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A NEW ESCAPE CHANNEL FOR ULTRACOLD NEUTRONS IN TRAPS

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A new surprising escape channel for ultracold neutrons (UCN) in traps was reported recently. It could be releavant to the long-standing puzzle of "too high" loss rate of UCN in traps, which is not yet completely understood and eliminated. In the present work we definitely identify the new phenomenon and investigate it in details. UCN escape from traps due to the rare events of small increase in their energy ($\sim 10^{-7}$ eV). The reason for such an energy gain as well as its impact to the physics of UCN storage is still to be investigated.

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Storage of ultracold neutrons (UCN, $E \sim 10^{-7}$ eV, $V \sim 5$ m/s) in traps is a unique tool in the fundamental physics experiments, particularly for the precision neutron lifetime measurement. The total reflection of UCN from trap walls allows their storage in closed traps. The thermal equilibrium is not achieved between such trapped neutrons and the walls: UCN reflect elastically from trap surfaces up to $\sim 10^5$ times subsequently, although the surface temperature is $\sim 10^5$ times higher than the temperature $\sim 10^{-3}$ K which would correspond to the UCN kinetic energy. Inelastic upscattering of UCN results to the neutron energy in $\sim kT$ range [1]. UCN could be also absorbed in a surface. However, these two known loss factors at trap walls are not sufficient for explanation of too high loss rate of UCN from traps. This is particularly evident in the phenomenon of so-called anomalous loss of UCN on beryllium surface: additional temperature-independent loss with probability $\sim 10^{-5}$ per collision [2]. General and detailed overview of UCN physics and application of UCN in fundamental physics covering the time period until 1990-91 could be found in [3, 4].

Unsuccessful attempts to provide long, theoretically predicted, storage times put constrain to the progress in experiments with storage of UCN. Besides, poor storage times indicate to a complementary phenomenon that has not been yet understood. Such inconsistency stimulated searches for UCN upscattering to a different energy range than the standard thermal range.

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UCN loss from traps, due to the surprising events of small increase in the energy of stored UCN, was reported in several publications [5 – 7]. In the present work we definitely identify such process. The energy gain is due to interaction of UCN with trap surface and it equals approximately to the initial UCN kinetic energy of $\sim 10^{-7}$ eV. The events of small increase and decrease in energy of UCN in traps are investigated in this article.

We used the method of UCN spectroscopy in the Earth's gravitational field. It is adequate to the investigated energy range of $\sim 10^{-7}$ eV that corresponds to ~ 1 m jumping height in the Earth's gravitational field. UCN and the "slightly heated" neutrons are stored simultaneously in one volume. The installation scheme is shown in Fig.1. In more details the installation and the method of measurement are described in [5, 6, 8, 9].

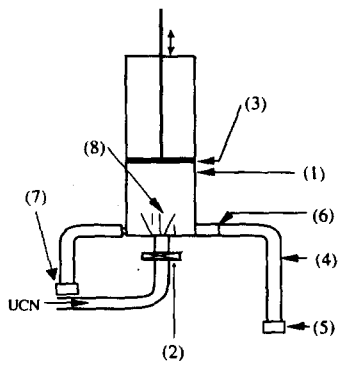

Fig.1. Scheme of the installation: *1* – gravitational spectrometer, *2* – entrance shutter, *3* – polyethylene absorber, *4* – curved neutron guide, *5* – UCN detector, *6* – thin Al foil, *7* – monitor detector, *8* – samples

