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Monte Carlo simulation of quasi-elastic scattering and above-barrier neutrons in the neutron lifetime experiment MAMBO I

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Motivated by the strong disagreement of a recent result for the neutron lifetime with the previous world average value we report results of a Monte Carlo simulation of the neutron lifetime experiment MAMBO I, which was carried out some 20 years ago. In addition to all experimental parameters and procedures known to us, the analysis included quasi-elastic neutron scattering on the surface of liquid fomblin oil wall coatings of the UCN storage vessel, and above-barrier neutrons. The original analysis, leading to the published result of 887.6 ± 3 s, did not take into account these effects. For an exemplary set of model parameters we find a negative correction of 6.0 seconds, which demonstrates that these hitherto neglected effects may be very important also in the analysis of other neutron lifetime experiments using UCN storage vessels with fomblin oil coating close to room temperature.

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Introduction. A recent neutron lifetime experiment [1, 2] has provided the value 878.5 ± 0.8 s. It differs by 6.5 standard deviations from the world average value 885.7 ± 0.8 s quoted by the particle data group (PDG) in 2006. The experiment employed a gravitational trap with low-temperature fluorinated oil (fomblin) coating, which provides several advantages with respect to previous experiments. First of all, a small loss factor of only $2 \cdot 10^{-6}$ per collision of UCN with trap walls results in a low loss probability of only 1% of the probability of neutron β-decay. Therefore the measurement of neutron lifetime was almost direct; the extrapolation from the best storage time to the neutron lifetime was only 5 s. In these conditions it is practically impossible to obtain a systematical error of about 7 s. The quoted systematical error of the experimental result [1, 2] was 0.3 s.

Most of the previous experiments using UCN storage employed fomblin coating at room temperature [3 – 6]. Parallel investigations revealed that fomblin surfaces at room temperature generate significant quasi-elastic scattering of UCN, which, however, is strongly suppressed at low temperature [7, 8]. Experiment [1, 2] has been carried out at ~ 120 K, leading to a full suppression of quasi-elastic scattering of UCN. A mechanism of quasi-elastic scattering induced by surface waves of the liquid was proposed in ref. [9]. The theoretical statements of this work were checked in laser experiments [9] and in a UCN experiment [8]. The observed low-energy heating of UCN during storage in a trap with fomblin oil coating was in reasonable agreement with the theoretical expectations [8]. Therefore we decided to use the theory described in [9] and realize a Monte Carlo (MC) simulation of the first experiment [3], nowadays called MAMBO I, in which coating with the same fomblin oil was used.

Scheme and method of the neutron lifetime experiment MAMBO I. Below we reproduce a short description of the experiment [3]. The setup is shown in Fig.1. The UCN storage volume is a rectangular box,

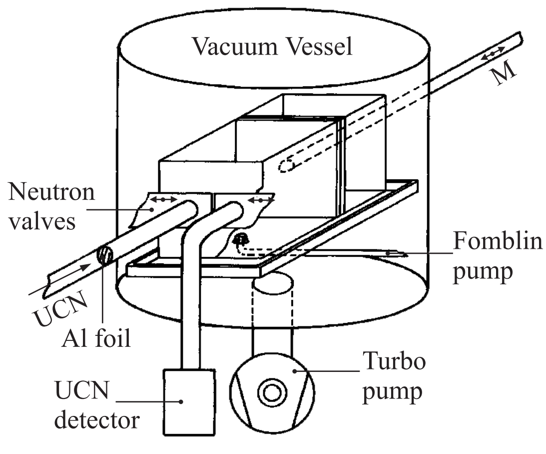

Fig.1. Sketch of the apparatus MAMBO I

with constant height 30 cm and width 40 cm but variable length $x < 55$ cm. The side walls and the roof of the box were made of 5-mm float-glass plates. The oil spray head is mounted on the metal base plate and the assembly is immersed in a 1-mm-deep lake of oil. The

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movable rear wall, composed of two glass plates with a 1-mm oil-filled gap in between, has a 0.1-mm play with respect to the neighboring walls, except for the base plate where it dips into the oil. The surface of the rear wall was covered with 2-mm-deep, 2-mm-wide sinusoidal corrugations. For half the surface the wave crests were horizontal, and for the other half vertical. This arrangement transforms within a few seconds the forwardly directed incoming neutron flux into the isotropic distribution essential for the validity of the mean-free-path formula $\lambda = 4V/S$. The UCN inlet and outlet shutters situated 8 cm above floor level are sliding glass plates with 65-mm holes matching holes in the front wall (Fig.1). More experimental details can be found in ref. [3].

