

Neutron lifetime measurement with the big gravitational trap for ultracold neutrons. Current state and future prospects.

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Abstract. A new measurement of the neutron lifetime, carried out with the aid of a large gravitational spectrometer made in Petersburg Institute of Nuclear Physics (PNPI) is presented: $\tau_n = 881.5 \pm 0.7 \pm 0.6$ s. In our experiment the measurement of neutron lifetime is carried out using the method of storing ultracold neutrons in a material trap with gravitational barrier. Further improvement of the obtained result can be achieved at the helium temperatures. Here we present our neutron lifetime result, modified installation scheme and the first results of cryogenic tests are discussed.

1. Introduction

Precise neutron lifetime measurement is of great importance for elementary particles and cosmology. Firstly, combining value of neutron lifetime with the measurement of the neutron beta-decay asymmetry [1] one can calculate value of the element V_{ud} in CKM-matrix which unitarity indicates the completeness of our ideas about the quark model of particles. Secondly, neutron lifetime turned out to be important in theory of Big Bang nucleosynthesis. Astronomers now can measure the amount of primordial Helium-4 in the interstellar clouds (Table in [2]) and the results of such observations can be used as a verification criterion for different theoretical models of the primordial nucleosynthesis. Thirdly, nowadays there are three measuring techniques for neutron lifetime measurements: beam method which uses beam of the cold neutrons passing through the experimental setup and two other methods use ultracold neutrons which are stored in a vessel with magnetic or material walls correspondingly. First method [3] obtains the result which is significantly divergent from the rest of measuring techniques and the reason of such discrepancy is yet to be discovered.



2. Theoretical concepts and experimental apparatus

Ultracold neutrons have energy of less than 100 neV and their velocity do not exceed few meters per second. Corresponding de Broglie wavelengths for such neutrons are thousands of angstroms therefore they interact not with the individual nuclei but with the effective potential also called neutron optical potential. If the material potential is positive and the neutron energy is small enough it would reflect from the surface like from classical rectangular barrier [4]. Also due to small kinetic energy trajectories of UCNs are parabolic which means that they stay confined in a trap even with the open top and we can measure neutron lifetime by counting the remaining particles.

Amount of neutrons in the trap exponentially decreases with time. Where storage time is the exponent index determined through a simple sum of the beta-decay rate and the rate of loss due to collisions with the walls of the trap:

$$\tau_{st}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1} \quad (1)$$

Turns out that the collision loss rate τ_{loss}^{-1} can be represented as a product of two functions one of which depends purely on temperature $\eta(T)$ and another on effective collision frequency $\gamma(E)$ which depends on UCN energy and trap size:

$$\tau_{loss}^{-1} = \eta(T)\gamma(E) \quad (2)$$

By using MC-simulation we can calculate the effective collision frequency $\gamma(E)$ and by using two different geometric configurations we can eliminate the factor eta, and determine neutron lifetime:

$$\begin{cases} \tau_1^{-1} = \tau_n^{-1} + \eta\gamma_1 \\ \tau_2^{-1} = \tau_n^{-1} + \eta\gamma_2 \end{cases} \Rightarrow \begin{cases} \eta = (\tau_2^{-1} - \tau_1^{-1})/(\gamma_2 - \gamma_1) \\ \tau_n^{-1} = \tau_1^{-1} - (\tau_2^{-1} - \tau_1^{-1})/[\gamma_2(E)/\gamma_1(E) - 1] \end{cases} \quad (3)$$

In the **Figure 1** 3D model of our apparatus is presented. It consists of two manufactured nitrogen tanks. The outer tank contains the insulating vacuum. The inner tank contains vessels for liquid nitrogen and the primary experimental components: the neutron trap and the insert. The neutron trap and insert are made of copper. Trap represent half-cylinder with radius 0.7 m and length 2 m and insert have the same shape but without end-caps with radius 0.6 m and length 1.8 m. In **Figure 2** we show our measuring procedure.

