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Identification of a new escape channel for UCN from traps

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Abstract

Ultra-cold neutrons (UCN) can be stored in a trap if their energy is lower than the trap wall potential. It is well known that the neutron density in a trap decreases due to neutron beta-decay, upscattering and absorption on surfaces but we have identified a complementary escape channel. This arises from a small increase in the energy of UCN during their interaction with a surface. Higher-energy neutrons can then escape into the bulk material or penetrate through the trap wall if it is thin enough.

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Keywords: Ultra-cold neutrons

1. Introduction

Long storage of ultra-cold neutrons (UCN) in traps is useful in fundamental physics, for instance, for precise neutron lifetime measurement. However, studies with UCN, since their discovery in 1968 [1,2], have given rise to a series of puzzles without clear answers. In all experiments with low estimated losses in trap walls the measured loss rate was too high. Since 1978 the additional UCN losses were supposed to follow mostly from upscattering on hydrogen surface impurities [3–6]. However, the large hydrogen concentrations needed to explain the UCN loss at low temperature, as well as the apparent impossibility of complete elimination of the losses by removing the hydrogen with standard techniques were nevertheless surprising. The lack of consistency became more evident in 1990 in the Gatchina experiment measuring the neutron lifetime [7], in which the phenomenon of the so-called anomalous UCN losses in Be traps was identified [8]. The additional losses were almost temperature independent. The corresponding loss rate of $\sim 10^{-5}$ per collision was ~ 100 times

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higher than theoretical predictions based on neutron capture. In a series of experiments at ILL we verified different hypotheses. One, by A.V. Strelkov and A.D. Stoica, assumed an enhanced upscattering of UCN to the 10^{-7}–10^{-4} eV energy range, which was inaccessible in previous experiments. The history of this study was surprising and has not yet come to an end.

2. Spectral measurements with UCN

A gravitational spectrometer for UCN was used to shape the neutron spectrum and also for neutron spectrum analysis. This method of UCN spectral shaping is particularly suited to the UCN energy range. This is evident from the relation: $E_{\mathrm{ucn}} = m_{\mathrm{n}} g h$, where E_{ucn} is the neutron energy, m_{n} is the neutron mass, g is the acceleration in the Earth's gravitational field and h is the maximal height in the Earth's gravitational field. One can estimate that ~ 100 cm of height increase in the Earth's gravitational field corresponds to a UCN energy of ~ 100 neV.

We describe here a simple configuration of this device and its principal of operation. Further modifications will be mentioned in the text when it is necessary.

The spectrometer (Figs. 1a–c) is a vertical stainless-steel cylinder with 0.6 m diameter and 2 m height. The critical energy of the stainless-steel walls is $E_{\mathrm{st.steel}} \sim 192$ neV which allows simultaneous storage of UCN with a broad spectrum in this volume. A plane polyethylene absorber can be placed at a fixed height providing an upper cut-off to the UCN spectrum. Polyethylene has a small negative critical energy (no repulsive potential) and a high upscattering cross-section for UCN to thermal energies. These properties allow efficient absorption of those neutrons that have enough kinetic energy to rise in the Earth's gravitational

