



Measurement of the neutron lifetime using a gravitational trap and a low-temperature Fomblin coating

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Abstract

We present a new value for the neutron lifetime of $878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{sys}}$. This result differs from the world average value (885.7 ± 0.8 s) by 6.5 standard deviations and by 5.6 standard deviations from the previous most precise result [Phys. Lett. B 483 (2000) 15]. However, this new value for the neutron lifetime together with a β -asymmetry in neutron decay, A_0 , of $-0.1189(7)$ [Phys. Rev. Lett. 88 (2002) 211801] is in a good agreement with the Standard Model.

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1. Introduction

The decay of the free neutron into a proton, an electron and an antineutrino is related to the weak interaction process. In the Standard Model the probability of this process or the lifetime of the free neutron is

related to the vector G_V and axial G_A weak interaction coupling constants. The neutron lifetime has important implications in particle physics, in neutrino-induced reactions and in cosmology. The neutron lifetime together with angular correlation coefficients of the decay of a polarised neutron allows deduction of the axial and vector coupling constants only from neutron decay data. The main element of the Kobayashi–Maskawa matrix, V_{ud} , has to be determined with the

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highest accuracy to check for eventual deviations from the Standard Model which are currently under discussion [3].

The observed deviation from the unitarity condition for the Cabibbo–Kobayashi–Maskawa matrix using present data is about 2.7 standard deviations. The origin of this deviation is unclear. This situation requires more precise measurements of β -asymmetry— A_0 and new measurements of the neutron lifetime.

Today, the weighed mean value of the neutron lifetime is 885.7(8) s. The accuracy of this world average was improved by the lifetime experiment of a group from KIAE, Russia [1]. Their result ($885.4 \pm 0.9_{\text{stat}} \pm 0.4_{\text{syst}}$) has an accuracy that is at least 3 times better than that of the other contributing experiments. So the present world mean value of the neutron lifetime is mainly determined by the result of only one experiment, therefore the new experimental measurements are important.

2. Experimental set-up and method of measurement

The present measurements were carried out at the high flux reactor at ILL in Grenoble, France using the PF2/MAM instrument; the experimental set-up is sketched in Fig. 1. It is a gravitational trap for ultra cold neutrons (UCN) and at the same time it can be used as a differential gravitational spectrometer. Therefore the distinguishing feature of this experiment is the ability to measure the UCN energy spectrum after its storage in the trap.

The UCN storage trap 8 is mounted inside a cryostat vacuum vessel 9. The trap 8 has a window that can be rotated about a horizontal axis so that UCN are held in the trap by gravity when the trap window is in its upper position.

UCNs enter the trap via the neutron guide 1, the opened UCN inlet valve 2 and the distribution flap valve 3. Filling takes place when the trap window is in the down position. After the trap is filled it is rotated into the up position.

A double walled vacuum system was used with separate “high” 6 and “rough” 5 vacuum vessels. The pressure in the cryostat vacuum vessel was 5×10^{-6} mbar; at this pressure, the residual gas has a small effect (0.4 s, see below) on storage time for the

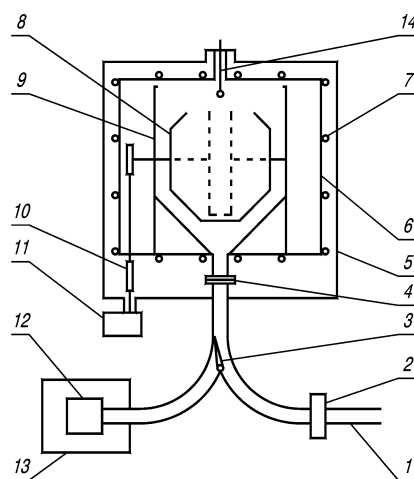


Fig. 1. The scheme of “Gravitrap”, the gravitational UCN storage system. 1: neutron guide from UCN Turbine; 2: UCN inlet valve; 3: beam distribution flap valve (shown in the filling position); 4: connection unit; 5: “high” vacuum volume; 6: “rough” vacuum volume; 7: cooling coils; 8: UCN storage trap (the narrow cylindrical trap is shown by a dashed line); 9: cryostat; 10: mechanics for trap rotation; 11: stepping motor; 12: UCN detector; 13: detector shielding; 14: evaporator.

