IRSTI 29.05.81

V.V.Nesvizhevsky[1],K.Turlybekuly[2,3], D.A.Kereibay[2], E.V.Lychagin[2],S.K.Sakhiyev[4]
[1]*Institut Laue-Langevin, Grenoble, France*
[2]*Joint Institute for nuclear researches, Dubna, Russia*
[3]*L.N. Gumilyov Eurasian national university, Astana, Kazakhstan*
[4]*Abay Kazakh national pedagogical university, Almaty, Kazakhstan*

SIMULATION OF LOSS COEFFICIENT MEASUREMENT EXPERIMENT AT DIFFERENT UCN VELOCITIES OF USING GRAVITATIONAL SPECTROSCOPY

Abstract. This work is devoted to simulation of precise experiment of loss coefficient measurement experiment at different velocities of UCN using gravitational spectroscopy and to choose optimal parameters of storage volume. The effect of various covers and materials of trap on loss coefficients preliminary was estimated.

As result of simulation the size of experimentalset-up, optimal time diagram of measurements and optimal area of sample to measure loss coefficient with given accuracy were chosen.

Keywords:loss coefficient, ultracold neutrons

Introduction

Ultracoldneutrons(UCN) are free neutrons defined via their most important property: they can be stored in vessels. They have very low kinetic energies below about 300 neV corresponding to $\simeq 3.5\,\mathrm{mK}$, hence their name: ultracold. They can be confined by the strong interaction (total reflection at any angle of incidence from surfaces of certain materials like Ni, Be, stainless steel), the magnetic moment interaction (repulsion of one spin component from field gradients due to the neutron magnetic moment) and due to gravitation (limited vertical reach).

Reflection of UCN neutrons on walls of trap due to strong interaction can be well described by the so-called Fermi potential

$$U = \frac{2\pi\hbar^2}{m} Nb,$$

where N is the number density in the material assumed to be homogeneous, b is the coherent scattering length and m is the mass of neutron.

In inhomogeneous magnetic fields, the kinetic energy change of the neutrons can be expressed as $\Delta E_{kin} = \pm 60 \cdot \mathrm{neV/T}$, taking the positive sign if the spin component is antiparallel to the field.

The gravitational interaction is on the same scale for UCN, $\Delta E_{kin} = \Delta h \cdot 103\mathrm{neV/m}$, where Δh is the height difference.

The effect of all three interactions can be combined and used for UCN traps.

The possibility to store UCN for relatively long observation times makes them unique and highly sensitive probes, testing our understanding of fundamental physics such the search for a permanent electric dipole moment of the neutron[1], measurement of the neutron lifetime[2] and measurement electric charge of neutron[3]. One of the key experiments is the search for permanent electric dipole moment of the neutron (nEDM). A finite nEDM violated time-reversal invariance and, therefore, might help to understand the matter-antimatter asymmetry in our universe. It is tightly linked to some of the open problems in modern physics, the so-called “strong CP-problem” and the “SUSY CP-problems”. Its observation would be a clear indication for physics beyond the electro-weak Standard Model of particle physics [4,5]. Another important study with UCN is measurement of the neutron lifetime. The precise value of the neutron lifetime plays an important role in nuclear and particle physics and cosmology. Also it plays a role in determining the helium to hydrogen ratio in Big Bang Nucleosynthesis.

Most of UCN experiments arestatisticallylimited. And we are today at a point at which fundemantal physics application require ***largerUCN intensities*** in order to further advance. But nowadays the intensities of UCN that we have are not enough and require further advance. Thus, most of researches centresare working on increasing of existing UCN sources or on building new intense sources of UCN to develop experiments of neutron measurement and to improve their accuracy.Various developments have allowed one to increase the intensity of UCN considerably over the years. One of them is work, which was provided by FLNP JINR physicists [6]. The principal idea of this work consists in installing a helium UCN source into an external beam of thermal or cold neutrons and in surrounding this source with a solid methane moderator/reflector. One of the important parts of this work is storage vessel of UCN,which has to store maximum number of UCN. Consequently, one should note that task of building a UCN production trap from a technologically convenient material with minimum loss coefficient and high optical potential. The moderator plays the role of external source of cold neutrons needed to produce UCNs.

This work is devoted to simulation of precise experiment of loss coefficient measurement at different velocities of UCN using gravitational spectroscopy and to choose optimal parameters of storage volume. The effect of various covers and materials of trap on loss coefficients preliminary was estimated.

As result of simulation size of experimentalset-up, optimal time diagram of measurements and optimal area of sample to measure loss coefficient with given accuracy were chosen.

Properties of UCN

The neutron-reflecting potential of the trap wall is defined by the average value (with the averaging made over the volume of the vessel wall material) of the real neutron-nucleus interaction potential; for slow neutrons, use can be made of Fermi quasi-potential instead [7]:

$$U(\mathbf{r}) = \frac{h^2}{2\pi m} b\delta(\mathbf{r}-\mathbf{r_0}),$$

where h is the Planck constant, m is the neutron mass, $\delta(\mathbf{r}-\mathbf{r_0})$ is the delta function, and b is the coherent scattering length for neutron scattering neutron scattering by bound niclei, which is determined from the measurements of the cross section for neutron scattering by these nuclei: $\sigma_s = 4\pi b^2$. USNs possess a relatively long de Broglie wavelength ($\sim 500\,\mathring{A}$), which far exceeds the interatomic distance ($\sim 2\,\mathring{A}$), and therefore the volume-averaged Fermi quasi-potential is the effective wall potential:

$$U(\mathbf{r}) = \frac{h^2}{2\pi m} bN.$$

Here, N is the volume density of nuclei with the scattering length b.

