A MEASUREMENT OF THE NEUTRON LIFETIME USING THE METHOD OF STORAGE OF ULTRACOLD NEUTRONS AND DETECTION OF INELASTICALLY UP-SCATTERED NEUTRONS

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Abstract

We present the results of our neutron lifetime experiment carried out in 2008-2010 at ILL. Taking into account systematic corrections, we reduce the data of three independent sets of measurements performed with different energy spectra of ultracold neutrons (UCNs) at different temperatures of UCN traps to the averaged neutron lifetime value equal to 880.2(1.2) s.

The experimental installation and the method

Precise measurements of the neutron lifetime are important for elementary particle physics, astrophysics and cosmology [1, 2].Preliminary results, which account for some corrections, are published in conference proceedings [3, 4].

A scheme of the installation is shown in Fig.1. A storage trap inside a double vacuum chamber, which is made of stainless steel, is shaped in a form of two vertical coaxial cylinders that are installed on a double flange. A coiled copper tube is entwined on the external surface of the internal cylinder in order to provide the circulation of liquid coolant, which is supplied from a refrigerating machine. The bottom flange of the chamber has a cavity with the depth of 3.4 cm with a cooling coiled tube in it. This cavity is filled in with liquid fluorine polymer so that the liquid covers the coiled tube.

A feed-through for the UCN guide tube is in the bottom flange. The upper plane of the guide tube is installed higher than the bottom flange by 5.5 cm. A plane UCN shutter could open and close the tube. The neutron guide system includes an input neutron guide with a UCN shutter; the guide is connected to a UCN source. The exit neutron guide is connected to a UCN detector with another shutter at its entrance. The UCN detector is a proportional gas counter filled in with gas mixture containing ^{3}He gas. The interior volume of the chamber is pumped on using a turbo molecular pump down to the residual gas pressure of 10^{-6} - 10^{-5} mbar.

18 thermal neutron SNM-57 counters are fixed outside the chamber; these counters are located in two sections. This detector system measures neutrons, which are scattered inelastically on the walls of the storage trap. The detector shielding is made of cadmium and borated polyethylene; the shielding surrounds the whole set-up.

Measurements are carried out in two geometries of the storage trap; these two options differ from each other by the frequency of UCN collisions with the trap walls arising due to different wall surface area open for UCN. In the geometry no.1 UCN are stored inside the copper cylindrical trap with the diameter of 40 cm and with the height of 95 cm. The bottom is covered with a layer of fluid fluorine polymer; the internal surface of the copper cylinder is covered with a thin layer of such polymer. During the UCN filling interval, UCN enter the trap throughopened shutters (2), (3), as well as throughthe plane shutter (16), while the detectorshutter (18) is closed. In order to restrict the energy of stored UCN from above, the polyethylene disk with the diameter of 35 cm is installed on a fixed height H_d. After completion the time interval t_{fill} = 150 s, the plane shutter (16) and shutter (3) are closed while the detector shutter (18) is opened; thus the cleaning interval starts. During the cleaning interval lasting for t_{clean} = 200 s, UCN energy spectrum is being shaped. Then the polyethylene disk rises up to the height of H_{max} = 95 cm, and the storage interval starts; it continues during the interval t_1 = 60 s. At the end of the storage interval, the plane shutter (16) is opened and stored UCN flow down into the UCN detector during the detection interval t_{reg} = 150 s. Then the filling and cleaning intervals are repeated again, however the UCN storage interval is different t_2 = 960 s. The total UCN loss probability during the storage time interval, is calculated as follows: $\lambda_1 = \frac{1}{t_2 - t_1} \ln \frac{N_1(t_1)}{N_1(t_2)}$, where $N_1(t_1)$ and $N_1(t_2)$ are numbers of detected UCN. In the geometry no.2, the additional surface consisting of 90 copper stripes with the thickness of 100 μm and the width of 15 mm is inserted in the storage trap. Besides, the copper foil ring with the thickness of 100 μm is inserted at the height of 1.4 cm above the trap bottom; an analogous foil is inserted at the height of 1.5 cm above the plane shutter (16). Surfaces of all stripes and both foils are covered with identical fluorine polymer layers. As a result, the total surface exposed for UCN increases by a factor of 3.

The intervals t_{fill}, t_{clean} and t_{reg} in measurements in the geometry no.1 are equal to those in the geometry no.2, while the storage intervals in measurements in the geometry no.2 are shorter by a factor of 3, and are equal accordingly to t_1 = 20 s and t_2 = 320 s. This shortening of the storage intervals is needed in order to provide equal total number of UCN collisions during the storage interval for the two geometries, with the purpose to keep identical UCN energy spectra. The total UCN loss probability during the storage interval is calculated for the geometry no.2 as follows $\lambda_2 = \frac{1}{t_2 - t_1} \ln \frac{N_2(t_1)}{N_2(t_2)}$, where $N_2(t_1)$ and $N_2(t_2)$ are the numbers of detected UCN.

