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Neutron life time value measured by storing ultracold neutrons with detection of inelastically scattered neutrons

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Abstract

The neutron life time τ_n was measured by storage of ultracold neutrons (UCN) in a material bottle covered with Fomblin oil. The inelastically scattered neutrons were detected by surrounding neutron counters monitoring the UCN losses due to upscattering at the bottle walls. Comparing traps with different surface to volume ratios the free neutron life time was deduced. Consistent results for different bottle temperatures yielded $\tau_n[\mathrm{sec}] = 885.4 \pm 0.9_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}$.

1. Introduction

The free neutron beta decay is a fundamental process in weak interaction. In a simple quark picture a *d* quark transforms into an *u* quark under emission of a virtual *W*- boson which in turn decays into an electron and an electron antineutrino. Consequently this semileptonic decay with a lifetime of about 15*min* was subject of many investigations and a number of important questions in particle and astrophysics were discussed with neutron decay data.

For the free neutron lifetime a breakthrough in precision has been achieved by storage experiments of ultra cold neutrons. In 1987 a precision of 3 s was obtained by this method [1] and since then two more experiments with similar precision were carried out [2,3]. Including results from the correlation coefficients between the decay partners, in particular the beta asymmetry coefficient A [4–6] the vector and axial vector coupling constants g_v and g_a were deduced from the neutron decay alone. The obtained value for g_v was compared with data from muon decay and superallowed beta-decays yielding stringent limits on possible deviations from the universality of the weak interaction coupling constants, on right handed currents and on the unitarity of the CKM matrix [4,7,8].

In neutron lifetime measurements by UCN storage the UCN's are contained by material walls due to the Fermi-pseudo potential, by gravity or by the interaction on the neutron's magnetic moment with a mag-

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netic field gradient. Conceptually those experiments are quite simple. UCN's are filled in a storage volume with suitable walls. After a storage period the surviving neutrons are counted. Repeating this experiment with different storage times yields the decay curve of the neutrons. The major problem encountered in this method is caused by losses of UCN in collisions with the trap walls. Different methods were used to separate wall loss rates from the loss rate due to beta decay. In [1,2] the trap size was varied and the number of surviving UCN compared for the same number of neutron wall collisions. Extrapolation to infinite trap size yielded τ_n.

In the present experiment a different method was used to separate wall losses from beta decay. The main loss process was monitored during storage by measuring the relative flux of inelastically scattered UCN by a set of neutron detectors surrounding the vessel, see Fig. 1. The survival probability of the UCN was measured by the usual UCN storage and disappearance method of the neutrons in the trap. The trap was arranged such that the UCN could be stored in two different sections with different surface to volume ratios and hence different total UCN survival times. Comparing the survival time and upscattering rates for the two volumes yielded the value of τ_n. The first experiment with this method was carried out at the ILL, Grenoble, France in 1990, resulting in a neutron life time $\tau_n[\text{sec}] = 882.6 \pm 2.7$. [3]. We have now improved the method considerably and present here the more precise result of a new measurement performed again at the ILL.

2. Basic idea of the experimental method

Assuming for the moment that only monoenergetic UCN are in the trap, the number of neutrons $N(t)$ in the trap changes exponentially during the storage time, i.e. $N(t) = N_0 e^{-\lambda t}$. The value λ is the total probability per unit time for the disappearance of UCN due to both the beta-decay and losses during UCN-wall collisions. In turn, losses are equal to the sum of the inelastic scattering rate constant λ_{ie}, and that for the neutron capture at the wall, λ_{cap}:

$$\lambda = \lambda_n + \lambda_{loss} = \lambda_n + \lambda_{ie} + \lambda_{cap} \quad (1)$$

The ratio $\lambda_{cap}/\lambda_{ie}$ is to a good approximation equal to the ratio of the UCN capture and inelastic scattering cross sections for the material of the wall surface since both values are proportional to the wall reflection rate of UCN in the trap. Hence σ_{cap}/σ_{ie} and the value

$$a = \lambda_{loss}/\lambda_{ie} = 1 + \lambda_{cap}/\lambda_{ie} = 1 + \sigma_{cap}/\sigma_{ie} \quad (2)$$

is constant for the given conditions, i.e. same wall material and temperature. During storage the upscattered neutrons are recorded with an efficiency ε_{th} in