The same expression for the effective potential is obtained by exactly solving the Schrodinger equation in the theory of multiple wave scattering based only on the amplitude of scattering by a single nucleus regadless of what potential generates this amplitude. For the majority of nuclei $b > 0$, and hence, U_{eff} is also positive for the materials of these nuslei. To penetrate into the material from a vacuum, neutrons must overcome the repulsive action of the material at the interface. When the kinetic neutron energy is lower than U_{eff}, the neutrons can not find their way into the material at any angles of incidence whatsover. This repulsive action of material trap wall on neutrons is caused only by the strong neutron-nucleus interaction, which is on the order of 10 MeV. However, owing to the short range of the nuclear forces and the small nuclear volume, the quantity U_{eff} (which plays the role of the work function in the transition of neutron from a vacuum into the material) turns out to be very small ($\sim 10^{-7}\,\text{eV}$). The kinetic neutron energy corresponding to U_{eff} is termed the limiting UCN energy (E_{lim}) for a given wall. UCNs with $E \le 10^{-7}$ eV have velosities $\text{v} \le 5\, m\cdot s^{-1}$, wavelength $\lambda \ge 500\,\mathring{A}$, and effective temperatures $\text{T} \le 10^{-3}\,\text{K}$. While reflecting from a wall, a UCN penetrates it by a very small depth:

$$X = \frac{h}{\sqrt{2mU_{\text{eff}}}} \approx 150\,\mathring{A}$$

While inside the wall material, UCNs may either perish due to the capture by nuclei or accelerate (and escape th UCN range) by gaining energy from the thermal nuclear vibrations (inelastic scattering). The UCN losses arising in these processes are decribed by adding to the effective potential a relatively small imaginary part, which is expressed by the dimensionless parameter

$$\eta = -\frac{\mathrm{Im}U_{\mathrm{eff}}}{\mathrm{Re}U_{\mathrm{eff}}} = -\frac{\mathrm{Im}b}{\mathrm{Re}b}.$$

On the strength of the optical theorem,

$$\mathrm{Im}b = -\frac{m}{2h}\sigma_{\mathrm{tot}}\mathrm{v},$$

where σ_{tot} is thetotalneutron-material interaction cross section. The processes prevailing at low velocities are the capture and the inelastic scattering, which obey the $1/\mathrm{v}$ law, and therefore the parameter η is independent of the UCN velocity and us in the $\approx 10^{-4} - 10^{-5}$ range for the majority of materials. The likelihood of losing a UCN in a single collision with the wall is $\mu = \eta \mathrm{v}/\mathrm{v}_{\mathrm{lim}}$. Therefore, prior to its disappearance (due to its capture or heating) a UCN in a vessel can experience over 10^5 collisions, which corresponds to a storage time of □ 2×10^3 s in a trap measuring □ 10 cm.

Method

UCN gas

Since UCN have wavelength 10^{-7} times smaller than the dimensions of the guides and vessels in which they are trapped they can be considered to follow classical trajectories between collisions with the walls of any confining vessel. In many ways they are very similar to the classical particles of kinetic theory and not too surprisingly many results from kinetic theory can be invoked to describe the behavior of UCN in bottles and neutron guides. It is this similarity that leads to the idea of UCN gas. One can consider the concept of UCN gas and derive the necessary theory to describe the various features of neutron storage.

UCN gas, although very similar to an ideal gas, has several distinct properties quite peculiar to itself. The most important and unique of these characteristics are listed here [8]:

UCN/wall collisions are for the most part elastic and specular. Any inelastic scattering will, almost invariably, results in the neutron being heated and lost from the UCN energy range. Since such processes always occur UCN gas can never be in true statistical thermal equilibrium. However, as the relaxation rate is often comparatively slow, the UCN gas does achieve a sort of quasi-statistical equilibrium which we will call mechanical equilibrium. Mechanical equilibrium is characterized by isotropy of neutron gas in velocity space at all points within the storage volume. The degree of specularityof the neutron reflection can be important when trying to decide whether we can truly apply those kinetic theory results are valid only in collisions of mechanical equilibrium.

The low UCN densities obtainable outside of reactors and the small size of the neutron mean that neutron-neutron collisions have a negligible probability of occurrence. Neutron-neutron energy exchange therefore does not occur and individual neutron trajectories are completely independent of each other. The UCN mean free path between are completely is totally characterized by the geometry of the confinement system and details of the UCN-wall collision mechanism. It is also important to note that randomization of the velocity direction in a UCN gas results purely from non-specular reflection at the bottle walls.

Bottles UCN gas densities decay during storage. This decay is due to both to the effects of wall collisions and the loss probability per bounce for a UCN is energy-dependent this density decay rate will also be energy-dependent for a given system.

Since UCN have very low speeds their motion is greatly affected by their gravitational interaction. A neutron rising against UCN velocities gravity loses 1.02 neV of kinetic energy per sm. As well as affecting UCN velocities gravity also has a significant effect on neutron density distributions within bottles.

Kinetic theory treatment of UCN storage

The results obtained are only valid when the system is in a state of mechanical equilibrium during the entire period of neutron storage.

After entering and being sealed into a trap the individual members of the group will, within a few tens of seconds, spread uniformly over the phase space which is available within the constraints of energy conservation and the trap geometry (Fig.1). The time taken to arrive at this uniformity in phase space is governed firstly, by the wall collision rate and given by $\upsilon = \frac{\mathrm{v}}{\lambda}$, where v is neutron velosity, λ is the mean free path between wall collisions. Secondly, it involves the probability per collision of significant nonspecular reflection.If lifetimes arising from wall losses alone are a few thousand seconds, the assumption of a quasi-steady state uniform distribution of UCN in all the accessible phase space after a few tens of seconds of containment should be accurate to about 1 part in 10^3.

