Preliminary results of a new neutron lifetime experiment using spectral measurements of UCN storage and counting of up-scattered neutrons

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Abstract

Preliminary results of a new neutron lifetime measurement are presented. The method is based on spectral measurements of storage times of ultracold neutrons (UCN) in two traps with different mean free path and counting of neutrons up-scattered in trap walls. All walls are coated with liquid fluorine polymer and kept at ambient temperature. A preliminary value of the neutron lifetime is 881.5 ± 2.2 s.

The present world mean weighted (WMW) value for the neutron lifetime is equal $\tau_n =$ 885.7 (0.8) s. [1]. However recent experiment with UCN provided significantly different result: $\tau_n = 878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}}$ s [2]. Precision of the WMW value is dominated by the work [3]; contribution of three other experiments [4 - 6] is an order of magnitude smaller. The experiments [3 - 5] use UCN storage in traps with walls coated with fluorine polymer. Potential sources of systematic errors in these experiments could be the following: 1) the wall loss extrapolation was too large because of large ratio of loss probability to β-decay probability: $\overline{\lambda_l} / \lambda_\beta \approx$ (10-30) %, ($\lambda_\beta = 1/\tau_n$); in general terms, systematic corrections are proportional to this ratio; 2) small UCN heating [7-12] had not been known then; therefore systematic spectrum-depended false effects could stay unnoticed. The mentioned above contradiction between various results of the neutron lifetime measurement as well as methods available to significantly improve reliability of preceding experiments motivate the present experiment.

The installation (see Fig.1) includes vertical cylindrical vacuum housing surrounded by thermal neutron counters. A vertical copper cylinder with a height of 95 cm and a diameter of 40 cm is placed in layer of liquid fluorine polymer YH VAC 18/8 on housing bottom. Internal surface of the cylinder is coated with equivalent fluorine polymer. This surface and the bottom layer form storage trap in 1st experiment (configuration no.1). UCN from a neutron guide (see Fig.3) fill in the trap for $t_{fill} = 150$ s when a shutter (3) and a valve (15) are open, while a shutter (17) in front of a detector (18) is closed. Upper boundary energy E_{max} of spectrum of stored UCN is defined by position of a polyethylene absorber (6), which is lifted to a height $H_{min}=55$ *cm* during filling. Then the shutter (3) and the valve (15) close while the shutter (17) opens in order to empty UCN to the detector. During interval t_{cl} =200 s UCN are stored in the trap while neutrons with energy $E>E_{max}$ are removed. Then the absorber rises to a maximum height $H_{max}=95$ cm and 1st storage period starts. Neutrons inelastically scattered at walls during storage interval t_{stor} are counted in thermal neutron detectors (7). UCN scattered due to small heating, stay trapped as their energy is not sufficient to reach a height of *95 cm* [7, 11]. After storage in the trap during interval $t_{stor} = t_1 = 60$ s survived UCN are counted in a UCN-detector for $t_{empt} = 150s$ giving $N_1(t_1)$. Then the detector background is measured for t_{bgr}. The second part of measuring circle starts from equivalent filling and cleaning procedures while storage interval is longer: $t_{stor} = t_2 = 960$ s. Then the number of survived UCN is counted for $t_{empt} = 150s$ giving $N_1(t_2)$. The background is measured for t_{bgr}. The number of inelastically scattered neutrons is counted for interval $t_2 - t_1 = 900$ s in thermal neutron counters giving J_1.

