Observation of heating of ultracold neutrons as the cause of the anomalous limitation of their confinement time in closed vessels

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The flux of neutrons with energies in the range 0.2×10^{-3}–25×10^{-3} eV, equal to the number of ultracold neutrons (UCN) escaping per unit time from a vessel storing them, is registered by an external detection system surrounding the vessel. For the maximum UCN confinement time attained (~23 sec), corresponding to 1.4×10^3 collisions of a UCN with the vessel walls, between 75% and 100% of all the UCN accumulated in the vessel escape from it by inelastic scattering at the walls.

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INTRODUCTION

The prediction by Zel'dovich in 1959[1] of the existence of a gas of ultracold neutrons[2)] (UCN) in closed vessels was first realized by Shapiro's group in 1968.[2] The attraction of using UCN in a number of projected fundamental experiments[3] lies in the possibility of confining them in closed vessels for a long time, limited, in principle, only by the β-decay of the free neutron ($\tau\sim10^3$ sec).

However, it has been noted that the UCN confinement times attainable in practice for vessels of beryllium, graphite, glass, aluminum and teflon are 10–100 times shorter than the expected times calculated by optical-potential theory from the data for the capture and inelastic-scattering cross sections. For vessels of copper, nickel and stainless steel this discrepancy (by a factor of ~3–5), although smaller, is nevertheless considerable. A surprising fact, confirmed in numerous experiments,[4–11,12] is that the average number of collisions with the vessel wall that can confine a UCN before it is lost does not exceed $\sim2\times10^3$ and is almost independent of the choice of material, and, within wide limits (from 80 to 600 K), of the vessel-wall temperature.

Losses of UCN in collisions with the wall can occur only as the result of absorption or inelastic processes (phonon capture, scattering by hydrogen-containing surface films, etc.), which lead to heating of the confined gas of UCN and to subsequent escape of the neutrons through the vessel walls.

The classical idea of inelastic scattering predicts a significant dependence of the confinement time on the temperature, but the experiments have not confirmed this. The existence of a strongly absorbing impurity film on the surface must be regarded as improbable, since it is difficult to accept that the same impurities will be present on the surfaces of very different substances, prepared by the most varied technology. Small mechanical perturbations, in the form of acoustic vibrations of the vessel walls, have also been found to have no influence on the UCN confinement time.

It is sometimes possible to associate the effect of anomalous loss of UCN quantitatively with one specific cause by theoretical investigations of certain (sometimes purely artificial) enhancements of the mechanism under consideration, be it roughness of the wall surface,[13–16] acoustic excitations from 10^2 to 10^3 Hz,[17–20] voids in the material,[21] or surface absorbing films.[22][3)]

In Refs. 23 and 24 assumptions are made about the existence of an as-yet unexplained absorption or heating mechanism, intrinsic to UCN only and absent for neutrons with higher energies.

With the purpose of overcoming the contradictions that have arisen between theory and experiment certain authors have put forward far-reaching hypotheses connected with the modernization of quantum mechanics itself,[25] and have even made the completely unexpected assumption that the neutron has a pre-decay state with spin 3/2,[26] which would explain the penetration of such neutrons through the walls.

Thus, it has seemed that in the present situation both absorption and heating of UCN have been ruled out as mechanisms of the possible anomalous leakages of UCN from closed vessels, but, at the same time, the assumption of some dematerialization of the UCN is also completely unacceptable.

The proposed experiment has the aim of elucidating where the UCN "lost" from the vessels get to. In leaving the vessel the neutrons must necessarily enter the vessel wall in some way, surmounting the reflecting potential barrier. If for the walls we choose a material with inelastic-scattering cross-section greater than the absorption cross-section we can be confident that the surmounting by the neutron of the reflecting barrier of the wall by any assumed mechanism will then lead to the familiar, ordinary inelastic scattering up to thermal velocities in the vessel-wall material and to subsequent detection in a thermal-neutron detection system surrounding the vessel.[4)]

EXPERIMENT

The experimental setup is shown in Fig. 1. Cylindrical vessels 1 for confining the UCN were placed, in

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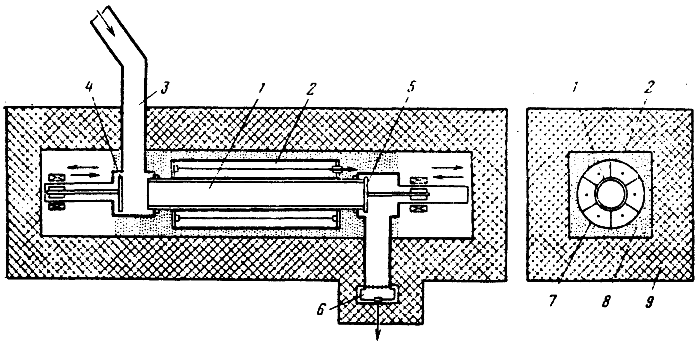

