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Neutron lifetime measurement with the UCN trap-in-trap MAMBO II

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ABSTRACT

We have measured the free neutron lifetime τ_n by storage of ultra-cold neutrons (UCN) in a Fomblin coated UCN trap of in situ variable size. The method was initially developed by W. Mampe et al. (1989) [10] with MAMBO I and improved by the addition of a prestorage volume yielding a well defined UCN spectrum for storage in the main trap. By extrapolation to infinite trap size using the time scaling method we obtain for the free neutron lifetime $\tau_n = (880.7 \pm 1.3 \pm 1.2)$ s. Data from different UCN spectra, trap temperatures and storage times were used for the evaluation. The present result is compared with other experimental neutron lifetime data.

1. Introduction

The beta decay of the free neutron is of fundamental importance as a semileptonic weak interaction process $n \rightarrow p + e^- + \overline{\nu_e}$. The value of the mean lifetime of the neutron τ_n (decay constant λ_n) is related to the weak interaction constants g_V and g_A by

$$\tau_n^{-1} = \lambda_n \propto \left(g_V^2 + 3g_A^2\right). \tag{1}$$

The constant in the proportionality comprises essentially phase space with radiative corrections and natural constants. Combined with correlation coefficients in neutron decay, the CKM matrix element V_{ud} can be deduced from the neutron decay alone and used for various sensitive tests of the Standard Model [1–3].

The neutron lifetime is also of relevance in astrophysics and cosmology. It enters as a parameter in the primordial element formation. Furthermore the cross section for the pp-cycle in stars is proportional to g_A^2 of the neutron apart from strong interaction corrections and the cross section for the charged current antineutrino reaction with protons is proportional to λ_n [4–6].

In recent years τ_n measurements were cited with improved precision and converged to a value of 885.7(0.8) s adapted by the PDG in 2008 [7]. The recent experiment by Serebrov et al. with $(878.5 \pm 0.7 \pm 0.3)$ s [8] is far off the world average and was even not yet considered for the average by PDG 2008, which claimed for that reason the present world average value as 'suspect' [7]; see also the recent review on τ_n measurements by S. Paul [9].

In the present Letter a free neutron lifetime experiment is described using the facility MAMBO II (MAMpe BOttle). The experimental approach is the successor of MAMBO I, which was a breakthrough in precision for UCN storage experiments and led to the result 887.6(3.0) s [10]. Based on their experience with MAMBO I, Mampe et al. started the concept and design of MAMBO II. The early death of W. Mampe prevented him from carrying out the experiment, but his ideas were the essential prerequisite for the work with the improved method we present here. Preliminary results of MAMBO II measurements were already published as 881(3) s [11, 12]. The set-up was slightly modified later on and new data were taken. The final result based on all data is given in this Letter.

2. MAMBO concept

The common feature of the neutron lifetime experiments MAMBO is a rectangular glass box as UCN trap, coated with Fomblin oil and placed in a vacuum chamber. The movable sidewall of the trap allows for a change of the volume without breaking the vacuum (piston (4), see Fig. 1). Fomblin has a pseudo Fermi potential for UCN of $V_F = 106$ neV and, being hydrogen free, its loss probability per UCN wall collision is as low as a few 10^{-5} at room temperature below the potential threshold. Fomblin oil covers smoothly the walls and seals possible small leaks. Conceptually the free neutron lifetime is deduced from the UCN storage constants in traps of different sizes through extrapolation by a proper method to an infinitely large trap.

