Present status and future prospects of nEDM experiment in Grenoble and in Gatchina

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for PNPI-ILL-PTI nEDM collaboration

Ascona, Switzerland, 2 – 6 November 2014
PNPI–ILL–PTI nEDM collaboration at ILL reactor in Grenoble
History of nEDM measurements. Results and prospects of PNPI-ILL-PTI collaboration

Theoretical Prediction:
- Electromagnetic
- Weinberg Multi-Higgs
- Minimal SUSY
- Cosmology
- Left-Right Symm.

Present limit of PNPI-ILL-PTI

Estimation of future limit of PNPI-ILL-PTI at PF2 EDM

Estimations of accuracy at super UCN source in Gatchina

Year
Gatchina EDM spectrometer 1975

The first result for nEDM with UCN method

\[ |d_n| < 1.6 \cdot 10^{-24} \text{ e}\cdot\text{cm} \]

(90% C.L.)

Altarev I.S. et al.,
Nuclear Physics A341 (1980) 269-283
Gatchina EDM spectrometer with UCN liquid hydrogen source in berillium reflector of WWR-M reactor

\[ |d_n| < 6 \times 10^{-25} \text{ e.cm} \ (90\% \text{ C.L.}) \]

Gatchina source of UCN and polarized cold neutrons 1985-1996

\[ |d_n| < 9.7 \cdot 10^{-26} \text{ e-см} \]
(90% C.L.)
ILL UCN facilities - PF2 MAM (in the past)
Installation of non-magnetic platform
Assembly of double-chamber EDM spectrometer in summer 2008 in the interval between reactor cycles
September 2008  -  Assembly and testing of detectors, magnetometers and electronics.  
October 2008  -  Start of the first measurements with the neutrons
Direct measurements of UCN density in the EDM spectrometer entrance and at the UCN turbine exit

\[
\rho_{\text{exp}} = \frac{N_0}{V} \frac{(\tau_{\text{st}} + \tau_{\text{fill}})(\tau_{\text{st}} + \tau_{\text{emp}})}{\tau_{\text{st}}^2}
\]

\[
\rho = 7.5 \text{ cm}^3
\]
Resonance curves for holding time 100s

\[ \alpha = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} \]

\[ \alpha_1 = 0.71; \quad \alpha_2 = 0.70 \]
From the counts of each of the detectors D1, D2, D3, D4 one can derive the corresponding experimental values $d_1, d_2, d_3, d_4$ for the neutron EDM.

$d_1$ - top trap, $d_2$ - bottom trap,
$d_3$ - top trap, $d_4$ - bottom trap

$\alpha_1 = 0.71, \alpha_2 = 0.7$
Principal scheme of measurements with false effect control

- $d_1$ - top trap
- $d_2$ - bottom trap
- $d_3$ - top trap
- $d_4$ - bottom trap

\[ \text{direct detectors} \]
\[ \text{side detectors} \]

\[
\begin{align*}
EDM &= \frac{1}{4}\left[ (d_1 + d_2) + (d_3 + d_4) \right] \\
\nu &= \frac{1}{4}\left[ (d_1 - d_2) + (d_3 - d_4) \right] \\
N^{(*)} &= \frac{1}{4}\left[ (d_1 - d_2) - (d_3 - d_4) \right] \\
z &= \frac{1}{4}\left[ (d_1 + d_2) - (d_3 + d_4) \right]
\end{align*}
\]

- EDM is EDM effect
- $\nu$ is effect of influence of electric polarity changing on the resonance conditions (magnetic field or frequency)
- $N^{(*)}$ is effect of influence of electric polarity changing on the detector counting rate
- $z$ is compensation of all effects, including EDM effects

(*) Difference of measurements for 90° and 270°
Experimental measurement of derivative in the working point and the method of resonance tuning out by means of frequency alteration.

\[
d_n = \frac{h(N^+ - N^-)}{2(E^+ + E^-)\frac{\partial N}{\partial f}}.\]
Preparation of Cs-magnetometers at PTI
8 (4x2)Cs-magnetometers inside EDM spectrometer
System of optical pumping with light guides
Stabilization of magnetic field during resonance measurements (system of stabilization of resonance conditions + feedback by means of current coils)