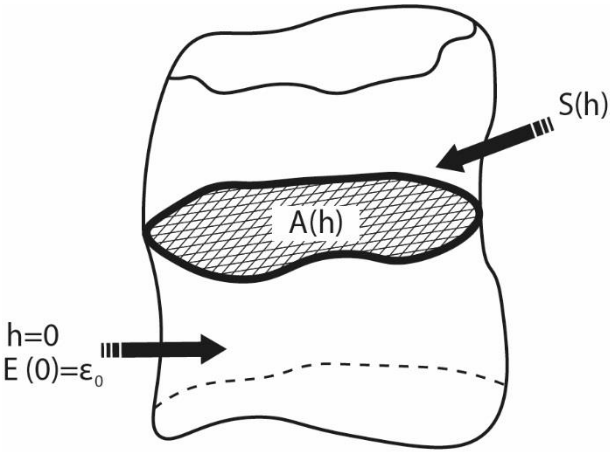


Figure 1–Generalized bottle geometry for neutron storage calculations

Thus, in the absence of gravity the neutrons will soon become uniformly distributed throughout the volume. The mean free path λ against wall collisions is then given by $\lambda = \frac{4V}{S}$, where V is the volume of the trap and S is the total area of all the internal walls. Continuing with zero gravity, the neutrons can be taken to have the same speed v and the same kinetic energy E. On reflecting from a wall a neutron has a probability of loss per collision, which, after averaging over all the angles of incidence for an isotropic distribution of velocities incident on a surface with an ideal step function profile is given by the expression[9]:

$$\bar{\mu}(E)=2\eta\left[\frac{V}{E}\arcsin\left(\sqrt{\frac{E}{V}}\right)-\sqrt{\frac{(V-E)}{E}}\right], \qquad (1)$$

where $\eta=\frac{W}{V}$ is the loss factor, W, V are the imaginary and real part of potential. If the trap walls are all of the same material, and still there is no gravity, the rate of loss of UCN through collisions per unit area is the same on all parts of the walls. Then the rate of change of the total number, $N(t)$ of UCN within the trap is

$$\frac{dN}{dt}=-\frac{N\bar{\mu}(E)v}{\lambda}-\frac{N}{\tau_n}, \quad (2)$$

where τ_n is the neutron lifetime.

Let E_0 be used for the total energy of the UCN and E, p for their kinetic energy and momentum respectively. The height coordinate z will be defined in the upwards sense relative to a horizontal datum plane $h=0$ where we will also take the UCN potential energy to be zero. Consequently, under the assumed conditions of elastic wall collisions, $\frac{p^2}{2m}=E_0-mgh$.We will consider a monoenergetic group of UCN, with energies in the range E_0 to E_0+dE_0 where $dE_0<<E_0$. The energies will remain within this same range δE_0 at all times in the future and at all accessible heights. To make use of the equilibrium condition that the points representing the UCN will have spread themselves uniformly through the available phase space we need to consider the available momentum space. The range $dE=dE_0$ implies a range dp, where $dE=\frac{pdp}{m}$ so that the available volume in momentum space may be expressed as

$$d^3p=4\pi p^2dp=C\sqrt{E}dE=C\sqrt{E_0-mgh}dE_0, \quad (3)$$

where $C=4\pi\sqrt{2m^3}$. The phase space density for the group is its real space density $n(E_0,t,h)$ divided by the volume it occupies in momentum space $C\sqrt{E(h)}dE_0$.When the phase space density has become uniform this ratio is independent of position, and therefore, of h, so that

$$\frac{n(E_0,t,h)}{C\sqrt{E(h)}dE_0}=\frac{n(E_0,t,0)}{C\sqrt{E(0)}dE_0}. \quad (4)$$

Hence,

$$\frac{n(E_0,t,h)}{n(E_0,t,0)}=\sqrt{\frac{E(h)}{E(0)}}=\sqrt{\frac{(E_0-mgh)}{E_0}}. \quad (5)$$

We also note that

$$\frac{v(E_0,h)}{v(E_0,0)}=\sqrt{\frac{E_0-mgh}{E_0}} \text{ and}$$

$$\frac{n(E_0,t,h)v(h)}{n(E_0,t,0)v(0)}=\frac{(E_0-mgh)}{E_0} \quad (6)$$

Eqs. (4), (5), (6) can only be applied to a UCN group for which dE_0 is small compared with the changes of mgh in the setup of interest.

At height h the trap horizontal section area will be called $A(h)$ and the perimeter of this section will be called $S(h)dh$ .The total population $N(E_0,t)$ of an energy group in a trap can then be calculated as

$$N(E_0,t)=\int_{h_{min}}^{h_{max}} n(E_0,t,h)A(h)dh\ , (7)$$

where h_{min} and h_{max} are the lowest and highest points in the trap. Using eq.(5) this becomes

$$N(E_0,t)=n(E_0,t,0)\int_{h_{min}}^{h_{max}} \sqrt{\frac{E_0-mgh}{E_0}}A(h)dh\ . (8)$$

In the absence of gravity this result could have been simply expressed as

$$N(E_0,t)=n(E_0,t,0)V\ , (10)$$

so that the integral of eq.(8) can be identified as an effective volume $V_{eff}(E_0)$ for the trap under the influence of gravity where

$$V_{eff}=\int_{h_{min}}^{h_{max}} \sqrt{\frac{E_0-mgh}{E_0}}A(h)dh\ . \quad (11)$$

