipole moment & measurement techniques
• ultracold neutrons
• nEDM experiments - European efforts
History of nEDM results

Experimental limit

- ORNL, Harvard
- MIT, BNL
- LNPI
- Sussex-RAL-ILL
- nEDM @PSI (expected 2019)
- n2EDM @PSI (goal)

Theory expectation

- SUSY

Weak interaction SM contribution:

\[ 1 - 6 \times 10^{-32} \text{ ecm} \]

C.-Y. Seng, PRC(2015)025502

comparable sensitivity goals for all worldwide efforts
new limit from PSI experiment expected soon!
Measurement of the difference of neutron precession frequencies in parallel/anti-parallel E and B fields:

\[ \mu_n = 60 \text{ neV/T} \]
\[ \vec{B} = 1 \mu T \]
\[ \nu_B \approx 29 \text{ Hz} \]
\[ \vec{E} = 11 \text{ kV/cm} \]
\[ d_n < 3 \times 10^{-26} \text{ e cm} \]
\[ \nu_E < 160 \text{ nHz} \]

\[ \nu_n = \frac{2\mu_n}{h} |\vec{B}| \pm \frac{2d_n}{h} |\vec{E}| \]

\[ d_n = \frac{1}{2E} \left( h \left( f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow} \right) + \mu_n \left( B^{\uparrow\uparrow} - B^{\uparrow\downarrow} \right) \right) \]

High-precision control and measurement of frequency and magnetic field necessary (fT level)
Experiment sensitivity

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

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

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

nEDM results are still statistically limited

→

the challenge: design apparatus to maximize UCN statistics and all parameters
The beam searches

\[ \delta(d_n) = \frac{\hbar}{2\alpha T E\sqrt{\dot{N}} \sqrt{t}} \]

\[ = 8.7 \times 10^{-22} \text{ecm} \frac{1}{\sqrt{\text{Hz}} \sqrt{t}} \]

- Dominant systematic effect:
  \[ B_v = -\frac{v \times E}{c^2} \]
  final result: \( \sigma(d_n) = 1.5 \times 10^{-24} \text{ecm} \)
due to misalignment of 0.1 mrad

- \( T = \frac{l}{v} \approx 0.015 \text{s}; \alpha > 0.9; \frac{E}{\text{cm}} \approx \frac{100 \text{kV}}{\text{cm}}; \dot{N} \approx 1 \times 10^6 \text{s}^{-1} \)

1 day: \( \sigma = 1 \times 10^{-24} \text{ecm} \)

Dres et al., PRD 15(1977) 9
new effort at Univ. Bern: Neutron EDM Experiment using a Pulsed Beam (BEAM-EDM)

- Unique, novel, and complementary EDM approach
- Project based at University of Bern – Start: 10/2016
- Full-scale experiment intended for the ESS / ANNI ($<10^{-26} \text{ e}\cdot\text{cm}$)
- Proof-of-principle experiments at PSI and ILL ($10^{-24} \text{ e}\cdot\text{cm}$)

Piegsa, *PRC 88, 045502 (2013)*

*Courtesy: Florian Piegsa*
Crystal diffraction neutron EDM

- spin rotation for neutrons close to the Bragg condition for the crystallographic plane in a non-centrosymmetric crystal.
- $n$ exposed to interatomic E-field (up to $10^9$ V/cm)
- a non-zero nEDM results in a spin rotation close to Bragg reflex
- Polarization tensor is sensitive to nEDM which would cause a phase shift

New project with sensitivity $2 \times 10^{-25}$ e cm per day for quartz crystal and PF1b beam ILL reactor is ready.