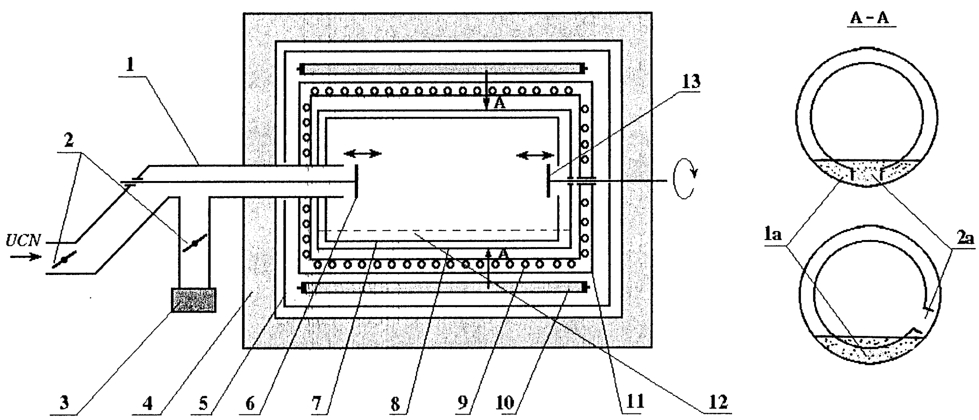

Fig. 1. The scheme of the experimental set-up. 1- UCN guide, 2- shutters, 3- UCN detector, 4-polyethylene shielding, 5- cadmium housing, 6-entrance shutter of the inner vessel, 7- inner storage vessel, 8- outer storage vessel, 9- cooling coil, 10- thermal neutron detector, 11-vacuum housing, 12- oil puddle, 13- entrance shutter of the gap vessel, 1a-oil puddle, 2a-slit.

the thermal neutron detector surrounding the storage trap. The corresponding counting rate is given by

$$j = \varepsilon_{th} \lambda_{ie} N(t) \tag{3}$$

Hence the total counts in the time interval T are equal to

$$J = \varepsilon_{th} \lambda_{ie}(N_0 - N_T)/\lambda \tag{4}$$

Here N_0 and N_T are the UCN populations in the trap at the beginning and the end of the storage time T, respectively. The UCN themselves are measured with an efficiency ε such that the detected UCN at the beginning (normalisation measurement) and the end of the storage time are equal to $N_i = \varepsilon N_0$ and $N_f = \varepsilon N_T$. respectively. We have then

$$\lambda_{ie} = \frac{J\lambda}{(N_i - N_f)} \frac{\varepsilon}{\varepsilon_{th}} \tag{5}$$

and

$$\lambda = \frac{1}{T}\ln(N_i/N_f) \tag{6}$$

The experiment is repeated with a different value for the wall loss rates. The ratio of the two corresponding λ values are built following Eq. (1) and including Eq. (2) with constant value a. Thus λ_n is given by

$$\lambda_n = \frac{\xi\lambda^{(1)} - \lambda^{(2)}}{\xi - 1} \tag{7}$$

where

$$\xi = \lambda_{ie}^{(2)}/\lambda_{ie}^{(1)} \tag{8}$$

The indices refer to the two measurements with different λ_{loss}. The expression Eq. (7), (8) contains then only the directly measured quantities J, N_i, N_f following Eqs. (5), (6) since the efficiencies of the neutron detection cancel. The value for λ_{loss} can be varied by changing the ratio of the surface to the volume of the bottle and hence the reflection rate with the walls. In order to keep the value a constant the (monoenergetic) energy of the UCN and the specification of the wall (temperature, type of wall, etc.) must be the same.

3. Method for a broad UCN energy spectrum

In a real experiment it is necessary to take into account the energy distribution of UCN since the scattering and capture cross section are in general energy dependent and losses are different for different parts of the UCN energy spectrum. Even if monoenergetic UCN are filled into the trap the gravitational potential would change the UCN kinetic energy over the height of the trap. But first order correction terms are sufficient since the dependence of λ_{ie} on the UCN energy is weak. Consequently a similar calculation as for the monoenergetic UCN case was performed, leading to only small correction terms compared to Eqs. (7), (8).