The total UCN loss probabilities are

$$\lambda_1 = \lambda_\beta + \lambda_{l1}, \; \lambda_2 = \lambda_\beta + \lambda_{l2}, \quad (1)$$

where λ_β, λ_{l1}, λ_{l2} are correspondingly the β-decay probability and the loss probabilities via neutron collisions with the walls for the two geometries. As far as the ratio $\xi = \frac{\lambda_{l2}}{\lambda_{l1}}$ is measured, the neutron β-decay probability is calculated as follows:

$$\lambda_\beta = \frac{\xi\lambda_1 - \lambda_2}{\xi - 1} \; . \quad (2)$$

The value of ξ could be measured using count J_1 and J_2 in the thermal neutron detectors during the storage intervals t_1 and t_2 for the geometry no.1 and for the geometry no.2:

$$J_1 = \frac{N_1(t_1) - N_1(t_2)}{\lambda_1} \lambda_{l1} \frac{\varepsilon_{th1}\sigma_{ie}}{\varepsilon_{ucn1}(\sigma_{ie} + \sigma_c)}, \quad (3)$$

$$J_2 = \frac{N_2(t_1) - N_2(t_2)}{\lambda_2} \lambda_{l2} \frac{\varepsilon_{th2}\sigma_{ie}}{\varepsilon_{ucn2}(\sigma_{ie} + \sigma_c)}. \quad (4)$$

Here ε_{ucn1} and ε_{ucn2} are the efficiencies of UCN detection for the geometries no.1 and no.2 respectively, ε_{th1} and ε_{th2} are analogous efficiencies of detection of neutrons inelastically scattered on the trap walls, σ_{ie} is the cross section of neutron inelastic scattering in the wall material, and σ_c is the cross section of neutron capture in the wall material.

If UCN numbers were defined correction-free, if the equalities ε_{ucn1} = ε_{ucn2} and ε_{th1} = ε_{th2} were precise, if no residual gas was present in the trap, if the temperatures of the main surface and that of the additional one were equal, then the ξ-value would be equal to

$$\xi = \xi_0 = \frac{J_2}{J_1}\frac{\lambda_2}{\lambda_1}\frac{N_1(t_1) - N_1(t_2)}{N_2(t_1) - N_2(t_2)}. \qquad (5)$$

The neutron lifetime value defined in Eqs. (1), (2), (5) is called below "uncorrected".