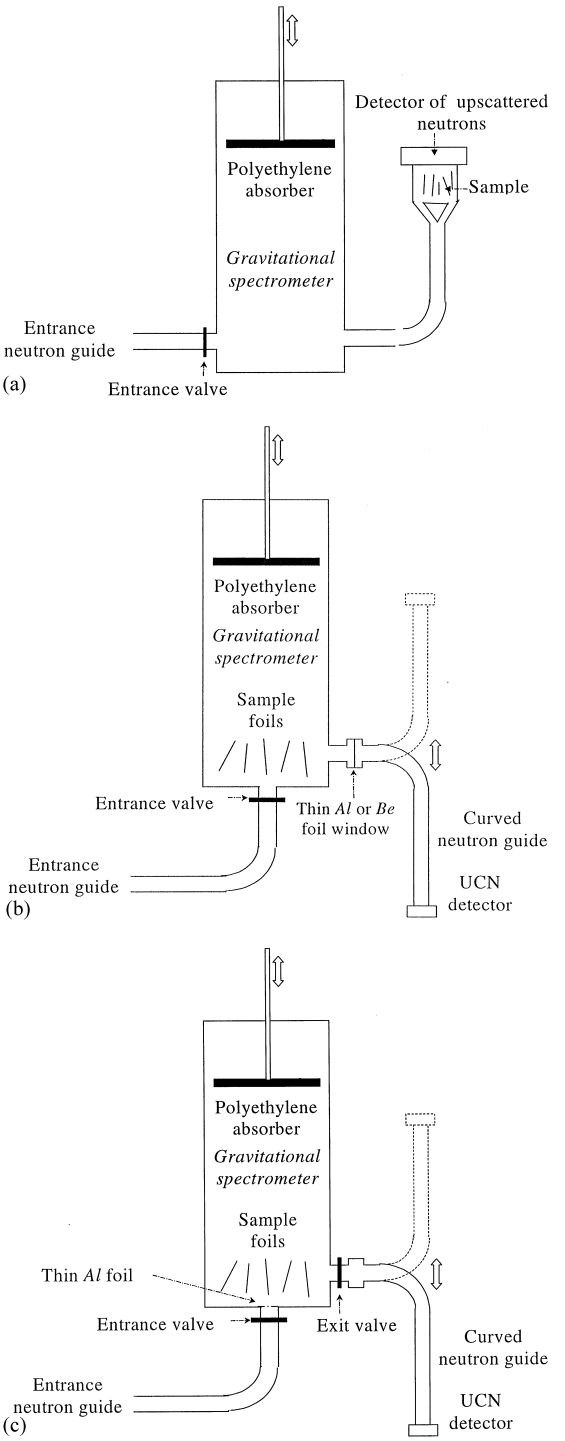

Fig. 1. (a) Installation scheme for the search for UCN upscattering to the energy range 10^{-7}–10^{-4} eV. (b) Installation scheme for the measurements of small increase in UCN energy. (c) Installation scheme for the measurements of small decrease in UCN energy.

field up to the absorber height h_{absor}. Correspondingly, the storage times for UCN with energy $E_{ucn} > m_n g h_{absor}$ are much shorter than for those with $E_{ucn} < m_n g h_{absor}$. Four identical ports in the spectrometer wall and one port in the bottom can be used as UCN entrance(s) or UCN exit(s). Shutters or thin vacuum-tight foils can be installed in the ports according to the measurement to be performed. Actual configurations will be described later for every particular measurement. All shutters are totally neutron-tight for UCN of any energy. Any thin separating foil is totally neutron-tight for UCN with energy lower than the critical energy of the foil material. However, it is partially transparent for higher-energy neutrons. The energy range of ~ 10 neV above the critical energy value corresponds to an intermediate case with particularly high losses. A He^3 UCN detector(s) is (are) connected to the spectrometer via a curved neutron guide(s). Careful design of the detector(s) shielding and electronics allowed a low typical background rate of $(5–8) \times 10^{-4}$ s^{-1} and no correlation between the flux of neutrons upscattered in the spectrometer and the detector(s) count rate.

The maximum UCN energy can be defined using the polyethylene absorber. First, the spectrometer is filled with a broad UCN spectrum. Then the shutters are closed. The portion of UCN with energy $E_{ucn} > m_n g h_{absor}$ decreases much faster than that of UCN with energy $E_{ucn} < m_n g h_{absor}$ because of additional losses in the absorber. A typical waiting time of ~ 100 sec allows spectral cleaning to the level of 10^{-6} or better while the UCN density in the range $E_{ucn} < m_n g h_{absor}$ decreases only by a small factor. Evidently, the edge in the UCN spectrum is not perfectly sharp at the energy $E_{ucn} = m_n g h_{absor}$. Therefore, the absorber is placed at the height significantly lower (~ 10 cm, for instance) than the desired (calculated) cut-off height.