In order to evaluate the rate at which the phase space density of a given energy group of neutrons decay in time we need to evaluate the rate at which neutrons are removed from the system via collisions on the bottle walls. This requires a knowledge of the wall collision rate $dJ(E_0,h,t)$ and the energy dependent UCN loss per bounce function $\bar{\mu}(E)$. The rate of collision per unit area of wall for a gas in equilibrium is given by the standard kinetic theory result $J=\frac{1}{4}n\bar{v}$, where $\bar{v}$ and n are the local gas average particle velocity and density respectively. If we include the effect of gravity, we need to rewrite the expression for the collision rate $dJ(E_0,h,t)$ at h as

$$\frac{dJ(E_0,h,t)}{dS(h)}=\frac{n(E_0,h,t)v(E_0,h,t)}{4} \quad (12)$$

We also note that

$$\frac{v(E_0,h)}{v(E_0,0)}=\sqrt{\frac{E_0-mgh}{E_0}} \text{ and}$$

$$\frac{n(E_{tot},t,h)v(h)}{n(E_{tot},t,0)v(0)}=\frac{(E_{tot}-mgh)}{E_{tot}} \quad (13)$$

We can express the current at height h to its speed at 0

$$dJ(E_0,h,t)=\left(\frac{E_0-mgh}{E_0}\right)dJ(E_0,0,t)\ . \ (14)$$

Now we can write a loss rate equation for neutrons within vessel

$$\begin{aligned}\frac{dN(E_0,t)}{dt}&=-\int_s S(h)\bar{\mu}(E_0,h)dJ(E_0,h,t)dh-\frac{N(E_0,t)}{\tau_\beta}=\\&=-\left(J(E_0,0,t)\int_s\sqrt{\left(\frac{E_0-mgh}{E_0}\right)}\bar{\mu}(E_0,h)S(h)dh\right)-\frac{N(E_0,t)}{\tau_\beta}=\\&=-N(E_0,t)\left\{\frac{v(E_0,0)}{4V_{eff}(E_0)}\int_a^{b^*}\sqrt{\left(\frac{E_0-mgh}{E_0}\right)}\bar{\mu}(E_0,h)P(h)dh+\frac{1}{\tau_\beta}\right\}=\\&=-N(E_0,t)\left(\underbrace{\frac{1}{\tau_w(E_0)}+\frac{1}{\tau_\beta}}_{\tau_{tot}(E_0)}\right)=-\frac{N(E_0,t)}{\tau_{tot}(E_0)}\end{aligned} \quad (15)$$

For convenience we shall assume that the neutrons enter the trapat $h=0$. The area of the input pipe is A_{in} and $n(E_0,0)dE_0$ the maximum real space density of UCN in range E_0, E_0+dE_0 obtainable from the UCN source at the bottle input port. Assuming (12) to hold in the vicinity of the input port we can write

$$\frac{d}{dt}N(E_0,t_{fill})=\frac{n(E_0,0)v(E_0,0)A_{in}}{4}-\frac{N(E_0,t)v(E_0,0)A_{in}}{4V_{eff}(E_0)}-\frac{N(E_0,t)}{\tau_{tot}(E_0)}\ ,(16)$$

where t_{fill} is the filling time, $V_{eff}(E_0)$ - effective volume of trap.

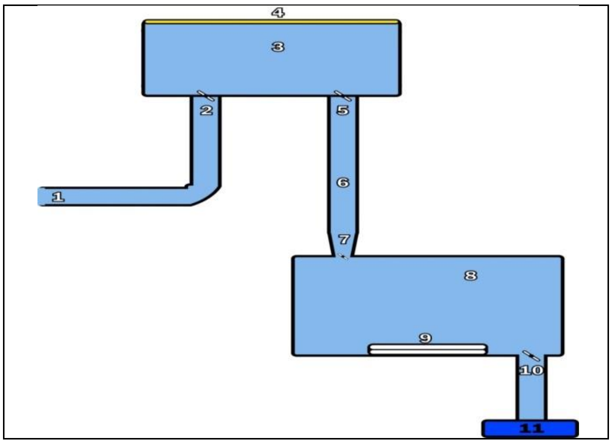
Experimental design

Description of set-up and method

A possible design of experimental setup so called gravitational spectrometry (GS) for measurement of UCN loss coefficient at different velocity could be in the form two cylindrical cups with next scheme (fig.2):firstlyneutrons will be stored in a storage volume №1 to form spectrum. Then they will fall to a storage volume №2 through vertical part of neutron guide and byfalling they will be accelerated. Thus, one can obtain needed neutron velocity by changing the height of vertical part of neutron guide. It is expected that construction of spectrometry allows us to make fast and convenient changing and to do other experiments.

Principal scheme of the GSspectroscopy is shown in fig.2Through neutron guide (1)neutrons enter upper storage volume №1 (3) of d=0.5 m diameter and h=0.3 height. After this entrance valve (2) will be closed. A spectrum of stored neutrons is cut in gravitational spectrometer with absorber, which is located at certain height H_{abs} of storagevolume №1. Neutrons with sufficient kinetic energy, which can bounce up and more to height H_{abs}, will be lost on absorber. Through output valve of storage volume №1 and vertical neutron guide (6) neutrons drop down to cylinder cup of d= 0.5 m diameter and h=0.3 m height, which forms lower (main) storage volume №2 (8). Such geometrical parameters of storage volumes are chosen so as to form narrow spectrum (from 0 upto 30 neV) and to obtain a large number of neutrons. To have a large number of neutronsnot only geometrical parameters are important, but also important thing is coating of storage wall. Since neutrons of low velocity are stored in storage volume №1, there is no necessary to use material with high potential. Thus,one can use material with minimal loss coefficient and low potential. Therefore, Fomblin oil with limited energy E_{lim}=106,5 neV and loss factor $\eta \approx 10^{-5}$ is well suited for these parameters. Sample with known limited energy E_{lim} is located on the bottom of storage volume №2. UCN detector (11) will count survive neutrons.

It is necessary to carry out two measurements to measure loss coefficient on sample, which located in storage volume №2: measurement with the sample and without. Thus, one can gain loss coefficient on sample at different velocity.