FIG. 1. Scheme of the apparatus: (1) vessel for confinement of UCN, (2) 4π-counter for heated neutrons, (3) neutron-guide for UCN, (4, 5) UCN entrance and exit shutters, (6) UCN detector, (7) cadmium, (8) boron carbide, (9) borated polyethylene.

turn, inside special six-cell helium counters 2 and filled with a gas of UCN through the neutron-guide 3 from the UCN sources described previously.[8,11] At both ends the vessels were tightly closed by an entrance shutter 4 and an exit shutter 5—copper disks that could be set in rotational-translational motion by magnets. At the vessel exit was placed a UCN detector 6—a proportional counter with an aluminum window of diameter 8.5 cm and thickness 0.1 mm, filled with a mixture of 5 Torr He^3, 10 Torr CO_2 and 760 Torr Ar,[5] with sensitivity to UCN of ~1 in the geometry used. The confinement time τ and the number N_0 of UCN collected inside the vessel were measured by this counter in the following way: with the exit shutter closed and the entrance shutter open the vessel is filled with a gas of UCN from the neutron-guide for a time ~2 sec, the entrance shutter is then closed, and the accumulated gas of UCN is stored for a certain time t, in the course of which some of the UCN are captured or heated and the remaining number $N(t)$ of UCN "flow out" of the vessel in ~2 sec to the UCN detector 6, connected to a time analyzer triggered off at the time the entrance shutter is opened.

The use of the time analyzer makes it possible for the UCN flowing out of the vessel to be distinguished clearly from the ever-present neutron background. Such cycles are repeated several times, and the results of the individual cycles are summed. The curve of the dependence of the number N of UCN remaining in the vessel on the storage time t is extrapolated to the time $t=0$, and from this the number N_0 of UCN collected in the vessel is obtained. The number of UCN remaining in the vessel at time t is approximately described by the law $N(t) = N_0 \exp(-t/\tau)$. The time τ in which this number decreases by a factor of e is called the confinement time.

After the confinement time was measured the exit shutter was fixed in the closed position and the time analyzer was switched over to the detection, by the six-cell counter, of the neutrons flowing out through the walls, and triggered off at the time the entrance shutter was closed.

If the neutron flux detected by the external counter 2 decreases in time in accordance with the same law as the measured (by the above-described method) time dependence of the density of UCN in the vessel, this will prove that the external counter is detecting the "heated-up" former UCN that have disappeared from the vessel. Knowing the detection efficiency of the six-cell heated-neutron counter, we can determine the fraction of UCN that leave the vessel via heating of the UCN.

The whole apparatus is placed in a composite, tightly assembled neutron shield of cadmium 7, boron carbide 8, and borated polyethylene 9, of total thickness ~30 cm. An additional quantity of borated polyethylene (~40 cm) and steel (~30 cm) was used in working with the UCN source.[11]

To store the UCN four cylindrical vessels were used, with slight differences in the overall dimensions because of constructional considerations.

Vessel No. 1 (length 96 cm, internal diameter 8.2 cm) was designed for seeking processes of tunneling penetration or slight heating of the UCN (to velocities 8–300 $m\text{-}sec^{-1}$). To reduce neutron capture the vessel walls were prepared from two layers of thin copper foil of thickness ~10 μm, thereby shutting off the direct passage of UCN through possible holes in the foil. The inner surface was pickled in HNO_3 and washed in distilled water.

Vessel No. 2 differed from the first in the thickness (~0.4 mm) of the rolled foil used an in the electropolishing of its inner surface.

Vessel No. 3 (length 68 cm, internal diameter 7.8 cm) was a cylinder of boron-free glass with wall thickness 0.5 cm, with beryllium of thickness 0.3 μm deposited on the inner surface.

Vessel No. 4 (length 70 cm, internal diameter 8.4 cm) was prepared from a solid-drawn copper pipe with wall thickness 1.5 mm and an electropolished inner surface.

Copper was chosen as the material of the vessel walls (Nos. 1, 2, 4), because it had been most fully studied in preliminary experiments[5,9] on the confinement of UCN and because the difference in the observed and calculated confinement times is a minimum for copper. According to the work of Steyerl and Vonach,[27] for copper the inelastic-scattering cross-section σ_{inel} for neutrons with velocities ~10 m/sec is much smaller than the capture cross-section σ_{cap}. In beryllium (vessel No. 3), on the other hand, the contradiction with theory is greatest and $\sigma_{\text{inel}} \gg \sigma_{\text{cap}}$.

The neutrons passing through the vessel walls were detected, in different stages of the experiment, by three types of specially prepared proportional counters. Below, for definiteness, we shall call these counters 4π-counters, despite the fact that they cover only about half the total surface of the vessel.