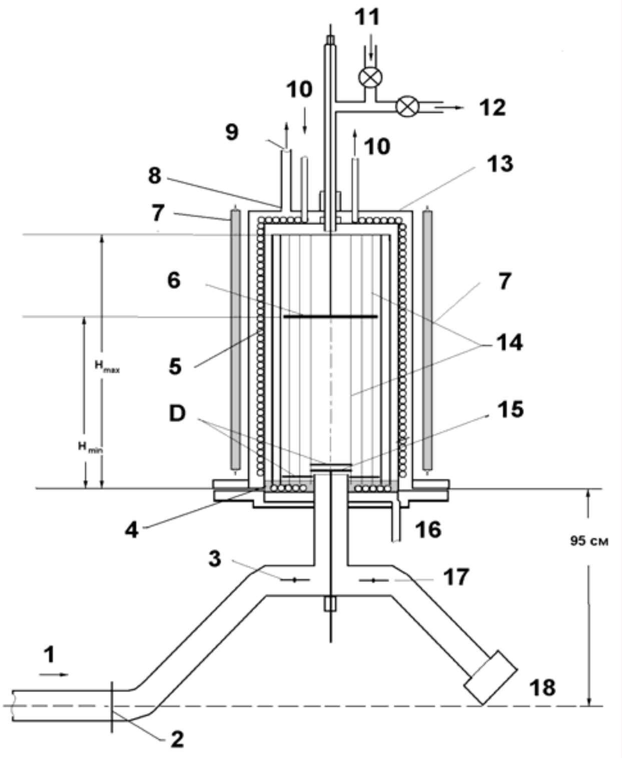

Fig.1. Scheme of the set-up. *1*-entrance UCN guide; *2*-Al-foil; *3*-entrance UCN shutter; 4-liquid fluorine polymer; 5-cooling system; 6-polyethylene disk-absorber; 7-thermal neutron counters; 8-vacuum housing; 9-to high vacuum pump; 10- tubes for cooling fluid from cooling machine; 11,12-He gas supply to accelerate getting thermal equilibrium between the internal housing cylinder and the storage trap; 13-external SS-cylinder of the housing; 14-additional stripes for experiment no.2; 15-trap UCN valve; 16-additional high vacuum pumping; 17-exit UCN shutter; D-bottom of the additional surface for experiment no.2.

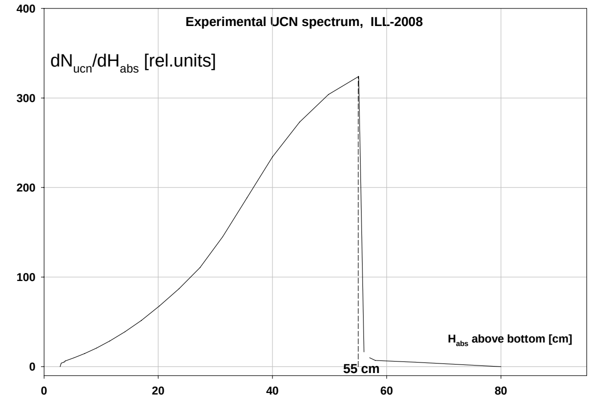

Fig.2. UCN spectrum after cleaning for 200 s (absorber 6, fig.1, at a height of 55 cm above the trap bottom) and storing for 20 s (absorber raised to a height of H = 95 cm). A fraction of UCN with energy in the range (55÷80) cm is < 2.8 % by the end of storage interval $t_1 = 60s$ Small UCN heating with a probability 1.6×10^{-5} per collision with trap wall during storage time $t_2 = 960s$ increases this fraction up to 10 % while the fraction of UCN with energy > 80 cm is < 0.5 %.

These data define UCN total loss probability per time unit as $\overline{\lambda_1} = \lambda_\beta + \overline{\lambda_{l1}} = \frac{1}{t_2 - t_1}\ln\frac{N_1(t_1)}{N_1(t_2)}$ and the probability of UCN loss due to capture and inelastic scattering as $\overline{\lambda_{l1}} = \frac{\varepsilon_{ucn}}{\varepsilon_{th}}\frac{(\sigma_{ie}+\sigma_c)}{\sigma_{ie}}\frac{J_1\overline{\lambda_1}}{(N_1(t_1)-N_1(t_2))}$. Here ε_{ucn} and ε_{th} are the detection efficiencies for UCN and thermal neutrons respectively, σ_{ie} and σ_c are the neutron inelastic and capture cross section in interaction with fluorine polymer.

To carry out 2nd experiment (configuration no.2), an additional surface made of copper foil 100 μm thick coated by equivalent fluorine polymer is inserted into the storage trap. Its side surface is a set of vertical 1.5 cm-broad stripes placed close to the trap cylinder surface.

