# MEASUREMENT OF THE NEUTRON LIFETIME BY STORING ULTRACOLD NEUTRONS AND MONITORING THEIR LOSSES BY COUNTING INELASTICALLY SCATTERED NEUTRONS
## (PHASE 2)

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## Abstract

In the 2nd phase of our project on precision measurement of the neutron lifetime we reduced systematic uncertainties and improved statistical sensitivity due to (i) keeping the UCN storage volume at a lower temperature, and due to (ii) increasing the total number of stored UCN. Before applying any corrections for the efficiency of the thermal-neutron detectors, we estimate the neutron lifetime as $\tau[\mathrm{s}] = 880.6\pm0.95_{\mathrm{stat}}\pm0.50_{\mathrm{syst}}$ for measurement at room temperature of the storage bottle and $879.7\pm0.95_{\mathrm{stat}}\pm0.45_{\mathrm{syst}}$. for temperature -26°C. The correction to efficiency of the thermal-neutron detectors will be measured in the 3d phase of this project.

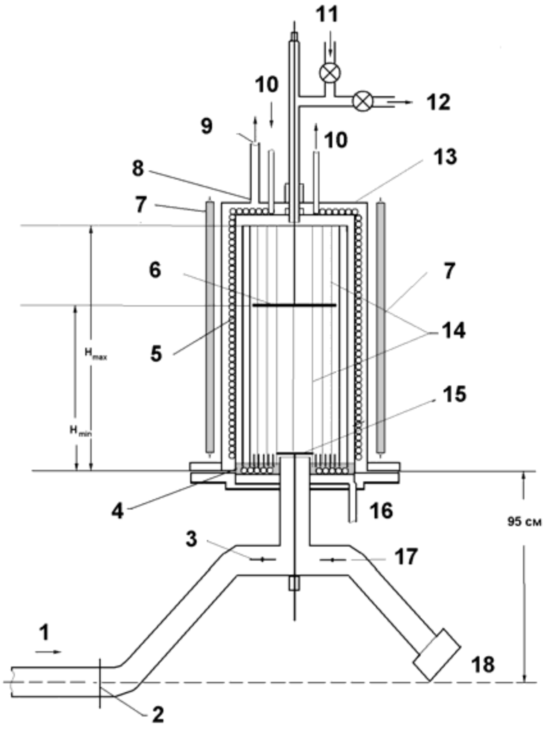
## 1. Introduction

A large discrepancy between the world average value of the neutron lifetime [1] (PDG data $\tau_n(s)=885.7(7)$) and the result of a most recent neutron lifetime experiment [2] ($878.5\pm0.7_{st}\pm0.3_{syst}(s)$) motivates this new experiment; its 1st phase was presented at ISINN-17. The accuracy of the PDG value is dominated by a single experiment [3]. A contribution of each other experiment [4-8] is at least an order of magnitude smaller. Both most precise experiments use storage of ultracold neutrons (UCN) in traps with Fomblin oil wall coatings. Although a list of possible false effects in these most precise experiments is under discussion, the reason for the mentioned discrepancy is not yet understood. Besides, the neutron lifetime value could affect the condition of unitarity of the Cabibbo-Kobayashi-Maskava matrix [1]. The matrix element $|V_{ud}|^2$ is the largest term in the unitarity sum $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$. Using the PDG neutron lifetime data and the expression $|V_{ud}|^2=(4908\pm4)/(\tau_n\cdot(1+3\cdot\lambda^2))$ one gets the sum equal to $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9997(40)$ in good agreement with the unitarity condition. The latest value for $|V_{us}|^2=0.2254\pm0.0021$ from K-decay [9-13] and the $|V_{ud}|^2$ value obtained from the recent $\tau_n$ value [2] result to the sum *1.0075(40)* that is in agreement with unity only at the level of two standard deviations.

Our new experiment aims to reduce largely systematic effects compared to those in preceding experiments due to: 1) keeping UCN loss probability as low as *3-5%* compared to the neutron $\beta$-decay probability due to use of fluorine polymer wall coatings (as in ref. [2]) and cooling the storage bottle (trap) to low temperature; 2) monitoring the loss probability *experimentally* (instead of estimating it theoretically) by means of measuring the inelastically scattered UCN in thermal neutron counters (as in ref. [3]); 3) minimizing any difference in UCN loss coefficients for the two traps; 4) excluding the effect of small UCN heating to the final result due to proper UCN spectrum shaping and monitoring (as in refs. [14-24]).