The 4π-counter No. 1 was manufactured to detect small UCN energy transfers from 1.5×10^{-7} to 4×10^{-4} eV, and was used with vessel No. 1. This counter (Fig. 1) consisted of two coaxial cylinders: an external one of stainless steel, with diameter 18 cm, and an internal one of duraluminum, with diameter 8.5 cm and wall thickness 0.5 mm. The ends of six tungsten filaments, of diameter 25 μm, stretched parallel to the axis of the cylinder, were fastened to the side collars. Aluminum plates partitioned the volume of the counter symmetrically into six cavities, thereby eliminating the regions of weak electric fields between the filaments. All the filaments were joined together and connected to the input of a single amplifier. The counter was outgassed by heating to 200°C and filled with the following gas mixture: 53 Torr He^3, 20 Torr CO_2 (stabilizing the discharge in the counter), and 1140 Torr Ar (to retain the products of the reaction $He^3(n, p)T$ in the gas).

On the assumption that the flux of neutrons escaping from the vessel was isotropic, the dependence of the detection efficiency on the velocities of the neutrons was calculated from the formula

$$\varepsilon=\left[1-\exp\left(-\Sigma_1 d\frac{V_0}{V}\right)\right]\exp\left(-\Sigma_2\frac{V_0}{V}\right),$$

where Σ_1 is the absorption coefficient in He^3, d is the mean free path of a neutron in He^3, $v_0=2200$ m-sec^{-1}, and Σ_2 is the absorption coefficient for 0.5 mm of duraluminum and 20 μm of copper. Figure 2a shows the results of the calculation of the dependence of the efficiencies of the counters on the neutron velocity, the number on each curve corresponding to the number of the counter.

The 4π-counter No. 2 was designed for the search for processes of heating of UCN up to thermal-neutron energies, and therefore the pressure of the detecting gas mixture was increased to 4.5 atm (1520 Torr He^3, 1900 Torr Ar and 25 Torr CO_2) and the thickness of the internal duraluminum wall was raised to 1.5 mm. The effective length of counters Nos. 1 and 2 was ~65 cm. The 4π-counter No. 3 was also used for the search for processes of heating of the UCN to thermal-neutron energies, in combination with vessels No. 3 and No. 4. The internal duraluminum wall of the counter was 3 mm thick and had diameter 10 cm, and the external wall had diameter 23 cm. The effective length was ~38 cm. To improve the "effect/background" ratio in the conditions of the expected large neutron background, the pressure of the He^3 in this counter was reduced to 400 Torr.

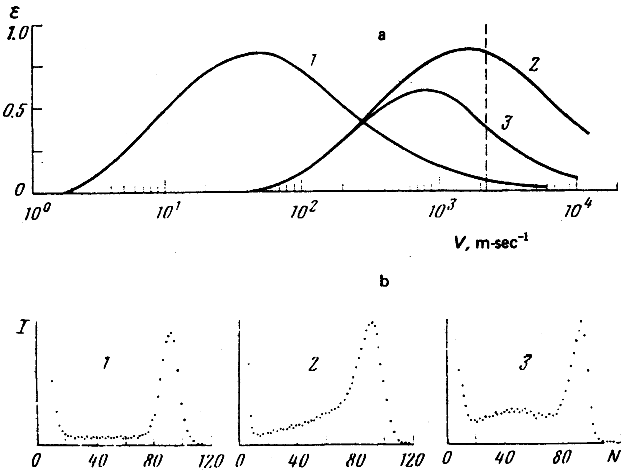

FIG. 2. (a) Dependence of the efficiency of the 4π-counters Nos. 1, 2, and 3 on the velocity of the detected neutrons. (b) Amplitude differential spectra of these counters; the peak in the spectra corresponds to the energy ~0.764 MeV of the reaction $He^3(n, p)T$.

All the counters operated in the proportional regime, with pulse amplitude ~2 mV. From the form of the amplitude differential spectra (Fig. 2b) it is possible to conclude that the probability of detection of a neutron absorbed by He^3 is ~1.

The background of the cadmium-encased counter No. 2 at the operating setting[11] was 2×10^5 sec^{-1} at the location of the apparatus and 1–2 sec^{-1} in the assembled shield. The use, in addition, of a ~25 cm hydrogen-containing shield lowers this background by a further factor of four.

It is probable that further improvements of the shield will make it possible to make a counter, containing ~15 liters He^3, that is almost insensitive to neutrons at a comparatively short distance (~7 m) from the active zone of a powerful reactor (~100 MW). In this case the residual background will be determined entirely by the natural α-activity of the constructional materials of the counter. For the 4π-counters used, this background amounts to ~0.2 sec^{-1}, which is somehwat greater than the results of Ref. 28.

