Additional neutron lifetime result obtained from ultracold-neutron storage experiments

V. K. Ignatovich

I. M. Frank Neutron Physics Laboratory, Joint Institute of Nuclear Research, 141980 Dubna, Moscow Region, Russia

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It is shown by an analysis of the results of neutron lifetime measurements in JETP Lett. **57**, 82 (1993) that one of the corrections—the correction for leakage from the slit in the gate closing off the vessel storing ultracold neutrons—must be positive. After this sign is reversed and the errors are averaged over the temperatures, the neutron lifetime is found to be $\tau_\beta = 887.6 \pm 2.3$. Although this result is in better agreement with the value currently adopted for τ_β, it is unreliable because the scatter in the values obtained (the possible source for this scatter is not discussed) is almost two orders of magnitude greater than the systematic error indicated by the authors. © *1995 American Institute of Physics.*

It has been repeatedly proclaimed in the literature that it is necessary to measure the neutron lifetime τ_β relative to β-decay with a high degree of accuracy (see, for example, Ref. 2). For this reason, every effort is being made in this direction to decrease the existing error in the value of τ_β to a level of the order of 0.1%.

To demonstrate how difficult it is to perform experiments with ultracold neutrons (UCNs), which nonetheless give the highest accuracy in determining τ_β, it is sufficient to give the results obtained by three competing groups.

The value

$$\tau_\beta = 887.6 \pm 3 \text{ s} \tag{1}$$

was obtained in Ref. 3 (Fig. 1a). The uncertainty is associated mainly with the systematic error arising from the need to introduce a correction for gravity. This error depends on the spectrum[4] and can be decreased either by choosing the required part of the spectrum of confined neutrons or by changing the experimental arrangement.[5]

The result

$$\tau_\beta = 888.4 \pm 2.9 \text{ s} \tag{2}$$

was obtained in Ref. 6 (Fig. 1b). In this work, in addition to a measurement of the storage time, the spectrum of confined neutrons and the change in the spectrum during storage were also measured. This result was refined in a comprehensive study[7] and the lifetime is now

$$\tau_\beta = 888.4 \pm 3.3 \text{ s}. \tag{3}$$

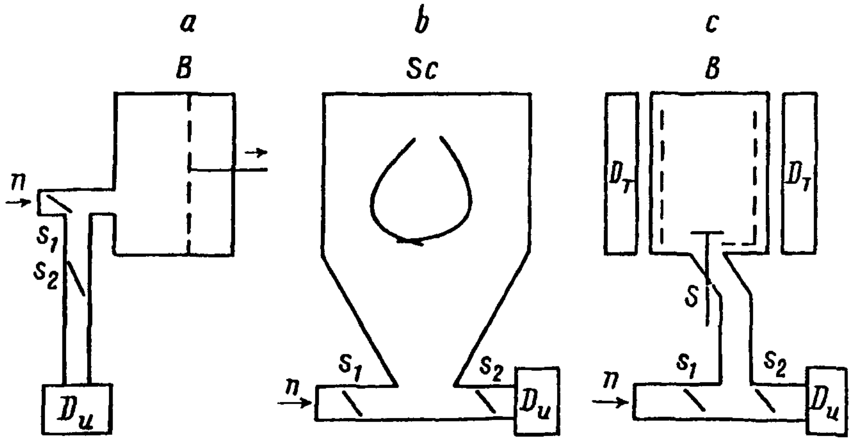

FIG. 1. Three main experimental arrangements for determining the neutron lifetime with the help of storage of ultracold neutrons. In the scheme a with the gate s_2 closed the neutrons n enter the apparatus through the open gate s_1. Then the gate s_1 is closed and the neutrons are stored for a prescribed time in the vessel B. In the scheme b the neutrons fill the vacuum chamber and are stored in the scoop Sc. In the case a the volume in the vessel can be changed by moving the wall represented by the dashed line. In the case c an additional surface, represented by the dashed line, can be introduced into the vessel. After a prescribed time the gate s_2 is opened and the neutrons stored in the vessel are allowed to propagate to the UCN detector D_u. In the case c neutron counters that record the number of UCNs that are heated to thermal energies in collisions with the walls during the storage period are placed around the storage vessel. S — additional plate-shaped gate, trapping the neutrons in the storage vessel.

It was also shown that the systematic error is of the order of 1 s and that the uncertainty is due mainly to the random error.

Finally, the result

$$\tau_\beta = 882.56 \pm 2.7 \text{ s} \qquad (4)$$

was obtained in Ref. 1 (Fig. 1c). We note that the errors in all of these results actually differ only in the second decimal place.

