Project of ultracold neutron source with superfluid helium at WWR-M reactor (PNPI, Gatchina) and scientific research program

A.P. Serebrov

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Conceptual idea of UCN source at WWR-M reactor

- Reactor core
- Membrane
- UCN shutter
- $\Phi(30K)=10^{12} \text{n cm}^{-2}\text{s}^{-1}$
- $\rho_{\text{ucn}}=10^4 \text{n cm}^{-3}$ (?)
- $W \approx 10 \text{ W}$ (?)
- Superconductive solenoid 5T
- UCN shutter
- Membrane
- He-II 1 K
- D$_2$ 20 K
- C 300 K
- Bi 300 K
Project of ultracold and cold neutron source
with superfluid helium at WWR-M reactor
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 negligible small at the temperature below than temperature of critical point.

UCN source based on superfluid He-II


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

\[ \lambda = 9 \text{ Å} \]
Storage time of UCN in He-II
(results of experiment)

Fig. 2. Storage of UCN in a liquid Helium filled vessel. $N(t)$ - number of observed detector counts after a storage time $t$.

Fig. 3. Loss rate due to the interaction of UCN with superfluid Helium as a function of temperature. The numbers in brackets on the vertical scale give the corresponding storage times and total cross section (for 4.6 m/s UCN), respectively. $\bullet$ Method A, $\circ$ Method B, $\circ$ Method A (corrected), $\circ$ Method B (corrected), see text. Dashed lines show the results for the two phonon scattering process calculated using Landau's Hamiltonian [4] (L-H) and by Griffin and Talbot [6] (G-T). Solid lines show the total loss rate using these two approaches.
H. Yoshiki experiment at ILL

Fig. 5. The UCN detector counts as a function of time, with the velocity selector set to 9 Å.

Fig. 4. Experimental measurement of the temperature dependence of UCN storage lifetime, together with the theoretical expectations [6] from two models of phonon and roton interactions.

UCN density in the source $\rho = C \tau$
$\Phi(\lambda=9\text{Å}) = 2.7 \cdot 10^7 \text{ n/(cm}^2\cdot\text{s} \cdot \text{Å})$
$C$ – UCN generation (0.9±0.1) n/(cm$^3$s)
$\tau$ – storage time in the source
$\rho \approx 10 \text{ cm}^{-3}$

Fig. 6. The UCN count rate recorded at wavelengths between 4 Å and 11 Å.
Thermal column of WWR-M reactor

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.

Cross section of WWR-M reactor
Idea

UCNs are generated in helium from cold neutrons of 9Å wavelength (12 K energy). It is correspond with phonon energy: cold neutron energizes 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 (9Å) penetrate through the wall of a trap, but ultracold neutrons (500Å) 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.
MCNP neutron flux calculation results and heat generation in thermal column of WWR-M reactor at 15 MW

\[ \rho_{ucn} = 10^4 \text{ cm}^{-3} \quad (\tau = 10 \text{ s}) \]
\[ \Phi = 4.5 \cdot 10^{12} \text{ n/(cm}^2\text{s)} \]
\[ \Phi(\lambda = 9 \text{ A}) = 3 \cdot 10^{10} \text{ n/(cm}^2\text{s)} \]
\[ Q_{\text{He}} = 6 \text{ W} \]
\[ Q_{\text{LD}_2} + Q_{\text{Al}} = 100 \text{ W} \]
\[ Q_{\text{C}} = 700 \text{ W} \]
\[ Q_{\text{Pb}} = 15 \text{ kW} \]
\[ \Phi = 10^{14} \text{ n/(cm}^2\text{s)} \]
\[ Q = 15 \text{ MW} \]
Cryogenic scheme of UCN source with superfluid He

UCN density

maximal density inside closed source

density in experimental trap with volume 35 l

density in experimental trap with volume 350 l
Comparison of expected UCN density with UCN density of present sources