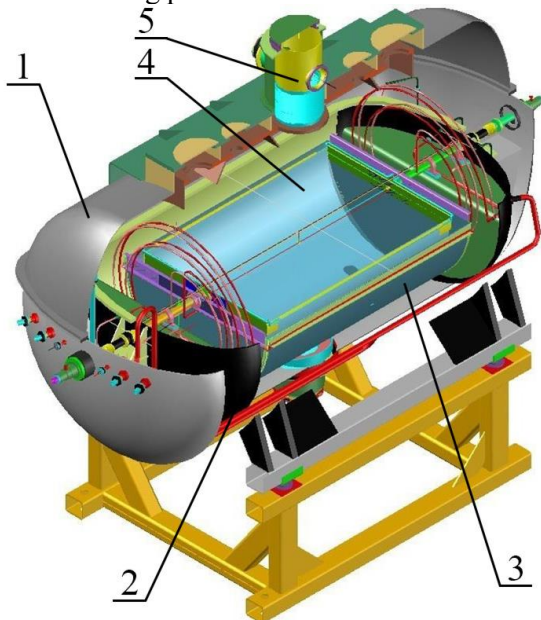


Figure 1. 1 – external vacuum vessel, 2 – internal vacuum vessel, 3 – trap, 4 – insert in low position, 5 – gear for pumping out internal vessel.

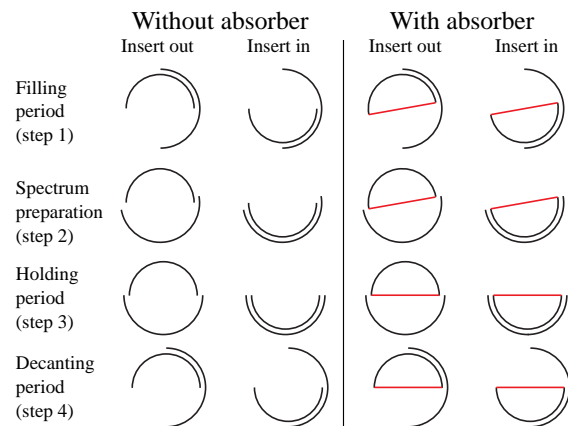


Figure 2. On stage one we fill our trap with neutrons for 150 s. On the second stage we tilt our trap on a certain angle to decant neutrons which energies are too large to be stored (500 s). Then we set the trap to a horizontal position and hold it for a periods of time t_1 (300 s) or t_2 (1600 s). After that follows several decanting sessions to split neutrons over different energy intervals. And finally we measure background.

3. Test measurements

Figure 3 shows detector count rate during the measurement cycle described in the **Figure 2**. In order to reduce the losses we use special hydrogen-less polymer oil which comprises of fluorine and carbon atoms. Moreover UCN losses are strongly suppressed at low temperatures (80-100K) along with small heating effect [5]. Preliminary measurements of the storage time in a titanium trap and insert, coated with Fomblin grease shown in the **Figure 4** prove that the covering can sustain such temperature change and the amount of uncovered area is less than $S_{Ti}/S < 0.1\%$.

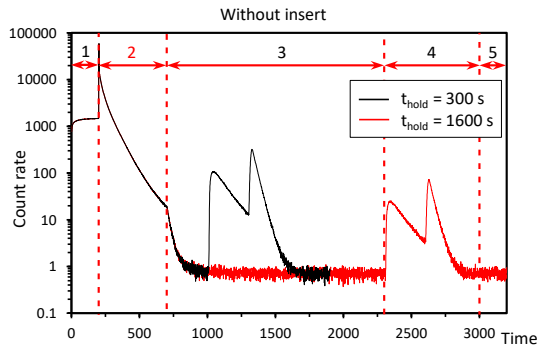


Figure 3. Detector count rate. 1 – filling, 2 – cleaning, 3 – storing, 4 – decanting, 5 – background measurement.

Having confirmed the coverage stability we measure same curves for the copper trap and insert and since copper has much less capture cross section we can directly observe how storage time increases when the temperature goes down in the **Figure 5**. By subtracting the supposed neutron lifetime we obtain that losses on the collisions represented in **Figure 6** are less than 1.5% of beta-decay.

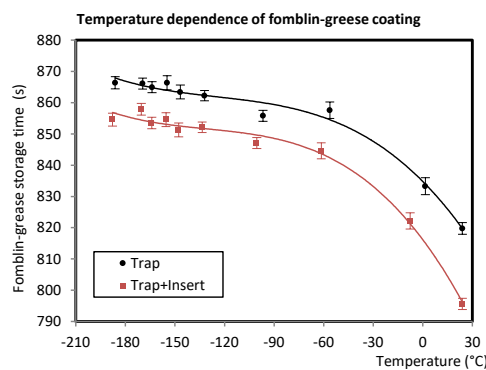


Figure 5. Temperature dependence of the UCN storage time.