The UCN energy spectrum changes with time as the different UCN energy group populations decay at different rates in the trap [9]:

$$N(t) = N_0 \exp\left(\int_0^t - \lambda(t')\,dt'\right) \tag{9}$$

The rate $\lambda(t) = \lambda_n + \lambda_{loss}(t)$ is now a function of the storage time due to changes of the UCN spectrum and λ_{ie} is a weak function of time which can be described in first order by

$$\lambda_{ie}(t) = \lambda_{ie0}(1 - \gamma t) \tag{10}$$

The quantity γ is in the order of $10^{-4}\ s^{-1}$ for usual experimental conditions when $T \ll 1/\lambda_{loss}$.

Using the parameter definition of Eq. (2) leads to $\lambda_{loss} = \lambda_{ie}(t) \cdot a$. The value of a in the case where trap walls are coated by a layer of hydrogenfree oil (Fomblin type) is close to unity: $a - 1 < 2 \cdot 10^{-2}$ and temperature dependent.

The mean value of $\lambda(t)$ over the time interval T is then given by

$$\bar{\lambda} = 1/T\int \lambda(t)\,dt = \lambda_n + \lambda_{ie0}\left(1 - \frac{\gamma T}{2}\right)a \tag{11}$$

It is measured in the experiment by detection of the UCN population at the beginning, N_i, and after the storage time T, N_f using the relation

$$\bar{\lambda} = \frac{1}{T}\ln\left(\frac{N_i}{N_f} \cdot \frac{\varepsilon_f}{\varepsilon_i}\right) \tag{12}$$

where the ratio of the UCN detection efficiency ε_i, ε_f varies slightly with T and is determined as shown in Section 5.