Alternatively, we can define the minimum UCN energy using a thin vacuum-tight Al foil in the entrance neutron guide. Only UCN with energy $E_{ucn} > E_{Al}$ can penetrate into the spectrometer. The edge in the resulting spectrum is not perfectly sharp and this should be taken into account.

More complicated experiments need the use of these two methods simultaneously. The spectral evolution during storage of UCN in the spectrometer is measured in every cycle in two steps: First, the spectrum is preliminarily shaped with closed entrance and exit shutters. Then the absorber height is changed (increased or decreased) in order to measure the spectral evolution.

In more details the installation and the measuring procedure are presented elsewhere [10,11].

3. Experimental results

3.1. Penetration of UCN inside a trap wall

In the first experiment [9] a sample of Al foil coated with Be was placed in an open geometry in front of the detector entrance window. A simplified scheme of this installation is shown in Fig. 1a. Such an Al entrance window was transparent for neutrons with kinetic energy higher than a few times 10^{-7} eV. No flux of upscattered neutrons from the sample was measured, which allowed us to demonstrate the absence of enhanced upscattering of UCN in the energy range between a few times 10^{-7} and a few times 10^{-4}, at least with the probability that is relevant to the problem of anomalous UCN losses. Moreover, no enhanced upscattering to any energy range up to thermal energies was found over a wide sample temperature range for samples cleaned by heating. But UCN still escape from traps. Therefore, we had to consider a complementary phenomenon during UCN storage.

In the above experiment, a very narrow energy range about the initial UCN energy was not accessible, even in this dedicated measurement of UCN upscattering, because of losses of such neutrons in the entrance window of the neutron detector. On the other hand, we noticed a surprising "background" effect: the detector counted additional neutrons even without a sample. This was only possible if UCN penetrate into a relatively thick Al detector window and then were upscattered in the material bulk. We did not expect such penetration because the initial UCN spectrum was shaped significantly below the critical energy for aluminum of $E_{Al} \sim 54$ neV.

Although the reason for such a "background" effect was not clear to us we made an assumption

that if a neutron penetrates *into* the foil bulk then it could probably penetrate *through* the foil without upscattering if the foil is thin enough.

3.2. *UCN penetrate through thin trap walls*!

To check this idea we measured UCN penetration through a thin vacuum-tight Be foil. The installation is shown in Fig. 1b. The critical energy for Be corresponds to ~ 2.5 m height in the Earth's gravitational field (1 cm–1 neV). The penetration probability was measured to be much higher than that expected for the tunneling effect [10].

If there is no penetration of UCN stored in the trap through the foil then there should be no neutrons counted when the storage volume is filled with sub-barrier UCN. $T = 0$ s in the time diagram of this measurement shown in Fig. 2 corresponds to the beginning of the spectrometer filling with open entrance shutter. $T = 100$ s corresponds to the entrance shutter closure. The high counting rate at $T < 100$ s is due to above-barrier neutrons in the initial (non-shaped) spectrum. Such neutrons easily penetrate the foil. For $T > 100$ s the spectrum is truncated by the polyethylene absorber at a height ~ 1.8 m. The time period T:120–300 s corresponds to "anomalous" penetration of UCN through the foil (the tunneling effect is negligible for such a foil thickness).

The neutron flux penetrating the foil was proportional to the UCN flux at the trap walls (and at the foil). Only neutrons with energy in the UCN range can be transported through a curved neutron guide without significant losses. An estimation of the energy range of the penetrating neutrons also follows from measurements of the reduction of the transmission of the curved neutron guide for such neutrons when it is filled with a definite pressure of air. This demonstrated beyond doubt that the energy of the penetrating neutrons was in the UCN range [10].