RESULTS

The attempt to detect small transfers of energy to the gas of UCN gave a negative result, and the counters designed for the thermal-neutron detection fixed the neutron flux outside the vessel, as illustrated in Fig. 3.

a) Figure 3a shows the results obtained for vessel No. 1 and 4π-counter No. 1, which was sensitive only to the region of small neutron energies. The solid line represents the time dependence, measured by the UCN counter, of the number (density) of UCN in the vessel. The confinement time was $\tau=9\pm0.5$ sec, and in one cycle ~6 UCN accumulated. The UCN source described in Ref. 5 was used in the experiment. The dashed line shows the 4π-counter detection intensity actually measured.

The experiment was stopped when the statistical accuracy attained made it possible to assert that, in the required energy range, a neutron flux greater than 10–55% of the unknown flux (corresponding to a confinement time $\tau\sim9$ sec) of UCN escaping from the vessel was not being detected.

b) Figure 3b shows the results obtained with the combination of vessel No. 2 and 4π-counter No. 2. The solid line shows[5)] that $\tau=8.5\pm0.25$ sec and $N_0=45.0\pm1.5$. The dashed line shows the dependence of the intensity of

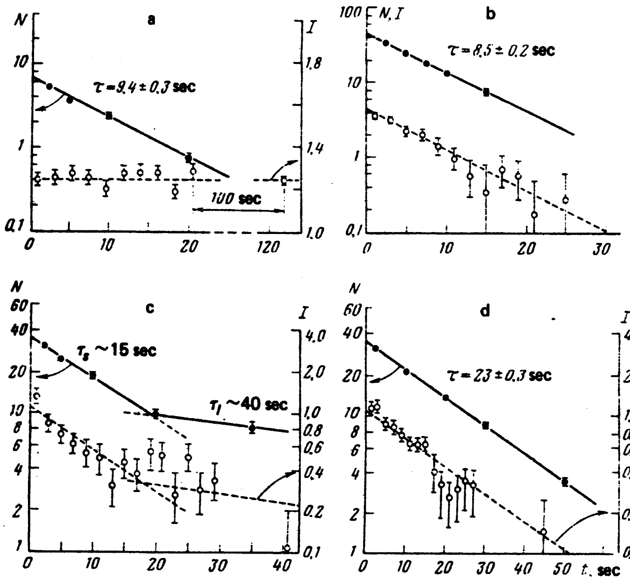

FIG. 3. Dependence, measured by the UCN detector, of the number N of UCN in the vessel on the time t from the moment of closure of the entrance shutter (the black points) and time dependence of the intensity I (neutrons/cycle-channel) of detection of neutrons by the 4π-counter, measured by a time analyzer with channel width 2 sec (the light points). (a) Vessel No. 1, counter No. 1; (b) vessel No. 2, counter No. 2; (c) vessel No. 3, counter No. 3; (d) vessel No. 4, counter No. 3.

detection of neutrons by the 4π-counter on the time elapsed after the closure of the exit shutter. The dashed line was found to have the same slope $\tau = 8.5 \pm 0.55$ sec as the solid line, and this proves that the neutrons detected by the 4π-counter were former UCN that had now been heated up and passed through 0.4 mm of copper and 1.5 mm of duraluminum. The area under this line corresponds to a number of detected neutrons equal to 16 ± 2. With corrections for a geometrical factor[6)] (almost half the vessel surface is covered by the counter) and for the efficiency of the counter, assuming heating of UCN to thermal energies (curve 2 in Fig. 2) we obtain that 75–80% of the UCN accumulated in the vessel leave it by way of inelastic scattering, being heated thereby to energies of the order of thermal-neutron energies.

c) Figure 3c shows the corresponding results obtained in the glass tube with beryllium deposited on the inside (vessel No. 3 and 4π-counter No. 3). As was observed also in preceding experiments, the confinement curve consists of two exponentials: a short-lived one, with $\tau_s \sim 15$ sec, and a long-lived one, with $\tau_l \sim 40$ sec.

It is clear that the presence of two exponentials in the confinement curve is explained by the comparatively rapid absorption in the glass (on the parts of the surface not covered by Be) of neutrons with velocities greater than the limiting velocity for glass (4.2 m-sec^{-1}). Only ~*1/4 of all the UCN* accumulated are found in the long-lived component, and therefore the statistics gathered are sufficient for the short-lived component. Taking into account the efficiency (which is somewhat altered in this setup) and geometry of the 4π-counter, we find that in this case the inelastic-scattering process is the principal cause of the loss of the UCN in the vessels, since the 4π-counter registered 90–115% of N_0.

