Physics Letters B 745 (2015) 79–89

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

A measurement of the neutron lifetime using the method of storage of ultracold neutrons and detection of inelastically up-scattered neutrons

S. Arzumanov [a], L. Bondarenko [a], S. Chernyavsky [a], P. Geltenbort [c], V. Morozov [a,b], V.V. Nesvizhevsky [c,*], Yu. Panin [a], A. Strepetov [a]

[a] NRC "Kurchatov Institute", 1 Akademika Kurchatova sqr., Moscow, R-123182, Russia
[b] NRNU MEPHI, 31 Kashirskoe sh., Moscow, R-115409, Russia
[c] Institut Max von Laue–Paul Langevin, 71 av. Martyrs, Grenoble, F-38042, France

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 24 March 2015
Accepted 11 April 2015
Available online 21 April 2015
Editor: M. Doser

ABSTRACT

We present estimations of systematic corrections and results of their experimental studies for our neutron lifetime experiment carried out in 2008–2010 at ILL. Taking into account these systematic corrections, we reduce the data of three independent sets of measurements (obtained during period 2008–2010) performed with different energy spectra of ultracold neutrons (UCNs) at different trap temperatures to the mean neutron lifetime value equal to 880.2(1.2) s.

1. The experimental installation and the method

Precise measurements of the neutron lifetime are important for elementary particle physics, astrophysics and cosmology [1,2]. In accordance to Particle Data Group (PDG) [3], the neutron mean lifetime world value is estimated using works [4–11]; it is equal to 880.3 ± 1.1 s.

The main contribution to the mean world value comes from work [6], which uses the method of storage of ultracold neutrons (UCNs); its result is $\tau_\beta = 878.5 \pm 0.7_{\mathrm{st}} \pm 0.3_{\mathrm{meth}}$ s. Other results using this method [4,5,7,8] are significantly less precise; uncertainties in these experiments are 2–3 s. Main limitations of the UCN storage method are related to systematic corrections.

The probability of UCN loss from a trap $\lambda = \lambda_l + \lambda_\beta$, where $\lambda_l = p\mu$ is the probability of UCN loss in the trap walls, $\lambda_\beta = 1/\tau_\beta$ is the probability of neutron decay, p is the frequency of UCN collisions with the trap walls, and μ is the probability of UCN absorption and inelastic scattering per bounce.

UCN storage experiments were often based on measuring the probability λ in two or several traps with equal values of μ and different frequencies p, which were calculated in accordance with certain assumptions about the behavior of UCNs in traps [6–8]. Then, λ_β was evaluated by linearly extrapolating the experimental data $\lambda(p)$ to the zero frequency $p = 0$. Within this approach, systematic corrections are related to the validity of the condition of equality of μ in the traps as well as to the accuracy of calculations of the frequency p.

Within an alternative approach [4], not only the probability λ, but also the probability λ_l were measured experimentally; the probability λ_l was measured in relative units using the flux of thermal neutrons originating from UCNs up-scattered on trap walls. Then, λ_β was evaluated by linearly extrapolating the experimental data $\lambda(\lambda_l)$ to the zero probability $\lambda_l = 0$. Systematic corrections inherent for this approach are related to the differences in the efficiency of detection of UCNs and thermal neutrons originating from UCNs up-scattered on trap walls.

Recently, results of many UCN storage experiments were largely shifted or selected a posteriori due to additional analysis or new data. Moreover, results of measurements using the method of UCN storage [4–8] and those using the method of in-flight decay of cold neutrons [9–11] differ by many seconds. Thus, the most precise in-flight experiment [11] provides the value of neutron lifetime $\tau_\beta = 887.7 \pm 1.2_{\mathrm{st}} \pm 1.9_{\mathrm{meth}}$ s that differs from the result [6] by 9.2 s, by far larger then the estimated uncertainties of these experiments. Apparently this difference is caused by systematic effects, which have not been properly identified. Therefore new neutron lifetime experiments with the accuracy of at least ~1 s (equal to the world average), and also with a reliable accounting for systematic effects is highly desirable.