The main idea of the experiment was to deduce the neutron lifetime from an extrapolation, by variation of the mean free path of UCN between wall collisions:

$$\tau_{st}^{-1} = \tau_n^{-1} + \mu(v)\nu(v) = \tau_n^{-1} + \mu(v)v/\lambda, \qquad (1)$$

where τ_{st}^{-1} is the inversed storage time constant, $\mu(v)$ is the neutron velocity dependent UCN loss factor per collision, $\nu(v)$ is the frequency of collisions, $\mu(v)\nu(v)$ is the probability of UCN losses, λ is the mean free path, and the relation $\lambda = 4V/S$ holds for an isotropic and homogeneous particle population in a trap of volume V and surface area S. Formula (1) shows that the inverse storage time is a linear function of inverse mean free path. The extrapolation of τ_{st}^{-1} to zero frequency of collisions will give the probability of neutron β-decay.

Unfortunately, a correct extrapolation is impossible for the case of a wide UCN spectrum, which changes its form during the storage process due to the velocity dependence of $\mu(v)$ and $\nu(v)$. To reduce the influence of this spectral dependence, it was proposed in [3] to fix the number of collisions for different trap sizes by a suitable choice of the UCN holding time. This leads to the following scaling relations,

$$\frac{t_2(i)}{t_2(j)} = \frac{t_1(i)}{t_1(j)} = \frac{\lambda(i)}{\lambda(j)} = \frac{t_2(i) - t_1(i)}{t_2(j) - t_1(j)}, \qquad (2)$$

where t_1 and t_2 are two different UCN holding times used to determine τ_{st}^{-1}, and the indices (i, j) correspond to different volumes. Unfortunately, even when the scaling conditions are fulfilled, the extrapolation is faked due to the gravitational field. The corresponding calculated correction was included in ref. [3].

Quasi-elastic scattering of UCN on the surface of liquid fomblin changes the UCN spectrum and therefore also has to be taken into account separately. A similar problem arises due to above-barrier neutrons. In this article we demonstrate the importance of this additional correction which was not taken into account in ref. [3].

Monte Carlo simulation. We performed MC simulations of the experiment [3] using a code able to take into account gravity and quasi-elastic scattering of UCN in the reflection from the fomblin coating. The code was written by A. Fomin specially for simulations with UCN. This code starts from an initial distribution of neutrons and calculates the track of each particle analytically until it reaches a material boundary. At each wall collision the loss and reflection probability is calculated, resulting in a new direction to calculate the trajectory until the next boundary is reached. The code uses specular and diffuse reflections with walls.

The relative importance of a particular effect (above-barrier neutrons or quasi-elastic scattering) to the final result can be investigated by switching it off in the simulation. Lacking the knowledge of the temperature at which the experiment [3] was carried out, we have performed our full analysis for 10 °C, for which an analytical description of the model for quasi-elastic scattering of UCN is available in ref. [9].

The calculations were done on computing clusters, in total lasting for about several months. In the following all detailed results are given for a reference volume with length $x = 55$ cm (see previous section) unless stated otherwise. Neutron reflection by the corrugated surface was approximated by 50% specular and 50% diffuse reflections from flat walls, if not stated differently. The time intervals of UCN holding were chosen the same as in the experiment. In all our simulations neutron lifetime was fixed to a definite value. The calculated corrections to the neutron lifetime extrapolated from our MC simulation were found to depend only weakly on the chosen value for τ_n.

Fig.2 shows for illustration some simulated data in comparison with experimental ones. It demonstrates that our model shows dependence similar to the experimental. Fig.2 from article [3] shows typical behavior only, without specified experimental conditions (for example, the surface structure of the movable wall). Without detailed experimental information we cannot reach full agreement with Fig.2 from [3]. It should be explained that the most important results are the extrapolated neutron lifetime values. Therefore it is more correct to compare the behavior of the extrapolated τ_n as function of holding time intervals.