The comparatively short confinement time in vessel Nos. 2 and 3 can, in principle, be explained by inelastic scattering, e.g., by hydrogen-containing dirty surfaces; the better results obtained earlier[3,5] for similar sizes of vessels amounted to $\tau \sim 25$ sec for copper and $\tau \sim 70$ sec for glass with deposited Be. In the experiment (c) the insufficient statistical accuracy of the detection by the 4π-counter of the inelastically scattered UCN belonging to the long-lived component (~40 sec) does not permit us to conclude with confidence that inelastic scattering is the main cause limiting the UCN confinement time for this component too.

Of greatest interest is an experiment with a vessel possessing a confinement time differing little from the maximum time achieved in the preceding experiments.

d) Figure 3d (vessel No. 4 with 4π-counter No. 3) shows the results for the copper vessel, for which $\tau = 23 \pm 0.5$ sec. This result is close to the best confinement-time results obtained for similar vessels,[3,5] with just a slight difference that may be due to the harder spectrum from the UCN source[11] used in this work. The slope of the dashed line determines $\tau = 23 \pm 1.5$ sec. The fraction of neutrons registered by the 4π-counter, with corrections introduced for the efficiency in this case too, amounted to 90–110% of $N_0 = 35 \pm 1.5$.

Consequently, inelastic processes are the principal cause of losses of UCN even in those cases in which the vessels were manufactured from materials for which $\sigma_{\text{inel}} \ll \sigma_{\text{cap}}$.

A control experiment was set up with the purpose of determining the effect of neutrons with velocities 6–10 m-sec^{-1}, i.e., somewhat greater than the UCN velocity, on the results obtained. Usually, such neutrons form the main background in the detection of the UCN.[6,11] A copper foil, 10 μm thick, that did not allow UCN to pass through but did not detail many neutrons with higher velocities, was placed inside the entrance section, across the entire cross-section of the neutron-guide (3 in Fig. 1). It can be seen from Fig. 4 that the effect disappeared completely. The background of the 4π-counter was also reduced by ~25%. Further shutting-off of the neutron-guide by a stainless-steel gate of thickness ~2 cm did not reduce the background. This is evidence that this addition (~25%) to the background is due to processes of heating of the UCN inside the shield in the neutron-guide system before the entrance shutter (4 in Fig. 1).[7)]

The introduction of a small piece of polyethylene film of mass 4.25×10^{-3} g and thickness ~30 μm in the center of the confining vessel reduced the confinement time measured by the UCN detector (6 in Fig. 1) by a factor of more than two and reduced by the same factor the decay constant of the intensity of detection by the 4π-counter, for a constant total number of detected neutrons per cycle. Introducing the correction for the geometry and extrapolating, by a $1/V$ law, the cross section for inelastic scattering of thermal neutrons by polyethylene from the value $\sigma_{\text{inel}}^{\text{therm}} \sim 8 \times 10^{-24}$ cm^2 to the value of the

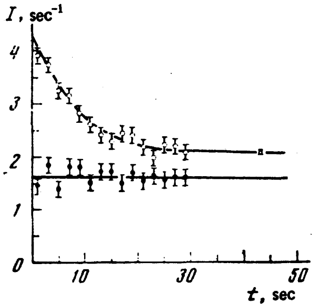

FIG. 4. Dependence of the intensity I of detection of neutrons by the 4π-counter on the time t after closure of the entrance shutter for vessel No. 2 (the light points). The neutron-guide for admission of the UCN was then partitioned at the entrance by a copper foil of thickness 10 μm (the black points).

cross-section corresponding to UCN energies, we obtain that the observed effect of inelastic scattering of UCN in the vessel with $\tau \sim 23$ sec is equivalent to scattering of the UCN by a film of a hydrogen-containing substance, of thickness ~100–150 Å, covering the entire inner surface of the vessel. An estimate shows that the technique used makes it possible to detect hydrogen-containing films of thickness down to ~5 Å and less on the surface of a material.

By increasing the area of the polyethylene placed at the center of the 4π-counter to the cross-section of the vessel (neutron-guide), we obtain, as in the work of Ref. 29, a UCN detector with a rather high efficiency $\sigma_{\text{inel}}/(\sigma_{\text{inel}}+\sigma_{\text{cap}}) \sim 1$ and low threshold energy $\sim 2\times 10^{-9}$ eV. This experiment was performed and confirmed this assumption. The UCN were detected with an intensity ~70 sec^{-1}. The background was measured with the entrance shutter (4 in Fig. 1) closed, and amounted to ~1.5 sec^{-1}. Obviously, the cumbersome shield does not permit us to make such a detector into a convenient experimental instrument, but it can turn out to be useful in a number of cases, e.g., in absolute measurements of the UCN flux.