The neutron lifetime experiment using storage of UCNs in traps and detection of neutrons, escaping from the storage trap via their

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* Corresponding author.
E-mail address: nesvizhevsky@ill.eu (V.V. Nesvizhevsky).

http://dx.doi.org/10.1016/j.physletb.2015.04.021

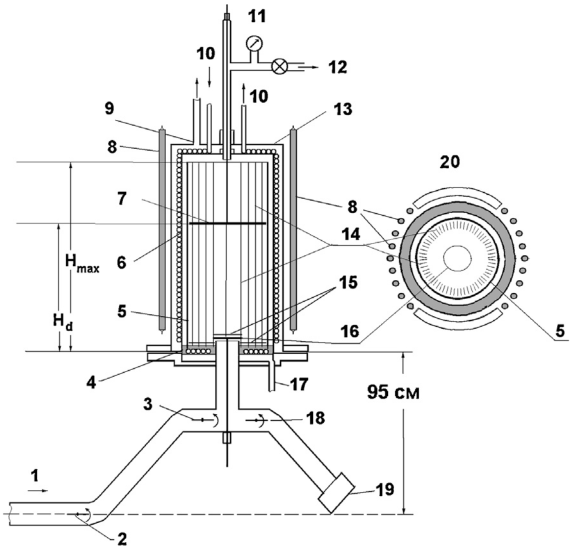

Fig. 1. A scheme of the experimental set-up for the neutron lifetime measurement. 1 – the entrance neutron guide, 2 – the UCN source shutter, 3 – the input shutter, 4 – fluid fluorine polymer, 5 – the copper cylinder, 6 – the cooling coil, 7 – the polyethylene disk, 8 – thermal neutron counters, 9 – 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.

inelastic scattering on the trap walls, was performed in 2008–2010 at the high-flux neutron reactor of Institut Max von Laue–Paul Langevin (ILL, Grenoble, France) [12]. Preliminary results, which accounted for some systematic corrections, were published earlier in conference proceedings [13,14]. In the present work, particular attention is devoted to analyzing all methodical effects of the method.

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 closed cycle refrigerator. The bottom flange of the chamber has a cavity with the depth of 3.4 cm with a coiled cooling tube in it. This cavity is filled with a liquid fluorinated 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 with a gas mixture containing ^{3}He gas. The entrance window of the detector is an aluminum foil with the thickness of 100 μm and the diameter of 15 cm. 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 counters SNM-57 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 in order to suppress external neutron backgrounds.

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 exposed to UCNs. In the geometry no. 1 UCNs 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 thick layer of fluid fluorinated polymer; the internal surface of the copper cylinder is covered with a thin layer of such polymer. During the UCN filling interval, UCNs enter the trap through opened shutters (2), (3), as well as through the plane shutter (16), while the detector shutter (18) is closed. In order to restrict the energy of stored UCNs 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, the UCN energy spectrum is shaped. Then the polyethylene disk is moved to a height of $H_{max} = 95$ cm. After the polyethylene disk reaches H_{max}, 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 UCNs 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 (per time unit) during the storage time interval, is calculated as follows: $\lambda_1 = \frac{1}{\tau_1} = \frac{1}{t_2 - t_1} \ln \frac{N_1(t_1)}{N_1(t_2)}$, where $N_1(t_1)$ and $N_1(t_2)$ are numbers of detected UCNs, τ_1 is the storage time. In the geometry no. 2, the surface area of the storage volume is increased by inserting 90 copper strips with a thickness of 100 μm and a width of 15 mm. In addition, a copper foil ring with the thickness of 100 μm is inserted at a 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). The surfaces of all strips and both foils are covered with identical fluorinated polymer layers. As a result, the total surface exposed to UCNs increases by a factor of 3.

The intervals t_{fill}, t_{clean} and t_{reg} for the measurements in the geometry no. 1 are equal to those in the geometry no. 2, while the storage intervals for the measurements in 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 (per time unit) during the storage interval is calculated for the geometry no. 2 as follows $\lambda_2 = \frac{1}{\tau_2} = \frac{1}{t_2 - t_1} \ln \frac{N_2(t_1)}{N_2(t_2)}$, where $N_2(t_1)$ and $N_2(t_2)$ are the numbers of detected UCNs, τ_2 is the storage time.

The total UCN loss probabilities (per time unit) are

$$\lambda_1 = \lambda_\beta + \lambda_{l1}, \qquad \lambda_2 = \lambda_\beta + \lambda_{l2}, \tag{1}$$

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:

$$\lambda_\beta = \frac{\xi \lambda_1 - \lambda_2}{\xi - 1}. \tag{2}$$

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

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

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