Information courtesy Vladimir Voronin

$$E_{(11\bar{2}0)} = 2.1 \cdot 10^8 \, V/cm$$

Experimental value for (110) quartz plane

*V.V. Fedorov, M. Jentschel, I.A. Kuznetsov et al., Physics Letters B 694, 25 (2010)*
Ultracold neutrons (UCN)

For highest sensitivity: optimize

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

UCN are neutrons which can be stored in material bottles

CN beamline (e.g. ILL - PF1b)

$$\dot{N} \approx 2 \times 10^9 \text{s}^{-1} \text{ @ } 440 \text{ m/s}$$

$$\alpha \approx 0.99; \quad E \approx 100 \text{kV/cm}$$

$$T = \frac{l}{v} = \frac{2 \text{ m}}{440 \text{ m/s}} = 4.5 \text{ ms}$$

$$\sigma(1\text{s}) = 2 \times 10^{-23} \text{ ecm}$$

UCN (e.g. EDM at PSI)

$$\dot{N} \approx 1000 \text{ s}^{-1}$$

$$\alpha \approx 0.9; \quad E = 15 \text{kV/cm}$$

$$T = 200 \text{s}$$

$$\sigma(1\text{s}) = 4 \times 10^{-24} \text{ ecm}$$

UCN < 300 neV ~ 8 m/s ~ 3 mK

$$\lambda = \frac{\hbar}{m \cdot v}$$

$$E_{\text{kin}} = \frac{mv^2}{2} = \frac{3}{2} kT$$

> 50 nm!
How to increase the statistical sensitivity

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

\[ = \frac{\hbar}{2ET\alpha_0 e^{-T/T_2} \sqrt{N_0 e^{-T/\tau_n}}} \]

\[ E \leq 20kV/cm : \text{ Limited by insulator} \]

\[ \alpha \rightarrow 1 : \text{ Polarization of neutrons} \]

\[ T \rightarrow \tau_n : \text{ Minimize losses} \]

\[ \sqrt{N_0} : \text{ Limited by transport losses} \]

\[ T_2 \rightarrow \infty : \text{ Magnetic field inhomogeneity} \]

- Make \( T_2, \alpha \) large \( \rightarrow \) large high performance magnetically shielded rooms and homogeneous magnetic field
- 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
Example: solid deuterium based sources - LANL - NCSU - MAINZ - PSI

- Pulsed 1.3 MW p-beam 590 MeV, 2.2 mA, 3% duty cycle
- Spallation target (Pb/Zr) (~8 neutrons/proton)
- Heavy water moderator → thermal neutrons 3.6m³ D₂O
- Spallation

- Long UCN guides - minimize UCN losses
- Cryo-pump minimize rest gas losses
- DLC coated UCN storage vessel minimize UCN losses
- Cold UCN-converter 5 kg solid D₂ at 5 K maximize UCN production minimize losses
- Exper.

Exper.

- Exper.
Worldwide efforts for higher UCN intensities

Comparison of ultracold neutron sources for fundamental physics measurements

Suggestion of "standard" method and device for UCN density measurement and comparison:
A NEW UPPER LIMIT ON THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON


Leningrad Nuclear Physics Institute of the Academy of Sciences of the USSR, Leningrad, USSR

Received 24 March 1981

New measurements have reduced the upper limit for the electric dipole moment of the neutron to $|d| < 6 \times 10^{-28}$ cm (90% confidence level).

Fig. 1. 1: magnetic shield, 2: coils, 3: chambers of storage of UCN, P: polariser, A₁, A₂: analysers, D₁, D₂, D₃, D₄: detectors; $H₀$ is the constant magnetic field, $H₁$ is the oscillating magnetic field, $E$ is the electric field.