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In a first approximation we omit the influence of gravity on the UCN in the trap (gravitational potential 103 neV per meter height in the earth field). The time development of an energy bin $dN = n(E)\,dE$ of the UCN population N in the trap is then described by an exponential decay with storage constant $\lambda_{st} = \tau_{st}^{-1}$

$$n(E,t) = n_0(E)\exp(-\lambda_{st}t) \tag{2}$$

$$\lambda_{st} = \lambda_n + \lambda_{\text{loss}} = \lambda_n + \frac{\upsilon}{\ell}\overline{\mu}(E) \tag{3}$$

The quantity ℓ is the mean free path in the trap, for an ideal gas $\ell = 4V/A$, with V volume, A surface. The UCN collision frequency with the trap walls is given by υ/ℓ. The UCN loss probability per collision averaged over incident angles (isotropic) is described by [13]

$$\overline{\mu}(E) = 2f\bigl(V_F/E\cdot\arcsin(\sqrt{E/V_F}\,) - \sqrt{(V_F-E)/E}\,\bigr) \tag{4}$$

with the UCN energy E and f the velocity independent but wall temperature dependent loss coefficient at the potential step of the Fomblin surface (ratio of imaginary W_F to the real part V_F of the Fermi potential).

For monoenergetic UCN the free neutron lifetime can be evaluated straight forwardly by measuring the storage constant λ_{st} via the exponential decay of the UCN population in traps of different sizes and thus different mean free path ℓ. The interception of the straight line $\lambda_n = \lambda_{st} - \upsilon/\ell\cdot\overline{\mu}(E)$ at $1/\ell = 0$ yields λ_n.

A broader UCN spectrum changes during storage since the loss rates are velocity dependent (collision frequency and $\overline{\mu}(E)$). By the time scaling method this effect can be compensated. A trap is filled at the time t_0 and the UCN population is measured after storage times t_1 and then, after the next filling, at t_2. The storage experiment is repeated with a different trap size and storage times t'_1 and t'_2. These storage times are chosen such that the integral number of wall collisions is the same as with t_1 and t_2 in the first trap respectively:

$$t'_{1,2} = \frac{\ell'}{\ell}t_{1,2} \tag{5}$$

In other words the UCN spectra are the same for the corresponding storage time t_1, t'_1 and t_2, t'_2, provided the initial spectrum is the same for these cases. We then get the trap population N_1, N_2 for the two storage times:

$$\begin{aligned} N_{1,2} &= \int n(E,t_{1,2})\,dE \\ &= \exp(-\lambda_n t_{1,2})\cdot\int n_0(E)\exp\left(-\frac{\upsilon}{\ell}\overline{\mu}(E)t_{1,2}\right)dE \end{aligned} \tag{6}$$

and correspondingly for the population $N'_{1,2}$ for the trap of different size. With the scaling Eq. (5) the integral of the right side in Eq. (6) is identical for the two trap sizes and cancels in the ratios N_i/N'_i, and hence in the logarithmic difference, thus

$$\ln\frac{N_1}{N_2} - \ln\frac{N'_1}{N'_2} = \lambda_n(t_2 - t_1) - \lambda_n(t'_2 - t'_1) \tag{7}$$

While the decay curve is in general not exponential, λ_{st} is defined by the two measured UCN population $\{N_1, t_1\}$, $\{N_2, t_2\}$ and for the other trap size correspondingly:

$$\lambda_{st} = \ln\frac{N_1}{N_2}/(t_2 - t_1) \tag{8}$$

$$\lambda_n = \frac{\lambda_{st}/\ell' - \lambda'_{st}/\ell}{1/\ell' - 1/\ell} \tag{9}$$

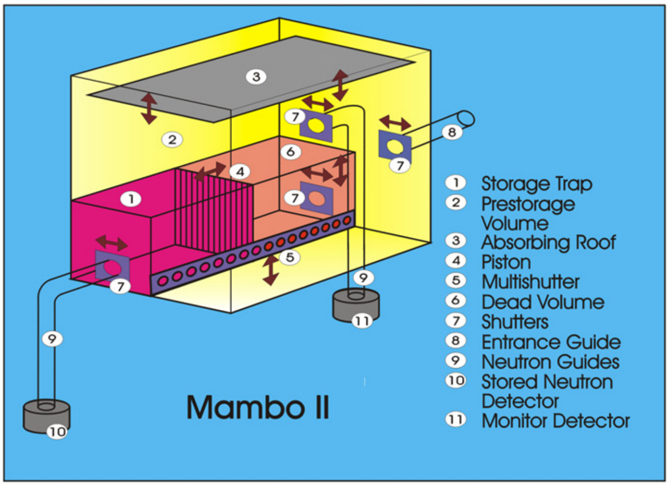

Fig. 1. Schematic view of the MAMBO II installation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