1- neutron guide, 2,7 – entrance valves, 3 – storage volume №1, 4 – polyethylene absorber , 5,10 – output valves, 6 –vertical neutron guide, 8 – lower (main) storage volume №2, 9 – sample, 11 – UCN detector.

Figure 2–Experimental setup.

Theabsorber (4) ismadeofpolyethylenewithnegativelimitedenergy. UCNenteringtheabsorbercanpenetrateintothesubstanceandeitherbecapturedbythenucleiofthesubstanceorheatuptothermalenergiesandescapethespectrometer. But UCNs can reflect from surface of absorber and go back to storage volume. To reduce this effect the absorber has development surface, which increases bounce number.

UCN detector is a wire chamber with ^{3}He gas, aluminum window of thickness 100 mkm and 60 sm^2.

The calculated time dependence of the number of neutrons in storage volumes on time is shown in Fig.3. During filling time of storage volume №1 entrance valve is open (from 0 s to 60 s), neutrons enter storage volume №1. After shutdown of entrance valve (60 s) neutrons of high energy (neutrons of initial spectrum with energy more than absorber height) will be lost on absorber. After some time (120 s), needed to eliminate all neutrons with energy more than absorber height from the storage volume №1, simultaneously output valve of the storage volume №1 and entrance valve of storage volume №2 will be open. Consequently the number of neutrons increases (blue line) and the storage volume №2 will be filled. Saturation of neutron in the storage volume №2 is about 10 s.

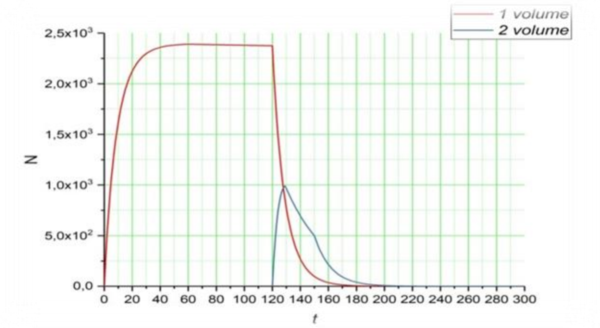


Figure 3–The calculated time dependence of the neutron number in storage volumes on time.

Measurement cycle

The measurement cycle comprises filling of the storage volume, spectrum cleaning, storage time, emptying and measurement of the surviving neutrons.

Filling (t = 0 to 60 s): During filling time of the storage volume №1 the entrance valve is open. Equilibrium neutron density is reached after 60 s, mainly determined by the geometry, the quality of the storage volume surfaces.

Spectral cleaning (t = 60 to 120 s): During spectral cleaning time the entrance valve is closed and all neutrons with energy more than absorber height must be lost. UCNs of initial spectrum with energy more than H_{abs} penetrate walls and escape storage volume №1. The further measurement cyclesare dependent on how fast and clean spectrum is formed. Therefore, it is necessary to wait as little as possible and at the same time to get clean spectrum.

Emptying the storage volume №1 and filling the storage volume №2 (t=120 to 130 s): in the period of time from 120 s to 130 s emptying the storage volume №1 is occurred. Neutrons go out through vertical neutron guide, which connects two storage volumes. And they fall to the storage volume №2.

Storage times (t=130 to 400 s): During storage time both valves (entrance and output) are closed. The storage time is defined by loss probability on walls due to capture and inelastic scattering on nuclei of walls.

Emptying and measurement of the surviving neutrons. StoredUCNsfall and enter the detector.

Statistics are collected by cyclically repeating the measurement procedure. Duration of cycles in measurements is 150-400 seconds.

Sample Description

It is expected that for carrying out experiment to use three type of coating material for sample: beryllium Be(Al), deuterated polyethylenedPE(Al) and diamond-like carbon DLC. Particular interest in using these materials is that they have high potential U and consequently high limited velocity $\mathrm{v}_{\lim}$. It is to be noted that the walls of thestorage volume №2 are coated with beryllium. Since beryllium has a high limited energyand coating technology of DLC is not developed yet.

Table.1. Sample properties

Samples	Limited velocity $\mathrm{v}_{\lim}$, m/s	Limited energy $E_{\lim}$, neV	Loss factor η
Deuterated polyethylene**dPE**	6.5	214	$1.3\cdot10^{-4}$ [10]
diamond-like carbon **DLC**	6.8	249	$3.5\cdot10^{-4}$ [11]
beryllium**Be**	6.9	249	$5\cdot10^{-4}$ [11]

Determination of loss coefficient for different samples

The storage time for UCN in a system with a loss vessel is given by

$$\tau_{\mathrm{st}}^{-1} = \tau_{\beta}^{-1} + \tau_{hole}^{-1} + \tau_{loss}^{-1}. \quad (1.1)$$

Here, the total UCN loss τ_{st}^{-1} comprisesthreeterms, namely, theprobabilityofneutron β decay τ_{β}^{-1}, and the probability loss on hole τ_{hole}^{-1}, and the probability τ_{loss}^{-1}.

The storage time is determined from UCN counts, N_i, after holding times t_i.

$$\tau_{\mathrm{st}} = \frac{t_2 - t_1}{\ln\left(\dfrac{N_1}{N_2}\right)} \quad (1.2)$$

where N_1 and N_2 are neutron number after holding times t_1 and t_2.

Since UCN are stored in material storage volume, τ_{loss}^{-1} loss probability on walls:

$$\tau_{\mathrm{loss}}^{-1} = \mu(T,\mathrm{v})\upsilon(\mathrm{v}), \quad (1.3)$$

where $\mu(T,\mathrm{v})$ is the UCN loss coefficient, which depends on UCN energy and wall temperature (see for.1 in chapter Kinetic theory), υ is the UCN collision frequency, which depends on UCN energy and storage volume geometry.