The officially adopted value,[8] averaged over all experiments, including ultracold-neutron experiments, is

$$\tau_\beta = 889.1 \pm 2.1 \text{ s}. \qquad (5)$$

In the present study we obtained a result, different from that given in Ref. 1, on the basis of a deductive[9] analysis of the data presented in Ref. 1 . The new result agrees much better with (5) and is identical to the result (1). It turns out that the measurement error can still be decreased by 0.4 s. Therefore, the results of the measurements in Ref. 1 make it possible to give one more figure:

$$\tau_\beta = 887.6 \pm 2.3 \text{ s}. \qquad (6)$$

This result raises a number of questions that cannot be answered at the present time. For example, why were five of the twenty series of measurements (or 25%) rejected in the analysis of the results?

The analysis is based on a study of a table which summarizes the corrections presented in Ref. 1. But before analyzing this table, we recall briefly how the experiment was performed and how the value of τ_β was extracted from it.

In the experiment two storage times were measured: τ_1 with no additional walls and τ_2 with additional walls (dashed lines in Fig. 1c):

$$\frac{1}{\tau_i}=-\frac{1}{t_i}\ln\frac{N_i(t_i)}{N_i(0)}, \tag{7}$$

where the index $i=1,2$ characterizes the type of experiment (without and with additional walls, respectively), $N(0)$ is the number of accumulated neutrons, and $N(t_i)$ is the number of neutrons remaining in the vessel after the ultracold neutrons are held in it for a time t_i.

To obtain τ_β, the values of τ_a and τ_{in}, which characterize the absorption and inelastic scattering in the walls, respectively, must be eliminated from τ_i. They are related to τ_i by the relations

$$\frac{1}{\tau_i}=\frac{1}{\tau_\beta}+\frac{1}{\tau_{i,a}}+\frac{1}{\tau_{i,in}}. \tag{8}$$

The times τ_{in} and τ_a, which are proportional to the area of the inner surface of the vessel walls, are eliminated as follows:

During the time that the neutrons are stored in the trap, the thermal-neutron detectors, which are placed on the outside of the trap (D_T in Fig. 1c), record the thermal neutrons which are produced by the heating of the ultracold neutrons in the walls. The total number $N_{i,in}$ of these neutrons recorded over the storage time t_i is assumed to be

$$N_{i,in}=\epsilon_{in}\frac{\tau_i}{\tau_{i,in}}[N_i(0)-N_i(t_i)], \tag{9}$$

where ϵ_{in} is the efficiency of the thermal-neutron detectors.

The ratio $r=N_{1,in}/N_{2,in}$ makes it possible to determine the quantity

$$\xi=\tau_{2,in}/\tau_{1,in}$$

with the help of the expression

$$r=\xi\,\frac{\tau_1}{\tau_2}\,\frac{N_1(0)-N_1(t_1)}{N_2(0)-N_2(t_2)}. \tag{10}$$

Here all quantities except ξ are measurable. Knowing ξ, we easily obtain

$$\frac{1}{\tau_\beta}=\frac{1}{1-\xi}\left(\frac{1}{\tau_1}-\xi\frac{1}{\tau_2}\right). \tag{11}$$

To improve the reliability, the experiments were performed at three temperatures: +20, −12, and −55 °C. The number of heated neutrons recorded by the detectors D_T should decrease as the temperature decreases, but the ratio ξ must remain constant.

We now investigate some corrections presented in Table I, which is a fragment taken from the table of corrections in Ref. 1.

TABLE I.

N	+20	−12	−55	Average
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
...	...	...	...	...
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	882.84±4.34	882.56±2.70

In this table the row 0 gives the values of τ_β extracted from the experiment with the help of expression (11), ignoring the corrections, and row 1 gives the corrections for leakage from the slit in the gate S (Fig. 1c) during storage of the ultracold neutrons. The sign of this correction cannot be negative under any conditions.

If leakage through the slit in the gate S occurs together with losses in the walls during storage of ultracold neutrons, then the time extracted using the expression (11) and indicated in the row 0 in Table I is not τ_β but rather a quantity τ'_β that contains the leakage time τ_s through the slit:

$$\frac{1}{\tau'_\beta}=\frac{1}{\tau_\beta}+\frac{1}{\tau_s}. \tag{12}$$

Hence

$$\frac{1}{\tau_\beta}=\frac{1}{\tau'_\beta}-\frac{1}{\tau_s}<\frac{1}{\tau'_\beta}, \tag{13}$$

so that $\tau_\beta>\tau'_\beta$. Therefore, any correction for leakage through the slit, and in the experiment of Ref. 1 it was measured according to the count in the UCN detector D_u, must be positive and not negative. We note that this correction for the leakage through the slit had to be taken into account previously, for example, in the well-known experiments of Ref. 10 to study of the ultracold-neutron anomaly. In Ref. 10, this correction was positive.