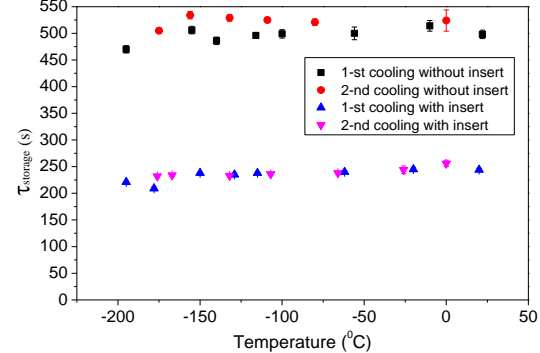


Figure 4. Temperature dependence of the UCN storage time in the experiment with the titanium trap and insert.

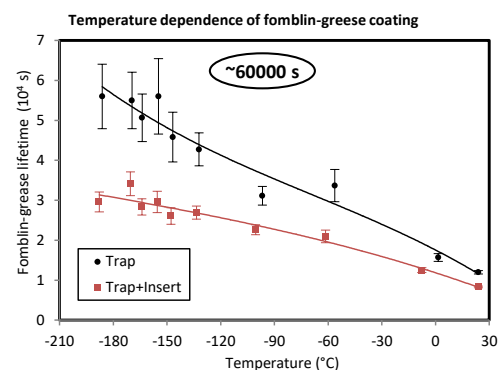


Figure 6. Temperature dependence of the coating lifetime.

4. Measurement results

We have been collecting data during years 2016-2017 at the ILL reactor located in Grenoble, France. This time corresponds to four reactor cycles 178-181. Between the reactor cycles 179-180 we installed titanium absorber on the insert to reduce the spectrum preparation time. After that operation the mean storage time in measurements without the insert was reduced by 2.5 seconds and, in measurements with the insert, reduced by 7 seconds. But despite the change in storage time the extrapolated neutron lifetime stayed intact. Results of our measurement are represented in **Figure 7**. MC-calculations show that results from geometric extrapolation (same energies held with different geometry configuration) is more consistent, therefore we used that approach. Since the storage times have changed we could not average them but we can average the result of the independent extrapolations.

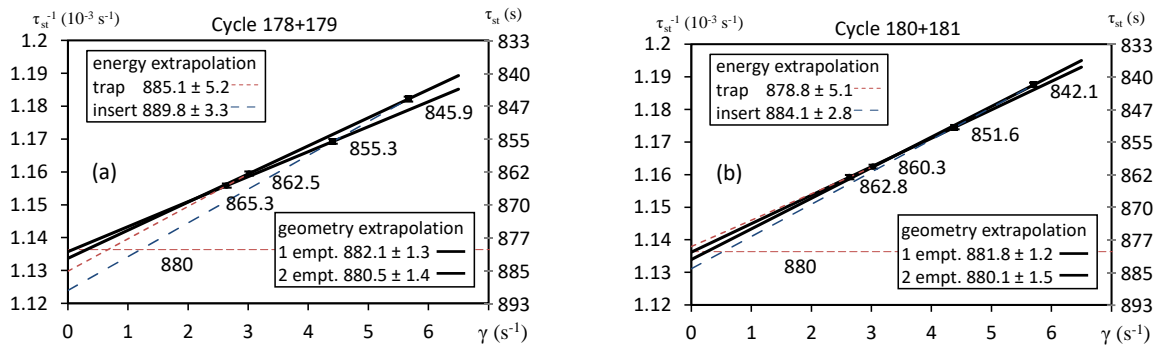


Figure 7. The extrapolation of measured storage times to the free neutron lifetime. Left: measurements without the titanium absorber. Right: measurements with the titanium absorber.

In order to obtain single value we average the results of energy extrapolation and have the result for neutron lifetime: $\tau_n = 881.3 \pm 0.7$ s.

Table 1. Full list of systematic errors

Source of uncertainty		Value, s
a)	Uncertainty of shape of function $\mu(E)$	± 0.3
b)	Uncertainty of trap dimensions (3 mm for diameter 1400 mm)	± 0.15
c)	Uncertainty of extrapolation method	± 0.1
d)	Uncertainty of trap angular position (2°)	± 0.1
e)	Uncertainty of difference for trap and insert coating	± 0.5
f)	The influence of the residual gas	0.2 ± 0.02
Total:		0.2 ± 0.6

Considering list of all possible systematic corrections represented in Table 1 we have final result:

$$\tau_n = 881.5 \pm 0.7 \pm 0.6 \text{ s.}$$

5. Future perspectives

Our existing apparatus provides us an opportunity to improve current results even more. It can be achieved if we are able to increase amount of neutrons in the trap or to decrease losses due to collisions with the walls. New more powerful source of UCN is still under construction and unavailable for now [6]. Therefore the only option is to decrease temperature of trap and insert and to investigate the behaviour of loss trend which is shown in the **Figure 8**.

