Measuring neutron lifetime by storing ultracold neutrons and detecting inelastically scattered neutrons

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The lifetime of the neutron has been measured by storing ultracold neutrons and simultaneously detecting neutrons scattered inelastically by the vessel wall. The result is $\tau_n = 882.6 \pm 2.7$ s.

The problem of measuring the lifetime of the neutron has usually been approached either by a beam method or by a method involving the storage of ultracold neutrons. When the latter approach is taken, it has been customary to carry out two or more experiments, in which the neutrons are stored in vessels in which neutrons collide with the wall at different frequencies.[1-5] One then calculates the ratio (ξ) of the probabilities for the loss of the neutrons in interactions with the walls of vessels differing in collision frequency. From the combined data on the typical storage times and the values of ξ, one determines τ_n. The largest error in the measurement of τ_n by this method is a systematic error, stemming from the circumstance that the ratio ξ is found by calculation. In calculations of this ratio it is customary to use certain assumptions or hypotheses whose experimental justification is not a trivial matter. For example, it may be assumed that the surface qualities of the vessels are identical, that the dependence of the loss coefficient on the velocity of the neutrons conforms to a theoretical law, or that the angular distribution of the neutron flux in the vessels is isotropic.

In the present letter we are describing a new method for measuring τ_n. This method is based on the storage of ultracold neutrons in vessels and the simultaneous detection of the neutrons which have escaped from the vessels in the course of inelastic interactions with the walls. A distinctive feature of this method is that the ratio ξ is determined experimentally, so the procedure for measuring τ_n reduces to the measurement of simply relative quantities.

When ultracold neutrons are stored in a vessel, the number of neutrons, $N(t)$, is known to fall off with the time t in accordance with $N(t) = N(0)\exp(-\lambda_{t1}t)$, where $\lambda_{t1} = \lambda_n + \lambda_1$ is the total probability for the loss of ultracold neutrons per unit time, averaged over the interval (0–t), $\lambda_n = \tau_n^{-1}$ is the probability for neutron decay, and λ_1 is the probability for losses in the course of collisions with the vessel wall. The quantity λ_1 is the sum of the probabilities for loss by the capture mechanism, λ_c, and by inelastic scattering: $\lambda_1 = \lambda_{c1} + \lambda_{ie1} = \lambda_{ie1}(1 + \lambda_{c1}/\lambda_{ie1})$. In experiments on the storage of ultracold neutrons one can determine λ_{t1} by measuring the initial number of neutrons in the vessel, $N(0)$, and by measuring the number of neutrons which are still in the vessel at some time t_1. If the vessel used experimentally is surrounded by thermal-neutron detectors capable of detecting ultracold neutrons which have been scattered inelastically (heated) by the vessel wall, then while the neutrons are stored one can determine the probability for leakage of ultracold neutrons by the inelastic-scattering mechanism, λ_{ie1}, for the given vessel:

$$\lambda_{ie1}=\frac{J_1\lambda_{t1}\epsilon}{[N_1(0)-N_1(t_1)]\epsilon_{th}}. \tag{1}$$

Here J_1 is the count of heated neutrons over the time interval $(0\text{–}t_1)$, $N(0)$ and $N(t_1)$ are the numbers of neutrons which are detected by the ultracold-neutron detector in the vessel for the beginning and final storage times, respectively, ϵ_{th} is the efficiency with which the heated neutrons are detected, and ϵ is the efficiency with which the ultracold neutrons stored in the vessel are detected. It can be seen from relation (1) that the quantity λ_{ie1} is determined within an unknown ratio of efficiencies ϵ/ϵ_{th}. It becomes possible to measure λ_n if the probability for the loss of ultracold neutrons as they interact with the wall in the vessel is altered in some controllable fashion. For this purpose, it is necessary to introduce an auxiliary surface in the vessel. This surface must be made of the same material as the vessel wall, so that ϵ, ϵ_{th}, and the ratio λ_c/λ_{ie} remain the same. By storing ultracold neutrons in a vessel with an auxiliary surface, one can find the total leakage probability λ_{t2} and the value