**quiet magnetic situation**

![Graph showing magnetic field stabilization over time](image-url)
Electronics for magnetic field generation

main coils and additional coils

$\Delta J/J = \pm 2.5 \cdot 10^{-7} \approx \pm 0.5 \text{ pT}$

$\Delta J/J = \pm 1 \cdot 10^{-7} \approx \pm 0.2 \text{ pT}$

$\Delta J/J = \pm 2.5 \cdot 10^{-7} \approx \pm 0.5 \text{ pT}$
Stabilization of magnetic field during resonance measurements (system of stabilization of resonance conditions + feedback by means of current coils)

Full day tests of bridge crane
The influence of external magnetic fluctuations on stability of resonance conditions in a spectrometer.
(factor of stabilization by mean of 8 Cs-magnetometers is about 10 – 15 times)

a) FM is the average frequency measured by means of eight Cs magnetometers;

b) FN is the frequency measured by the additional Cs magnetometers in working volume;

Difference FN – FM.
Electronics for stabilization system of neutron resonance conditions

(F_1+F_2)/2 Box

4 Channel Frequency Measurement Box

Gate Time Box

Frequency Divider

PC

EDMS

PNPI
Experimental measurement of derivative in the working point and the method of resonance tuning out by means of frequency alteration.

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

Resonance curve (Tstorage 100s)
\( (\alpha_1 = 0.71, \alpha_2 = 0.7) \)
Neutron guide coatings,
UCN trap coatings
For reduction of UCN losses the neutron guides and storage chambers (glass-ceramics rings and electrodes) were sent to PNPI where their surfaces were cleaned and freshly coated with 58Ni-Mo and BeO, Be, respectively.

PNPI installations for coating of neutron guides and storage chamber.
Coating facilities at PNPI (installation for coating of flat surface of UCN guides and electrodes (Ni$^{58}$Mo, Be) and cylindrical surface of UCN trap (BeO))

Near installation
A.Kharitonov, E.Siber, O.Rozhnov
UCN guide with a big diameter
(replica technology)

Installation for coating of Ni^{58}Mo on the float glass

foil after separation from glass (size 700x470 mm^2)

preparation of a UCN guide

UCN guides of different diameters
Coating facilities at PNPI (installation for coating of cylindrical UCN guides inside (Ni$^{58}$Mo, Be))

Near installation
M.Lasakov, A.Vasiliev
Glass ceramics rings (insulators) and new entrance guide after coating by BeO and 58Ni-Mo
Measurement of Storage Time

Top chamber

Bottom chamber

\[ \tau_{\text{top}} = 101 \pm 3 \text{ s} \]

\[ \tau_{\text{bott}} = 95 \pm 4 \text{ s} \]
The best result with HV
\((+_\_)+175\text{kV}/8.7\text{cm} = 20\text{kV/cm}\)
The recent measurement of nEDM at ILL
Direct measurement of sensitivity of EDM spectrometer with UCN density 4 ucn/cm³ (at entrance) with electric field 18 kV/cm and T(hold) = 100 s

\[ D_t = (2.59 \pm 3.90) \cdot 10^{-25} \]
\[ D_b = -(3.98 \pm 4.22) \cdot 10^{-25} \]
\[ D = -(0.70 \pm 2.17) \cdot 10^{-25} \]

\[ \delta D_{edm} \sim 1.7 \cdot 10^{-25} \text{ e}\cdot\text{cm/day} \]

The best run

15 hours of measurement
Preliminary results of measurements in units $10^{-26}$ e·cm

<table>
<thead>
<tr>
<th></th>
<th>Old</th>
<th>New</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM</td>
<td>0.7±4.0</td>
<td>0.363±4.68</td>
<td>0.56±3.04</td>
</tr>
<tr>
<td>$\nu$</td>
<td>-22.8±9.2</td>
<td>-10.04±5.98</td>
<td>-13.8±5.01</td>
</tr>
<tr>
<td>$N$</td>
<td>-14.5±4.4</td>
<td>18.62±5.15</td>
<td>-0.53±3.35</td>
</tr>
<tr>
<td>$Z$</td>
<td>-0.8±4.0</td>
<td>3.68±4.72</td>
<td>1.05±3.05</td>
</tr>
</tbody>
</table>

$|nEDM| \leq 5.5 \times 10^{-26}$ e·cm

90% CL
Control of false effect due to magnetometers

\[(H_{\text{up}} - H_{\text{down}})^+ - (H_{\text{up}} - H_{\text{down}})^- < 10 \text{ fT/m} \rightarrow 2 \cdot 10^{-27} \text{ e\cdot cm}\]