So far the initial, but identical UCN spectrum does not have to be known and λ_n is the intercept at $1/\ell = 0$ for a straight line defined by the two points $\{\lambda_{st}, 1/\ell\}$ and $\{\lambda'_{st}, 1/\ell'\}$.

Including gravity the UCN spectrum varies with height h in the trap. For this purpose λ_{loss} is written as (see [14])

$$\lambda_{\text{loss}} = f\gamma = \frac{\iint(\overline{\mu}(E)n(E,h)\upsilon/4)\,dA\,d\varepsilon}{\iint n(E,h)\,dV\,d\varepsilon} \tag{10}$$

$$n(E,h)\upsilon = \frac{\varepsilon - mgh}{\varepsilon}\cdot n(\varepsilon)\cdot\sqrt{\frac{2\varepsilon}{m}} \tag{11}$$

where ε denotes the UCN energy at the bottom of the trap, hence kinetic plus potential energy in the trap relative to the bottom. The expression $n(E,h)\upsilon/4$ is the collision frequency per unit of the surface. The integrals run over the surface area A and the volume V of the trap. For a spatial uniform $n(E)$, Eq. (10) corresponds to Eq. (3) and Eq. (6) since $\ell = 4V/A$. The effective collision rate is represented by the parameter γ and has to be calculated for each trap size [11,12,14,15] including all internal structures of the main storage trap such as corrugated piston and shutters. The neutron lifetime is then derived similarly to Eq. (9), where $1/\ell$ is replaced by γ:

$$\lambda_n = \frac{\lambda_{st}\gamma' - \lambda'_{st}\gamma}{\gamma' - \gamma} \tag{12}$$

For simplicity the equations are given for two trap sizes. Combining more trap sizes, a straight line fit is applied on the linear function equation (12) with the points $\{\lambda_{st}^{(i)}, \gamma^{(i)}\}$ to evaluate the intercept λ_n $(=\lambda_{\gamma\to 0})$.

The difference in the lifetime value calculated with and without gravity ($g = 0$ in Eqs. (10), (11), equivalent of using Eq. (12) instead of Eq. (9)), denoted in the following gravity effect, depends on the neutron spectrum and $\overline{\mu}(E)$ and amounts from 5 to 8 s in our case [12,15].

For the calculation of γ the UCN spectrum must be known. It should be emphasized however that UCN filling and emptying constant for the trap as well as detector efficiency enter only in the neutron lifetime evaluation if they differ as function of storage time in a trap.

3. MAMBO II set-up

In order to avoid UCN with energies close to V_F of Fomblin in the trap and to fill the trap with the same UCN spectrum independent of the trap size MAMBO II was designed. A prestorage volume (outer trap) was added to shape the UCN spectrum before filling the main storage trap. The MAMBO II set-up is shown in Fig. 1. During the time of data acquisition it was mounted at the UCN turbine PF2 at the ILL Grenoble, France [16]. The UCN source provides a typical UCN density of 30 UCN/cm^3 for velocities up to 9 m/s.