UCN in the trap. To cool the trap we used heat exchange between the trap and the cryostat tank; to do this helium gas was flowed through the cryostat vacuum vessel and removed before carrying out the neutron lifetime measurements.

The height of the trap window relative to the trap bottom defines the maximum energy of UCN that can be held in the trap. Different window heights correspond to different cut-off energies for the UCN spectrum. Such a rotatable trap is a gravitational spectrometer. The spectral dependence of the storage time can be measured by turning the trap window downward in steps. The trap was kept in each intermediate position during 100–150 s to detect UCN in the corresponding energy range. The same procedure also measures the spectrum of the trapped UCN.

The neutron lifetime is measured with the size extrapolation method using two sizes of UCN trap. The first is a quasi-spherical trap consisting of a cylinder about 84 cm in diameter and 26 cm wide, capped by two truncated cones each 22 cm high, with small diameters of 42 cm and the second a 76 cm diameter cylindrical trap that was 14 cm long between its end faces. The second trap increases the neutron collision rate with the walls of the trap by a factor of about 2.5.

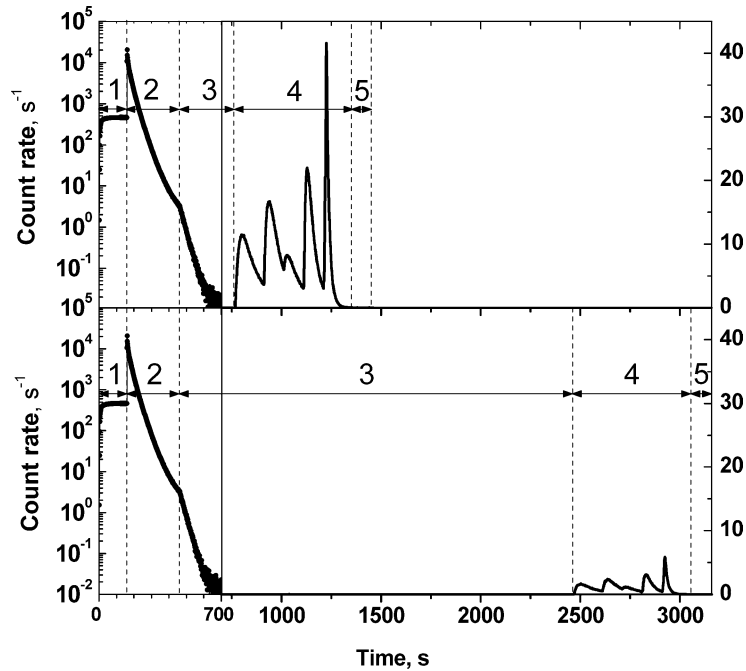


Fig. 2. Time diagrams of the storage cycle for two different holding times. 1: filling 160 s (time of trap rotation (35 s) to monitoring position is included); 2: monitoring 300 s; 3: holding 300 or 2000 s (time of trap rotation (7 s) to holding position is included); 4: emptying has 5 periods 150, 100, 100, 100, 150 s (time of trap rotation (2.3, 2.3, 2.3, 3.5, 24.5 s) to each position is included); 5: measurement of background 100 s.

The narrow cylindrical trap is shown in Fig. 1 by a dashed line.

