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Mechanism of Small Variations in Energy of Ultracold Neutrons Interacting with a Surface

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Abstract—The cause of the small heating of ultracold neutrons (UCNs) by $\sim 10^{-7}$ eV with a probability of 10^{-8}–10^{-5} per collision with a surface was investigated. Neutrons heated in this way will be called vaporized UCNs (VUCNs). It was established that a preliminary heating of a sample in vacuum up to a temperature of 500–600 K can increase small-heating probability P_{VUCN} by a factor of at least ~ 100 and 10 on a stainless steel and copper surfaces, respectively. For the first time, an extremely vigorous small heating of UCNs was observed on a powder of diamond nanoparticles. In this case, both the VUCN spectrum and the temperature dependence of probability P_{VUCN} were similar to those previously obtained for stainless steel, beryllium, and copper samples. On the surface of single crystal sapphire, neither the small heating of UCNs nor nanoparticles were found. All these facts indicate that VUCNs are likely produced by inelastic scattering of UCNs on weakly bound surface nanoparticles being in permanent thermal motion.

In 1997, we found an additional channel of losses of ultracold neutrons (UCNs) from traps [1]. These losses occur because UCNs increase their energy by $\sim 10^{-7}$ eV with a probability of 10^{-8}–10^{-5} per collision with a surface. If the energy of a neutron after this inelastic scattering exceeds a certain critical value, it leaves a trap. This process is similar to the "vaporization" of UCNs from the trap (see Fig. 1). For this reason, such neutrons are named "vaporized" UCNs (VUCNs).

For investigating the nature and characteristics of this phenomenon, a big gravitational spectrometer (BGS) was constructed. This spectrometer can simultaneously detect stored UCNs and formed VUCNs (see Fig. 2). Contrary to previous setups, the BGS provides the detection of VUCNs in a wider energy range (50–150 neV) and with higher efficiency (~50%). This efficiency is measured rather than estimated over the entire energy range in order to ensure the accuracy and reliability of results. The spectrometer was designed so that samples can be rapidly and conveniently replaced, and the setup can be adapted for various experimental problems. The spectrometer volume hermetically separated from the vacuum enclosure can be heated up to 600 K or cooled down to 80 K.

The layout of the BGS is shown in Fig. 3. A sample (*1*) is mounted at the spectrometer bottom inside cylinder *2*, which forms a storage volume for UCNs and presents a gravitational barrier for neutrons. Ultracold neutrons fill the spectrometer through the inlet neutron guide and are locked by valve *3*. A calibrated orifice in the spectrometer bottom allows measurements of neutron flux by monitoring detector *4*. Absorber *5* in the lower position removes UCNs of energies above the gravitational barrier. When the absorber is in the upper position, VUCNs formed in collisions of UCNs with the sample surface or

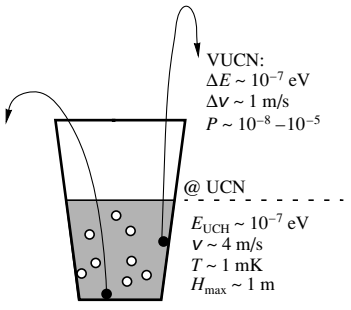

Fig. 1. Illustration of losses of UCNs via the formation of VUCNs. The parameters of UCNs: $E_{\mathrm{UCN}} \sim 10^{-7}$ eV, $v \sim 4$ m/s, $T \sim 1$ mK, and $H_{\max} \sim 1$ m (shown by the horizontal straight line inside the vessel). The parameters of VUCN formation: $\Delta E \sim 10^{-7}$ eV, $\Delta v \sim 1$ m/s, and probability $P \sim 10^{-8}$–10^{-5}.