One can express UCN collisions by UCN fluxdirected to surface $f(\mathrm{v})$ and neutron density in volume $n(\mathrm{v})$. For isotropic flux:

$$f(\mathrm{v}) = \frac{1}{4}\cdot n(\mathrm{v})\cdot \mathrm{v}$$
$$n(\mathrm{v}) \square\ \mathrm{v} \quad (1.4)$$
$$\mathrm{v} = \sqrt{\mathrm{v}_0^2 - 2\cdot g\cdot h}$$

where v is the UCN velocity at the height, v is the velocity on the bottom of the storage volume.

Loss probability can be written in the next form:

$$\tau_{\text{пот}}^{-1} = \mu(E)\upsilon(E) = \frac{\int_S f(E)\cdot\bar{\mu}(E)\cdot dS}{\int_V n(\mathrm{v})\cdot dV} = \frac{\int_S v^2\cdot\bar{\mu}(E)\cdot dS}{\int_V \mathrm{v}\cdot dV}, \quad (1.5)$$

It is necessary to carry out two storage time measurements for determination loss coefficient on the sample, which located in the spectrometry: with sample and without. Since the walls of spectrometry are coated with beryllium Be, for such pair of measurement with sample coated with the same material one can write the next equation system:

$$\begin{cases} \dfrac{1}{\tau_{\mathrm{st}}^{\mathrm{I}}} = \dfrac{1}{\tau_{\beta}} + \dfrac{1}{\tau_{\mathrm{hole}}} \\ \dfrac{1}{\tau_{\mathrm{st}}^{\mathrm{II}}} = \dfrac{1}{\tau_{\mathrm{samp}}} + \dfrac{1}{\tau_{\beta}} + \dfrac{1}{\tau_{\mathrm{hole}}} \end{cases} \rightarrow \quad \frac{1}{\tau_{\mathrm{st}}^{\mathrm{I}}} - \frac{1}{\tau_{\mathrm{st}}^{\mathrm{II}}} = \frac{1}{\tau_{\mathrm{samp}}} = \mu(\mathrm{v})_{\mathrm{samp}} \upsilon(\mathrm{v})_{\mathrm{samp}}$$

where $\dfrac{1}{\tau_{\mathrm{st}}^{\mathrm{I}}}$ is the UCN storage time in empty spectrometry, $\dfrac{1}{\tau_{\mathrm{st}}^{\mathrm{II}}}$ is the UCN storage time in spectrometry with sample, $\upsilon(\mathrm{v})_{\mathrm{samp}}$ is the UCN collision frequency on sample. From these measurements one can extract $\mu(\mathrm{v})_{\mathrm{samp}}$:

$$\mu(\mathrm{v})_{обр}^{Be} = \frac{\dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}} - \dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}}}{\upsilon(\mathrm{v})_{обр}}.$$

By writing similar expressions for measurements with other samples, you can determine the loss coefficient for other samples:

$$\mu(\mathrm{v})_{обр}^{DLC} = \frac{\dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}} - \dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}}}{\upsilon(\mathrm{v})_{обр}}, \quad \mu(v)_{обр}^{dPE} = \frac{\dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}} - \dfrac{1}{\tau_{\mathrm{xp}}^{\mathrm{II}}}}{\upsilon(v)_{обр}},$$

where $\mu(\mathrm{v})_{\mathrm{samp}}^{Be}$ is the loss coefficient for*Be*, $\mu(\mathrm{v})_{\mathrm{samp}}^{DLC}$ is the loss coefficient for diamond-like carbon DLC, $\mu(\mathrm{v})_{\mathrm{samp}}^{dPE}$ is the loss coefficient fordeuterated polyethylenedPE.

Results

Simulation of processes of filling, neutron spectral cleaning, neutron refilling from one storage volume to another storage volume, storage in lower storage volume, counting in detector was done. From obtained data the accuracy of loss coefficient measurement was determined. Measurement results of loss coefficient at different velocity of UCN on surface of deuterated polyethylenedPE are shown in fig.4. From the figure one can see that when UCN velocity increases, the loss coefficient increases. Accuracies were obtained with area 135 cm^2 and measurement time 20 hours.

Similar measurement results of loss coefficient at different velocity of UCN on surface of diamond-like carbon DLC and Be with area 135 cm^2 and measurement time 20 hours are shown in fig.5-6.

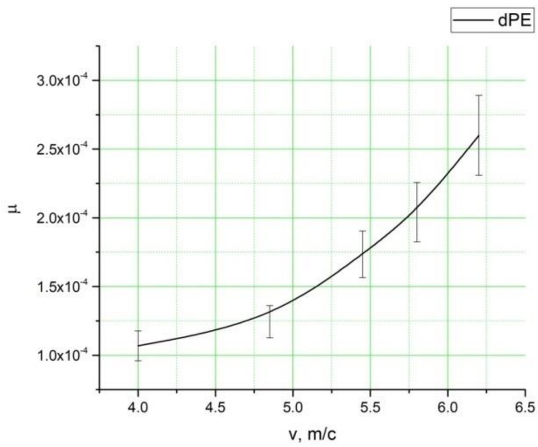


Figure 4–Loss coefficient on deuterated polyethylenedPEsurface .

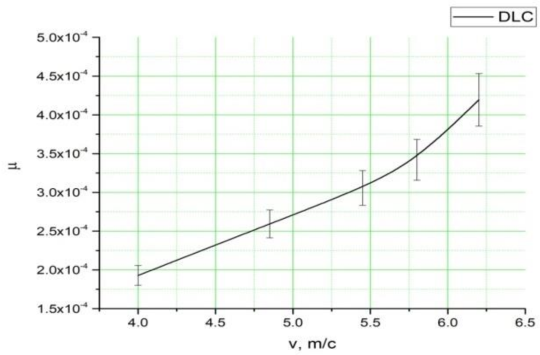


Figure 5–Loss coefficient on diamond-like carbon DLC surface.