UCN from source via the entrance neutron guide fill the gravitational spectrometer (= storage volume) *1*. They are trapped in it when the entrance shutter *2* is closed. The gravitational spectrometer is a pumped out down to the residual pressure of $\sim 10^{-5}$ torr cylinder with diameter 60 cm and height 200 cm. It is made of polished stainless steel. The critical energy is ~ 190 neV, (mg·1 cm $\approx$ 1 neV). Inside the spectrometer a polyethylene absorbing disk *3* is installed. It moves up or down along the total spectrometer height. UCN with energy $E > mgh_{absor}$(where m is the neutron mass, g is the acceleration in the Earth's gravitation field, h_{absor} is the absorber height above the spectrometer bottom)can penetrate in the absorber. The absorber has no reflecting potential and it has high upscattering cross-section. Such properties provide perfect absorbing efficiency. The kinetic energy of a neutron, that has been upscattered in the polyethylene, is in $\sim kT$ range. Such neutron is not trapped. It leaves the spectrometer. Thus, after UCN have filled the spectrometer and have stored in it for some time (with closed entrance valve), the spectrum is shaped so that there are no neutrons in it with energy $E > mgh_{absor}$. A ^{3}He gaseous UCN detector *5* with thin Al entrance window is installed ~ 1 m lower than the spectrometer bottom. It is connected to the spectrometer via a curved neutron guide *4*. The curvature of the neutron guide allows protection of the detector against thermal neutrons produced in/on the separating foil *6* and spectrometer surfaces. Besides, this neutron guide provides an increase in the efficiency of UCN detection due to their acceleration in the Earth's gravitational field. Such increase in the UCN velocity allows their easier penetration through potential barrier of the detector's Alwindow. The curved neutron guide and the detector are separated from the storage volume by a vacuum-tight 10.5 μm-thick Al foil *6*. The UCN flux in the spectrometer is measured with a monitor detector *7*, which is analogous to the main detector *5*. It is separated from the storage

volume by a thick foil with a small ($\sim 1\,\mathrm{cm}^2$) hole. Samples *8* with large surface area can be placed on the spectrometer bottom.

Separation of the storage volume from the detector by a vacuum-tight Al foil with critical energy $E_{\mathrm{Al}} \sim 52\,\mathrm{neV}$ allows detection of UCN with energy $E > 52\,\mathrm{neV}$ only. During filling the absorber is at a smaller height $h_{absor} < E_{\mathrm{Al}}/mg$ (in the present measurement $h_{absor} = 46\,\mathrm{cm}$). The count rate is expected to drop down rather fast to the background level after closure of the entrance shutter. The characteristic time for such decrease corresponds to the cleaning time for UCN with energy $E > mgh_{absor}$. In fact, after such fast drop down of the count rate with expected characteristic time there is nevertheless some count rate that is significantly higher than the background. Such count rate decreases in time in parallel (with the same characteristic time) with the UCN density in the spectrometer (Fig.2, lower curve). After raising the absorber (for $\sim 12\,\mathrm{s}$, starts in 80 s after the entrance shutter closure) the count rate increases ~ 25 times (Fig.2, upper curve). We suppose that the only reasonable interpretation for such data is a small gain in energy for stored UCN that allows overcoming the potential barrier of separating Al foil. Neutrons with energy $E_{\mathrm{Al}} < E < mgh_{absor}$ are not absorbed (when the absorber is raised up) and they are detected more efficiently than with the absorber down.

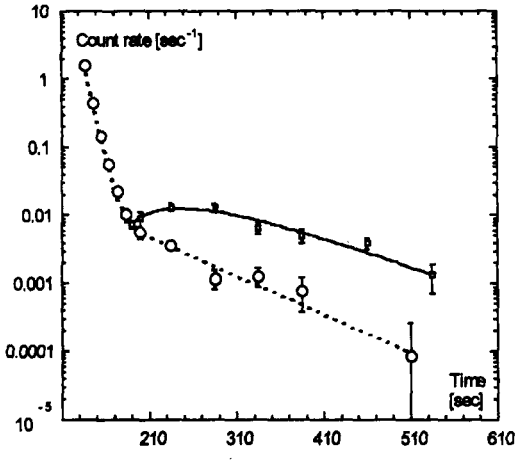

Fig.2. Time dependence for the count rate of neutrons penetrating through Al foil in the stainless steel spectrometer. Lower curve corresponds to the fixed-height absorber. Upper curve corresponds to the absorber that is raised up in 80 s after the entrance shutter closure. Background is subtracted

Generation of the slightly heated UCN in traps is similar to a vaporizing process. Therefore we call them (VUCN). Raising the absorber up to different height allows measurement of VUCN spectrum (Fig.4).