A typical count rate diagram during the UCN storage cycle is shown in Fig. 2. First the trap is filled with UCN with the hole in the down position. Then the trap is rotated to the monitoring position where the height of the trap window is 10 cm lower than when in the holding position with the hole upward. The filling process can be observed by means of the detector 12 through the slits in the distribution valve. When the trap reaches the monitor height the distributive valve is changed to the detection position. The trap is kept in the monitoring position for 300 s. During this period the neutrons whose energy exceeds the gravitational barrier of the trap escape (see Fig. 2). Then the trap is rotated to the holding position. Overall this process takes about 460 s and the counting rate is shown on a logarithmic scale on the left side of Fig. 2; the counting rate for the subsequent procedures (700–3160 s) is shown on a linear scale on the right side, in order to show more details. After a short (top part of Fig. 2) or long (bottom part of Fig. 2) holding time, the trap is rotated to five successive positions and is held in

each position for 100 to 150 s in order to count UCN. The neutrons counted after each rotation have a different average energy. When the UCN trap is empty the background measurement is started. The angle positions of the trap are: $\theta = 30^\circ$ (monitoring position), $\theta = 40^\circ$, $E_{\text{UCN}} = 58$ cm; $\theta = 50^\circ$, $E_{\text{UCN}} = 52$ cm; $\theta = 60^\circ$, $E_{\text{UCN}} = 46$ cm; $\theta = 75^\circ$, $E_{\text{UCN}} = 39$ cm; $\theta = 180^\circ$, $E_{\text{UCN}} = 25$ cm. The angles were chosen so as to obtain similar counts for each portion of the UCN spectrum (unfortunately, the third portion of was not successfully optimised as may be seen in Fig. 2).

Any neutron lifetime measurement using the UCN storage method is based on the rather simple equation: $\tau_{\text{st}}^{-1} = \tau_{\text{n}}^{-1} + \tau_{\text{loss}}^{-1}$. The total probability of UCN losses τ_{st}^{-1} is broken up into two parts: the first part is the probability of neutron beta-decay τ_{n}^{-1} and the second one is the probability of other possible UCN losses τ_{loss}^{-1} .

The UCN storage time τ_{st} is calculated from the measurements of the number of neutrons remaining in the trap after different holding times: $\tau_{\text{st}} = (t_2 - t_1) / \ln(N_1/N_2)$, where N_1 and N_2 are the numbers of neutrons remaining in the trap after holding times t_1

and t_2 , respectively. There is no need to know the efficiency of the UCN detector, the UCN loss rate during its transport to the detector, etc., since the equation uses only the ratio of N .

As the UCN are held by the trap material then τ_{loss}^{-1} contains the probability of losses at the trap walls: $\tau_{\text{loss}}^{-1} = \mu(T, E) \cdot \nu(E)$, where $\mu(T, E)$ is the UCN loss factor per reflection, which depends on the UCN energy and the temperature of walls T , and ν is the UCN collision frequency, which depends on the UCN energy and the size of the trap.

We can now rewrite the last equation as the product of separate energy and temperature dependent factors: $\tau_{\text{loss}}^{-1} = \eta(T) \cdot \gamma(E)$, where $\eta(T)$ is written for the energy independent part of the loss factor and $\gamma(E)$ for the effective frequency of collisions, which depends on the UCN energy and the trap size. The neutron lifetime value can be obtained by a linear extrapolation of τ_{st}^{-1} to zero value of γ . Different values of the UCN effective collision frequency γ are obtained using traps of different size and using different UCN energies. The UCN loss factor η is then the slope of the extrapolation line. The UCN effective collision frequency γ can be calculated. So we can use the method of energy extrapolation and the method of size extrapolation.

The method of size extrapolation based on two traps allows large suppression of the systematic errors arising from uncertainties in our knowledge of $\mu(E)$.

3. The low-temperature Fomblin coating of traps

In the experiment, we have used a new type of wall coating, a low-temperature Fomblin (LTF) that can be evaporated onto the surface in vacuum. This perfluorinated oil has a composition containing only C, O and F and thus a low neutron capture cross section. Earlier investigations [4] of several types of LTF found that quasi-elastic UCN scattering and thermal inelastic scattering are significantly lower at temperatures below -120°C than for ordinary Fomblin oil close to room temperature. The quasi-elastic UCN scattering is suppressed completely below -120°C [4] and the expected UCN loss coefficient η due to up-scattering is about 2×10^{-6} [5,6].