## 2. The experimental setup and measuring procedure

The experiment uses storage of UCN in two traps with significantly different mean free path. The trap walls are coated with a low-temperature liquid fluorine polymer. The experimental setup is shown in Fig. 1.



It consists of a double vertical cylindrical vacuum housing (13) with a cooling system (10) and pumping (9). It is surrounded with 18 thermal neutron counters (7). A thick layer of a liquid fluorine polymer (4) is applied to the inner volume bottom. A vertical cooper cylinder (5) with a height of *95 cm* and a diameter of *40 cm* is installed on it. Its surface is coated with equivalent fluorine polymer of YH VAC 18/8 type. This cylinder and the bottom fluorine polymer layer form a storage trap of the experiment in the configuration “number 1”. In the configuration “number 2”, an additional surface (14), coated with equivalent fluorine polymer, is inserted inside the copper cylinder thus increasing the wall surface area nearly 3 times. UCNs fill in the trap when a shutter (3) and a valve (15) are open, while a shutter (17) in front of a detector (18) is closed. The upper boundary $E_{max}$ of the spectrum of stored UCN is defined by position of a polyethylene absorber (6), which is lifted to the height $H_{min}=56$ *or* $75$ *cm* during filling period. Then the shutter (3) and the valve (15) close while the shutter (17) opens in order to empty UCN from neutron guide to the detector. In a time interval $t_{cl}$ sufficiently long to remove UCN with energy $E>E_{max}$ from the storage trap, the absorber rises to a maximum height of $H_{max}=95$ cm and the storage period starts. The neutrons scattered inelastically at walls during their storage are counted in the detectors (7) while UCN up-scattered in a small heating process stay inside the trap, if its energy is not sufficient to reach the height of *95 cm*.

During the UCN storage time interval $t$ the mean value of total loss probability (per time unit) is equal to $\bar{\lambda} = \lambda_\beta + \lambda_l = \frac{1}{t}\ln\frac{N(0)}{N(t)}$ (1)

where $N(0)$, $N(t)$ are the numbers of UCN at the beginning and at the end of this interval respectively, $\lambda_\beta$, $\lambda_l$ are the probabilities of the $\beta$-decay and the UCN loss via its interaction with wall. Counting of inelastically up-scattered neutrons in the configuration “number 1” and “number 2” during time intervals $t_k$ ($k$ is the configuration number $k=1,2$) allows to calculate $\lambda_{lk}$:

$$\bar{\lambda}_{lk} = \frac{\varepsilon_{ucn}}{\varepsilon_{th}} \frac{(\sigma_{ie}+\sigma_c)}{\sigma_{ie}} \frac{J_k \bar{\lambda}_k}{(N_k(0)-N_k(t_k))} \tag{2}$$

where $\varepsilon_{UCN}$ and $\varepsilon_{th}$ are the detection efficiencies for UCN and thermal neutrons respectively, $\sigma_{ie}$ and $\sigma_c$ are the inelastic and capture cross section, $J_k$ is the number of counts in the thermal neutron detector during the interval $k$. Thus we could measure two pairs of values $\overline{\lambda_1}, \overline{\lambda_{l1}}$ and $\overline{\lambda_2}, \overline{\lambda_{l2}}$ in two traps with different mean free path and identical other conditions, and calculate the reciprocal neutron lifetime as:

$$\lambda_\beta = \frac{\bar{\lambda}_1 \xi - \bar{\lambda}_2}{\xi - 1}, \quad \xi = \bar{\lambda}_{l2} / \bar{\lambda}_{l1} \tag{3}$$

The experimental uncertainty estimation for this value is:

$$\frac{\delta\lambda_\beta}{\lambda_\beta} = \sqrt{\left(\frac{\xi}{\xi-1}\right)^2 \left(\frac{\delta\overline{\lambda_1}}{\lambda_\beta}\right)^2 + \left(\frac{1}{\xi-1}\right)^2 \left(\frac{\delta\overline{\lambda_2}}{\lambda_\beta}\right)^2 + \left(\frac{\overline{\lambda_{l1}}}{\lambda_\beta}\right)^2 \left(\frac{\delta\xi}{\xi-1}\right)^2} \tag{4}$$

where $\delta\bar{\lambda}_1, \delta\bar{\lambda}_2, \delta\xi$ are the experimental accuracies.