Fig.3 is shown as a benchmark test of the extrapolated τ_n. One can see that we can reproduce the behavior of the extrapolated τ_n from holding time intervals for different type of the surface of the movable wall due to changes of specular reflectivity. The main part of mea-

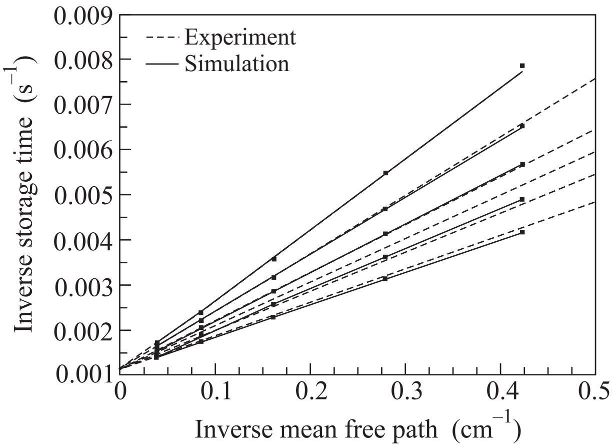

Fig.2. Measured inverse bottle lifetimes as a function of the bottle inverse mean free path and for different holding intervals (dotted lines). Experimental data stem from ref. [3], which were quoted there as typical. Results of simulation are shown by solid lines

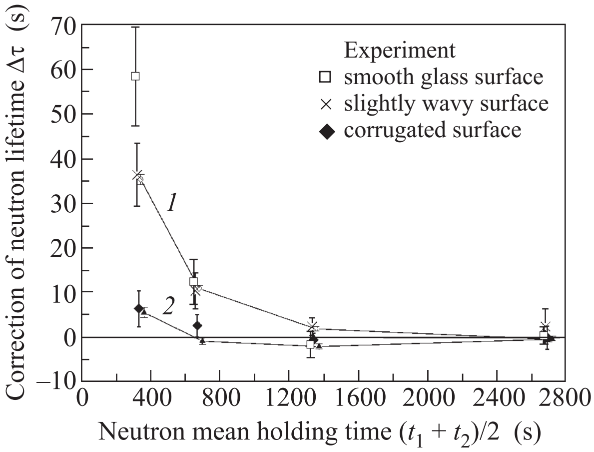

Fig.3. Dependence of the uncorrected experimental neutron lifetime on the holding time intervals for different bottle surface structures in comparison with results of the simulations with different probability of specular reflections from the walls: *1* – with 99% specular and 1% diffuse reflections, *2* – with 50% specular and 50% diffuse reflections

surements of [3] has been carried out with corrugated surface because in Table 1 of [3] just this data is shown. In our future analysis we use 50% specular and 50% diffuse reflections that describes reasonably the corrugated surface of the movable wall.

Next we investigated the dependence of simulation results on the initial UCN spectrum, which experimentally was known only poorly. Fig.4 demonstrates that this dependence is rather weak, particularly for the most important points with long holding time (but except for low holding time which anyway had negligible statistical

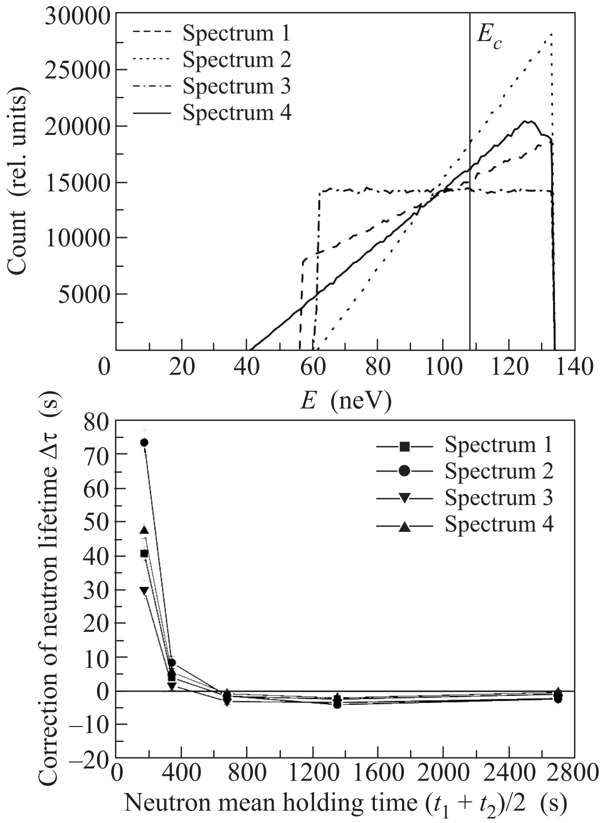

Fig.4. Results of simulations with different initial UCN spectra in the trap. E_c is critical energy of fomblin oil (108 neV)

weight in the result presented in [3], see also Table 1 further below). The corrections at the short holding time are proportional to amplitude of spectrum at critical energy 108 neV. In our future calculations we used the spectrum 4 shown by solid line in Fig.4.