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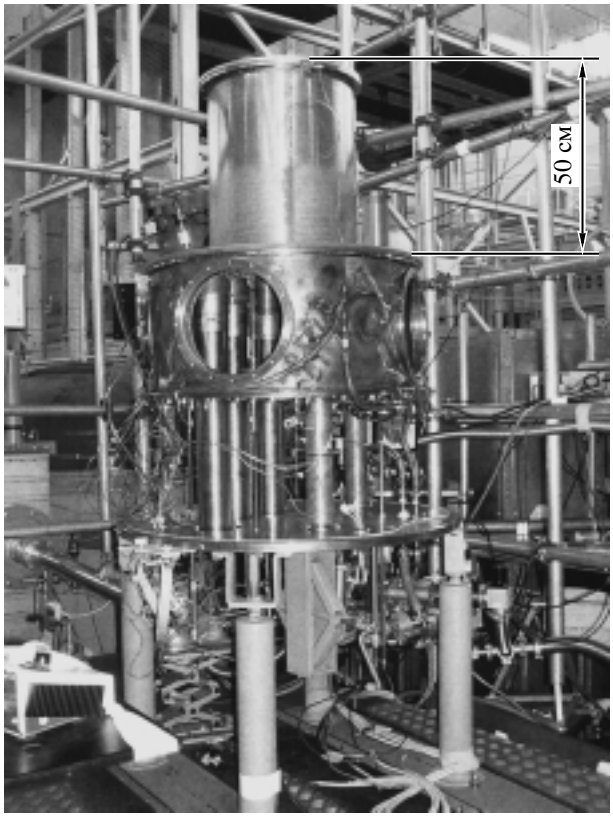

Fig. 2. Lower section of the big gravitational spectrometer. The height of the inner UCN-storage volume (gravitational barrier) is shown.

walls can jump over the gravitational barrier and enter detector *6* through outlet valve *7*, which is opened throughout the measurements.

Figure 4 shows the typical time dependences of the detector count rate with various samples. During filling the spectrometer (0th–100th s), the absorber is in the lower position. Neutrons of energies higher than the gravitational barrier penetrate in the detector through the gap between the absorber and walls of the

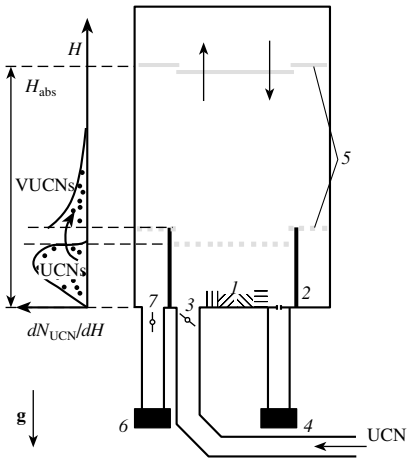

Fig. 3. Layout of the setup: (*1*) sample, (*2*) gravitational barrier, (*3*) inlet valve, (*4*) monitor, (*5*) absorber, (*6*) detector, and (*7*) outlet valve.

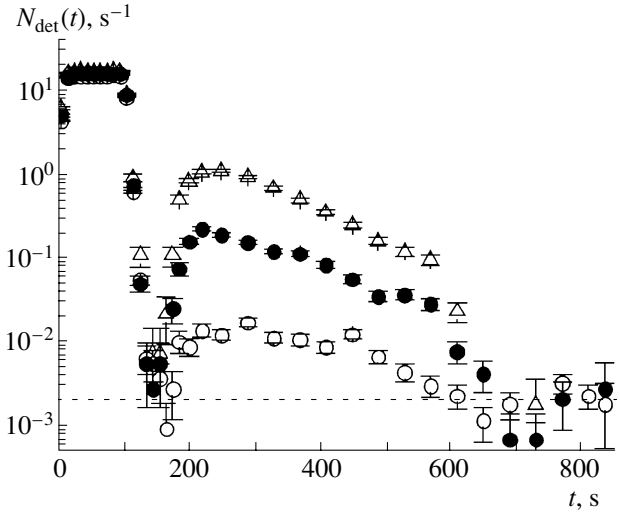

Fig. 4. Count rate as a function of time: measurements (○) on the surface of the empty copper spectrometer, (●) with stainless steel samples (SS2-2), and (△) with the diamond-nanoparticle powder. The dashed line shows the background level.

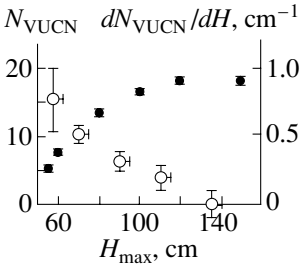

Fig. 5. (Left-hand ordinate axis, solid circles) Integral and (right-hand ordinate axis, open circles) differential spectra of neutrons heated on the stainless steel surface (SS1-3 sample) vs. the height of the upper position of the absorber. The integral spectrum is the number of VUCNs detected per cycle. The differential spectrum is obtained by the numerical differentiation of the integral spectrum corrected to the efficiency of VUCN detection.