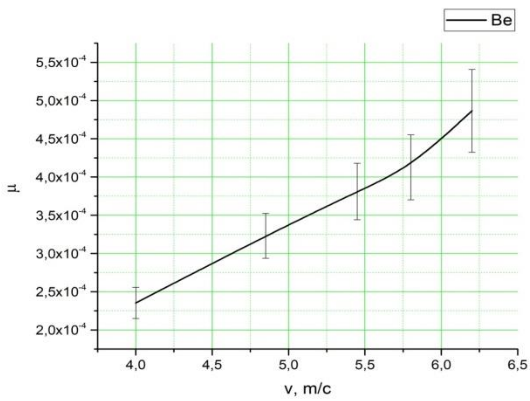


Figure 6–Loss coefficient on Be surface

Loss coefficient of limited neutrons with velocity from 6 m/s to 6.4 m/s is most interest. What measurement time is needed to measure UCN loss coefficient with accuracy 11% and area of sample 135 cm^2 is shown in fig.7. UCN loss coefficient and its accuracy for sample with area 135 $cm^2$and measurement time 5.72 hours are shown in fig.8. What loss coefficient one can measure in 5.72 hours with accuracy 11%

and different area of sample. This is shown in fig.9.

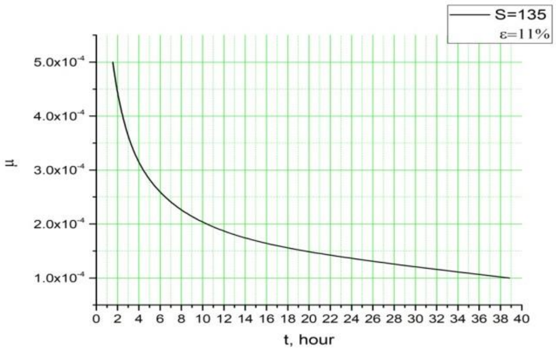


Figure 7–The dependence of the loss coefficient on the measurement time with fixed accuracy ε andsample area S .

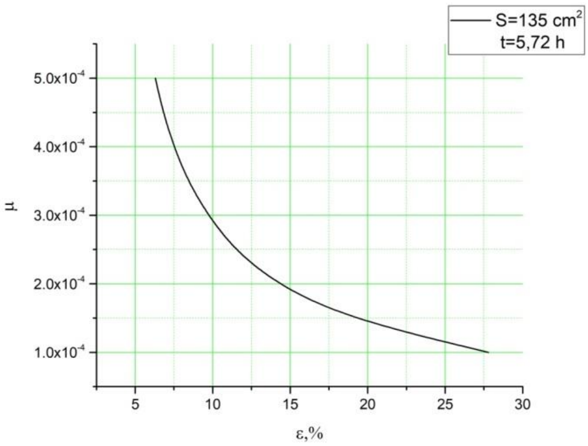


Figure 8–The dependence of the loss coefficient on the measurement accuracy with fixed measurement time t andsample area S .

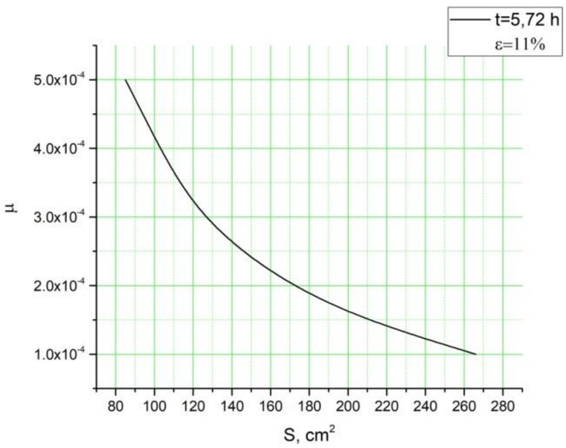


Figure 9–The dependence of the loss coefficient on the sample area with fixed measurement time t andmeasurement accuracy ε .

It is seen that from fig.6. to obtain loss coefficient about $1.5\cdot10^{-4}$ with fixed measurement accuracy 11% and sample area $S = 135\,cm^2$ necessary time to carry out experiment is about 20 hours. A further extension of the experiment time does not lead to a significant change.

Conclusion

During the work the geometry of experimental setup was chosen and calculations were done. A program was written to simulate dynamic of neutron density in experimental setup. Simulation let us determine optimal measurement time diagram and optimal sample area with fixed measurement accuracy for measurement loss coefficient. Obtained data and program will be used for construction experimental setup.

References

1. A.P. SerebrovIssledovanijafundamental'nyhvzaimodejstvijvPIJaFNICK-Isnejtronamiinejtrinonareaktorah // UFN. Tom. 185, № 11.
2. Fred E. Wietfeldt, Geoffrey L. Greene Colloquium: The neutron lifetime // Reviews of modern physics, vol.83, oct-dec 2011.
3. C. Siemensen, C. Düsing, P. Geltenbort, C. Giebel, T. Reich, and C. Plonka Search for an electric charge of the neutron // Physical Review D 97, 052004 (2018)
4. N. F. Ramsey, Ann. Rev. Nucl. Part.Sci. 32 (1982) 211.
5. M. Raidal et al., Eur. Phys. J. C57 (2008) 13.
6. E.V. Lychagin, V.A. Mityukhlyaev, A.Yu. Muzychka, G.V. Nekhaev, V.V. Nesvizhevsky, M.S. Onegin, E.I. Sharapov, A.V. Strelkov «UCN sources at external beams of thermal neutrons. An example of PIK reactor», Nuclear Instruments and Methods in Physics Research A 823 (2016) p. 47–55.
7. А.В. Стрелков Хранение нейтронов // УФН Том. 174, № 5.
8. R. Golub, D. J. Richardson, S. K. Lamoreaux, Ultra-cold Neutrons (Adam Hilger, Bristol, 1991).
9. J .M. Pendlebury , D.J . Richardson Effects of gravity on the storage of ultracold neutrons // Nuclear Instruments and Methods in Physics Research A337 (1994) 504-511