Pioneering efforts by the PNPI - Lobashev group using for the first time a double UCN storage chamber
Pioneering efforts by the RAL-Sussex-ILL collaboration using for the first time a cohabiting magnetometer - polarized 199-Hg set the present limit.
Several improvements and upgrades to the original nEDM apparatus at PSI

- Four-layer Mu-metal shield
- Vacuum chamber
- Precession chamber
- Mercury lamp or UV laser
- Mercury polarizing cell
- Mercury lamp
- High voltage lead
- Electrode (upper)
- Photomultiplier or photodiode
- Magnetic field coils
- Cesium magnetometer
- Switch
- 5 tesla magnet
- Spin analyzers & neutron detectors
- UCN
Several improvements and upgrades to the original nEDM apparatus at PSI
How to improve:
optimize UCN storage time
and UCN statistics

Chamber made of
dPS insulator ring
and
DLC electrodes

\[ \sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}} \]
Simultaneous spin detection
(also pioneered at PNPI)

- Spin dependent detection
  - Adiabatic spinflippper
  - Iron coated foil
- $^6$Li-doped scintillator GS20

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S. Afach et al., EPJA (2015)51: 143
Neutron transversal depolarization time

\[ T_2 \sim 1000 \text{s} \]

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

\[ \alpha(T) = e^{-\Gamma_2 T} - \frac{\gamma_n^2 g_z^2 T^2}{2} \cdot \langle dh^2 \rangle_{\text{eff}} \]

magnetic field homogeneity \( 10^{-3} \rightarrow 10^{-4} \)

new variometer method of B-field homogenization

Afach et al., PRD92(2015)052008
Afach et al., PRL115(2015)162502
Hg co-magnetometer

\[ \nu_{\text{Hg}} = \gamma_{\text{Hg}} |\vec{B}| \approx 8 \text{ Hz} \]
Analysis: Frequency ratio $R = \frac{f_n}{f_{\text{Hg}}}$

Center of mass offset $\delta h$
Non-adiabaticity $\rightarrow$ new systematic effects
motional (false) EDM

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

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

\[
\frac{\gamma_{n}}{2\pi} \approx 30 \text{ Hz}/\mu\text{T}
\]

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

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

Measure $R$ as function of $dB/dz$
extracting the neutron frequency / \( R \)-curve

\[
R = \frac{f_n}{f_{Hg}} \approx \frac{\gamma_n}{\gamma_{Hg}} \left( 1 \pm \frac{Gh}{B_0} \pm \delta_{B_{\perp}} \pm \delta_{Hg_{\text{Light}}} \pm \delta_{\text{Earth}} \right)
\]

+ new physics
Analysis: Frequency ratio $R = f_n/f_{\text{Hg}}$

Measurement of a false electric dipole moment signal from $^{199}\text{Hg}$ atoms exposed to an inhomogeneous magnetic field.

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

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

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

Fig. 5. Motional false mercury EDM versus the vertical gradient $g_z$ for $B_0^0$ (red up triangles) and $B_0^1$ (blue down triangles). The solid lines correspond to a linear fit, and the dashed line to the theory discussed in Section 2. The horizontal error bars are smaller than the symbol size.
However, it is important also to take higher order gradients into account.

Important:
Cs magnetometry to map online

B-field decomposition

TABLE I. Associated Legendre polynomials up to $l = 5$.

<table>
<thead>
<tr>
<th>$l$</th>
<th>$m$</th>
<th>$P_l^m(\cos \theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$\cos \theta$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$-\sin \theta$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$\frac{1}{2}(3\cos^2 \theta - 1)$</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>$-3\cos \theta \sin \theta$</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>$3\sin^2 \theta$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$\frac{1}{2} \cos \theta(5\cos^2 \theta - 3)$</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>$-\frac{3}{2}(5\cos^2 \theta - 1) \sin \theta$</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>$15\cos \theta \sin^2 \theta$</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>$-15\sin^3 \theta$</td>
</tr>
</tbody>
</table>

+ higher orders
magnetic impurities:  
example: Electrode maps

Local dipoles -> mapping of electrodes and co-magnetometer

after degaussing

Maximum peak to peak: ~20 pT,  
or $d_{f,dipole} \leq 4 \times 10^{-28}$ ecm!