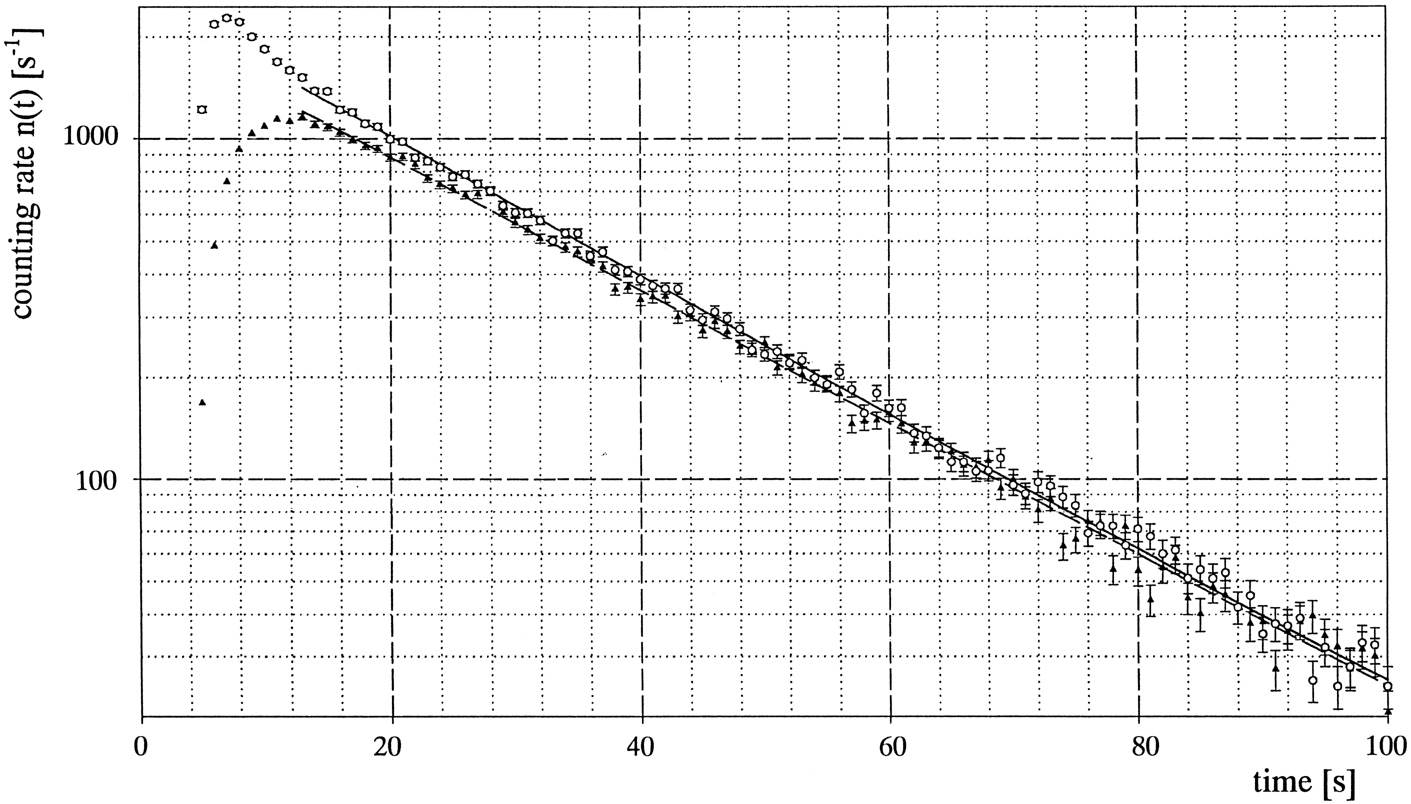

Fig. 2. Counting rate $n(t)$ in the detector as function of the time after opening of the shutter towards the UCN detector. A typical curve for emptying the inner vessel (circles) in comparison to the outer vessel (triangles) is shown. The upper part of the curves are fit to an exponential form (straight lines in the semilogerithmic plot). The slope for the inner vessel data is steeper and hence the emptying time shorter, which corresponds to a higher efficiency for detection of the UCN population in the vessel at the time of opening the shutter $t = 0$.

The full counts of the thermal neutron detector during storage is equal to $J = \int_0^T j(t)dt = \varepsilon_{th} \int_0^T \lambda_{ie}(t) N(t) dt$. Using Eqs. (9), (10), (11) leads to

$$J = \varepsilon_{th} \lambda_{ie0} N_0 \int_0^T (1-\gamma t) \times \left[\exp - \left(\lambda_n + \lambda_{ie0} a \gamma (T-t)/2 \right) t \right] dt \qquad (13)$$

Expanding the second part of the exponent, neglecting the γ^2 terms, using Eq. (11) and solving for λ_{ie0} gives

$$\lambda_{ie0} = \frac{\bar{\lambda} J}{(N_i - N_f)\Phi} \cdot \frac{\varepsilon}{\varepsilon_{th}} \qquad (14)$$

where

$$\Phi = 1 - \frac{\gamma}{\bar{\lambda}} \left(1 + \frac{1}{2} \lambda_{ie0} a T \right) \frac{I_2}{I_1} + \frac{1}{2} \lambda_{ie0} \frac{\gamma a}{\bar{\lambda}^2} I_3 / I_1 \qquad (15)$$

and $I_1 = \int_0^{\bar{\lambda} T} e^{-x} dx$; $I_2 = \int_0^{\bar{\lambda} T} e^{-x} x dx$; $I_3 = \int_0^{\bar{\lambda} T} e^{-x} x^2 dx$.

Introducing in Eq. (14) the measured value

$$\bar{\lambda}_{ie} = \frac{J \bar{\lambda}}{(N_i - N_f)} \cdot \frac{\varepsilon}{\varepsilon_{th}} \qquad (16)$$

and performing the pair of measurements with two different loss rate values, the λ_n value is derived analogous to Eq. (8), (9):

$$\lambda_n = \frac{\xi \bar{\lambda}^{(1)} - \bar{\lambda}^{(2)}}{\xi - 1} \qquad (17)$$

where the ξ-value is determined by

$$\xi = \frac{\bar{\lambda}_{ie}^{(2)}}{\bar{\lambda}_{ie}^{(1)}} \cdot \frac{\left(1 - \frac{\gamma^{(2)} T^{(2)}}{2} \right) \Phi^{(1)} a^{(2)}}{\left(1 - \frac{\gamma^{(1)} T^{(1)}}{2} \right) \Phi^{(2)} a^{(1)}} \qquad (18)$$