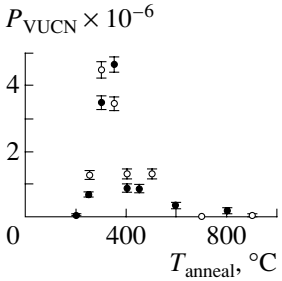

Fig. 6. Probability of the small heating of UCNs as a function of the annealing temperature for the stainless steel samples (solid circles) SS4.1 and (open circles) SS4.2.

storage volume; therefore, the detector count rate is high. After closing the inlet valve (the 100th second), these neutrons are rapidly absorbed in absorber, and the detector count rate falls abruptly. If the absorber is listed to the upper position after a certain time interval (the 170th second) in which all the UCNs of energies higher than the gravitational barrier are removed from the spectrometer, the detector count rate rises and, after a certain time, becomes proportional to the flux density of UCNs closed by the gravitational barrier in the spectrometer. This behavior is explained by the permanent production of VUCNs with energies higher than the gravitational barrier in the storage volume. At the 590th second, the absorber is sunk to the lower position, and the detector count falls down to the background value.

The probability of the small heating of UCNs interacting with a metal (stainless steel or copper) surface is measured with a higher accuracy by a more reliable method than in previous experiments [1–3]. In this case, the new measurement corroborates our previous results obtained with similar samples for both the probability of this process and the shape of the integral spectrum of heated neutrons.

For the first times, the integral spectrum of heated neutrons (see Fig. 5) was measured with an accuracy sufficient for calculating the differential spectrum.

We have established that the probability of small heating of UCNs depends on the procedure of preparing a stainless steel sample. Indeed, a preliminary heating of the sample at a temperature of 500–600 K during four hours abruptly increases the probability of small heating of UCNs by a factor of about 100. The independent measurements with identical samples indicate that this result is well reproducible (see Fig. 6). The similar abrupt increase in the probability of small heating (by a factor of 10) after heat treatment was also observed for the interaction of UCNs with a copper surface. It should be noted that the preliminary heating of surfaces of traps and samples up to these temperatures is the routine preparatory procedure in UCN-storage experiments. Therefore, the interpretation of experiments where UCN losses caused by small heating are not explicitly measured is unreliable.

We considered the acceleration of UCNs by the thermal motion of solid nanoparticles weakly bound to a surface as the most probable cause of the small heating of UCNs [4]. In order to verify this hypothesis, we deposited a powder ($\sim$1 cm^3) of diamond nanoparticles with a mean size of $\sim$5 nm (Ultradiamond-90) on an area of $\sim$150 cm^2 on the copper bottom surface of the spectrometer. In this case, the VUCN flux increased strongly (see Fig. 4), and the probability of VUCN formation reduced to this area was equal to $\sim 10^{-3}$ per collision. The VUCN spectra measured in this study and in [1–3] on the stainless steel surface coincide with the spectrum measured on the nanoparticle-powder surface (see Fig. 7). The temperature dependence of small-heating probability measured in the range of 100–300 K for the diamond-nanoparticle powder coincides with the dependences measured in [2] for the beryllium and copper surfaces. Furthermore, the VUCN

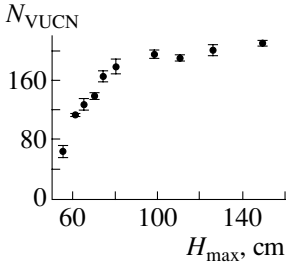

Fig. 7. Number (integral spectrum) of VUCNs detected per cycle, which were heated on the diamond-nanoparticle powder, as a function of the upper-position height of the absorber.

spectrum is virtually independent of temperature in the temperature range 100–300 K.

Whereas we observed a high VUCN flux from the nanoparticle powder, small heating of UCNs on the surface of a sapphire single crystal was not detected. The probability of this heating was measured to be $(0.0 \pm 1.2) \times 10^{-8}$ per collision. In this case, the scanning atomic force microscope observed no nanoparticle on this surface.

The results of this study indicate that the small heating of UCNs interacting with a surface is caused by their acceleration in collisions with very small solid particles that are weakly bound to the surface and are in permanent thermal motion.

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