<table>
<thead>
<tr>
<th></th>
<th>UCN density (cm(^{-3}))</th>
<th>Gain factor</th>
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</thead>
<tbody>
<tr>
<td>Present project</td>
<td>10(^4)</td>
<td></td>
</tr>
<tr>
<td>ILL (turbine source)</td>
<td>10</td>
<td>10(^3)</td>
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</tbody>
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Cryogenic and vacuum equipment

At present there are some equipment for UCN source at WWR-M reactor:

- Helium refrigerator TCF 50 (3000 W @ 15 K, Linde Kryotechnik AG)
- Helium liquefier L280 (80 l/h, Linde Kryotechnik AG)
- Vacuum pump station (BOC Edwards)
Helium refrigerator
Gas management systems
Helium liquefier
Helium tank
Vacuum equipment
General view
General view
General design
Installation of UCN source on WWR-M reactor

a – Pb shielding mounting; b – graphite block mounting; c – mounting of cryostat, UCN superconductive polarizer and UCN switchboard; d – mounting of biological shielding.
New facilities of WWR-M reactor
Ultracold and cold neutron source at WWR-M reactor with neutron guide halls
Program of fundamental research with ultracold neutrons

1. Neutron EDM and problem of CP-violation
2. Precise measurements of neutron β-decay and search for deviations from Standard Model
3. Search for neutron-antineutron oscillations
Fundamental interaction of elementary particles. Methods of research

1. High-energy physics $E \leq 10^{13}$ eV.

2. Cosmology, astrophysics, cosmic rays, neutrino physics.

3. Precise investigations, search of small deviations to Standard law of physics. One of a way is the investigation with UCN of $10^{-7}$ eV.
Problem of CP-violation and Neutron EDM
Neutron EDM and problem of CP-violation

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

Year

Neutron EDM Experimental limit (e·cm)

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

reached limit

estimation of precision of PNPI project at ILL

estimation of precision of PNPI project at WWR-M reactor, Gatchina
Neutron decay, Standard Model and Cosmology
Neutron decay and cosmology

\[ (f \tau_n)^{-1} = \frac{G_F^2}{2} \frac{(1 + 3g_A^2)}{\pi^3} m_e^5 \]
\[ \Gamma = \left( \frac{7}{60} \right) \pi (1 + 3g_A^2) G_F^2 T^5 \]
\[ H \approx \left[ (8/3) \pi G \rho_\gamma \right]^{1/2} \]
\[ \rho_\gamma = \frac{\pi^2}{30} g_\ast T^4 \]
\[ T_f \approx 1 \text{ MeV} \]
\[ n/p = \exp\{-\Delta m/T_f\} \]
\[ Y_p \approx 2n/(n + p) = 2(n/p)/(n/p + 1) \]
\[ \Delta \tau_n = 1\% \rightarrow \Delta Y = 0.75\% \ (\pm 0.61\%) \]
\[ \Delta \tau_n = 1\% \rightarrow \Delta \eta = 17\% \ (\pm 3.3\%) \]

New \( \tau_n = (878.5 \pm 0.8) \text{ s} \) confirms \( n_b/n_\gamma \) from CMB.
Studies of the structure and dynamics of nanostructures by means of cold and very cold neutrons
Studies of the structure and dynamics of solid state
Studies of nanostructures by means of cold neutrons

hall of cold neutrons

Reflectometer “Reverans”

SAPNS Diffractometer “Vector”

2-axes Diffractometer

3-axes Spectrometer

SESANS

Neutron Guide Hall

CN 8 - 15 Å

CN 6 - 12 Å

CN 4 - 10 Å
Studies of nanostructures by means of very cold neutrons
30 Å - 100 Å
Biological micro-molecules and structures:
DNA, Proteins, Ferments, Cell membranes.
Current state of UCN source project at PNPI

✅ 1. Cryogenic and vacuum equipment

✅ 2. Design

❓ 3. Budget
Movie
“How it will be”