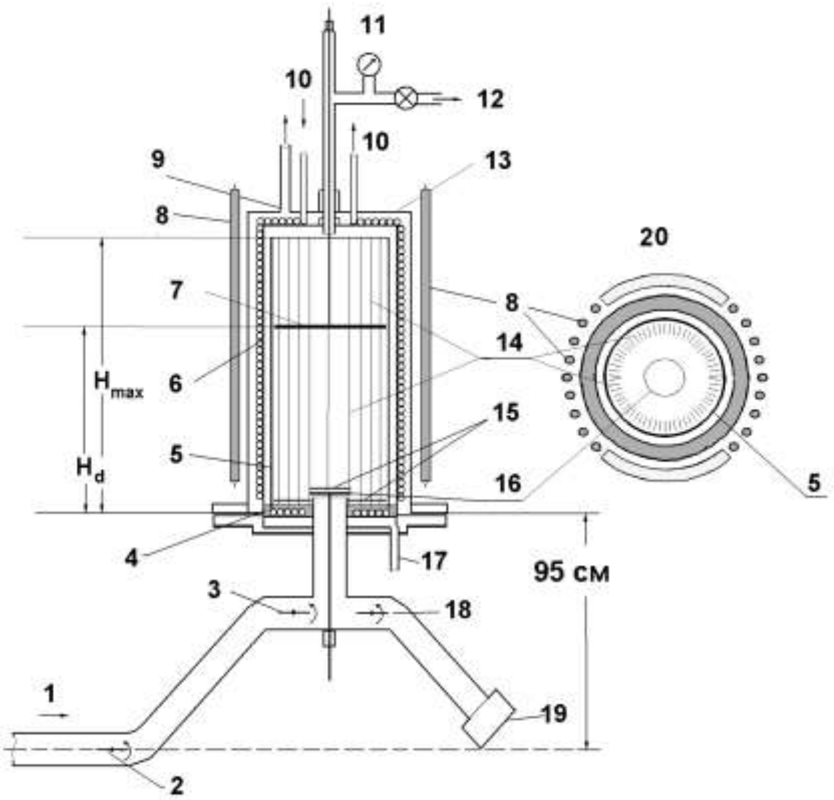

Fig. 1. A scheme of the experimental set-up for the neutron lifetime measurement. 1 - the entrance neutron guide, 2 - the UCN source shutter, 3 - the input shutter, 4 - fluid fluorine polymer, 5 – the copper cylinder, 6 - the cooling coil, 7 – the polyethylene disk, 8 - thermal neutron counters, 9 - the pumping tube, 10 - the cooler tube, 11 - the valve of the He filling line, 12 - the tube of the high-vacuum line, 13 - the vacuum set-up chamber, 14 – copper stripes, 15 – the additional surface above the trap bottom and the entrance shutter, 16 – the entrance plane shutter, 17 – the pumping tube for the chamber bottom, 18 - the detector shutter, 19 - the UCN detector, 20 - a horizontal cross section of the set-up with blocks of polyethylene reflector for thermal neutrons.

The measurement results

Fig.2 shows the number of UCN in the trap as a function of the height H_d of the polyethylene disk. For each height H_d of the polyethylene disk in the geometry no.1, the trap is filled in following a usual procedure. Most neutrons with the large enough maximum raising height in the gravitational field $H>H_d$ leave the trap during 200 s via their inelastic scattering in the disk material. The fraction of residual UCN with the maximum raising height $H>H_d$ is smaller than (1 - 2) % by the end of the cleaning interval; at this moment UCN are released to the UCN detector.

For the present neutron lifetime experiment, two options for the absorber height are used: H_d= 55 cm and H_d = 75 cm. The number of UCN in the trap is equal respectively to ≈ $7.0\cdot10^4$ and ≈ $13.7\cdot10^4$. Small heating of UCN [5 -8] during the storage interval occurred with the probability of $1.3\cdot10^{-5}$ per one wall reflection and populated the neutron spectrum at heights $H>H_d$; the typical energy difference (H - H_d) was lower than (15 - 20) cm. To decrease systematic effects resulting from this small UCN heating on UCN storage times, we raised up the polyethylene disk to the height of $H_{\max}$ = 95 cm when the storage interval starts.

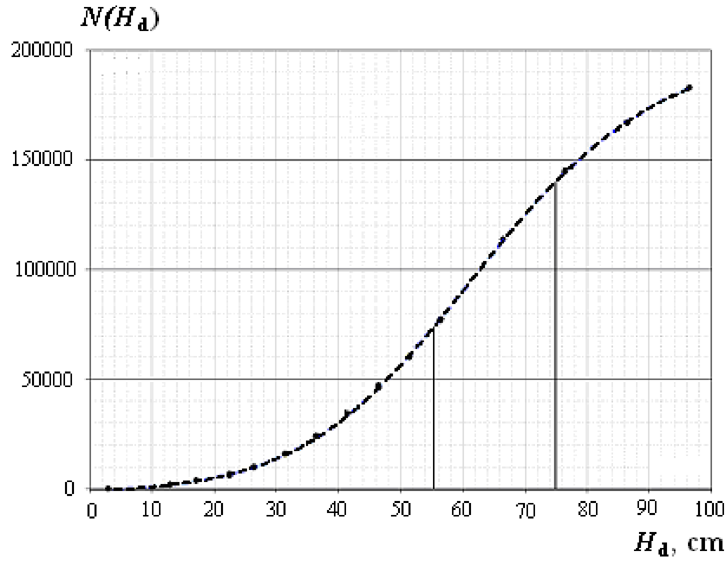

Fig.2. The number of UCN in the trap as a function of height H_d of the polyethylene disk.

We performed three independent neutron lifetime measurements under different experimental conditions that resulted to the following uncorrected values of τ_β:

1. H_d = 55 neV, t = + 23° C; $884.15 \pm 2.10_{st}$
2. H_d = 75 neV, t = + 23° C; $884.30 \pm 0.95_{st}$
3. H_d = 75 neV, t = - 26° C; $883.60 \pm 0.95_{st}$

Systematic corrections

The main systematic correction arises from the partial loss of count rate in the UCN detector; it shifts the values of probabilities λ_{l1}, λ_{l2} as well as the value of ξ_0. During the detection interval, measured count rate in the UCN detector $J_m(t)$ rises up to the value of ~ 10^4 s^{-1}, then it decreases exponentially down with a typical emptying time constant of (11-14) s. The loss in the count rate is caused by a non-zero dead time τ_d of the electronic units. The true value of the count rate would be equal to $J = J_m(1+J_m\tau_d)$. The value of the dead time τ_d of the electronic units is measured forJ_m(t) in the range of (1000-20000) s^{-1}; it is equal to $\tau_d = (2.7 \pm 0.1)\cdot10^{-6}$ s . All measured values of $N_1(t_1)$, $N_1(t_2)$, $N_2(t_1)$, $N_2(t_2)$ are corrected, then the corrected values of λ_{l1}, λ_{l2} and ξ_0 are used to calculate the corrected value of τ_β. The results are given in Table 1.