The MAMBO II concept works as follows (Fig. 1). The neutrons are fed into the prestorage volume (2) through the stainless steel entrance neutron guide (8) and the entrance shutter (7) 49 cm above the bottom of the trap defining the lower cut off of the spectrum to $\varepsilon = 50$ neV. The prestorage volume is a rectangular box approximately 1 m^3 in size, made of stainless steel and covered with Fomblin grease (mixture of Fomblin oil with Teflon powder). A polyethylene absorbing roof (3) of variable height cuts the UCN spectrum according to the gravitational potential. Through the multishutter (5) the UCN are fed into the rectangular main storage trap (1) of fixed width and height of 43 cm and 42 cm, respectively, and a variable length of 0 to 75 cm by a movable piston (4). The piston has a corrugated glass surface to avoid quasi-stationary orbits of the UCN in the trap and to maintain a homogeneous UCN momentum distribution. The complete inner surface of the storage trap is covered with Fomblin oil. The piston is sealed gas tight against the walls by a groove continuously supplied with Fomblin oil. To refresh the wall surfaces with Fomblin, the oil is filled via the piston grooves into the storage trap, the volume is reduced by moving the piston forward until the oil fills this volume completely and then moved backwards. The storage trap was tested for possible leakage with 1 mbar nitrogen gas in the main storage trap while the prestorage volume was evacuated. No decrease of the pressure was observed in holding tests of days. The dead volume (6) behind the piston is covered with Fomblin grease and is used for the necessary mechanics to move the piston and for the supply with Fomblin oil. After the storage the remaining UCN are emptied through the exit shutter (7) and neutron guide (9) into the stored neutron detector (10). The detector events were recorded time resolved. The detector is a microstrip detector [17] filled with 50 mbar ^{3}He and 1000 mbar CF$_4$ added as buffer gas. The monitor detector (11) is similar to the main detector and used to monitor the UCN density in the prestorage volume.

By heating and cooling of the bottom aluminum plate the temperature of the traps could be controlled and varied between 4 and 50 °C. The whole set-up is placed inside a vacuum vessel with a total volume of about 2500ℓ, evacuated to a vacuum of $8 \cdot 10^{-6}$ mbar or better. A mass spectrometer and various Penning gauges allow constant monitoring of the vacuum conditions. All movements of the shutters and the absorbing roof were controlled by a PC as well as the data acquisition of the UCN counters and the overall timing of the experiment.

4. Measurements and result

The following standard cycle for the various measurements was established. During the whole cycle the shutter to the monitor detector was fixed at 10% of the maximum open position to allow for constant monitoring of the UCN density. First the UCN were filled into the prestorage volume while the main storage trap was closed, achieving more than 90% of the equilibrium density in 150 s. Then the entrance shutter was closed and the UCN were stored in the prestorage volume for a cleaning time of 100 s to remove the faster neutrons by up-scattering at the absorbing roof. The measured mean cleaning time was 46 s, the mean storage time of the UCN in the prestorage volume about 320 s. Then the multishutter was opened for 40 s to fill the main storage trap (mean filling time 6 s). In the next step the multishutter was closed, the shutter opened to the monitor detector and in the main storage trap the UCN were held for the chosen storage time ranging for the large trap length of 75 cm from 100 to 3000 s. Then the detector shutter was opened and the surviving UCN were counted in the stored neutron detector. Finally all shutters were opened for 200 to 400 s to allow the whole installation to be drained of all remaining UCN and for vacuum pumping. The typical initial UCN density in the main storage trap was 0.5 UCN/cm^3. The recorded number of UCN in the stored neutron detector was typically 40 000 after 100 s storage time with 75 cm trap length and 90 cm height of the absorbing roof (see Fig. 2). The subtracted background amounted to about 0.1 cts/s.