DISCUSSION OF THE RESULTS. CONCLUSIONS

1. It has been shown that inelastic processes with energy transfer (~20 meV) from the wall to a neutron constitute the principal cause of loss of UCN in the experiments on the confinement of UCN. It may turn out, however, that this circumstance will not be the only difficulty on the road to achieving the limiting neutron confinement time $\tau \sim 10^3$ sec, limited only by the β-decay of the neutron. At the present time, the UCN heating process discovered does not make it possible to realize more than $\sim 2\times 10^3$ collisions of a UCN with the vessel walls.

2. The transfer of energy to a neutron from the wall occurs in one impact. The assumption that some kind of quasi-elastic scattering is possible, leading to energy broadening of the spectrum of the confined neutrons and to subsequent escape from the vessel of neutrons with energy greater than the threshold energy, is thereby rejected. If such an effect existed, such neutrons ought, with overwhelming probability, to be captured inside the material of the wall (for copper, $\sigma_{\text{inel}} \ll \sigma_{\text{cap}}$). The detection by the external detector of neutrons escaping from the copper vessel does not confirm this.

3. The difference between the number of UCN accumulated and the number of heated neutrons detected by the 4π-counter should be equal to the number of UCN captured in the walls. (For the copper vessel, for which $\tau \sim 23$ sec, this fraction amounts to ~0.25–0.30). The uncertainty in the efficiency of detection of the heated neutrons, principally because of the absence of exact data on the spectrum of the heated neutrons, makes it impossible to determine the fraction of UCN captured in the copper. Applying the reverse argument and assuming that the fraction of UCN captured in the copper is ~0.25–0.30, we can conclude that the UCN are heated to velocities somewhat lower than thermal velocities.

4. The physics of the process of energy transfer from the wall to a UCN is not yet clear. In principle, it is most logical to postulate heating in a hydrogen-containing film of thickness ~50 Å (or less in the presence of surface roughness). The thickness of this film depends on the method of preparation of the vessel surfaces. Evidently, the difference in the results described above for the confinement times in copper vessels (8.5 ± 0.25 sec and 23 ± 0.5 sec) and also for glass vessels (25 ± 2 sec and 104 ± 7 sec) is connected with this.[3]

However, the hypothesis of the existence of a hydrogen-containing film contradicts the experiments in which there was no temperature dependence of the UCN confinement time.[4,6,10] To clarify this situation the authors of this paper performed an additional experiment to measure the temperature dependence of the cross-section for inelastic scattering of UCN by a hydrogen-containing film (polyethylene, 30 μm), and this showed normal behavior of the temperature dependence of the inelastic-scattering cross-section (see Fig. 5). The results of measuring the temperature dependence of the yields of UCN from hydrogen-containing convertors also point to this.[5,30]

The validity of the hypothesis of a hydrogen-containing film can be reconciled with the absence of temperature dependence if we assume that, in the experiments performed earlier to measure the temperature dependence of the confinement time, the temperature variation of the inelastic-scattering cross-section was cancelled by the change in the thickness of the condensed hydrogen-

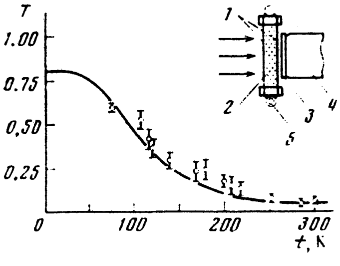

FIG. 5. Dependence of the transmission T of UCN (3.5–5.7 m-sec^{-1}) by polyethylene on the temperature t (°K). The solid line shows the calculated temperature dependence of the transmission. The scheme of the experiment is shown in the inset: (a) 35 μm polyethylene films; (2) helium ~20 Torr; (3) UCN detector (LiOH + ZnS); (4) photomultiplier; (5) coolant-gas pipes.

containing film with temperature. In principle, this process is possible, since all the vessels previously used for confinement of UCN were not hermetically sealed from the neutron-guide cavity and the vacuum system, and the residual pressure ~10^{-4}–10^{-6} Torr still permits significant mass transfer and redistribution of the thicknesses of the films on the walls of the vacuum system with change of temperature. An experiment currently being prepared to measure the temperature dependence of the confinement time of UCN in a hermetic vessel in which the number of impurities that can possibly be present on the vessel surface is fixed will help to clarify this.

However, another explanation is also possible, if we postulate the existence of inelastic scattering of UCN by hydrogen-containing films with special properties such that temperature dependence of the inelastic scattering appears only in the region of ultralow temperatures, where there are, as yet, no experimental data. Here we note only an apparently contradictory circumstance in the hypothesis of such a hydrogen-containing film. The hydrogen atoms in this film should have a small binding energy with the surface, in order that the dependence $\sigma_{\text{inel}}(T)$ for these atoms be sufficiently weak. On the other hand, the binding energy of the hydrogen atoms should be large in order to hold a sufficient number of layers of hydrogen atoms on the surface, as experiments at temperatures ~600 K and higher have shown. In the assumed model of a two-dimensional gas of hydrogen atoms on the surface it is possible to satisfy both conditions by assuming the existence of strong binding of the hydrogen atoms in the direction normal to the surface and weak binding parallel to the surface.[31,32] In this case, the angular distribution of the heated neutrons should have definite directionality along the surface. This fact will lead to error in the calculations (with the assumption of isotropy) of the efficiency of the 4π-counter (Fig. 2a), and consequently, to inaccuracy in the estimate of the energy of the heated neutrons.