Other corrections are introduced via calculating the value $\xi = \xi_0 + \Delta\xi$, where $\Delta\xi$ is a systematic correction, which meets the following equation for the corrected value of the neutron lifetime τ_β: $\frac{\Delta\lambda_\beta}{\lambda_\beta} = \frac{\lambda_{l1}}{\lambda_\beta}\frac{\xi}{\xi-1}\frac{\Delta\xi}{\xi}$. A corresponding neutron lifetime τ_β-correction is $(\Delta\tau_\beta) = -\tau_\beta \frac{\Delta\lambda_\beta}{\lambda_\beta}$, where τ_β-value is assumed to be equal to the world mean weighted value 880.0 s.

To calculate the corrections were used the results of methodical experiments. Table 1 presents the following corrections, calculated in this way:

- a correction caused by residual gas inside the trap which is a source of additional scattering and capture of UCNs during the storage interval;

- a correction caused by the difference in the UCN detection efficiencies in the geometries 1 (ε_{ucn1}) and 2 (ε_{ucn2});this difference arises because of different values of the UCN emptying and storing times in measurements in the geometries no.1 and no.2;

- a correction caused by the difference in the UCN detection efficiencies at the initial ($\varepsilon_{ucn}^{(i)}$)and final ($\varepsilon_{ucn}^{(f)}$) moments of the UCN storage;this difference could arise if the corresponding UCN energy spectra are different at initialt_1 and final t_2 time moments;

- a correction caused by the difference in the detection efficiencies of the inelastically scattered neutrons in the thermal neutron detectors in the geometries 1 (ε_{th1}) and 2 (ε_{th2});

- a correction caused by the difference in temperatures of the storage trap in the geometries 1and 2;

-a correction caused by eventual UCN leak through the UCN shutter of the storage trap;

- acorrection for an eventual inequality of the cross section ratios $\left(\frac{\sigma_{ie}}{\sigma_{ie}+\sigma_c}\right)_1$ and $\left(\frac{\sigma_{ie}}{\sigma_{ie}+\sigma_c}\right)_2$ in the geometries 1 and 2;this correction could arise if the main surface and the additional one were partly uncovered with fluorine polymer;

- a correction caused by the presence of a weak UCN heating during storage, as a resulta small fraction of UCN could reach after weak heating the polyethylene disk located at a height H_{max} = 95 cm and thus inelastically scattered in it [8].

Table 1. The systematic corrections estimated above.

The reason for correction	Time [sec]		
	H_d = 55 cm, T = + 23° C	H_d = 75 cm, T = + 23° C	H_d = 75 cm, T = - 26° C
Uncorrected τ_β-values	$884.15 \pm 2.10_{stat}$	$884.30 \pm 0.95_{stat}$	$883.60 \pm 0.95_{stat}$
Partial count rate loss in the UCN detector	- 1.28 ± 0.15	- 3.01 ± 0.18	- 3.82 ± 0.14
Scattering of UCN on residual gas	- 1.84 ± 0.31	- 0.43 ± 0.12	0.17 ± 0.10
Difference in ε_{ucn1} and ε_{ucn2}	- 0.61 ± 0.11	- 0.23 ± 0.06	- 0.24 ± 0.03
Difference in $\varepsilon_{ucn}^{(i)}$ and $\varepsilon_{ucn}^{(f)}$	-0.15 ±0.06	0. ±0.06	0. ±0.06
Difference in ε_{th1} and ε_{th2}	1.00 ± 0.40	0.46 ± 0.24	0.18 ± 0.09

Difference in temperatures in the geometries 1 and 2	No correction	No correction	0.11 ± 0.06
Eventual leak through the trap UCN shutter	0 ± 0.05	0 ± 0.05	0 ± 0.05
The cross section ratios inequality	0 ± 0.03	0 ± 0.03	0 ± 0.01
Weak heating	-0.38 ± 0.38	-0.52 ± 0.52	-0.03 ± 0.03
The total systematic correction	- 3.26 ± 1.49	- 3.73 ± 1.26	- 3.63 ± 0.57
τ_β-values with all systematic corrections	880.89 ± 3.59	880.57 ± 2.21	879.97 ± 1.52

Conclusion

A resulting systematic correction in each column in Table 1 is evaluated by means of linear summing of all partial corrections. The last line in the Table presents three independent results for the neutron lifetime τ_β-value. The result of measuring τ_β-value averaged over three independent results in the last line in Table 1 is equal to τ_β = (880.2 ± 1.2) sec.

This value agrees with results of other works based on the method of storage of UCN [9-13] and included by Particle Data Grope in their analysis concerning the world average value [14]. However, our present result as well as all the data [9-13] is noticeably different from the results measured using the beam method [18-20].

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