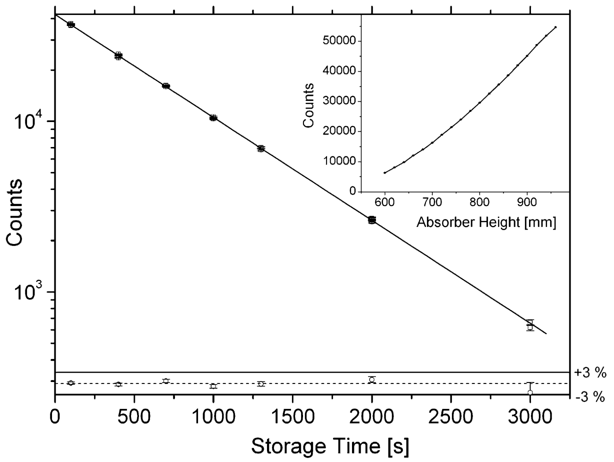

Fig. 2. The decay curve of UCN population in the main storage trap is very close to exponential, represented by the line with one exponent, yielding a mean storage time of 719.4(3.4) s (here 75 cm trap length, 90 cm absorber height, 22 °C). The residuals are given at the bottom in percent of the counts. The inset shows the measured UCN population as function of absorber height. By differentiation the UCN spectrum $n(\varepsilon)$ was deduced and could be well approximated by $n(\varepsilon) = n_0(\varepsilon - 50\ \text{neV})^{0.58}$, with cut-off at the absorber position.

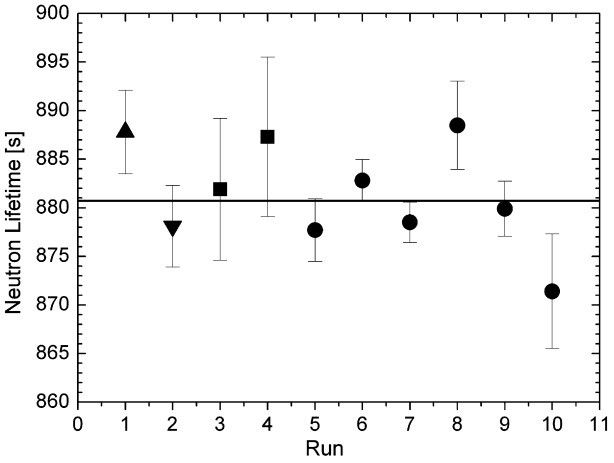

Fig. 3. Result of the neutron lifetime for the different runs including residual gas and trap emptying corrections. Statistical uncertainties are shown. The wall temperature was 4 °C for run 1, 10 °C for run 2 and 22 °C for all others. The run 3 to run 10 differ in the scaled storage times (see also Table 1). The UCN spectrum was shaped with the absorbing roof at 90 cm. The average value of 880.7 s is indicated as a horizontal line.

The neutron lifetime data were recorded in two separate periods of about 6 months of beam time and spread over about two years each. Data from the first period (run 1 to run 4 in Fig. 3) were used for the preliminary result [11]. The measurement cycles described above were repeated with unchanged parameters during 2 days. Then the surface coatings were refreshed and the

Table 1

Parameters for some of the experimental neutron lifetime runs (see Fig. 3). The values in parentheses denote the length of the main storage trap in cm. The storage times are given for 75 cm length and were scaled as $t_i = t_{1,2}\ell_i/\ell_{1,2}$ for the other lengths. The final value τ_n is calculated with the given effective collision rates γ (Eq. (12)), and corrected for residual gas and the efficiency.

	Runs				Trap length [cm]	Mean fr. path ℓ [cm]	Eff. coll. r. γ [s^{-1}]
	Run 1	Run 2	Run 6	Run 9			
Wall temp.	4 °C	10 °C	22 °C	22 °C			
t_1; t_2 (75)	780; 2900	720; 2900	100; 1900	1000; 2800			
τ_{st} (75) [s]	771.4(1.5)	762.2(1.8)	736.5 (0.7)	733.1(1.0)	75	32.25	13.256
τ_{st} (19.2) [s]	708.6(1.5)	702.6(3.1)	663.8(1.7)	659.7(2.4)	19.2	19.04	22.049
τ_{st} (6.8) [s]	588.5(3.6)	580.7(2.7)	528.1(1.5)	524.7(1.7)	6.8	9.19	45.005
$\tau_{\gamma\to 0}$ [s]	887.3(4.3)	876.6(4.2)	881.7(2.2)	878.8(2.8)			
Res. gas [s]	+0.7	+1.2	+0.8	+0.8			
Eff. corr. [s]	+0.3	+0.3	+0.3	+0.3			
τ_n [s]	888.3(4.3)	878.1(4.2)	882.8(2.2)	879.9(2.8)			