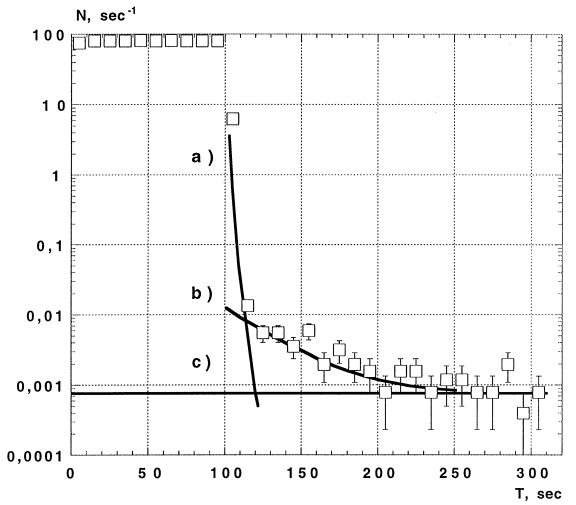

Fig. 2. Penetration of stored UCN through thin Be foil. Squares: measured data points. The data can be described using 3 curves: (a) Theoretical calculation of the above-barrier neutron flux, (b) The neutron flux at the foil position normalized to the penetrating neutron flux. The VUCN flux and the penetrating flux are decreasing in parallel. (c) Constant background level. If the background is subtracted then the curve (b) transforms to an almost pure exponential (or a straight line on the logarithmic scale).

3.3. *Identification of small energy changes for stored UCN*

In order to reveal the reason for such penetration and also to measure more precisely the energy of the penetrating neutrons we carried out an experiment [11] in which the Be foil was replaced with an Al foil. The low critical energy for aluminum $E_{\mathrm{Al}} \sim 54$ eV allowed us to simultaneously store sub-barrier and above-barrier neutrons ($E_{\mathrm{ucn}} < 54$ neV and $E_{\mathrm{ucn}} > 54$ neV respectively). All such neutrons are sub-barrier for the trap wall materials (stainless steel or fomblin grease with ~ 196 and ~ 106 neV critical energy respectively).

The measuring procedure is analogous to the previous one. The difference consists only in the absorber height and in the characteristic periods of the time diagram (Fig. 3). The absorber now is significantly lower than in previous measurement ($E_{\mathrm{Al}} \sim 54$ neV whereas $E_{\mathrm{Be}} \sim 250$ neV).

The entrance shutter is closed at $T = 110$ s Neutrons counted after $T = 190$ s penetrate the foil in an "anomalous" way as it was with a Be foil. The time dependence of the UCN flux inside the trap was calibrated in a separate experiment. To do this the thin separating foil was replaced by a thick foil with a small hole in it.

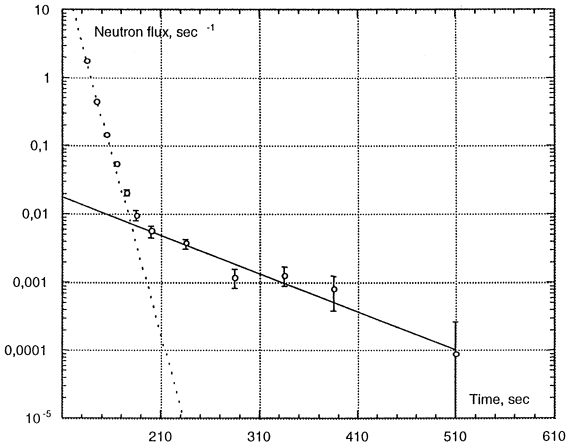

Fig. 3. Penetration of stored UCN through thin Al foil. The dashed line was calculated for the counting rate of initial above-barrier neutrons. The solid line is the normalized sub-barrier UCN flux at the foil position. The background is subtracted.