There is no correlated changing of magnetic field gradient in big volume to simulate \[d > 2 \cdot 10^{-27} \text{ e\cdot cm}\]
Possible systematic because of leakage current

Monte-Carlo simulation

\[ \Delta \theta = \pm 15^\circ \]
\[ \Delta \varphi = \pm 2.5^\circ \]
**Possible systematic because of leakage current**

**EDM is EDM effect**

\[ \chi^2/\text{DoF}=1.47 \]

Influence on the resonance conditions

\[ \Delta \nu \]

\[ \chi^2/\text{DoF}=0.99 \]

Influence on the detector counting rate

\[ \Delta N \]

\[ \chi^2/\text{DoF}=0.47 \]

Compensation of all effects

\[ Z \]

\[ \chi^2/\text{DoF}=1.62 \]

We do not observe any systematic because of leakage current.
Distribution of EDM results for different leakage current

\[ \text{EDM} \left[ 10^{-25} \text{e} \cdot \text{cm} \right] \]

\[ d_{\text{leak. current}} / J_{\text{current}} < 10^{-28} \text{e cm/nA} \]

\[ |d_{\text{leak. current}}| < 1 \cdot 10^{-26} \text{e cm} \text{ for 100nA} \]
The magnitude of the effect is estimated using the formula:

\[
D_{geo} = -\frac{J\hbar}{2} \left( \frac{\partial B_{0z}}{\partial z} \right) \frac{v_{xy}^2}{c^2} \left[ 1 - \left( \frac{\omega_r^*}{\omega_0^2} \right)^2 \right]^{-1}
\]

\[
\omega_r^* = \frac{\pi^2}{6} \left( \frac{v_{xy}}{R} \right)^2 \quad v_{xy}^2 = \frac{1}{3} v_{max}^2
\]

The half-width of the neutron resonance at the storage time of UCN in the trap spectrometer 100s is 5 × 10⁻³ Hz, which corresponds to a change of the magnetic field 0.17 nT.

Adjustment of resonance is ¼ period therefore \( \frac{\partial B_{0z}}{\partial z} = 0.8 \text{ nT/m} \)

\[
D_{geo} \leq 7.5 \times 10^{-28} \text{ e\cdotcm}
\]
Quadratic $v \times E$ effect

$$\vec{B} = -\frac{1}{c^2} \left[ \vec{v} \times \vec{E} \right]$$

$$B_{\text{eff}} = \frac{4\pi}{c^2} \cdot 10^{-2} \cdot \frac{2}{3} v \cdot E \approx 100 \text{ pT}$$

$$B = \sqrt{B_0^2 + B_{\text{eff}}^2} \approx B_0 + \frac{1}{2} \frac{B_{\text{eff}}^2}{B_0}$$

$$B - B_0 = \frac{1}{2} \frac{B_{\text{eff}}^2}{B_0} \approx 2.5 \text{ fT}$$

$$D_f < 5 \cdot 10^{-28} \text{ e} \cdot \text{cm}$$

Effect is compensated by double chamber scheme.
# Table of systematic errors

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Value, e·cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage currents (&lt;100 nA)</td>
<td>&lt; 1\cdot10^{-26}</td>
</tr>
<tr>
<td>Quadratic $\mathbf{v} \times \mathbf{E}$</td>
<td>0</td>
</tr>
<tr>
<td>Non-parallelism $\mathbf{B}$ and $\mathbf{E}$</td>
<td>0</td>
</tr>
<tr>
<td>Geometric phase</td>
<td>&lt; 7.5\cdot10^{-28}</td>
</tr>
</tbody>
</table>
OUR current result

\[ |nEDM| \leq 5.5 \cdot 10^{-26} \text{ } e \cdot cm \]

90\% CL

Present limit of RAL/Sussex

\[ |nEDM| \leq 3 \cdot 10^{-26} \text{ } e \cdot cm \]

90\% CL
Possible improvement of accuracy of nEDM measurement at PF2
PF2  position EDM
Comparison of UCN density at the different beam positions of PF2

<table>
<thead>
<tr>
<th></th>
<th>1999 September A.V. Strelkov (without Al foil) UCN/cm³</th>
<th>1999 September A.V. Strelkov (with Al foil) UCN/cm³</th>
<th>2008 November–December PNPI (without Al foil) UCN/cm³</th>
<th>2008 November–December PNPI (with Al foil) UCN/cm³</th>
<th>2013 April–May PNPI (with Al foil) UCN/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM position</td>
<td>42.6</td>
<td>21.5</td>
<td></td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td>MAM position</td>
<td>13.7</td>
<td>5.6</td>
<td>7.5</td>
<td>4.3</td>
<td></td>
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<tr>
<td>Ratio EDM/MAM</td>
<td>3.1</td>
<td>2.9</td>
<td></td>
<td></td>
<td>3 - 4</td>
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</tbody>
</table>
EDM spectrometer at the PF2 EDM position