$$\lambda_{ie2}=\frac{J_2\lambda_{t2}\epsilon}{[N_2(0)-N_2(t_2)]\epsilon_{th}}, \tag{2}$$

where J_2 is the count of thermal neutrons by the external detector over the time interval $(0\text{–}t_2)$, and $N_2(0)$ and $N_1(t_2)$ are the number of ultracold neutrons which are detected by the detector for the initial and final storage times, respectively. It follows from (1) and (2) that the ratio of loss probabilities ξ for a vessel with an auxiliary surface and for a vessel without one can be written

$$\xi=\frac{\lambda_2}{\lambda_1}=\frac{\lambda_{ie2}}{\lambda_{ie1}}=\frac{J_2\lambda_{t2}[N_1(0)-N_1(t_1)]}{J_1\lambda_{t1}[N_2(0)-N_2(t_2)]}. \tag{3}$$

If λ_{t1},λ_{t2}, and ξ are known, the decay probability can be found from

$$\lambda_n=\frac{\lambda_{t1}\xi-\lambda_{t2}}{\xi-1}. \tag{4}$$

The method described above has been implemented in an intense beam of ultracold neutrons at a reactor of the Laue–Langevin Institute (in Grenoble, France). The simple version of the apparatus, shown schematically in Fig. 1, was used. The ultracold neutrons were accumulated and stored in a cylindrical vessel 27 cm in diameter and 106 cm high. The inner surface of this stainless-steel vessel was coated with a layer of hydrogen-free Formblin oil. The ultracold neutrons entered the vessel through inlet gates along a vertical neutron guide with an aluminum gate and were blocked by a plate-shaped gate at the bottom of the vessel. The initial number of ultracold neutrons in the vessel, $N(0)$, and the final number, $N(t)$, were detected by a gas proportional detector containing ^{3}He. A polyethylene absorber of ultracold neutrons was placed on the upper flange of the vessel in order to impose a limit on the energy spectrum of the neutrons which were stored. The vessel was hermetically sealed, pumped down to

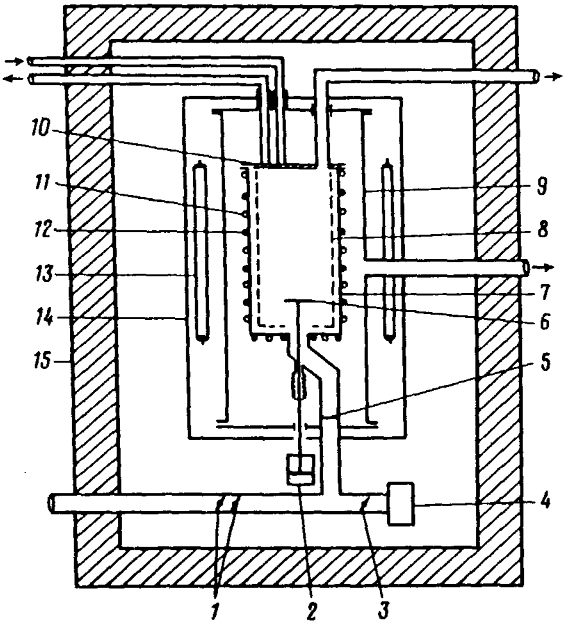

FIG. 1. Experimental layout. *1*—Entrace gates of the guide for the ultracold neutrons; *2*—mechanism which controls the plate-shaped inlet/outlet gate *6* of the storage vessel; *3*—gate of the detector of ultracold neutrons; *4*—the detector of the ultracold neutrons; *5*—thin (0.1-mm) aluminum diaphragm which separates the high-vacuum chamber of the storage vessel from the neutron guides; *6*—plate-shaped gate; *7*—storage vessel; *8*—auxiliary surface; *9*—outer vacuum jacket of apparatus; *10*—scatterer which removes "supercritical" ultracold neutrons from the spectrum; *11*—coiled tube for cooling the storage vessel; *12*—heater for the storage vessel; *13*—detectors of thermal neutrons which result from inelastic scattering of ultracold neutrons by the surface of the storage vessel; *14*—cadmium shielding.