The correction terms relative to the monoenergetic case, Eq. (9), are quite small if cleaning times ($t_{cl}^{(1),(2)}$, see next section) are chosen properly to start the storage time with almost the same UCN spectra. In addition the product γT is constant to a good approximation, when storage times are scaled such that the same average number of wall reflections occur in T. This fact was already used by Mampe et al. [1]. The deviation of Φ and a from unity are in the percent range, if the specification of the wall (temperature, type of wall, etc.) is the same, and depend only via the spectral development during storage on the surface to volume ratio. The values for Φ and a could be determined in particular from the time dependence $j(t)$ of the upscattering rate during the storage time.

The UCN detection efficiency ε includes also the UCN losses in the vessel during the emptying time of the vessel into the UCN detector. This time is of the order of 50 s and thus not small compared with the life time of the UCN in the bottle. A change of the spectrum of the UCN or of the bottle shape will also change the emptying time and hence the so defined efficiency. Thus for a real experiment Eq. (17) is not exact since ε is slightly different for the pair of measurements. To take into account this effect the counting rate $n(t)$ of the UCN detector during the emptying phase has to be corrected for the decay rate $\bar{\lambda}$. Thus a shorter emptying time corresponds to a higher efficiency for detection of the UCN population at the end of the storage period (see Fig. 2). The size of this correction is discussed in Section 5.

4. The experiment

Following the above concept the experiment was designed and carried out at the UCN source of the ILL High Flux Reactor in Grenoble.

Fig. 1 presents the scheme of the experimental set-up. The storage vessel (7), (8) is composed of two coaxial horizontal cylinders made of Aluminium of 2 mm thickness. The cylinder walls were coated with a thin layer of Fomblin oil which has very low UCN losses. In order to maintain this oil layer on the surface, the cylinder walls were first coated by a layer of Fomblin grease of about 0.2 mm thickness.

The inner cylinder (7) was 33 cm in diameter and 90 cm long, while the dimensions of the outer one (8) were larger by a gap of 2.5 cm. The shutter (6) connects the inner cylinder to the intermediate chamber which has connections (i) to the neutron guide (1) of the TGV UCN source by the entrance shutter and (ii) to the UCN detector (3) by shutter (2). The shutter (13) connected the inner cylinder to the volume of the annular gap between both cylinders.

The inner cylinder had a long slit (2a) of a special form (see Fig. 1a) along a cylinder surface. The edges of the slit were dipped into a Fomblin oil puddle (1a) with level (12) when the slit was situated at the bottom position during storage. The construction allowed to rotate the cylinders in common about its horizontal axis without a vacuum break to refresh the oil layers on the cylinder walls.

The storage vessel was placed inside the vacuum housing (11). The vessel volume was hermetically sealed from the housing. The housing was formed by two coaxial cylinders of stainless steel. The outer surface of the inner cylinder had a serpent tube (9) to cool the bottles. The cooling system stabilised the bottle temperature which could be set in the range $+20°C \div -26°C$.

The turbomolecular pump provided a residual gas pressure of about $(1 \div 5) \cdot 10^{-6}$ torr in the bottles.

The set-up was surrounded by the thermal neutron detectors comprising a set of 24 counters of the SNM-57 type(10), each counter being a ^{3}He filled tube of 3 cm diameter and 100 cm long. The UCN detector was a ^{3}He loaded proportional counter (3) with an *Al* entrance window of 100 μm thickness.

The whole installation was placed inside the shielding (5) of 1 mm thick Cd and the shielding (4) of 16 cm thick boron polyethylene.

The construction permitted us to store UCN either in the inner cylinder or in the annular space between the inner and outer cylinder, thereby changing the UCN loss rate by a factor of about 5 without breaking the vacuum.

All the UCN shutters were operated by an IBM PC program. The detector counting system had two parallel electronics channels with (i) amplitude and (ii) time analysers. All information was kept in the computer memory and then recorded on disk.