In Table II the total correction is given in the row S and the final result at a given temperature is given in row R. If the sign of the leakage correction in row 1 of Table I is changed, then the fragment should look like Table II, from which the result (6) presented above follows.

A surprising and fortunate coincidence, as a result of which the final figure is identical to the figure given in Eq. (1), should be noted.

TABLE II.

N	+20	−12	−55	Average
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
...	...	...	...	...
S	+2.32±4.48	+1.64±2.30	+8.01±1.73	+0.48±2.24
R	882.48±8.22	882.91±2.84	900.00±4.34	887.6±2.28

We note that changing the offset does not change the error, so that all errors in Table II remain the same as in Table I, with the exception of the final value indicated in the right-hand bottom corner of Table II. This is connected with the fact that the method for calculating the final error is different from that used in Ref. 1. It is determined by averaging over all data in the last row of Table II and not as the rms sum of the errors in the average value (upper right-hand corner in Table I) and the average error (last row in the last column).

In other words, if the error at the intersection of row N and column $i+1$ is designated as $\sigma_{N,i}$, then the final error $\sigma_{R,4}=2.28$ presented in Table II is calculated from

$$\sigma_{R,4}=1/\sqrt{\sum_{i=1}^{3} 1/\sigma_{R,i}^2}, \tag{14}$$

while the error $\sigma_{R,4}=2.70$ presented in Table I is obtained from

$$\sigma_{R,4}=\sqrt{\sigma_{0,4}^2+\sigma_{S,4}^2}. \tag{15}$$

In our opinion, Eq. (14) must be used to calculate the error.

Unfortunately, the results of Ref. 1 were not published in a detailed form so as to be able to judge how different corrections were calculated or estimated. The correction for the temperature dependence of the efficiency of the detectors D_T is very important. According to Ref. 1, this correction is equal to -0.32 s. This result, however, contradicts the scatter in the value of τ_β (last row in Table II), which is almost 20 s and could indicate a systematic error.

One source of systematic error could be the assumption that the efficiencies ϵ_{in} in Eq. (9) are the same for storage with and without an additional surface. If the efficiency of the detection of heated neutrons changes when an additional surface is introduced, then in the relations (9) ε_{in} must be replaced by $\varepsilon_{i,in}$:

$$N_{i,in}=\epsilon_{i,in}\frac{\tau_i}{\tau_{i,in}}[N_i(0)-N_i(t_i)], \tag{16}$$

where $\epsilon_{i,in}$ is the efficiency with which the heated neutrons are recorded without $(i=1)$ and with $(i=2)$ such a surface.

Correspondingly, the additional factor $\zeta=\epsilon_{i,in}/\epsilon_{2,in}$ appears in the ratio r (10):

$$r=\zeta\xi\frac{\tau_1}{\tau_2}\frac{N_1(0)-N_1(t_1)}{N_2(0)-N_2(t_2)}. \tag{17}$$

An attempt to eliminate τ_{in} and τ_c from the storage time τ determined with an UCN detector yields the following result:

$$\frac{1}{\tau_1}-\frac{\zeta\xi}{\tau_2}=\frac{1-\zeta\xi}{\tau_\beta}+\frac{1-\zeta}{\tau_{1,in}}+\frac{1-\zeta}{\tau_{1,c}}, \tag{18}$$

i.e., an error proportional to $1-\zeta$ arises.

A correction for the change in the efficiency on introduction of an additional surface is presented in Ref. 1, but the result is only 0.13 s and cannot explain the final temperature scatter of 20 s.

It appears that here a large error can arise for the following reasons. Let the heating of the neutrons in the side walls be described by the time τ_w and assume that these neutrons are recorded by the counters D_T with efficiency ϵ_w. Let the heating in collisions with the bottom be described by the time τ_b and assume that the neutrons are recorded with efficiency ϵ_b. Since the position of the side walls and the bottom of the additional surface with respect to the detectors D_T are different from the positions of the corresponding parts of the main surface, ϵ_w and ϵ_b for the main and additional surfaces are different. Moreover, the neutrons heated on the inner side of the additional surface are scattered on the way to the detector and absorbed inside the additional walls. This is an additional source of the change in the detection efficiency. This is especially important for low temperatures, where the spectrum of heated neutrons becomes softer.

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