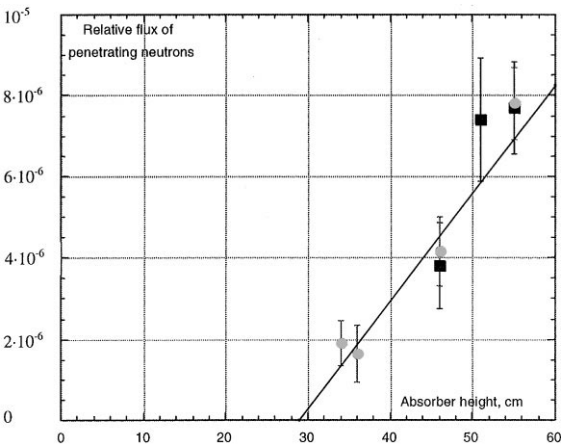

Fig. 4. The ratio of the penetrating flux to the initial flux versus the absorber height. Cycles correspond to the measurement with a single Al foil. Squares correspond to the measurement with two Al foils separated by a polyethylene ring. The squares are scaled to account for the differing thickness of Al in the beam.

We checked carefully and eliminated the most probable experimental errors: residual above-barrier neutrons from the initial spectrum; a delay in the spectrum shaping due to a significant probability of specular reflections resulting in non-ergodic behavior; penetration through pin holes in the foils; possible spectral broadening due to vibrations [11]. This allowed us to conclude that some physical process is responsible for the observed penetration.

The penetrating flux for different absorber heights was measured for Al (Figs. 4 and 6) and Be foils. All curves show similar behavior: (1) The greater the UCN energy, the greater the penetrating flux. (2) There is no penetration (linear extrapolation of the penetrating flux/absorber height dependence) if there are no neutrons in the initial spectrum with energies higher than about half of the foil barrier. The experiment showed that this is valid both for Al and Be foils although the values for their potential barriers differ by almost a factor of 5.

In order to estimate the energy of penetrating neutrons we carried out a special experiment: Two Al foils (in Fig. 4, squares) were separated by a polyethylene ring which was mounted in such a way that it was out of the direct beam. The transmission probability for above-barrier neutrons through two foils or one foil of double thickness is almost equal. On the other hand, sub-barrier neutrons (if they penetrate the first foil) would be trapped in the inter-foil region and totally lost in the polyethylene ring. The result of this measurement showed that the observed penetration was due to above-barrier neutrons. Since no above-barrier neutrons remain from the initial UCN spectrum this implies that UCN gain energy by interacting with surfaces. This idea was also verified by variation of the detector height (above what would correspond to the initial spectrum cut-off, see Fig. 1b) and counts were still seen.

Once UCN gain sufficient energy, they are mostly lost immediately in the polyethylene absorber. When the absorber was lifted up, after having established the spectrum ($T = 190$ s), the penetrating flux increased by a factor of ~ 25 over that observed with a fixed absorber position. This is shown in Fig. 5 (squares and solid curve) in addition to the same data as in Fig. 4. The solid line in Fig. 5 was calculated using the measured time dependence for the UCN flux at the foil position. The only assumption was that the generation probability for above-barrier neutrons from the stored ones is time independent (the actual value for the generation probability is a free parameter in this fit). This

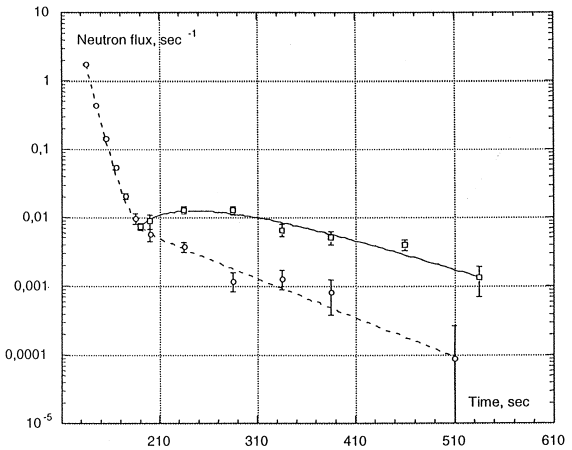

Fig. 5. Penetration of stored UCN through thin Al foil in the measurements with fixed absorber (the same dependence as in Fig. 3) and with the absorber being raised after the spectrum cleaning. The absorber was raising by 0.5 m after the spectrum cleaning ($t > 190$ s) in every measuring cycle. Squares are the data points. The solid line was calculated for the constant VUCN generation rate and measured storage times in the spectrometer. The background is subtracted.

