Storage of ultracold neutrons in a vessel long enough for β decay

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Cooling a hermetically sealed aluminum vessel to 80 K lowers the probability for the loss of ultracold neutrons to a level near the theoretical level. The additional loss in aluminum vessels is shown to be caused by a heating of the ultracold neutrons, for which the probability depends strongly on the temperature. A "clean" vessel in which ultracold neutrons can be stored for a time equal to their lifetime with respect to β decay can be produced by freezing heavy ice on the surface of an aluminum vessel.

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The additional leakage of ultracold neutrons from aluminum vessels can be effectively reduced to a level four or five times the theoretical level by heating the vessel in a vacuum or oxygen. Cleaning the surface by means of a gas discharge has made it possible to reduce the probability for the loss of ultracold neutrons in an aluminum vessel to a level differing from the theoretical level by a factor of two.[2] The probability for the residual additional leakage of ultracold neutrons depends significantly on the wall temperature of the vessel over the interval 300–800 K (Ref. 3).

Together, these facts indicate that the most probable cause of the leakage is heating by hydrogen on the surface of the walls and in a surface layer. If this hypothesis is correct, the probability for heating of ultracold neutrons should be reduced sharply by cooling the vessels. The heating probability should also be reduced by freezing on the

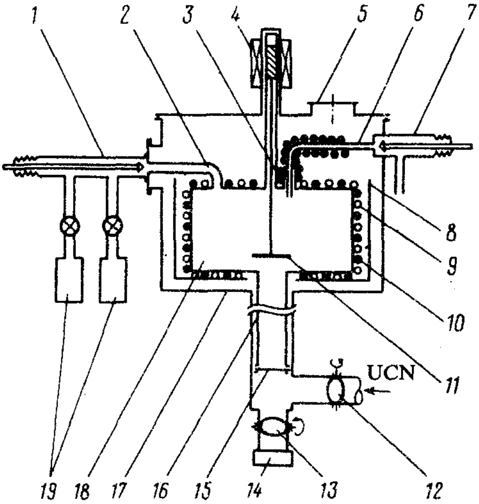

FIG. 1. The experimental apparatus. 1,7—valves; 2—pipe; 3,9—heaters; 4—solenoid; 5—pumping pipe; 6—tube; 8—screen; 10—cooling tubes; 11–13—slide valves; 14—ultracold-neutron detector; 15—aluminum foil; 16—neutron duct; 17—vacuum chamber; 18—storage vessel; 19—vacuum pumps.

walls of the cooled vessel a substance which has a high boundary velocity and a small inelastic cross section (heavy water, for example).[4–6]

To test these possibilities for reducing the additional leakage of ultracold neutrons we used the apparatus shown schematically in Fig. 1. The ultracold neutrons are stored in a hermetically sealed aluminum vessel 18, which is 52 cm in diameter and 28 cm high. The vessel is inside a vacuum chamber 17, which is pumped through branch pipe 5 to $\sim 10^{-4}$ Torr by a diffusion pump. On the outer surface of the vessel there are electric coils 9 and tubes (10) for cooling by liquid nitrogen. The vessel is filled with neutrons through duct 16, made of stainless steel. The ultracold neutrons enter the neutron duct through gate 12 and aluminum membrane 15, positioned at the lower end of the neutron duct. The neutrons are trapped in the vessel by disk valve 11, controlled by solenoid 4. The ultracold neutrons in the vessel are detected by gas-filled proportional detector 14.

The storage vessel is pumped down to 10^{-6} Torr by adsorption and magnetic-discharge pumps through pipe 2, which is hermetically closed by valve 1. Tube 6 with heater 3 is used to admit heavy-water vapor into the vessel. After the vapor is admitted into the volume of the vessel, this tube is hermetically sealed by valve 7.

The total probability for the leakage of ultracold neutrons from the vessel can be written

$$\lambda = \lambda_d + \lambda_t + \lambda_s,$$

where $\lambda_d = \tau_d^{-1}, \tau_d = 877$ s is the lifetime of the neutron with respect to β decay,[7]

$$\lambda_t = (\eta g / \mathrm{v}_b)\left[1 + \left(0.3 + 0.4\frac{\mathrm{v}_b^2}{Rg}\right)\left(\frac{\mathrm{v}}{\mathrm{v}_b}\right)^2\right]$$

is the theoretical probability for loss due to inelastic processes, $\eta = K(\sigma_a + \sigma_{\text{in}})/4\pi b_{\text{coh}}$, K is the wave number, σ_a is the capture cross section, σ_{in} is the cross section for inelastic scattering, b_{coh} is the coherent-scattering length, R is the radius of the vessel, g is the acceleration due to gravity, $v_b = 3.2$ m/s is the boundary velocity of aluminum, v is the velocity of the ultracold neutrons at the bottom of the vessel, and λ_s is the probability for additional leakage of ultracold neutrons.

The vessel was raised above the neutron duct a distance calculated to make the average velocity of the ultracold neutrons at the bottom of the vessel equal to 2m/s. The values of the parameter η for aluminum at 300 and 80 K are 0.21×10^{-4} and 0.14×10^{-4}, respectively. When the additional leakage of ultracold neutrons is completely suppressed, the total loss probability λ should be 1.26×10^{-3} s^{-1} and 1.22×10^{-3} s^{-1} at 300 and 80 K, and the corresponding storage times should be 790 and 820 s.