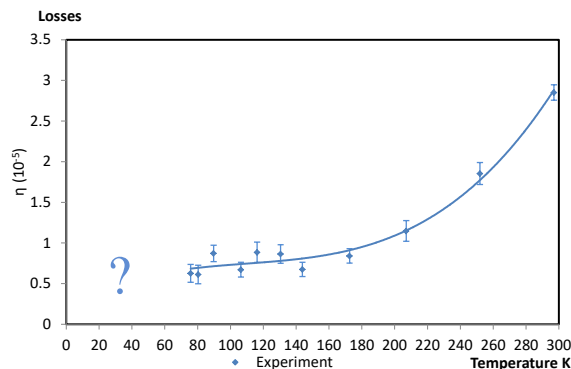


Figure 8. Loss temperature dependence.

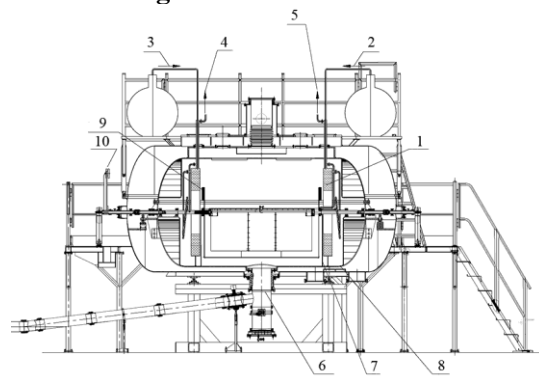


Figure 9. 1 – helium tank, 2 – helium trap admission, 3 – helium insert admission, 4 – helium insert outlet, 5 – helium trap outlet, 6 – aluminum membrane, 7 – barrier, 8 – titanium, 9 – trap counterbalance, 10 – insert counterbalance.

In the **Figure 9** the concept for the big gravitational trap upgrade is shown. All necessary estimations such as heat flow to the trap and insert and stress calculations for the liquid helium vessels have been made and results of these procedures are shown in **Figure 10**:

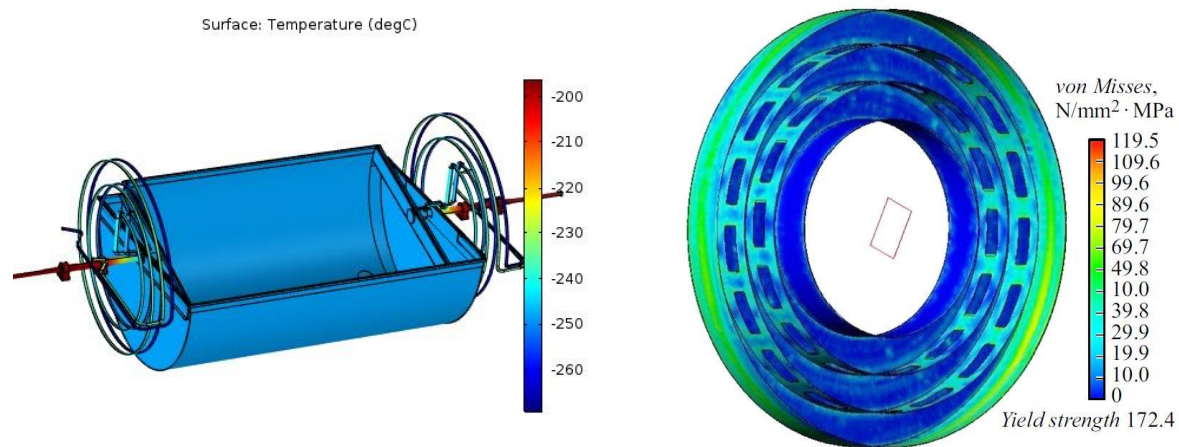


Figure 10. Left: External heat flow to the trap and insert. Right: liquid helium vessel stress calculation.

All required equipment recently have been manufactured then transported to the ILL and successfully installed. Now we perform preliminary tests to confirm that all our estimations are correct.

More detailed information can be found in [7].

Acknowledgements

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