measurements continued for different parameters, although even 7 days without refreshment did not change the mean storage times. According to the scaling method the storage constants λ_{st} were deduced from pairs of UCN population at the scaled times (see data in Table 1).

Various characteristic values were determined in view of the neutron lifetime determination. For the determination of the UCN spectrum the above measurement cycle was carried out for different absorber heights with a constant trap length and the same storage time in the main trap (200 s). The corresponding counts in the stored neutron detector yield the integral UCN spectrum as function of absorber height (inset of Fig. 2). In this type of investigations also the different mean time constants for UCN filling, cleaning and emptying were determined. These were then used as the base for the timing of the standard measurement cycle as described above. The decay of the UCN population in the trap was observed to be exactly exponential (see Fig. 2) although the UCN spectrum was not monoenergetic. To understand this not obvious exponential decay we simulated the decay of the UCN population in the main storage trap using Eq. (6) with Eq. (4) and the measured UCN spectrum. With this rather narrow UCN spectrum and since $\lambda_{\text{loss}} \ll \lambda_n$ we obtained the observed exponential characteristic. This characteristic is not a prerequisite for the scaling method, but possible systematic uncertainties due to the chosen scaling times were negligible. The measurements were timed and the data evaluated according to the scaling method.

Due to the energy dependent losses the UCN spectrum softens with storage time and thus the mean emptying time measured with the stored neutron detector should increase, causing a reduction of the detection efficiency for the UCN population. The UCN detector counting rate showed an exponential emptying curve within the statistical accuracy down to the background proving that the isotropic rearrangement of the UCN population by the corrugated surface of the piston worked very effectively. For the largest trap length used (75 cm) and 90 cm absorber height the mean emptying time was measured as 57.8(3) s and 58.2(6) s after 720 s and 2880 s storage time respectively and thus differed only by 0.4(7) s, again due to the narrow UCN spectrum and $\lambda_{\text{loss}} \ll \lambda_n$. From this experimental result we deduced a possible decrease of the detection efficiency of $(0.05 \pm 0.09)\%$ between those two storage times. Thus the mean storage time for the big trap size is corrected by 0.14 ± 0.22 s. In combination with data from a short trap (typically 6.8 cm, negligible efficiency effect) the correction for τ_n results in +0.3 s with an uncertainty of 0.5 s.

The measured lifetimes were corrected for UCN up-scattering and absorption by the residual gas, the composition and absolute pressure of which were measured before and after the storage period by a mass spectrometer and a vacuum gauge, respectively, placed in the neutron guide (9) to the stored neutron detector. In a reasonable approximation the UCN are at rest and the gas molecules move with the ambient temperature. The reaction rate R of a UCN with gas molecules of density n_{gas} is then given by the common relation

$$R = n_{\text{gas}} \upsilon_{\text{gas}} \sigma = \lambda_{\text{loss, gas}} \tag{13}$$

This loss rate is dominated by inelastic scattering with water molecules (bound cross section 150 barns). The loss probability, including neutron capture at hydrogen, is then $\lambda_{\text{loss,gas}} = 0.24\ \text{mbar}^{-1}\,\text{s}^{-1}$ for water vapor of 300 K (mean velocity 600 m/s). For the first runs, the pressure was increasing in the closed storage trap during UCN storage due to the out gassing of the Fomblin oil and the correction for τ_n was up to 1.4 s. In the second set of measurements the out gassing of the Fomblin oil in the storage trap was significantly reduced by a cleaning loop in the prestorage volume. Then the pressure remained stable at typically $5 \cdot 10^{-6}$ mbar (partial pressure 80% water vapor, 20% nitrogen) in the closed main trap during the storage time (correction in τ_n of +0.8 s). We estimated an uncertainty of 0.4 s for these corrections which is mainly caused by the residual gas measurements carried out in the neutron guide (9) after opening the shutter instead of directly in the main storage trap.