The experiment was carried out using a the following sequence of procedures.

1. The chosen vessel, annular or central (see Fig. 2), was filled for 200 s. For filling only the central vessel the shutter 13 was closed. For the annular vessel shutter 13 was open and the UCN removed from the central vessel in the following step.

2. The trapped neutron spectrum in the storage vessel was given time to clean during t_{cl} (200 s to 1000 s). This procedure was necessary as the UCN source provided a rather broad neutron spectrum. During the cleaning time t_{cl} UCN with velocity exceeding the limiting velocity of Fomblin escaped from the vessel. When the annular vessel was chosen the shutter 6 and the shutter to the UCN detector were opened during t_{cl} to empty the central vessel.

3. The UCN were emptied to the detector from the chosen vessel and counted for 200 s yielding the initial quantities N_i and $n_i(t)$, where $n_i(t)$ denotes the counting rate in the UCN detector during the emptying time t and N_i the integral over $n_i(t)$. On emptying the inner vessel both its shutters were opened to make the emptying conditions more equal for the two vessels.

4. Steps 1. and 2. were repeated once more to fill the chosen vessel and to clean the UCN spectrum before the storage period. Due to the stable intensity of the UCN source the initial conditions were essentially identical.

5. Storing: After the cleaning time the UCN were further stored in the chosen vessel for the time T and

Table 1
Typical examples for measured quantities in the storage experiment. The total UCN survival life time $1/\bar{\lambda}$ in the bottle ranged from 500 s to 780 s.

Temp. (°C)	Vessel	t_{cl} (s)	T (s)	N_i	N_f	J	$\bar{\lambda}$ (10^5 s^{-1})	$\bar{\lambda}_{ie} \cdot \varepsilon_{th}/\varepsilon$ (10^5 s^{-1})
+20	inner	750	500	74189	32363	2359	166	9.36
	annular	150	100	64664	48056	1831	297	32.7
−9	inner	1000	1000	59027	15684	1369	133	4.20
	annular	250	250	58718	35906	2089	197	18.0
−26	inner	700	1000	107828	29813	2332	128	3.83
	annular	200	300	78146	46146	2820	177	15.6

the inelastically scattered and leaked neutrons were counted during that interval in the thermal neutron and UCN detector, respectively.

6. Recording of the final UCN quantity N_f and $n_f(t)$ by counting for 200 s (same procedure as step 3).

7. The background of the detectors was measured during 150 s after all UCN have left the vessel.

Table 1 presents as example the current measured values for some experimental runs.

The procedures no. $1 \div 7$ were carried out twice for the chosen vessel. Then the other vessel was chosen and procedures no. $1 \div 7$ were performed also twice. Thus the elementary experimental run was completed. These elementary runs were repeated as many times as was necessary to get sufficient statistics.

As discussed for Eq. (18), the storage time intervals $T^{(1)}, T^{(2)}$ in the inner vessel ($^{(1)}$) and the annular vessel ($^{(2)}$) as well as $t_{\mathrm{cl}}^{(1)}, t_{\mathrm{cl}}^{(2)}$ were chosen to make almost the same evolution of the UCN spectra.

Groups of experimental runs were performed at the different temperature $+20$°C, -8°C, -9°C and -26°C, respectively.

5. Evaluation of the data and result

A data evaluating program was developed based on the above method.

In the experiment the storage vessels were covered homogeneously with Fomblin oil and the temperature of the vessel was stabilised and constant over the wall surface within 0.1 °C for room temperature and 1.5 °C for the lower temperatures. Thus the parameter a was constant for a run at the same wall temperature.

An important correction arose from the ratio of the UCN detection efficiencies $\varepsilon^{(1)}/\varepsilon^{(2)}$ which was not equal to unity as assumed for Eq. (17). As explained in Section 3 the detection efficiencies include the different UCN emptying times of the storage vessel through the intermediate chamber. From the measured time dependence of the counting rates $n(t)$ (see Fig. 2) combined with measured values for $\bar{\lambda}$ the ratio $\varepsilon^{(1)}/\varepsilon^{(2)}$ was experimentally determined. Thus a correction for τ_n of -3.10 ± 0.36 s was deduced compared to an evaluation using simply Eq. (17). The uncertainty is mainly statistical from those measured time spectra $n(t)$.