For studies of this process at different surfaces the corresponding samples were placed inside the spectrometer. Additional rate of generated VUCN was measured. It was relatively low for many samples compared to the generation rate at the spectrometer walls. Therefore later we replaced the stainless steel spectrometer by a copper cylindrical spectrometer with diameter 20 cm and height 180 cm.

A reverse (compared to an increase in energy of UCN) events of decrease in energy were measured in the stainless steel spectrometer. A 10.5 μm-thick Al foil was installed just above the entrance shutter. At the spectrometer exit a shutter replaced thin separating foil (that was used in the measurement of increase in energy). After UCN have filled the spectrometer (with the exit shutter closed) the entrance shutter is closed also. The UCN spectrum in the spectrometer is shaped so that there are no neutrons with energy

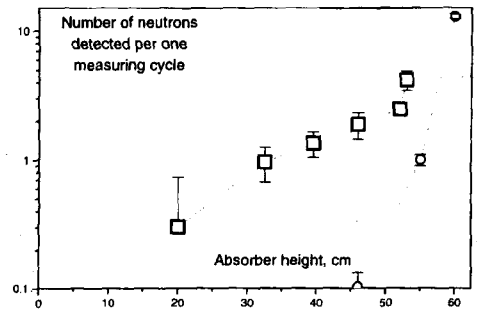

Fig.3. "Integral" spectrum of cooled down neutrons in the stainless steel spectrometer. Squares correspond to the number of cooled down neutrons versus the absorber height during the spectrum cleaning (the absorber height during filling is 160 cm). Circles correspond to the fixed-height absorber ("background" measurement)

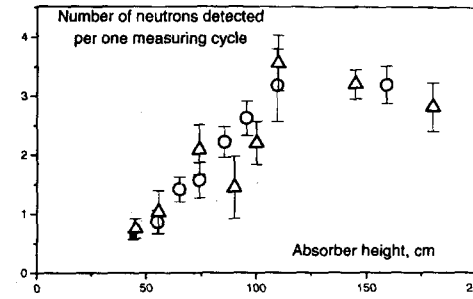

Fig.4. "Integral" VUCN spectrum. Circles correspond to VUCN generation at stainless steel spectrometer walls. Triangles correspond to VUCN generation at stainless steel sample in the copper spectrometer. Square — to the fixed-height absorber in the stainless steel spectrometer

$E < E_{\mathrm{Al}}$ or $E > mgh_{absor.up.}$. If, after some time period, the absorber is lifted down to a height lower than E_{Al}/mg (in present measurement $h_{absor} = 46$ cm) then it absorbs all UCN in the spectrometer. If some UCN are scattered down to the energy $E/mg < 46$ cm then such neutrons survive because they never hit the absorber. Later they are counted when the exit shutter is then open (Fig.3). Variation of the maximal absorber height (during filling and storage) and the minimal one (during cleaning) allows the estimation from/to which energies UCN are scattered down.

The generation rate for both measured processes (increase and decrease in energy of UCN) is proportional to the surface area. This indicates that namely the collisions of UCN with surface are responsible for the phenomenon of small energy changes.

Average probability of UCN heating to VUCN range equals to the ratio of the VUCN generation rate to the UCN surface collision rate. Storage times for UCN and VUCN in the spectrometer, the collision frequency and the detection efficiency for VUCN depend on energy. Therefore the estimation of the average heating probability should be based on a precise knowledge of the initial spectrum, its evolution, VUCN spectrum and spectral dependence for VUCN detection efficiency. A significant disadvantage of the present installation consists in complete insensitivity to the VUCN with energy approximately $E < E_{\mathrm{Al}} + 15$ neV. Such slightly above-barrier neutrons do not penetrate efficiently the foil because of the high probability for back reflection and losses in the foil. On the other hand the present installation and the method allow in principal direct measurement of just such changes in energy that cause UCN losses in standard storage experiments. Also the probability estimation depends on the model of one-step or many-step changes in energy.