The results for the different runs are shown in Fig. 3, already corrected for the residual gas and mean emptying time effect. For illustration the parameters for some runs which different wall temperatures and storage time pairs, respectively, are given in Table 1. The values were evaluated using Eq. (12) which includes already the gravity effect. With the data of Table 1, the intercept $1/\ell = 0$ in Eq. (9) gives, compared to $\tau_{\gamma\to 0}$, lower τ values by 6.0 s, 6.0 s and 7.8 s for 4 °C, 10 °C and 22 °C wall temperatures, respectively. These differences correspond to the size of the gravity effect. When comparing the mean storage times for one trap length, the dependence of the loss coefficient f on the wall temperature can be seen. The first four runs were already used for the preliminary MAMBO II result [11] and reevaluated for the present results. The weighted mean of the data gives a neutron lifetime of 880.7 s with a statistical error of 1.1 s and a χ^2 of 1.4, leading to a statistical accuracy of 1.3 s. The different temperatures of the trap wall and different scaled storage time pairs yielded consistent results for τ_n within the statistical uncertainty. Higher statistical accuracy in the test and the decay measurements was limited due to the rather low UCN density available.

The neutron lifetime values used for the average (Fig. 3) were taken with the absorbing roof height of 90 cm. Also measurements with a roof position of 60 cm were performed. However these data were used only for the investigation of $\overline{\mu}(E)$ as explained below, since the statistical accuracy for the neutron lifetime was low resulting in 886(11) s. In addition a possible efficiency correction due

Table 2
Summary of systematic uncertainties. The total systematic uncertainty results in ±1.2 s.

Kind of uncertainty	Shift in τ_n	Uncertainty $\Delta\tau_n$
Length of trap	–	0.7 s
Volume by Fomblin	–	0.3 s
Residual gas	$+0.7 \cdots +1.4$ s	0.4 s
Loss coefficient f	–	0.4 s
Shape of μ	–	0.5 s
Mean emptying time	+0.3 s	0.5 s
Temp. gradient 22 °C	–	0.1 s
Temp. gradient 4 °C, 10 °C	–	< 0.3 s

to the mean emptying times could not be deduced reliably because of the low statistical precision of the data.

For the systematic precision further effects were considered (Table 2). Geometrically the position of the piston was only reproducible within 0.3 mm corresponding to an uncertainly in τ_n of 0.7 s. An uncertainty of 0.3 s is estimated for a possible volume change by the Fomblin flow in the trap. In the gravity effect the loss probability $\overline{\mu}(E)$, Eq. (4), enters and quasi-elastic scattering [16] may be of concern. The loss coefficient f can be deduced from the different pairs of measuring points and should show up in a straight line $\lambda_{st} = \lambda_n + f\gamma$ for the data of various trap lengths. For 4 °C, 10 °C and 22 °C we derived $f = 1.3(1) \cdot 10^{-5}$, $1.4(1) \cdot 10^{-5}$ and $1.8(1) \cdot 10^{-5}$, respectively. A similar value was found in the MAMBO I experiment ($1.6 \cdot 10^{-5}$, ambient temperature, Ref. [10]). The gravity effect is linear in the collision coefficient f [14,15]. Thus we derive for instance for 22 °C with that uncertainty in f of 5.5% an uncertainty of $0.055 \cdot 7\ \text{s} = 0.4$ s on the gravity effect and hence τ_n.

