Potential for the Neutron Lifetime Measurements in Traps

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The present situation in the neutron lifetime measurements is considered. Some new possibilities of the neutron lifetime measurement by the method of ultracold neutron storage in material traps and additional possibilities for the neutron storage in the magnetic storage ring are pointed out.

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1. INTRODUCTION

The neutron lifetime is still one of the least accurately measured fundamental nuclear constants. It is known that precision measurement of the neutron lifetime along with other neutron decay experiments has significant impact on the Standard Model parameters. Recent reviews are published in [1–4].

There are two principal ways to measure the neutron lifetime. In a neutron beam experiment the β-activity of a beam of cold neutrons is measured, and the neutron lifetime precision is determined by the accuracy of absolute measurement of neutron beam density in a well-defined fiducial volume in the beam and by the accuracy of absolute measurement of the neutron decay products (protons or electrons) count rate.

In the ultracold neutron (UCN) storage method the neutron lifetime is measured by counting surviving neutrons in a magnetic or material trap as a function of time. No absolute measurement is necessary in this case but serious problem arises in view of UCN losses in traps. In the UCN magnetic storage experiments the problem is in possible neutron spin-flip followed by its escape from the magnetic storage volume. Another problem is the marginal neutron trapping due to specular reflection of superbarrier neutrons from the ideally smooth magnetic mirror leading to appearance of quasi-bound neutron orbits.

In material traps the main problem is to account properly for the UCN losses in their collisions with the surface of a material confinement cavity. One tries to minimize these losses choosing the materials with the lowest neutron capture and suppressing the neutron upscattering by lowering the trap temperature.

The value of necessary corrections and systematic errors in inferring the neutron lifetime from the UCN storage data depend on these losses.

The present experimental data base for the free neutron decay is large but contains significant discrepancy between data.

The Table shows the values of the neutron lifetime obtained in the beam experiments and in the UCN storage experiments. Only the results with uncertainties not exceeding 10 s were taken into consideration.

Results of the neutron lifetime measurements in the beam experiments and in the UCN storage experiments

Beam experiments	Storage experiments
891±9 (1988) [5]	877±10 (1989) [11]
*893.6±3.8±3.7 (1990) [6]	870±8 (1989) [12]
889.2±3.0±3.8 (1996) [7]	887.6±3.0 (1989) [13]
*886.8±1.2±3.2 (2003) [8]	888.4±3.3 (1992) [14]
*886.6±1.2±3.2 (2004) [9]	882.6±2.7 (1993) [15]
886.3±1.2±3.2 (2005) [10]	885.4±0.9±0.4 (2000) [16]
	881.±3.0 (2000) [17]
	878.5±0.7±0.3 (2004) [18]
	* $874.6^{+4}_{-1.6}$ (2007) [19]
	878.2±1.9 (2009) [20]
Averaged value	**Averaged value without [18] and [20]**
887.6±2.7	885.±0.82
	Average value including [18] and [20]
	881.3±0.53

The data marked with the * are not used for obtaining the average values, only the last results of the corresponding experiment are taken into consideration.

The world average value [21] based on [5,7,10,13,14,15,16] is 885.7±0.8 s.

The latest publication of the MAMBO-II group [22] with the result for the neutron lifetime of 880.7$\pm 1.3 \pm 1.2$ s supports their earlier figure in [17] with better precision.

It is seen that the most precise UCN storage results may be divided in two groups: one – Refs.[13-16] and another – Refs.[18,20], with the work [17,22] between these groups.

These results are shown in Fig.1 as Gaussians with their mean values as the measured neutron lifetimes and the widths for the reported uncertainties.