@PTB Berlin
PSI experiment finished data taking in Oct. 2017
→ record statistical sensitivity
→ apparatus dismounted
→ analysis is ongoing (double blinded)

\[ \sigma_d = \frac{\bar{h}}{2E\alpha T \sqrt{N}} \]

54362 cycles
(exclude runs with issues)

\[ \sigma = 0.94 \times 10^{-26}\text{ecm} \]
(before cuts)
Example physics results on the way with blinded data: PSI EDM together with RAL-Sussex data limit on ultra-light axions from oscillating nEDM

Oscillating EDM could come from the interaction of ultra-light axions which could be the dark matter in the Universe

nEDM places the first laboratory limit

C. Abel et al, PHYSICAL REVIEW X 7, 041034 (2017)
New generation UCN storage apparatus
various efforts worldwide

European projects
currently under construction

- PNPI @ILL and @PIK
- TUM @FRMII / moved to ILL
- n2EDM@PSI my generic example
Current: \( d_n < 5.5 \times 10^{-26} \text{ emc} \)

Improvement by factor 3 at new position and with new precession cell

ILL > 2020:

future source at PNPI:

\[
\begin{align*}
\text{ILL > 2020:} & \quad d_n < 2 \times 10^{-26} \text{ emc} \\
\text{future source at PNPI:} & \quad d_n < 1 \times 10^{-27} \text{ emc}
\end{align*}
\]

Reinforcement of platform for earthquake safety is under way - start measurements as soon as allowed by ILL safety
PNPI UCN source at WWR-M reactor

- UCN density $>1 \times 10^4 \text{ cm}^{-3}$
- All hardware exists
- Necessary cooling power test succesful
- Unclear whether and when WWR-M will get permission to operate
PSI Strategy:

Maximize UCN statistics with adequate adaption of systematics.

Construct a baseline apparatus ready in 2020 and upgrade from there.

Goal: \( d_n \sim 1 \times 10^{-27} \text{ e cm} \) for baseline apparatus
Main features of the new apparatus
baseline setup

Inspired by the pioneering Gatchina double-chamber setup
I. Altarev et al. JETP Lett. 44(1986)460
and several years of our own upgrade
and operating experience with the present nEDM setup

- 2 neutron precession chambers with ID=80cm
- coating R&D ongoing
- Hg co-magnetometer in both chambers with laser read out
- Surrounded by calibrated Cs arrays on ground potential (>50 sensors)
- Large NiMo ($^{58}$NiMo) coated UCN guides
Analysis: Frequency ratio \( R = \frac{f_n}{f_{\text{Hg}}} \)

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

\[ \gamma_n \approx 30 \text{ Hz/\mu T} \]

\[ \nu_{\text{Hg}} \approx 160 \text{ m/s} \quad \text{vs.} \quad \nu_{\text{UCN}} \approx 3 \text{ m/s} \]

\( \Delta h \)

Center of mass difference \( h \)

Single chamber analysis - B and G fluctuations compensated by comagnetometer but gradient fluctuations introduce error term proportional to gravitational shift

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

Analysis: based on R as function of dB/dz extrapolate to 0
Analysis: Frequency ratio $R = \frac{f_n}{f_{Hg}}$

$^{199}\text{Hg} + \text{UCN}$  

$\Delta h^t$

$\Delta h^b$

double chamber - linear $\frac{\partial B}{\partial z}$ is almost perfectly compensated but due to different $h_t$ and $h_b$ gradient fluctuations still cause an error on a lower level though

$$R^T - R^B = \frac{2E}{\pi \hbar f_{Hg}} d_n + \frac{\gamma_n}{\gamma_{Hg}} (h^T - h^B) \frac{G}{B_0}$$

Analysis: based on $(R^T - R^B)$ as function of dB/dz extrapolate to 0
Selected requirements for the given statistics goal

- Vertical uniformity $\partial B_z/\partial z$
- Horizontal uniformity $\partial B_z/\partial x, y$

Requirements:
- $0.7 \text{ pT/cm}$
- $8 \text{ pT/cm}$

- Same frequency for the $\pi/2$ pulses for both chambers:
  - Larmor frequency should be the same in both chambers.
  - $\partial_x B_z$ must be small.