In a similar way the value of λ depended on the efficiency ratio of $\varepsilon_i/\varepsilon_f$ due to the spectral development of the UCN during storage. The corresponding time distributions n(t) were used to obtain the ratio of $\varepsilon_i/\varepsilon_f$ with a similar precision.

The ratio $\varepsilon_{\mathrm{th}}^{(1)}/\varepsilon_{\mathrm{th}}^{(2)}$ of the thermal neutron detection depend on the geometry of the vessels and was calculated by the Monte Carlo method using mean values for the capture and scattering cross sections (also measured in special experiments) for neutrons that were inelastically scattered during the storing time. The correction in τ_n was 0.6 ± 0.3 s. The systematic error in this calculation reflects the uncertainty of the geometry, the upscattering cross sections and the spectrum of upscattered neutrons.

Time distributions $j(t)$ were used to determine the γ-parameter of the time dependence for λ_{ie}. It was included into the ξ-value calculation in Eq. (18)

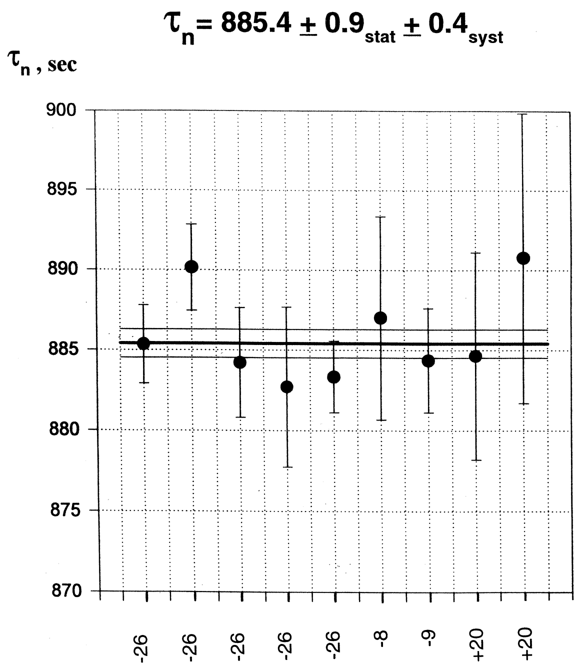

Fig. 3. Experimental values for the neutron life time from the different runs. The code for the experimental groups corresponds to the bottle temperatures -26°C, -9°C, -8°C and $+20$°C, respectively. The total measuring time summed up to 100 days.

(Compared to a monoenergetic UCN spectrum the correction in τ_n was -2.0 ± 0.3 s).

A consistent set of neutron life time values was obtained for the different bottle temperatures (see Fig. 3). Since the different bottle temperatures lead to very different loss rates (see Table 1) this consistency gives confidence in the experimental method used.

Including the above corrections the mean value yielded the final result: $\tau_n[\text{sec}] = 1/\lambda_n = 885.4 \pm 0.9_{\text{stat}} \pm 0.4_{\text{syst}}$.

The uncertainties in τ_n due to the ratios $\varepsilon^{(1)}/\varepsilon^{(2)}$ (0.36 s) and $\varepsilon_i/\varepsilon_f$ (0.3 s) and due to γ (0.2 s) are included in the statistical error since they are based on the measured time spectra of detector counting rates $n(t)$.

The possible systematic error for τ_n is composed of the uncertainty in $\varepsilon_{\text{th}}^{(1)}/\varepsilon_{\text{th}}^{(2)}$ (0.3 s), the influence of the UCN scattering at the residual gas in the bottle (0.2 s), the impurity of epi-Fomblin neutrons in the UCN spectrum (0.2 s) and the temperature difference over the walls of the vessels (0.15 s). The systematic uncertainties add up in quadrature to 0.4 s.

The present experimental result is in agreement with the recent evaluation of earlier data on the neutron life time of 886.7(1.9) s by the Particle Data Group [10].

Acknowledgements

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