$(2\text{–}3)\times 10^{-6}$ torr by a turbomolecular pump. The vessel temperature was varied from $+25$ °C to -55 °C by pumping a coolant through the coil on the surface of the vessel.

To alter the probability for the loss of ultracold neutrons in the volume of the vessel, we introduced an additional surface, made of stainless steel with a thickness of 150 μm. This surface was formed by a thin-walled cylindrical vessel coated on both sides with a layer of Formblin oil. The diameter of this vessel was 25 cm, and its height 105 cm. There was a system of apertures at the lateral surface and at the bottom. The vessel was placed inside an aluminum vacuum jacket, which was evacuated to 5×10^{-5} torr. The detector of heated neutrons consisted of 28 cylindrical ^{3}He neutron counters mounted vertically on the lateral surface of the vessel. The length of each counter was 1 m, and its diameter 3 cm. The detection efficiency in an isotropic neutron flux was 78%. The apparatus was covered by a cadmium sheath and boron-loaded polyethylene to shield the detector from the external neutron field of the reactor.

In the course of the experiment, 20 series of measurements of λ_n were carried out, for various storage times and for three vessel temperatures ($+20$, -12, and -55 °C). The average number of stored neutrons at the beginning of the storage was (35–45)

TABLE I. Summary table of corrections.

N	+20	−12	−55	Mean
0	880,16 ± 6,89	881,27 ± 1,67	891,99 ± 3,98	882,08 ± 1,50
1	0,00 ± 0,02	−0,16 ± 0,02	−8,78 ± 0,88	−0,73 ± 0,36
2	−6,36 ± 2,01	−2,24 ± 1,30	−2,38 ± 1,19	−2,43 ± 1,32
3	−1,48 ± 0,74	−0,51 ± 0,26	−0,32 ± 0,16	−0,54 ± 0,27
4	+6,12 ± 3,60	+2,85 ± 1,82	+0,13 ± 0,29	+2,62 ± 1,69
5	+0,72 ± 0,36	−0,21 ± 0,11	−0,58 ± 0,29	−0,21 ± 0,11
6	+3,09 ± 1,55	+0,74 ± 0,37	+0,37 ± 0,19	+0,80 ± 0,40
7	+0,23 ± 0,05	+0,85 ± 0,24	+2,01 ± 0,76	+0,96 ± 0,22
S	+2,32 ± 4,48	+1,32 ± 2,30	−9,55 ± 1,73	+0,48 ± 2,24
R	882,48 ± 8,22	882,59 ± 2,84	882,44 ± 4,34	882,56 ± 2,70

Here N is the correction number; the $N=0$ row shows uncorrected values of τ_n; the R row shows the values of τ_n after the corrections; and the S row shows the weighted-average corrections.

$\times 10^3$. The typical storage times in a vessel without an auxiliary surface, $\tau_1 = \lambda_{t1}^{-1}$, were 700, 770, and 820 s at the vessel temperatures of 25, −12, and −55 °C. In each separate measurement of λ_n, we determined (at a fixed temperature) λ_{t1}, λ_{t2}, and the corresponding values of λ_{ie1} and λ_{ie2}, which were specified in relative form under the assumption of a ratio $\epsilon/\epsilon_{th} = 1$. Figure 2 illustrates the results with the relationship between the values of $\lambda_{t1}, \lambda_{t2}$ and $\lambda_{ie1}, \lambda_{ie2}$ found in three series of measurements at various temperatures.

A preliminary report[6] stated a result of $\tau_n = 883.2 \pm 2.9$ s. Several methodological errors and corrections to λ_n found directly from Eqs. (1)–(4) have been taken into account more accurately in the determination of the final value. Here are the primary sources of methodological errors in these measurements.

1. Neutrons leak through the slit of the plate-shaped gate. The corresponding correction to λ_n was found experimentally by detecting the neutrons which escaped through the slit by a detector of ultracold neutrons.