Clarification of the situation on this question will be facilitated by the observation and measurement of the thickness of the hydrogen-containing film by other independent methods, e.g., observation of the production of UCN from thermal neutrons in surface films (it seems that the most desirable arrangement of such an experiment is possible by the technique described in Ref. 12), use of resonance in the reaction $N^{15}(p,\gamma)O^{16}$,[33] etc.

5. Also of interest are experiments on confinement of UCN in vessels with wall surfaces that are clean, or at least not covered by a hydrogen-containing film. We can cite certain proposed variants of the practical realization of such "clean" vessels.

a) Construction of vessels using a supervacuum ~10^{-11}–10^{-12}. Such a vacuum is necessary in order that a surface, one made clean in some way, does not become covered by a monolayer of hydrogen in a time $\tau \sim 10^3$ sec.

b) Magnetic vessels for confining UCN, in which the UCN are reflected from nonmaterial walls—magnetic fields.[34] At the present time such systems are at the launching stage.[35,36]

c) Screening of the hydrogen-containing film by a layer of condensed matter that is also a reflecting wall (e.g., by condensation of oxygen on the surface of a vessel cooled to a temperature ~4.2 K).

To prevent subsequent entry of hydrogen from the uncooled neutron-guide system it is advisable to construct a permanently hermetic vessel for confining the UCN, letting the UCN in and out by moving the whole vessel with a velocity exceeding the threshold velocity for the material of the vessel wall.

The possibility of confining UCN in a "dynamically clean" vessel also seems alluring. The UCN are confined in a vessel and, simultaneously, atoms of a material from which UCN are reflected (e.g., aluminum) are steadily deposited, by vaporization, on the walls, it being necessary that the flux of such atoms exceed the flux of all possible impurities on to the surface. The flux being deposited effectively screens the constantly condensing impurities, so that the UCN will be reflected only from a freshly prepared layer of the material being deposited. (In an ordinary vacuum ~10^{-5}–10^{-6} Torr the rate of condensation of atoms of the material being vaporized should ensure a rate of increase of the thickness of ~10 Å per second.)

6. The potentialities of the technique used to detect the heated neutrons make it possible, with some modernization of the method, to perform measurements down to the heated-neutron fluxes corresponding to confinement times $\tau \sim 10^3$ sec and longer. For this it is necessary:

a) to increase further (by a factor of about 2) the thickness of the neutron shield of the 4π-counter;

b) to improve the energy resolution of the 4π-counter and further constrict the amplitude window corresponding to the peak at $E \sim 0.764$ MeV in the spectrum of the neutrons from the reaction $He^3(n,p)T$;

c) to introduce a system of cathode grids in the 4π-counter, enabling us to make it considerably less sensitive to the background from the natural α-activity of the constructional materials of the counter casing;

d) to increase artificially the number of collisions in the vessel by introducing into it thin plates of the vessel-wall material being tested;

e) to increase the size of the vessel for confinement of the UCN;

f) to use more-intense UCN fluxes; at the present time there already exist UCN fluxes[37] fifty times greater than that used in the present work.

7. The interpretation of the spectra of inelastically scattered neutrons is substantially simplified in the case of UCN, since the initial neutron momentum can be assumed to be practically equal to zero. Such spectra contain information on the dynamics and bonding of atoms in surface films and artificially condensed films. At the present time preparations are being made

for an experiment to measure the spectra of neutrons scattered inelastically by surfaces of different materials by the method of varying the efficiency of the surrounding heated-neutron detection system.

CONCLUSION

Thus, after a long period of confusion about the reason for the anomalously short confinement time for UCN, at least the route by which the UCN principally leave the vessels has become known, namely, by heating of the UCN, in all probability in the hydrogen-containing films that cover the vessel walls. The directions for further research have been significantly narrowed. The pessimism concerning the practical realizability of long confinement times that was induced by postulates about the existence of some insuperable fundamental mechanism of escape of UCN from the vessels has passed.

It is possible that "clean vessels" will increase significantly the confinement time of a neutron gas. The potentialities of the fundamental experiments with the use of UCN under preparation (the search for violation of T-parity, and the determination of the free-neutron lifetime) will be thereby substantially expanded. Clean vessels make it possible to realize in practice the proposal for the production in vessels of the average UCN density (up to 10^3 times greater than that attainable at the present time) corresponding to the peak value of the neutron flux in a pulse when a pulsed source of neutrons is used.[38]

The spectroscopy of inelastically scattered UCN may also be important in its own right.