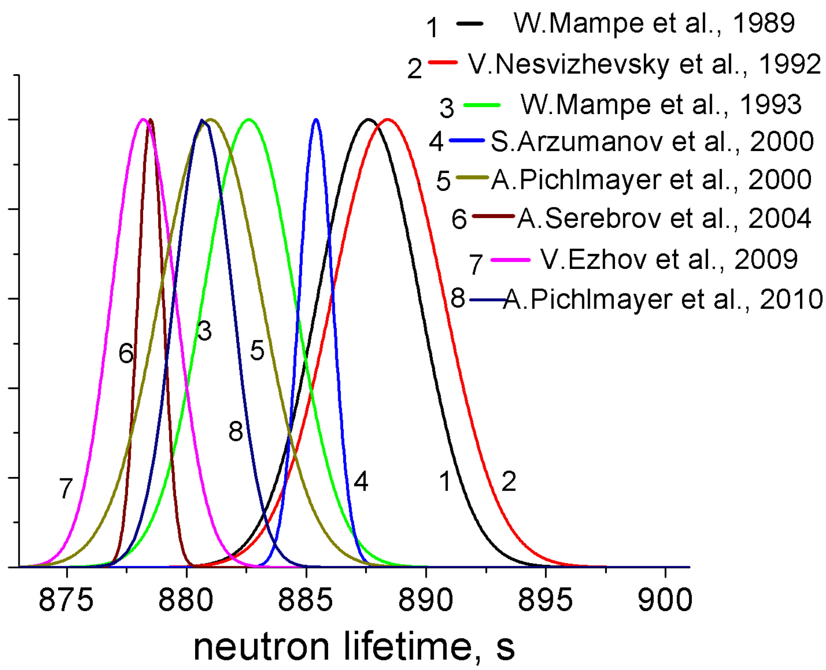

Figure 1: The resutls of the neutron lifetime measutrements shown as Gaussians with their mean values for the measured neutron lifetime and the widths for the reported uncertainties.

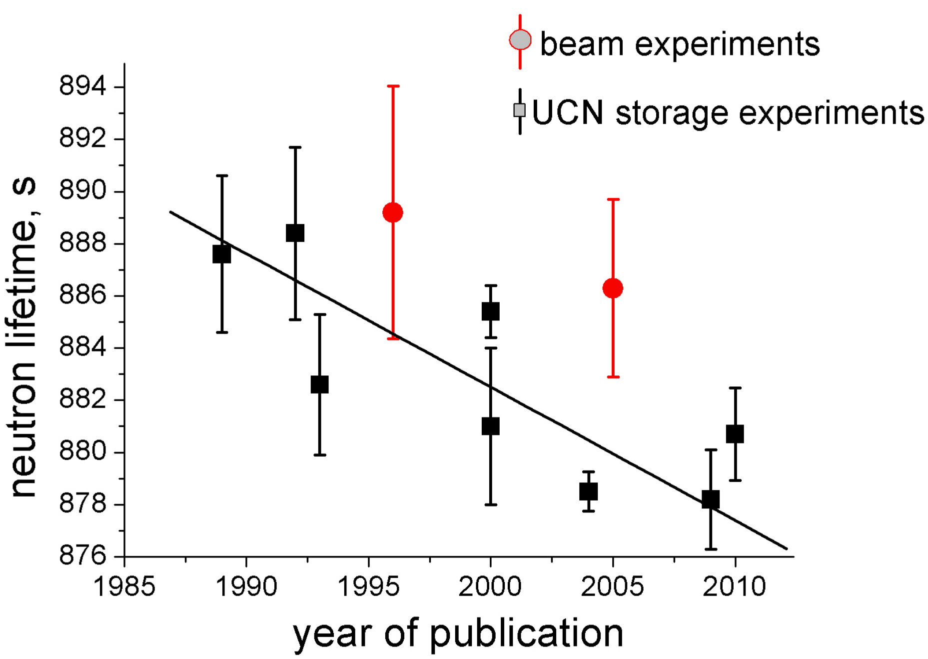

Figure 2: The resutls of the neutron lifetime measutrements shown as a function of the publication time.

Fig. 2 demonstrates interesting time drift of these results.

In view of this disagreement between UCN storage measurements and some difference between the results of the beam and the UCN storage experiments, new precision measurements of the neutron lifetime by different methods are desirable. It is essential that in the UCN storage experiments the total neutron disappearance probability is measured, whereas the beam experiments are only sensitive to the neutron beta decay.

2. UCN MATERIAL TRAPS

Different geometries of storage volume for the neutron lifetime measurement were considered in [23]: cylindrical with vertically and horizontally directed axis of the cylinder in respect to the Earth gravitational field, spherical, paraboloidal, conical, and vase.

It was shown that from practical point of view the geometry of vertical cylinder storage chamber (with perfect horizontal disc-absorber of neutrons at the upper side of the storage chamber for formation of the stored UCN spectrum) is the most optimal.

The results of simulation of the experiment with the UCN energy extrapolation is illustrated were presented in [23] for the vertical cylinder trap of the radius 50 cm.

The storage times and the values of collision losses were calculated for 6 different cut-offs of the initial stored UCN spectrum: from 20 neV to 100 neV. It was assumed that the storage times were measured with a statistical uncertainty of 4×10^{-4} (100 and 1000 s measurements, each with 10^7 counts), and were distributed randomly. It turned out that to reach this statistical precision needs ~ 530 cycles of fillings the neutron storage cavity if the number of stored neutrons in full spectrum with the E_{max}=100 neV is 10^6 per filling and linearly depends on the cutoff energy.