- EDM spectrometer
- turbine
- installation "Big gravitrap"
New scheme of UCN trap in EDM spectrometer

Expected factor UCN transmission intensity is about 2 - 3 times
High voltage test of new EDM traps construction
High voltage test of new EDM traps construction
New EDM traps construction
New EDM trap constructions are ready for transportation
EDM sensitivity at PF2 EDM position

• New position at PF2 (EDM instead of MAM) Factor in UCN density is about 3 – 4 times in respect to MAM position.
• New scheme of UCN trap in EDM spectrometer
• Expected factor UCN transmission intensity is about 2 - 3 times

\[ \rho_{\text{ucn at entrance}} \sim 20 \text{ ucn/cm}^3, \]
\[ \delta D_{\text{edm}} \sim 1 \cdot 10^{-25} \text{ e}\cdot\text{cm/day} \]

Upper limit of sensitivity:
\[ 1 \cdot 10^{-26} \text{ e}\cdot\text{cm/100 days} \]
History of nEDM measurements. Results and prospects of PNPI-ILL-PTI collaboration

Theoretical Prediction:
- Electromagnetic
- Weinberg Multi-Higgs
- Minimal SUSY
- Cosmology
- Left-Right Symm.

<table>
<thead>
<tr>
<th>Year</th>
<th>Present limit of RAL/Sussex</th>
<th>Estimation of future limit of PNPI-ILL-PTI at PF2 EDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>$10^{-28}$</td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>$10^{-27}$</td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>$10^{-26}$</td>
<td></td>
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<tr>
<td>1980</td>
<td>$10^{-25}$</td>
<td></td>
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<td>1985</td>
<td>$10^{-24}$</td>
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<td>1990</td>
<td>$10^{-23}$</td>
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<tr>
<td>1995</td>
<td>$10^{-22}$</td>
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<td>2000</td>
<td>$10^{-21}$</td>
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<td>2005</td>
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<tr>
<td>2010</td>
<td>$10^{-19}$</td>
<td></td>
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<tr>
<td>2015</td>
<td>$10^{-18}$</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>$10^{-17}$</td>
<td></td>
</tr>
</tbody>
</table>
Oliver Zimmer UCN source with superfluid He at ILL.

**Future prospects 2**

New position at H172B, UCN source with superfluid He at ILL. Factor in UCN density is about 10 times in respect to PF2 EDM position.

\[ \rho_{ucn \ at \ entrance} \sim 200 \ ucn/cm^3, \]
\[ \delta D_{edm} \sim 3.5 \cdot 10^{-26} \ e\cdot cm/day \]

Upper limit of sensitivity:

\[ 3.5 \cdot 10^{-27} \ e\cdot cm/100 \ days \]
PNPI–ILL–PTI collaboration at Gatchina UCN supersource at PNPI reactor WWR–M

future prospects 3
Project of ultracold and cold neutron source with superfluid helium at WWR-M reactor in Gatchina
Vertical cross section of WWR-M reactor.
1 – reactor core, 2 – reactor tank, 3 – concrete protection, 4 – chamber above the reactor, 5 – horizontal channel, 6 – thermal column, 7 – vertical channel.
Neutron scattering in liquid helium

I.Ya. Pomeranchuk “Selected works”

About neutron scattering with energy a few degree in fluid Helium II

The scattering of slow neutron in He-II is considered. It is shown that the scattering is a negligible small at the temperature below than temperature of critical point.


UCN source based on superfluid He-II


\[ E_{\text{beg}} = 12 \text{ K} \rightarrow E_{\text{UCN}} \approx 10^{-3} \text{ K} \]

\( \lambda = 9 \text{ Å} \)
Idea

UCNs are generated in helium from cold neutrons of 9 Å wavelength (12 K energy). It is correspond with phonon energy: cold neutron produce phonon, practically stops and becomes an ultracold one. UCN can “lives” in superfluid helium for tens or hundreds of seconds until a phonon be captured.

Cold neutrons (9 Å) penetrate through the wall of a trap, but ultracold neutrons (500 Å) are reflected, that is why UCN can be accumulated up to the density defined by the time of storage in the trap filled with superfluid helium.