The effect of the spectral changes during the storage process is shown in Fig.5. One can see that quasi-elastic scattering changes the form of the UCN spectrum considerably. Such changes are important as they can cause a systematic error. Above-barrier neutrons can be stored for a long time, particularly if the energy is near the critical one.

The results of extrapolations to neutron lifetime are shown in Fig.6 for different settings of the simulation in- or excluding different effects. Excluding above-barrier neutrons and quasi-elastic scattering (curve *1*) we can study the gravitational correction separately. Bigger volumes have larger relative area of the bottom plate and hence more UCN collisions with higher energy due to gravity, resulting in lower values of extrapolated neutron lifetime. The gravitational correction is practically independent from the UCN holding time. The extrapolated neutron lifetime is found lower than the neutron

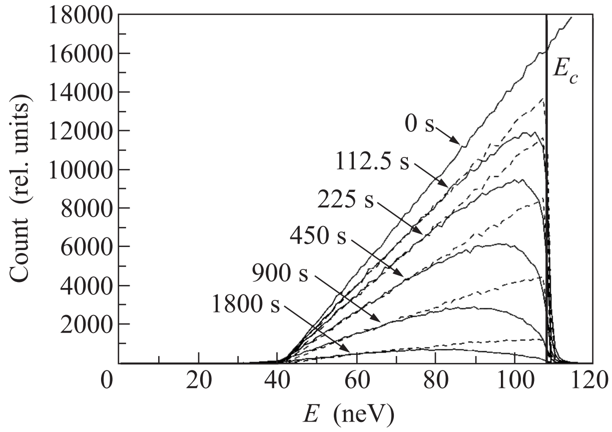

Fig.5. UCN spectra in the trap after different holding intervals without taking into account quasi-elastic scattering (dotted lines), and taking into account quasi-elastic scattering (solid lines). E_c is critical energy of fomblin oil (108 neV)

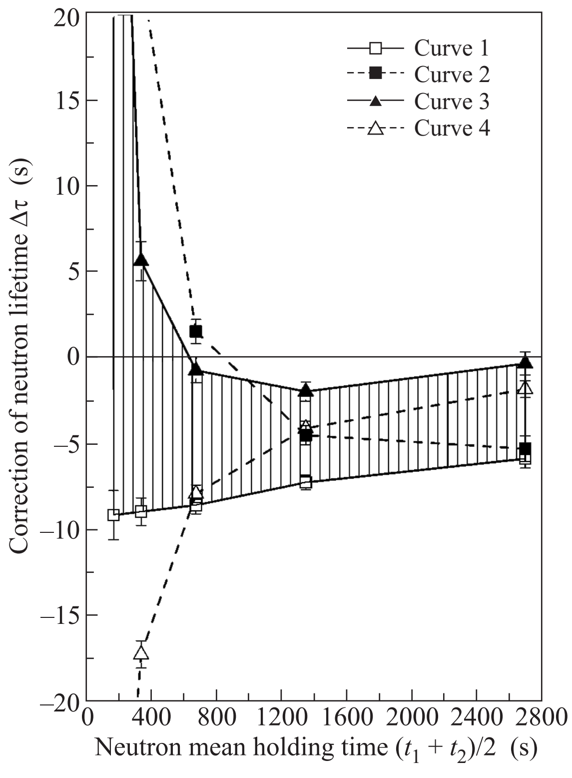

Fig.6. Results of MC simulations of the extrapolated neutron lifetime for different holding intervals: *1* – without quasi-elastic scattering and without above-barrier neutrons, *2* – without quasi-elastic scattering and with above-barrier neutrons, *3* – with quasi-elastic scattering and with above-barrier neutrons, *4* – with quasi-elastic scattering and without above-barrier neutrons. The difference between the curves *1* and *3* provides the correction due to above-barrier neutrons and quasi-elastic scattering which was not taken into account in work [3]

lifetime by 7.5 ± 0.3 s. This result is similar to the gravitational correction introduced in the work [3].