An additional bottom consists of two plain disks; one is placed 1.2 cm above the liquid fluorine polymer surface, the second one is installed 1 cm above the trap UCN valve (fig.1, 15,*D*). As a result, the area of internal surface of storage trap is enlarged by a factor of 3 while the detection efficiency ε_{th} remained almost unchanged for neutrons inelastically scattered on surfaces. The efficiency ε_{ucn} of UCN detection is nearly equal in both experiments as well.

In 2^{d} experiment the UCN with equivalent energy spectrum are stored for intervals t_1 = 20 s and t_2 = 320 s. These measurements allow evaluating the probabilities $\overline{\lambda_2}, \overline{\lambda_{l2}}$:
$\overline{\lambda_2} = \lambda_\beta + \overline{\lambda_{l2}} = \frac{1}{t_2 - t_1} ln \frac{N_2(t_1)}{N_2(t_2)}$ and $\overline{\lambda_{l2}} = \frac{\varepsilon_{ucn}}{\varepsilon_{th}} \frac{(\sigma_{ie} + \sigma_c)}{\sigma_{ie}} \frac{J_2 \overline{\lambda}_2}{(N_2(t_1) - N_2(t_2))}$ where $N_2(t_1), N_2(t_2)$ are the number survived UCN by the end of intervals t_1, t_2 while

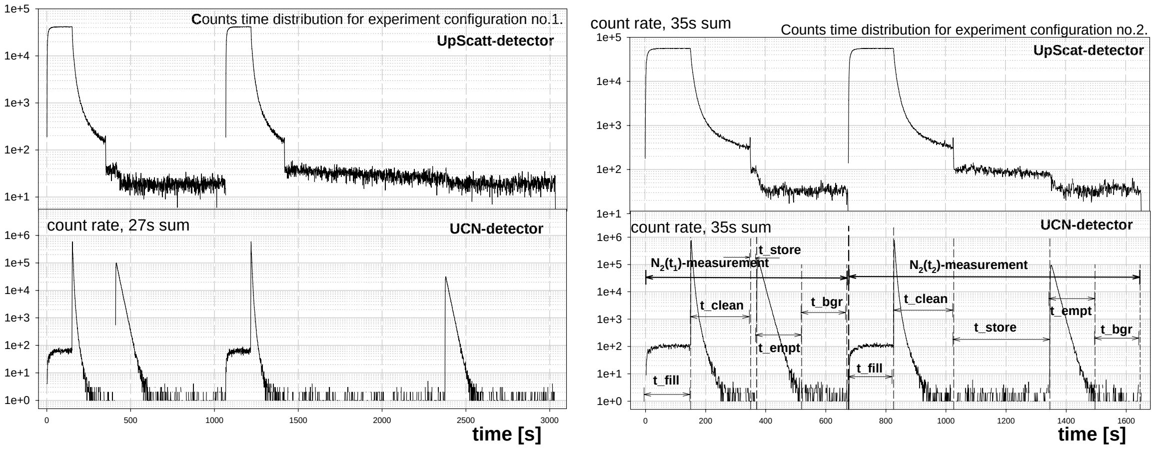

Fig.3. Counts time distribution of detectors (UCN and inelastic scattered neutrons) during one measuring procedure. Left side of the figure shows this procedure during measurement in storage vessel of configuration no.1 (see below in text) while the right one – analogue for configuration no.2. The upper distribution in both figure's parts shows the registration by the detector of inelastic scattered neutrons (marked in Fig. as "UpScatt-detector"). Parameters that are shown at the right-down part of the Fig. are explained in the text.

J_2 is the number of counted inelastically scattered neutrons during interval $t_2 - t_1$. Thus the β-decay probability is defined using only experimental data $\lambda_\beta = \frac{\overline{\lambda_1}\xi - \overline{\lambda_2}}{\xi - 1}$ where

$$\xi = \frac{\overline{\lambda_{l2}}}{\overline{\lambda_{l1}}} = \frac{J_2 \overline{\lambda_2}(N_1(t_1) - N_1(t_2))}{J_1 \overline{\lambda_1}(N_2(t_1) - N_2(t_2))} \approx 3.$$

The measurements were carried out at ambient temperature. The UCN spectrum by the end of cleaning is shown in Fig.2. It is evaluated by differentiating the numbers of UCN $N(H)$ measured in 1st experiment as a function of the absorber height H < 55 cm.