UCN $\lambda=500$ Å, $T=10^{-3}$ K

CN $\lambda=9$ Å, $T=12$ K
MCNP neutron flux calculation results and heat generation in thermal column of WWR-M reactor at 15 MW

- He, $T=1.2$ K
- LD$_2$, $T=20$ K
- C, $T=300$ K
- Pb, $T=300$ K

\[ \rho_{ucn} = 10^4 \text{ cm}^{-3} \quad (\tau=10 \text{ s}) \]
\[ \Phi = 4.5 \cdot 10^{12} \text{ n/(cm}^2\text{s)} \]
\[ \Phi(\lambda=9 \text{ A}) = 3 \cdot 10^{10} \text{ n/(cm}^2\text{sA)} \]
\[ Q_{He} = 6 \text{ W} \]
\[ 19 \text{ W} \]
\[ 19 \text{ W} \]
\[ 19 \text{ W} \]
\[ LD_2, Q_{LD2+Al} = 100 \text{ W} \]
\[ C, Q_C = 700 \text{ W} \]
\[ Pb, Q_{Pb} = 15 \text{ kW} \]
\[ \Phi = 10^{14} \text{ n/(cm}^2\text{s)} \]
\[ Q = 15 \text{ MW} \]
UCN density in EDM trap $10^4$ cm$^{-3}$

- **Maximal density inside closed source**
- **Density in experimental trap with volume 35 l**
- **Density in experimental trap with volume 350 l**

- $P_{He}$, mm Hg
- $T$, K
- $\tau_{He-ill}$, S
- $Q$, W

- $10^8$ to $10^3$ UCN density, cm$^{-3}$

Graph showing UCN density as a function of $P_{He}$, $T$, $\tau_{He-ill}$, and $Q$.
Cryogenic scheme of UCN source with superfluid He

Vacuum test of full-scale model of UCN source
Cryogenic test of full-scale model of UCN source
The full-scale technological model of a source of ultracold neutrons with superfluid helium is mounted.
The full-scale technological model of a source of ultracold neutrons with superfluid helium is mounted.
Vacuum equipment
Plan of implementation of the project

Degree of readiness of the equipment - 40%.

Necessary additional financial investments of 182 million rubles.

<table>
<thead>
<tr>
<th>Project Description</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of elements and construction of R/A storage</td>
<td></td>
<td>44 million rubles</td>
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<tr>
<td>Production of &quot;warm&quot; intra reactor part and protection</td>
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<td>56 million rubles</td>
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<tr>
<td>Dismantle of a thermal column</td>
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<td>12 million rubles</td>
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<tr>
<td>Installation of &quot;warm&quot; intra reactor part with protection</td>
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<td></td>
<td></td>
<td>10 million rubles</td>
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<tr>
<td>Production of &quot;cold&quot; intra reactor part</td>
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<td></td>
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<td>50 million rubles</td>
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<tr>
<td>Installation of &quot;cold&quot; intra reactor part</td>
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<td></td>
</tr>
</tbody>
</table>

Total by years, million rubles. 64 65 43 10
Center for researches with the ultracold neutrons

The purpose – creation of a supersource of ultracold neutrons with a density of 100 times is higher, than all existing world analogs

The project is developed
PIK reactor
The project of sources of ultracold neutrons on the PIK reactor with superfluid helium

UCN density on the PIK reactor is expected $1.3 \cdot 10^3 \text{ см}^{-3}$
It will be less than on BBP-M in 10 times
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Present limit of PNPI-ILL-PTI
Present limit of RAL/Sussex
Estimation of future limit of PNPI-ILL-PTI at PF2 EDM
Estimations of accuracy at super UCN source in Gatchina

Year
Neutron EDM Experimental limit (e·cm)
$10^{-20}$ $10^{-21}$ $10^{-22}$ $10^{-23}$ $10^{-24}$ $10^{-25}$ $10^{-26}$ $10^{-27}$ $10^{-28}$

MIT-BNL
ORNL-Harvard
ORNL-ILL...
ILL-Sussex-RAL...
PNPI

Cosmology

Estimation of future limit of PNPI-ILL-PTI at PF2 EDM
Estimations of accuracy at super UCN source in Gatchina
The purpose - creation of a supersource of ultracold neutrons with a density of 100 times is higher, than all existing world analogs.
Thank you for attention
Best regards from Russia