Therefore we present only minimal limits for heating probabilities and leave more accurate estimations for future. We assumed here one-step process, monolines with energies 46 neV and 110 neV respectively for UCN and VUCN spectra and equality of storage times for UCN and VUCN. Every this assumption corresponds to the most conservative, minimal estimation for the heating probability.

The estimate for the probability of small decrease in UCN energy is almost model-independent.

The estimations are listed in Table. The stainless steel sample was degassed at $\sim$ 1100 K for $\sim$ 30 min. Such heating of the sample decreased the magnetic permeability $\sim 10^3$ times but the VUCN generation did not change significantly. This means that VUCN generation has no direct relation to ferro-magnetic properties of the sample.

Sample	$\mu \cdot 10^{-4}$	$P_+ \cdot 10^{-7}$	$P_- \cdot 10^{-7}$
Surface of stainless steel spectrometer	18.3 $\pm$ 0.2	>5.5$\pm$ 0.4	1.0 $\pm$ 0.1
Surface of copper spectrometer	12.7 $\pm$ 0.5	>0.68$\pm$ 0.13	
Sample of stainless steel	6.2 $\pm$ 1.4	>3.1$\pm$ 0.6	
Degassed sample of stainless steel	0.1$\pm$ 0.9	>1.4$\pm$ 0.3	
Sample of beryllium	$\sim$ 5.0	>1.0$\pm$0.25	
Degassed sample of beryllium	< 1	>1.0$\pm$0.25	

In columns: 1^{st}) The sample material. 2^{nd}) The loss probability under the assumption of 46 neV UCN monoline spectrum and for experimentally measured storage times. 3^{rd}) Minimal limit for the probability P_+ of increase in energy that is calculated using the model described above. 4^{th}) The probability P_- of decrease in energy. Actual values for the probability of increase in energy are significantly higher than the presented here minimal estimations.

Investigation of VUCN spectrum in the stainless steel spectrometer shows that it is shaped from above at the energy $\sim$ 110 neV while the initial spectrum was shaped at $\sim$ 46 neV (Fig.4). One should underline again that the installation is not sensitive to VUCN with energy approximately $E < E_{\mathrm{Al}} + 15$ neV. Therefore Fig.4 could be used only for qualitative estimation of VUCN spectrum.

In Fig.3 the number of cooled down neutrons is shown versus the minimal absorber height. This corresponds to the integral spectrum of cooled down neutrons.

We verified and definitely identified the new phenomenon of small energy heating of UCN at trap surfaces reported in [5, 6]. It causes additional losses of UCN from traps. The nature of such energy changes is not quite clear yet.

At stainless steel surface the kinetic energy for some UCN increases about twice maximally. The probability for such an energy gain is higher than $\sim 10^{-6}$ per collision. It does not depend strongly on loss coefficient and magnetic permeability of material. This seems to contradict to the idea of quasi-elastic scattering of UCN at surface hydrogen impurities also to the relation of such process to ferro-magnetic properties of wall materials. Measured absolute probabilities as well as their qualitative behavior (independence on standard inelastic scattering probability) contradict to the results presented in [7]. However, different energy spectra measured in these experiments do not allow a clear comparison. We identified also for the first time a small energy increase for UCN at copper and beryllium surfaces. This indicates to the universal nature of this phenomenon.

We measured also the events of small decrease in energy of UCN at stainless steel surfaces. Such phenomenon was earlier reported in [10]. Probably it has common physical reason with the small heating of UCN. The probability for such decrease in energy is at least 10 times lower than that for the increase in energy.

In future we intend to measure directly the impact of the small energy heating to UCN storage times and particularly to the additional "unavoidable" anomalous UCN losses. The temperature dependence for such process is of significant interest because it could clarify the nature of this effect.

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