The UCN energy dependence of $\overline{\mu}(E)$, Eq. (4), can be checked by the measured trap mean storage times for different UCN spectra (absorber heights). This check includes also possible quasi-elastic scattering, which is anyhow a small effect in our case (probability $<10^{-6}$ for scattering beyond V_F, i.e. energy gain more than 13 neV [18]). For absorber height 60 and 90 cm (trap length 75 cm, 10 °C) the measured λ_{st}^{-1} were 808.6(2.3) s and 761.8(0.6) s, respectively. For the UCN energy range relevant in the present storage experiment the dependence of $\overline{\mu}$ on (E/V_F) can be well approximated by a straight line to

$$\overline{\mu}(E) = 2f\bigl(\alpha \cdot (E/V_F) + \beta\bigr) = 2f\bigl(0.93 \cdot (E/V_F) + 0.11\bigr).$$

The above λ_{st}^{-1} values with their error bars are reproduced by that slope within 8% accuracy. Approximately the gravity effect is proportional to that slope α (see quantity a_2 in Ref. [14] when evaluated with a straight line for $\overline{\mu}(E)$), and in analogy to the case of f we derive an uncertainty of 0.5 s for τ_n.

The systematic uncertainties, added in quadrature, give an overall value of 1.2 s. The final result of our MAMBO II measurement with statistical and systematic uncertainties is thus

$$\tau_n = (880.7 \pm 1.3 \pm 1.2)\ \text{s} = (880.7 \pm 1.8)\ \text{s}$$

5. Discussion and conclusion

We have derived from MAMBO II a τ_n value of 880.7 s with 1.8 s precision. The possible systematic uncertainties were mostly estimated from measured quantities.

A rather large extrapolation from the mean storage time in the storage trap to the free neutron lifetime was necessary in our experiment, ranging up to 150 s, while the derived systematic uncertainty is 1.2 s. However apart from the gravity effect (5 to 8 s) the dominant part of this extrapolation is based only on the knowledge of the geometry of the main storage trap and a homogeneous coverage of its walls with Fomblin and thus is well controlled (see Table 2, first two entries: absolute uncertainty about 0.8 s, i.e. about 0.7% relative to the size of the extrapolation). The UCN spectrum and the UCN energy dependent loss probability in wall collisions enter only in the rather small gravity effect, and were derived with an absolute uncertainty of about 0.7 s, i.e. about 10% relative to the gravity effect.

Concerning the MAMBO I result (887.6(3.0) s) [10] contradictory statements about the validity of that value can be found in the literature. Lamoreaux et al. [19] included quasi-elastic scattering in a simulation of MAMBO I and claimed that the scaling method used still works, while a Monte Carlo calculation by Serebrov et al. [20] suggests that the MAMBO I value has to be lowered. A firm judgment on the MAMBO I result however is difficult without additional spectral measurements with this no longer assembled set-up, which are obviously impossible. The MAMBO I value differs from the present MAMBO II result by only 2σ. The authors of MAMBO I had already realized that various uncertainties in the derived τ_n could not definitely be controlled in the MAMBO I set-up, such as the differences in the initial spectra between small and big trap, effects from the UCN spectrum ranging till V_F and the decay of the UCN population in the trap not being very close to exponential. For that reason the MAMBO II project was started!

In comparison to other τ_n measurements the present MAMBO II value lies below the PDG 2008 average of 885.7(0.8) s [7] by 2.5σ and above the recent result of Serebrov et al. with 878.5(0.9) s [8] by 1.1σ. The τ_n data scatter significantly more than by their uncertainty allowed when the PDG 2008 evaluation, the value of [8] and of the present MAMBO II are combined. Using this set of τ_n values results in an average of 881.8(1.4) s, where the error is scaled up by a factor of 2.7 according to the PDG rules. Our MAMBO II result makes the PDG2008 present average neutron lifetime value even more ‘suspect’. To resolve this issue new and improved measurements are required using different methods including almost loss free UCN storage by magnetic traps (see for instance [9] and references cited therein).

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