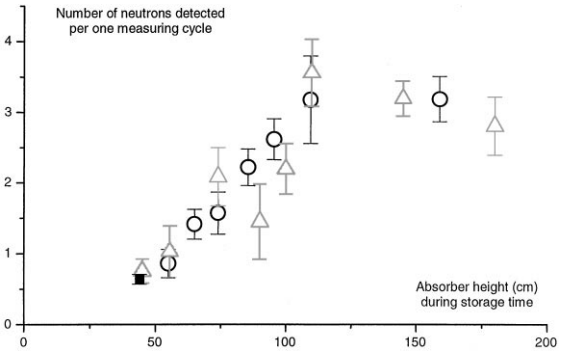

Fig. 6. Integral VUCN spectrum at the walls of a stainless-steel spectrometer: the number of counted neutrons (circles) versus the absorber height during the UCN storage. The black square corresponds to a fixed absorber height. Triangles are measured in another experiment [13] with a stainless-steel sample in a copper spectrometer. The triangle data points are scaled so that the normalization at high absorber high is the same. The results coincide within the statistics. The background is subtracted.

process can be thought of as the evaporation of the faster neutrons from the trap. Therefore, we call them VUCN ("Vaporized Ultra-Cold Neutrons"). Their spectrum has been measured by raising the absorber to different heights during the UCN storage (after the spectrum cut-off). The VUCN spectrum saturates for absorber positions above a certain height (Fig. 6). The absorber movement itself does not produce a noticeable false "heating effect".

This small gain in energy at stainless-steel and fomblin surfaces is a different process from normal upscattering to thermal energies. Thus, the UCN scattering probability to a very narrow energy range ($\sim 10^{-7}$ eV) is about as large as the total probability for upscattering at clean surfaces to all other energies. Now the question arises: is this a universal phenomenon? and what effect might this have on other experiments with UCN?

3.4. Investigation of the small energy changes

In Ref. [13] we investigated this phenomenon in more detail.

Two spectrometers were used in this study: the present stainless-steel spectrometer and a copper spectrometer. The modification was caused by a high measured rate of VUCN generation at the stainless-steel surface of the spectrometer. Such "background" VUCN generation at spectrometer walls is undesirable in experiments with samples. On the other hand, the generation rate at copper surfaces was measured to be much lower (it was not even identified in the presence of the much higher generation from the stainless-steel spectrometer walls).

The copper spectrometer of smaller diameter (20 cm) was installed inside the stainless-steel spectrometer. It allowed significant suppression of the "background" VUCN generation at spectrometer walls. Also the VUCN detection efficiency became higher due to an improved ratio of the storage time to the emptying time for such neutrons. This device, with a sample inside, could be heated up to 300°C or cooled down to liquid-nitrogen temperature allowing measurements of temperature dependences.

In order to show that the interaction of UCN with a surface is responsible for the milli-heating we carried out an experiment with a stainless-steel sample placed inside the stainless-steel spectrometer (see

Fig. 1b). This allows increase of the total stainless-steel surface area, which is irradiated with neutrons. As expected the generation rate was measured to be approximately proportional to the total surface area. Another measurement was carried out with a stainless-steel foil sample in a copper spectrometer (Fig. 6, triangles). There approximately the same VUCN generation was measured.

A special measurement with cleaned (by heating) stainless-steel foil showed almost the same generation rate as before such cleaning although the macro-magnetic properties (magnetic permeability) and hydrogen surface impurities were shown to be significantly suppressed.

In addition to the measurements of VUCN generation at stainless-steel and Fomblin oil surfaces in the stainless-steel spectrometer, this phenomenon was found also at beryllium and copper surfaces in measurements made in a "pure" copper-walled spectrometer (Fig. 9).