Data of a separate measurement show that the fraction of UCN with energy in the range (55÷80) cm is < 2.8% by the end of storage interval $t_1 = 60s$. This fraction is schematically shown as a "tail" above H = 55 cm. Small UCN heating with a probability 1.6×10^{-5} per collision with trap wall during storage time $t_2 = 960s$ increases this value up to 10 %. The fraction of UCN with energy > 80 cm is < 0.3 %.

So, as the scaling rule (number of UCN wall collisions during storage intervals in experiments no.1 and no.2) was followed, evolution of the UCN spectrum is equivalent in these experiments. Thus, small UCN heating does not affect results of the neutron lifetime measurement in this experiment.

In the experiment no.1 after the cleaning and UCN storage for $t_1 = 60s$ the number $N_1(t_1)$ of UCN accumulated in the trap is equal $N_1(t_1) \approx 65700$. Corresponding UCN storage time is $\tau_{st}^{(1)} \approx 784$ s; the ratio $\overline{\lambda_{l1}} / \lambda_\beta \approx 13\%$. Analogous data for experiment no.2 (with the additional surface) were: $N_2(t_1) \approx 62000$ for $t_1 = 20s$, and $\tau_{st}^{(2)} \approx 643$ s. They correspond to the UCN loss factor $\eta \approx 2.1 \times 10^{-5}$.

Preliminary results:

	Uncorrected value	885.7s		± 2.0s
	Sources of correction		Correction's values, s	Uncertainty
1	UCN count rate loss		-1.1	0.2
2	Emptying correction		-3.0	0.3
3	Up-scattered neutron detector efficiency (calculations)		0.0	0.8
4	Residual gas influence on λ_{ie}		-0.1	0.3
5	UCN leakage through the trap UCN valve		< 0.03	
	Total		-4.2± 0.9	
	Current result	881.5		± 2.2

Comments to the preliminary results.

1. Correction no.1. "UCN count rate loss" is due to the UCN detector dead-time caused by high counting rate ($(1.5 - 4.5) \times 10^3$ s^{-1}) during first seconds of UCN counting in each circle. It changes ratios between values $N_1(t_1), N_1(t_2)$, $N_2(t_1), N_2(t_2)$. This correction is evaluated using electronic units' data as well as computer simulations.
2. The "Emptying correction" is due to different values of the UCN emptying time from the trap into the UCN detector: $t_{empt}^{(1)} = 14.87 \pm 0.04s$ for experiment no.1 while $t_{empt}^{(2)} = 10.66 \pm 0.02s$ for experiment no.2. This correction is evaluated using experimental data on UCN storage time $t_{stor}^{(compl)}$ inside a complex trap consisting of the storage trap and intermediate volume of the neutron guide between UCN shutters (3) and (17), see Fig.1. For configurations no. 1, 2 the values of $t_{stor}^{(compl)}$ were equal to $t_{stor}^{(compl.1)} = 210.76 \pm 0.63s$ and $t_{stor}^{(compl.2)} = 201.10 \pm 1.17s$
3. This correction arises due to possible small difference between values $\varepsilon_{th}^{(conf.1)}, \varepsilon_{th}^{(conf.2)}$. This difference is due to different positions of surfaces in these

configurations. Presently this efficiency is studied; the current estimation of the uncertainty is (± 0.8) sec.

4. This correction appears due to inelastic scattering and capture of UCN on residual gas molecules. Our method is only weakly sensitive to these losses as the thermal neutron detectors count neutrons inelastically scattered on gas molecules. It was defined experimentally that the loss factor is $p \times \tau = 5.3 \pm 0.8$ mbar×s, where p is a gas pressure and τ is the neutron lifetime in this gas. This correction is calculated accounting for the residual gas pressure in both experiments as well as for the efficiency of detection of inelastically scattered neutrons on gas molecules.
5. The upper limit of this correction is defined experimentally using counts of the UCN detector during storage interval.

We are going to continue measurements at lower temperature. That would allow us to suppress UCN losses down to $\overline{\lambda_l} / \lambda_\beta \approx$ (3-5) % thus decreasing systematic corrections.

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