After the vessel was etched in NaOH, the ultracold-neutron storage time was 460 ± 30 s at 300 K. The storage time was determined with allowance for the escape of ultracold neutrons through the slit in the disk valve, determined experimentally. When the vessel was cooled to 80 K the storage time rose to 790 ± 100 s, corresponding to $\lambda = (1.26 \pm 0.2)\times10^{-3}$ s^{-1}. The value found for λ is, within the experimental error, $\lambda = \lambda_d + \lambda_t = 1.22\times10^{-3}$ s^{-1}. This result tells us that λ_s falls off sharply with decreasing vessel temperature.

In an effort to reduce the amount of hydrogenous impurities on the surface of the vessel, we heated the vessel for 3 h at 750 K. During the heating, oxygen was continuously pumped through the vessel at ~0.1 Torr. After this procedure, the ultracold-neutron storage time at 300 K turned out to be 670 ± 60 s, and λ was $(1.49 \pm 0.14)\times10^{-3}$ s^{-1}. Cooling the baked vessel to 80 K increased the storage time to 840 ± 100 s, which corresponds to $\lambda = (1.18 \pm 0.14)\times10^{-3}$ s^{-1}. The cooling of a vessel which had been subjected to both chemical etching and baking in oxygen thus reduced the probability for the loss of ultracold neutrons, λ, to the theoretical level. Adopting as a criterion the error in the determination of λ, we may assert that if an additional leakage remains after the cooling of the vessel its probability is $\lambda_s \ll \lambda_t$.

If the additional leakage from aluminum vessels results from their heating by

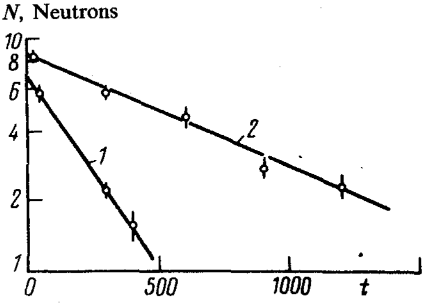

FIG. 2. Time dependence of the number of neutrons remaining in the vessel. 1—In an aluminum vessel at 300 K after etching; 2—in an aluminum vessel subjected to an oxygen treatment with frozen walls of heavy ice.

surface hydrogen, the freezing of heavy water on the surface of a vessel should result in a layer of heavy ice which screens out the hydrogen. In a vessel with walls of heavy ice formed in this manner the loss probability is $\lambda_t = 6\times10^{-5}\ \mathrm{s}^{-1}$ at 80 K; i.e., the ultracold-neutron storage time should be essentially equal to the neutron lifetime. To test this possibility, we froze a layer of heavy ice ~2000 Å thick on the surface of the vessel. Before the freezing was carried out, the storage time in the vessel (after etching in NaOH) was 250 s at 300 K (curve 1 in Fig. 2). After the freezing of the ice, the storage time rose to 890 ± 90 s. When the vessel was heated to 300 K, the storage time returned to 250 s. Freezing of ice was also carried out on the surface of a vessel which had been baked in oxygen; the resulting storage time was 950 ± 60 s (curve 2 in Fig. 2).

The results of this experiment show that the freezing of the heavy ice screens out the surface impurities. The apparent reason why no freezing effect was observed in Refs. 4–6 is that the frozen layer of heavy water has a low boundary energy because of its "porosity," and the condition for total reflection from it is satisfied for only the low-velocity ultracold neutrons used in the present experiments.

On the whole, these results prove conclusively that the primary reason for the additional leakage of ultracold neutrons from aluminum vessels is the heating of the neutrons, whose probability depends strongly on the temperature. When the vessel is cooled to 80 K, the total loss probability drops to the level predicted theoretically. This experiment on the storage of ultracold neutrons in a "clean" vessel, with walls of heavy ice, shows that it is possible in principle to store neutrons for a time sufficient for their β decay. This result revives the possibility (recently in doubt) that ultracold neutrons can be used for several fundamental experiments.

[1] Yu. Yu. Kosvintsev, Yu. A. Kushnir, V. I. Morozov, and G. I. Terekhov, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 257 (1980) [JETP Lett. **31**, 236 (1980)].

[2] W. Mampe, P. Ageron, and R. Gaehier, Z. Phys. **B45**, 1 (1981).

[3] Yu. Yu. Kosvintsev, Yu. A. Kushnir, and V. I. Morozov, Zh. Eksp. Teor. Fiz. **77**, 1277 (1979) [Sov. Phys. JETP **50**, 642 (1979)].

[4] Yu. Yu. Kosvintsev, Yu. A. Kushnir, V. I. Morozov *et al.*, Preprint R3-80-91, JINR, Dubna, 1980.

[5] V. P. Alfimenkov, A. D. Stoĭka, and A. V. Strelkov, JINR Report R3-80-761, Dubna, 1980.

[6] A. A. Akunets, A. V. Antonov, O. F. Galkin *et al.*, Kratkie Soobshcheniya po Fizike **1**, 25 (1982).

[7] L. N. Bondarenko, V. V. Kurguzov, Yu. A. Prokop'ev, E. V. Rogov, and P. E. Spivak, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 328 (1978) [JETP Lett. **28**, 303 (1978)].

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