Identification of events with small increase in UCN energy suggests that there may also be events with small energy decreases. Moreover, the measurement of such a process (events of small decrease in UCN energy) had been already reported in Ref. [14]. Therefore, it was interesting to measure such an effect in the same installation that was used previously for the milli-heating measurement. The stainless-steel sample was chosen because this material produces a high VUCN generation rate and it was reasonable to expect a correspondingly high probability for decrease in UCN energy.

The installation scheme is shown in Fig. 1c. The measurement is analogous to the UCN- heating experiment. However, now the trap is filled with neutrons with energies higher than the critical energy for Al through the Al foil in the entrance guide. If during filling some UCN were cooled down to the energy range 0–54 neV then they are trapped and could be counted after cleaning the spectrum to eliminate all above-aluminum neutrons by means of the polyethylene absorber installed at the appropriate height. The exit valve allows accumulation of the cooled down neutrons in the storage volume during the time period corresponding to the spectral cleaning from above-aluminum neutrons in the initial spectrum. Then the exit valve is opened and the remaining neutrons are counted.

In fact, events involving a decrease in UCN energy were detected. The probability of down-scattering at a stainless-steel surface appeared to be significantly lower than that of upscattering. The spectrum of cooled down neutrons is shown in Figs. 7 and 8. The production rate of the cooled down neutrons was measured to be also proportional to the total surface area,

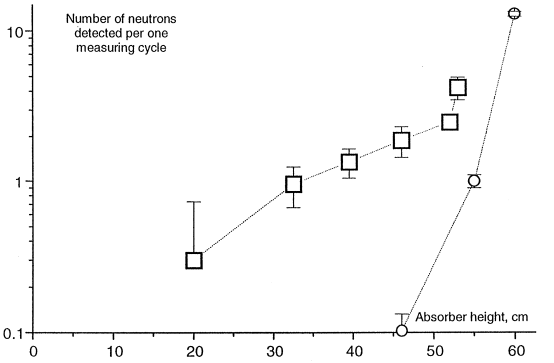

Fig. 7. Squares correspond to the integral spectrum of cooled down neutrons ($E_{ucn} < 54$ neV) in the stainless-steel spectrometer (there were no such neutrons in the initial spectrum). $E_{ucn} > 54$ neV range corresponds to residual UCN from the initial spectrum. Circles correspond to the background measurement with fixed-height absorber.

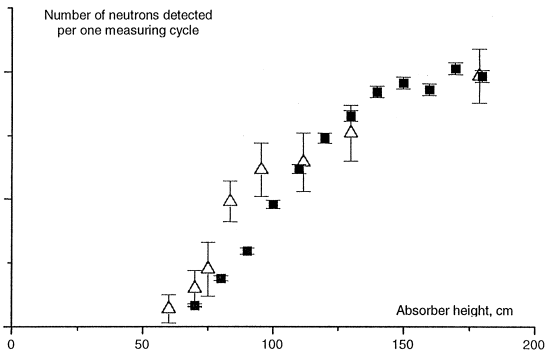

Fig. 8. The number of neutrons down-scattered to the energy range $E < 54$ neV (triangles) in the stainless-steel spectrometer versus the upper cut-off in the initial spectrum (there were no neutrons with the energy $E < 54$ neV in the initial spectrum). The initial UCN spectrum is shown with squares.

which shows that the interaction of UCN with the stainless-steel surface is responsible for this effect.

4. Discussion

Precise estimation of absolute probabilities can be done only after more detailed investigation. Two values are of interest: (1) The probability for any detectable change in UCN energy P_{vucn}. Presently, such a value can only be extracted using assumptions about the nature of the process. (2) The probability for neutron loss due to the events resulting in small changes in UCN energy, P_{loss}.