The next simulation shown in Fig.6 was done including above-barrier neutrons in the UCN spectrum but without quasi-elastic scattering (curve *2*). One can see that for short holding time the extrapolated neutron lifetime is much higher in comparison with the previous case for the gravitational correction (curve *1*), but for long holding time the extrapolated neutron lifetime comes rather close to it. However, note again that the contribution of results with short holding time in the final result of [3] is very small because of poor statistical accuracy of these measurements. The points with a holding time of (900–1800) s and (1800–3600) s bring the main contribution.

The next simulation shown in Fig.6 was done taking into account quasi-elastic scattering but without above-barrier neutrons (curve *4*). One can see that with increasing of holding time the extrapolated τ_n is increased due to appearance of new above-barrier neutrons.

The next simulation shown in Fig.6 was done taking into account quasi-elastic scattering and above-barrier neutrons (curve *3*). One can see that due to appearance of new above-barrier neutrons from quasi-elastic scattering the extrapolated τ_n cannot reach curve *1* at the long holding times. As result curve *3* has independence from the long holding times. This independence was interpreted in [3] that process of cleaning from above-barrier neutrons is finished and extrapolated τ_n at the long holding times can be accepted as a correct value. Unfortunately, it is not true due to effect of quasi-elastic scattering.

The difference between curves *1* and *3* is the total effect due to above-barrier neutrons and quasi-elastic scattering. These effects were not taken into account in the work [3]. In the work [3] two corrections were introduced: gravitational correction (+0.6%) and correction connected with the small differences in the initial spectra depending on the bottle size (+0.3%). Table quotes data from the work [3] with our additional corrections due to above-barrier neutrons and quasi-elastic scattering effects. In this table we use the data for long holding time intervals which bring the main contribution and do not depend from entry conditions (the form of initial spectrum, diffusion of a covering). As total correction we find -6.0 ± 1.6 s. Our correction is negative one and roughly compensates corrections from [3]. The systematic uncertainty in [3] is estimated about 3 s. It can cover substantially a lack of the information on experiment details. The resulting corrected value for the neutron lifetime would agree with the result 878.5 ± 0.8 s of the work [1, 2].

Results for neutron lifetime τ_n obtained from different holding intervals: τ_n is the result from work [3], $\Delta\tau$ [3] is the correction from [3], $\Delta\tau$ (this article) is the correction due to above-barrier neutrons and quasi-elastic scattering calculated in this work, and $\tau'_n = \tau_n$ (corrected [3]) + $\Delta\tau$ (this article)

Holding interval, s	τ_n, s (uncorrected [3])	$\Delta\tau$, s [3]	τ_n, s (corrected [3])	$\Delta\tau$, s (this article)	τ'_n s
112.5–225	893(10)	~ -2	891(10)		
225–450	885.0(4)	+3.5	888.5(4)		
450–900	881.2(2.5)	+8	889.2(2.5)	−7.84 (0.87)	881.36 (2.65)
900–1800	878.0(1.5)	+9	887.0(1.5)	−5.29 (0.70)	881.71 (1.65)
1800–3600	878.5(2.6)	+8.6	887.1(2.6)	−5.54 (0.87)	881.56 (2.74)
			$\tau_n = 887.6(1.1)$ s		$\tau'_n = 881.6(1.2)$ s

Finishing the article we have to say that we are unable to propose an official correction of the result of experiment [3]. This is matter of the authors of that work which know all experimental details, such as the temperature of the UCN storage volume. Our goal was to demonstrate that hitherto neglected effects of quasi-elastic scattering and above-barrier neutrons in UCN storage experiments using fomblin oil coating close to room temperature may fake neutron lifetime experiments by many seconds.

We would like to give a high regard to the main initiator of the experiment [3], Walter Mampe, who made a very significant contribution to the development of UCN experiments at ILL, and who succeeded in uniting physicists from different countries to carry out these tasks. We are very grateful to Mike Pendlebury for useful discussions in course of this work. We also would like to thank Oliver Zimmer for critical remarks on the manuscript. The given investigation has been supported by RFBR grant 07-02-00859. The calculations were done at computing clusters: PNPI ITAD cluster, PNPI PC Farm.

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