The extrapolation to zero losses was performed in different assumptions concerning possible deviations of the incident spectrum from Maxwell-like form and more serious difference of the real dependence of UCN losses on the neutron energy from calculated for the ideal step potential.

Analysis showed that the UCN loss energy dependence should be determined in this experiment with the precision no less than 5%.

It is obvious that for higher precision the loss corrections have to be evaluated more precisely and should be made as low as possible.

The low loss probability per one neutron collision with the wall is expected from the result of recent experiment [18], where the low temperature fluoropolymers [24] were used tocover the walls of the styorage chambers, and it was obtained the loss coefficient $\eta \approx 2 \times 10^{-6}$ for the low temperature fluorinated oil (PFPE), and there is hope to decrease further this value below 10^{-6} [25,26]. On the other hand, larger size storage traps compared to [18] should decrease the loss rate due to a decrease of the wall collision rate.

The computer simulation of the interesting proposal in the paper [27] to use the UCN trap in the form of a bellows with horizontal axis was also performed in [23]. When the length of bellows and consequently the volume of the trap is changed, the surface is remained unchanged. In this case extrapolation to zero losses is straightforward. The project to realize this approach is published in [28].

The result of these calculations was rather optimistic: at the loss coefficient $\eta = 10^{-5}$ the systematic effect arising from the deformation of the UCN storage volume at the size extrapolation is about 5×10^{-8} s^{-1} for the inverse lifetime or ≈ 0.04s for the neutron lifetime and does not depend on energy.

3. MAGNETIC RING

One of the most interesting methods of slow neutron storage has been proposed and experimentally demonstrated by Paul and collaborators [29,11]. It was a toroidal hexapole magnetic trap for very slow neutrons in the μeV energy range: the neutrons with longitudinal velocities between 8 and 15 m/s and radial velocity spread up to 4 m/s were stored in the ring with the diameter of $\sim$ 110 cm. The neutron injection from the neutron guide into the magnetic ring was performed with the help of fast pneumatically driven neutron mirror reflector. The final experiments [11], in which the neutron lifetime was measured with the precision 10 s, were performed at the very cold neutron channel of the PF-2 neutron source [30] of the ILL High Flux Reactor.

The great advantage may be achieved using pulsed injection of neutrons from the pulse neutron source [31,32]. In this method the neutron bunch from the UCN converter after spreading over the neutron guide can be trapped in the UCN cavity with high efficiency.

The detailed MCNP calculations for a solid para-hydrogen converter with an optimal cold ortho-hydrogen premoderator located in the radial channel of the MARK-2 TRIGA reactor yield the production of $\sim 10^8$ neutrons/Mole/10 MJ reactor pulse in the neutron velocity half-cylinder with the radius of 4 m/s and the longitudinal velocity interval from 8 to 15 m/s . Possible size of one-mole para-hydrogen converter: the diameter of 7 cm, the thickness of 0.5 cm is optimal for the reactor radial channel and for the neutron extraction in this energy range.

At the distance L from the neutron source to the entrance to the storage ring, and the neutron velocity interval of stored neutrons between v_1 and v_2, the length of the neutron bunch passed this distance is $L((v_2/v_1) - 1)$. The length of the neutron guide at the TRIGA reactor from the moderator to the entrance of the magnetic ring may be as short as about 5-6 m/s, and at the length of the storage ring $\sim$350 cm [31] practically optimal condition may be realized for the neutron injection: almost all the bunch in the longitudinal velocity range 8-15 m/s fills the storage ring during one reactor pulse. With larger storage ring and consequently larger orbit time the injection and storage will be more effective.

The neutron injection efficiency is not reported in [29]. In an assumption that the neutron survival during transport through the neutron guide and injection is only 1% it is expected up to 10^6 neutrons trapped in the ring per one filling. It is three orders of the magnitude larger than reported in [29,11].

The additional advantage consists in the possibility to variate the spectrum of injected neutrons with help of the pulse injector due to time-of-flight separation of neutrons in the neutron guide.

Similar possibility of pulsed neutron filling from pulse neutron source exists for other types of the magnetic traps for ultracold neutrons [32] if one provides the magnetic trap with pulse magnetic shutter.

It seems possible, in principle, to control neutron losses from magnetic ring by placing very slow neutron detector based on the low temperature scintillator (for example pure CsI [33]) at the outer side of the ring storage volume and PMT in the central part of the ring.

Another possibility – the decay proton counting is possible placing proton counters in the center of the storage ring and introducing accelerating electric field between the walls of the storage volume and the proton detectors.

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