## 3. Results

During the 1st project phase, we measured at ambient temperature with a soft UCN spectrum of up to $H_{max}=56$ *cm.* The numbers of UCN accumulated in the trap were equal $N_1$,

$N_2 \approx 6.2\text{-}6.6\times10^4$; the UCN loss coefficient was equal $\eta \approx 2.1\times10^{-5}$, and the preliminary neutron lifetime value was equal $881.5 \pm 2.2$ s.

The following modifications were implemented in the 2nd project phase: 1) the maximum UCN energy increased to $H_{max}=75\ cm$. As a result, the numbers of UCN accumulated in the trap increased twice: $N_1, N_2 \approx 1.3\times10^5$. 2) the precision of UCN loss monitoring improved due to increase in the UCN numbers accumulated in the trap as well as due to installing between the thermal detector sections the reflectors for inelastically scattered neutrons. 3) the measurements were carried out at low temperature (-28÷-30 $C^o$) that allowed us to decrease twice UCN loss coefficient thus achieving the ratio $\overline{\lambda_{l1}}/\lambda_\beta \approx$ 5.8%.

Before applying any corrections for the efficiency of the thermal-neutron detectors, we got during 50 days cycle at the ILL reactor a preliminary result in the 2nd phase presented below (where all data in [s]; all figures were rounded off to 0.05 s):

**Table of the preliminary result of the second phase of experiment**

| Trap temperature | Neutron lifetime | Statistical uncertainty | Systematic effect | Correction value | Correction uncertainty |
|---|---|---|---|---|---|
| **+(22-24) C** | (uncorrected)<br>884.30 | 0.95 | | **0.00** | |
| | | | c/rate loss | **-3.20** | **0.30** |
| | | | emptying | **-0.05** | **0.05** |
| | | | reasidual gas | **-0.45** | **0.15** |
| | (corrected)<br>**880.60** | **0.95** | total | **-3.70** | **0.50** |
| **-(27.5±2.5) C** | (uncorrected)<br>883.60 | 0.95 | | **0.00** | |
| | | | c/rate loss | **-3.60** | **0.30** |
| | | | emptying | **-0.15** | **0.05** |
| | | | reasidual gas | **-0.15** | **0.05** |
| | | | temperature difference | **+0.10** | **0.05** |
| | (corrected)<br>**879.80** | **0.95** | total | **-3.80** | **0.45** |

Comments to the preliminary results.

The measurements made with two different temperatures of the storage bottle are independent:

$880.6\pm0.95_{stat}\pm0.50_{syst}$ and $879.7\pm0.95_{stat}\pm0.45_{syst}$. where the resulted systematical uncertainties in both cases were calculated as a sum of particulars. These results should be corrected on the possible difference of the efficiency of registration of the thermal-neutron detectors for two configurations of the storage bottle. The third phase of the Project will be devoted to experimental investigation of this difference.

1. Correction “c/rate loss” appears due to the UCN detector dead-time caused by high counting rate (7÷9×$10^3$ $s^{-1}$) 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 the special investigation of the dependence of the loss on the count rate. Taking into account that this correction has the main value, this investigation will continue with the aim to decrease of the uncertainties that were referred in the Table.
2. The emptying correction (“emptying”) originates due to different values of the UCN emptying time into the UCN detector for the different trap configurations. This correction was calculated with taking into account the different values of the UCN storage time for the different trap configurations.
3. The correction “reasidual gas” appears due to inelastic scattering and capture of UCN on residual gas molecules. Our method gets to register neutrons that were inelastic scattered on gas molecules by the same way as on the wall of storage vessel. Experimentally it was defined that the $p \times \tau$ -factor is equal to $p \times \tau = 5.6 \pm 0.8$ mbar×s, where $p$ is a gas pressure and $\tau$ is the neutron lifetime at this gas. This correction was calculated taking into account the residual gas pressure during storage at both experiments. The value of the registration efficiency inelastic scattered neutrons on gas molecules that was defined experimentally.
4. The upper limit of the correction “valve leak” was defined experimentally lower than 0.05 s using the counts of the UCN detector during storage time interval.

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