2. There is a weak, linear time dependence of λ_{ie}. This dependence arises because the ultracold neutrons stored in the vessel have a fairly wide energy spectrum (from 0 to 10.5×10^{-8} eV). To determine this error experimentally, we studied the count rate of the heated-neutron detector as a function of the time. A correction which altered the value of λ_n was then made to the result of the ξ measurements.

3. As the neutrons are being stored, the efficiency ϵ_{th} becomes a weak function of the time, because of the progressive softening of the neutron spectrum in the vessel. This dependence is different for the vessels with and without the auxiliary surface. The effects of these factors on the measured value of ξ was determined by calculations for various model spectra of ultracold neutrons, with an analysis of their time evolution.

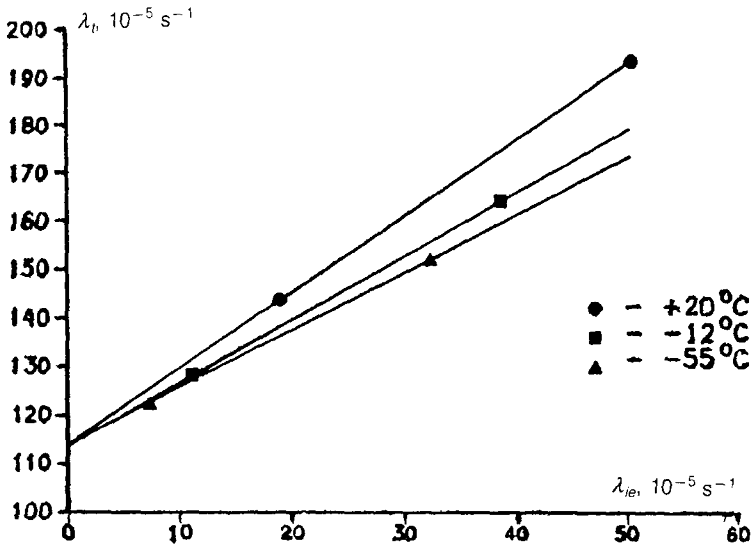

FIG. 2. Total loss probability versus the probability for inelastic scattering.

4. There is a small difference between the value of ϵ_{th} during the detection of heated ultracold neutrons at the beginning of the storage for vessels with and without the auxiliary surface. This difference stems primarily from a difference in the spatial position of the lateral surface of the vessel and of the auxiliary surface. To some extent, a difference in ϵ_{th} values also arises because of an additional absorption of heated neutrons in the material of the auxiliary surface. This correction to λ_n for this difference was made by calculations which incorporated the experimental geometry.

5. The efficiency (ϵ) at which the numbers of neutrons in the vessel $[N(0)$ and $N(t)]$ are detected varies, because the spectrum of ultracold neutrons transforms (becoming softer) as time elapses. The efficiency with which the number $N(0)$ is detected turns out to be slightly lower than the efficiency for $N(t)$. As a result, there are errors in the determination of both λ_{t1} and λ_{t2} (on the one hand) and ξ (on the other). A correction to λ_n was made in this case by calculations based on experimental data and the time scales for the escape of ultracold neutrons from the vessel and the time dependence of the count rates of the heated-neutron detector.

6. There is some difference between the detection efficiencies ϵ for the vessels with and without the auxiliary surface. This difference arises because of differences in the characteristic storage times in the two measurement configurations and differences in the time over which the neutrons reach the detector. A corresponding correction to λ_n was made to the experimental data on the time scales for storage and escape of ultracold neutrons.

7. There is some deviation from the condition $\lambda_{c1}/\lambda_{ie1}=\lambda_{c2}/\lambda_{ie2}$ because of a difference between the temperature of the vessel wall and the wall of the auxiliary

surface. A correction was made by calculations based on data on the cross sections for the capture and inelastic scattering of neutrons by Formblin oil.

As the result of an analysis of 15 of the 20 series of measurements, and after corrections for the errors listed in paragraphs 1–7 just above, we found the following final value for τ_n:

$$\tau_n = 882.6 \pm 2.7 \text{ s.}$$

Table I shows values of the methodological corrections, along with their errors, to the raw value of τ_n. The scatter within each series was taken into account.

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