10. Th. Brenner, P. Fierlinger, P. Geltenbort, E. Gutsmiedl, A. Hollering, T. Lauer, G. Petzoldt, D. Ruhstorfer, J.Schroffenegger, K. M. Seemann, O. Soltwedel, St. Stuiber, B. Taubenheim, D. Windmayer, and T. ZechlauDeuterated polyethylene coatings for ultra-cold neutron applications // Applied physics letters 107, 121604 (2015)

11. F. Atchison, T. Bry´s, M. Daum, P. Fierlinger, P. Geltenbort, R. Henneck,S. Heule, M. Kasprzak, K. Kirch, A.Pichlmaier1 C. Plonka, U. Straumann, C. Wermelinger, and G. ZsigmondLoss and spinflip probabilities for ultracold neutrons interacting withdiamondlike carbon and beryllium surfaces // Physical Review C 76, 044001 (2007)

Accepted to print at 30.10.18

V.V.Nesvizhevsky[1],K.Turlybekuly[2,3], D.A.Kereibay[2], E.V.Lychagin[2],S.K.Sakhiyev[4]

[1]Institut Laue-Langevin, Grenoble, France

[2]Joint Institute for nuclear researches, Dubna, Russia

[3]L.N. Gumilyov Eurasian national university, Astana, Kazakhstan

[4]Abay Kazakh national pedagogical university, Almaty, Kazakhstan

SIMULATION OF LOSS COEFFICIENT MEASUREMENT EXPERIMENT AT DIFFERENT UCN VELOCITIES OF USING GRAVITATIONAL SPECTROSCOPY

Abstract. This work is devoted to simulation of precise experiment of loss coefficient measurement experiment at different velocities of UCN using gravitational spectroscopy and to choose optimal parameters of storage volume. The effect of various covers and materials of trap on loss coefficients preliminary was estimated.

As result of simulation the size of experimentalset-up, optimal time diagram of measurements and optimal area of sample to measure loss coefficient with given accuracy were chosen.

Keywords: loss coefficient, ultracold neutrons

В.В. Несвижевский[1], К.Турлыбекулы[2.3], Д.А.Керейбай[2], Е.В.Лычагин[2], С.К.Сахиев[4]

[1]Институт Лауэ-Ланжевена, Гренобль, Франция

[2]Объединенный институт ядерных исследований, Дубна, Россия

[3]Евразийский национальный университет им. Гумилёва, Астана, Казахстан

[4] Казахский национальный педагогический университет им. Абая, Алматы, Казахстан

МОДЕЛИРОВАНИЕ ЭКСПЕРИМЕНТА ПО ИЗМЕРЕНИЮ УТЕЧКИ ПРИ РАЗЛИЧНЫХ СКОРОСТЯХ UCN ПРИ ИСПОЛЬЗОВАНИИ ГРАВИТАЦИОННОЙ СПЕКТРОСКОПИИ

Аннотация. Данная работа посвящена моделированию точного эксперимента по измерению коэффициента потерь при различных скоростях УХН с использованием гравитационной спектроскопии и выбору оптимальных параметров объема хранения. Предварительно было оценено влияние различных покрытий и материалов ловушки на коэффициенты потерь.В результате моделирования были выбраны размер экспериментальной установки, оптимальная временная диаграмма измерений и оптимальная площадь образца для измерения коэффициента потерь с заданной точностью.

Ключевые слова: коэффициент потерь, ультрахолодные нейтроны

В.В.Несвижевский[1], К.Турлыбекұлы[2,3], Д.А.Керейбай[2], Е.В.Лячинь[2], С.К.Сахиев[4]
[1]*Лауэ-Ланжевен институты, Гренобль, Франция*
[2]*Ядролық зерттеулер институты, Дубна қаласы, Ресей*
[3]*Гумилев атындағы Еуразия ұлттық университеті, Астана, Қазақстан*
[4]*Қазақ ұлттық педагогикалық университеті, Алматы, Қазақстан*

ГРИВИТИЦИЯЛЫҚ СПЕКТРОСКОПТЫ ПАЙДАЛАНҒАНДА КЕЗ КЕЛГЕН ЖЫЛДАМДЫҚТАҒЫ ҰЛТРАСАЛҚЫН НЕЙТРОНДАРДЫҢ ЕСЕПСІЗ ҚАЛУЫН ЭКСПЕРИМЕНТАЛ МОДЕЛДЕУ

Аннотация. Бұл жұмыс гравитациялық спектроскопияны қолдану арқылы UCN түрлі жылдамдықтарында жоғалу коэффициентін өлшеу экспериментінің дәл экспериментін модельдеуге және оңтайлы параметрлерін таңдауға арналған. Тұзақ материалдарыныңтүрлі қаптамалар мен шығын коэффициенттері алдын-ала бағаланды.Симуляцияның нәтижесі бойынша эксперименттің өлшемі, өлшеудің оңтайлы уақыт диаграммасы және осы дәлдікпен жоғалу коэффициентін өлшеу үшін оңтайлы аймақ таңдап алынды.

Түйінді сөздер: жоғалу коэффициенті, ультрасалқын нейтрондар