- $\partial_{x,y} B_z$ should be small enough not to induce intrinsic depolarization of UCNs and decrease the visibility $\alpha$.

Mathematical expression:

$$T_2^{\text{gr}} \approx \frac{9\pi \nu}{D^3 \gamma_n^2 (\partial B_z/\partial x)^2}$$
Main features:
- large central chamber
- 2.93m × 2.93m × 2.93m
- intermediate chamber large enough to walk and place sensitive components (e.g. pre-amps etc.)
- MSR provides additional thermal shielding in both walls
- 3 doors
- total weight 47 tons (MSR)
- largest openings Φ=220mm

expected performance:
- quasistatic shielding factor guaranteed >80'000 (expected >100'000)

Supplier: VAC - Hanau, Germany

all parts in the innermost chamber have to be magnetically insignificant
all MSR parts were already checked
all apparatus parts checked at PTB
Area B-field mapping
MSR setup
Finished outer MSR cabin
Important: minimizing the remanent field

B-field equilibration scheme and coils layout based on PTB-Berlin experience
innermost layer more complex coil scheme

planned minimization from outside to inside for each layer and direction possible

- innermost room has additional 2 coils on all sides and in all 3 directions to drive magnetic flux in all walls and wall centers
Field coil system - 1µT

- mount coil system
- commission individual coils
- field mapping

Design @LPC CAEN

adapted box-shape B0 coil which uses MSR as return yoke provides adequate homogeneity and stability via current stabilization

goal is uniformity better than $10^{-4}$

PhD
Pierrick Flaux
Cs magnetometer array

- homogenisation & control of B field
- (higher) gradient measurement and control in all directions
- measurement of correlations with E-fields
- crucial for systematics control

work of Georg Bison

- develop $^3$He magnetometry further for absolute B measurement and sensor calibration
Cs magnetometer array

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ILL/TUM effort:
Berkeley, 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)      $4.2 \times 10^{-28} \text{ecm}$
Several effort to search for a neutron EDM in Europe

- prototype beam EDM at U Bern
- crystal EDM at ILL

stored UCN

- PSI: ongoing analysis of blinded data set with \( \sim 1 \times 10^{26} \) ecm statistical sensitivity - result 'soon'.

Installation of new setup n2EDM ongoing - factor 10 sensitivity improvement for baseline setup

- ILL / PNPI waiting for reinforced platform to start measuring
- ILL / TUM installation of MSR and apparatus ongoing, UCN source ready at ILL 2019 ? - UCN source at TUM ?

- PNPI PIK reactor / waiting for reactor start ?
thank you
cordial thanks for providing transparencies to Anatoli Serebrov, Vladimir Voronin, Skyler Degenkolb Florian Piegsa, Philipp Schmidt-Wellenburg, Georg Bison
\[ \delta_{\text{Earth}} = \mp \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( \frac{f_{\text{Earth}}}{f_n} + \frac{f_{\text{Earth}}}{f_{\text{Hg}}} \right) \sin(\lambda) \]

\[ = \mp 5.3 \times 10^{-6} \]
R-curve analysis / earth rotation
Foucault's UCN pendulum

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

\[ = \mp 5.3 \times 10^{-6} \]

*S. Lamoreaux
PRL98(2007)149101
The spatial homogeneity of the magnetic field is characterized with a movable robot to map the magnetic field of each trimcoil and the main field.
Example physics results on the way: neutron/Hg magnetic moment

PSI result with UCNs:

$$\frac{\gamma_n}{\gamma_{Hg}} = 3.842457(3)$$

Fig. 4. 1-sigma allowed regions in the $\gamma_n$, $\gamma_{Hg}$ plane. Our final value for the neutron to mercury magnetic moment ratio (18) here labeled as “PSI 2012” forms the diagonal band. The horizontal band is the neutron magnetic moment (1) value from Greene et al. and the vertical band is from the measurement of the mercury magnetic moment (2) by Cagnac.