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In conclusion we note that a proposal to set up an analogous experiment was made back in 1970 by F. L. Shapiro.

[1] Institut Laue-Langevin, Grenoble, France.

[2] By ultracold neutrons we mean neutrons with energy $E_{\rm UCN} \sim 0-10^{-7}$ eV, which, owing to their unique ability to experience total reflection from the walls at all angles of incidence, can be confined in closed vessels; $E_{\rm UCN} \le 2\pi\hbar Nb/m$, where m is the neutron mass, N is the number of nuclei per unit volume, and b is the coherent scattering length for the scattering of a neutron by nuclei of the wall material.

[3] The correctness of applying the theory to materials with a large absorption cross-section has been demonstrated by Groshev *et al.*[5]; however, in this case, the theory gives an accurate prediction only of the much shorter confinement times but does not reveal the causes of the limitations of the much longer confinement times attainable in other experiments.

[4] This was suggested by V. K. Ignatovich.

[5] The considerable increase (~8-fold) in the number of UCN accumulated in one cycle is expalined by the fact that all the following experiments were transferred to the more powerful UCN source described in Ref. 11. It was found to be sufficient to use this source at intensities well below its capacity; therefore, to preserve the convertor it was moved to a distance ~12 cm from the surface of the active zone of the reactor.

[6] This factor (~0.6) was determined as the ratio of the intensities of detection by the 4π-counter of UCN scattered inelastically from a thin polyethylene filament in two positions inside the vessel: stretched along the whole length of the vessel, along the axis, and (using the same filament) crumpled into a loose ball and placed at the center of the vessel.

[7] In principle, an analogous effect could also be induced by heating, in the vessel itself, of the UCN leaking through possible gaps in the closed entrance shutter; however, opening the exit shutter did not change the intensity of detection by the 4π-counter, despite the fact that the density of UCN in the vessel was then reduced practically to zero.

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Interaction of classical Yang–Mills charges and the problem of quark confinement

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Equations and boundary conditions are obtained for the field produced by two point Yang–Mills charges at rest. A nontrivial property of this static system is the existence of a magnetic field. The connection between this model and the problem of quark confinement is discussed.

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It is well known that the classical solution for the field of a point Yang–Mills charge reduces to the ordinary Coulomb form, despite the formal nonlinearity of the equations. It is helpful to establish why this happens. We write down the equations of the Yang–Mills field for the case when its source has only a time component:

$$(\delta^{\alpha\gamma}\partial_n - g\varepsilon^{\alpha\beta\gamma}b_n{}^{\beta})(\partial_n b_0{}^{\gamma} + \partial_0 b_n{}^{\gamma} + g\varepsilon^{\gamma\delta\epsilon}b_0{}^{\delta}b_n{}^{\epsilon}) = \rho^{\alpha}, \tag{1}$$

$$\begin{gathered}(\delta^{\alpha\gamma}\partial_0 + g\varepsilon^{\alpha\beta\gamma}b_0{}^{\beta})(\partial_n b_0{}^{\gamma} + \partial_0 b_n{}^{\gamma} + g\varepsilon^{\gamma\delta\epsilon}b_0{}^{\delta}b_n{}^{\epsilon}) \\ + (\delta^{\alpha\gamma}\partial_m - g\varepsilon^{\alpha\beta\gamma}b_m{}^{\beta})(\partial_n b_m{}^{\gamma} - \partial_m b_n{}^{\gamma} + g\varepsilon^{\gamma\delta\epsilon}b_m{}^{\delta}b_n{}^{\epsilon}) = 0.\end{gathered} \tag{2}$$

All the terms on the left-hand side of the time equation (1) except Δb_0^{α} contain the spatial components of the vector potential b_n^{α}. In the spatial equation (2) in the static case, the only term which does not vanish when $b_n^{\alpha}=0$ has the form $g\epsilon^{\alpha\beta\gamma}b_0^{\beta}\partial_n b_0^{\gamma}$. It is therefore clear that if the direction of the field b_0^{α} in the isotopic space does not depend on the coordinates (and this is obviously the situation in the case of a single charge when $\rho^{\alpha} = gt^{\alpha}\delta(\mathbf{r})$), this term vanishes, so that $b_n^{\alpha}=0$ serves as a solution of Eq. (2). Simultaneously, Eq. (1) for b_0^{α} reduces to the ordinary Poisson form, and the problem as a whole to the trivial Coulomb problem.

At the first glance, it would seem from this to be an inescapable conclusion that to obtain nontrivial static

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