We measured the average probability for UCN milli-heating from the initial energy window 0–45 neV to some final energy window. To enable clear interpretation of the results we provided such experimental conditions that the windows do not overlap each other. A dead energy zone of 15–20 neV exists between the absorber height during filling and the lower edge of the transparency energy window for the Al foil. The minimum estimate for P_{loss} lies in the range 2×10^{-6}–2×10^{-8} for fomblin, stainless steel, beryllium and copper in order of decreasing probability. In reality, the correct values for the probabilities of upscattering to the energy window corresponding to the apparatus sensitivity are expected to be 5–10 times higher. This follows from low detection efficiency for VUCN due to losses in the Al window, in the foil holder, in the spectrometer walls, in the polyethylene absorber during its raising up and so on. Such an estimate for P_{loss} of $(10^{-5}$–$2\times10^{-7})$ gives again only a lower limit for the loss probability in an actual storage experiment. VUCN with too high and too low energies were undetectable in the present experiment (Fig. 9).

Also, actual probabilities for any changes in energy P_{vucn} are higher because some changes do not cause UCN loss. Any precise calculation requires knowledge of the energy transfer probability distribution. Some information is available for stainless steel only (see Fig. 6 and other results in Refs. [10,11,13]). The maximum energy transfer is approximately equal to the initial energy. The maximum decrease in energy (Figs. 7 and 8) was measured to be $\sim10^{-7}$ eV.

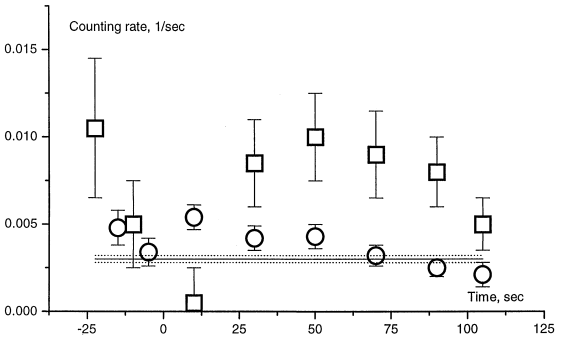

Fig. 9. The counting rate of the foil penetrating neutrons. Circles correspond to the measurement without sample (VUCN generation at $\sim0.2\ \mathrm{m}^2$ of copper walls of the spectrometer, not cleaned by heating). Squares correspond to the measurement with beryllium foil ($\sim1\ \mathrm{m}^2$, cleaned by heating) in this spectrometer. The measuring procedure is the same as in the stainless-steel spectrometer. 0 s is chosen as the moment of starting raising the absorber. The horizontal line is the constant background level.

5. Future measurements

Low and poorly known efficiency for the detection of VUCN complicates the absolute probability calculation. To avoid such a problem in the future we intend to carry out a comparative measurement of two storage times: one for a fixed absorber height and another where the absorber is raised up during the storage time. In the first case VUCN that gain enough energy to reach the absorber are lost. In the second case such neutrons are stored in the trap if their energy is lower than the upper absorber position. The difference between the two loss probabilities gives the partial loss due to the VUCN generation. If the decrease in storage lifetimes due to this process were significant then its elimination (using the procedure mentioned above, for instance) would allow significant progress in precise neutron lifetime measurement to be made.

6. Conclusion

In the present experiments we identified a new escape channel for UCN from traps. Neutron loss results from a permanent admixture of above-barrier neutrons in the spectrum even for a trap with a very efficient method of spectral cleaning, such as an almost perfect polyethylene absorber.

We suppose that it results from events of small changes in energy of UCN due to their interaction with surfaces. This is a different process from normal up-scattering to thermal energies but the result is that higher-energy neutrons can then escape into the bulk of the material where they can be up-scattered or absorbed or can penetrate through the trap wall if it is thin enough. We used both a stainless-steel and a copper gravitational storage spectrometer with different sample foils inside. A measurement of the same phenomenon was reported also by another group in Ref. [12] with a different method in a flow-through mode.

The reason for the low-energy changes needs to be understood. Our present ideas provide guidelines for future investigations but not yet the correct estimations for the probabilities and the energy changes (to be published). Hopefully the near future will clarify the physical interpretation for this phenomenon as well as its role in the UCN anomalous loss [7] and other UCN experiments.

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