The new type of LTF used in our experiment has a molecular weight $M = 2354$ and a vapour pres-

sure $P = 1.5 \times 10^{-3}$ mbar at room temperature. For preparation of the trap coating, the oil was delivered to an evaporator through a vertical tube driven by He pressure. A spherical evaporator with small holes was heated up to $+140^\circ\text{C}$ by means of an electric heater, and then 3 cm^3 of oil were ejected onto the interior trap walls held at a temperature of -150°C . The evaporator was moved up and down during the deposition to obtain a uniform coating.

To test the oil film quality we measured the UCN lifetime in a titanium-coated Cu trap with various coating of LTF. Titanium has a negative scattering length and UCN cannot be held in this trap when uncoated. The trap was a cylinder of diameter of 76 cm and length 50 cm. A stable storage time $\tau_{\text{st}} = 869.0 \pm 0.5$ s was reached after several LTF evaporations (total thickness of $15 \mu\text{m}$) at a wall temperature of between -140°C and -150°C , then warming the trap up to room temperature and finally re-cooling to -160°C . Due to this process, the oil at room temperature filled all the gaps and cracks in the wall and formed a perfect surface. Additionally, the LTF have been degassed in a thin layer at room temperature. The coating is very stable and no significant change of storage time was found over an 8 days observation period. Further evaporation did not change the storage time.

For the final measurements we used Be-coated traps (quasi-spherical and narrow cylindrical). Since Be is a good UCN reflector, we can use even lower wall temperatures, making the development of any micro-cracks in the coating less detrimental to the storage time. The LTF was deposited at -140°C , and then the trap was slowly warmed up to -50°C and finally cooled again to -160°C . In this way we covered layer defects by the oil when it was sufficiently liquid. Following this temperature cycle we obtained a higher storage time, 872.2 ± 0.3 s, than immediately after evaporation (850 ± 1.8 s). Taking into account the different sizes of the Ti- and Be-traps we find that difference of the expected storage time for Ti-trap and the obtained storage time is 1.9 ± 0.6 s. It means that the uncoated part of Ti-trap surface is $(4.4 \pm 1.3) \times 10^{-7}$ only. This indicates that reproducible oil films can be obtained due to the oil surface tension independently of substrate material and the shape of the trap. Therefore we have no reason to consider different loss factors, η , for the different traps with Be-substrate under LTF.

The stability and integrity of the coating of the different traps is the most important condition for validity of the size extrapolation method for the neutron lifetime measurement. Therefore the quality of the LTF coatings was verified many times during the course of the measurements. Eight storage time results for the quasi-spherical trap and seven storage time results for the narrow trap were obtained in the course of the experiment. The measurements were carried out after new evaporations, warming and cooling, new evaporations and so on. As a final improvement, the pressure in the trap was reduced from 5×10^{-6} to 3×10^{-7} mbar by installing a LHe cryopump near the storage volume. The storage times over the course of the neutron lifetime experiment agreed within about 1 s for the wide trap and by a little bit more for the narrow trap. This gives confidence in the stability and the reproducibility of LTF coating for the different traps.

4. Results of measurements and extrapolation to the neutron lifetime

The results of measurements of the UCN storage time for different energy intervals and for different traps (wide and narrow) are presented in Fig. 3 as a function of effective frequency of collisions γ . The extrapolation of all data to the neutron lifetime gives a value of 877.60 ± 0.65 s with a χ^2 of 0.95. This means that joint extrapolation is possible. Nevertheless, we have done the energy extrapolation for each trap and on combining both results we obtain 875.55 ± 1.6 s.

For the size extrapolation method we have to connect the values for the different traps for the same UCN energy interval, and then to calculate the average value of all determinations of the neutron lifetime. The average value of the neutron lifetime from the size extrapolation method is 878.07 ± 0.73 s.

The results obtained from the two methods differ by 1.5 standard deviations which cannot be considered as disagreement. The loss factor, $\eta = 2 \times 10^{-6}$, obtained in this experiment is in agreement with that obtained in a transmission experiment [6]. As the final value for the neutron lifetime we prefer to use the more precise result from the size extrapolation, moreover this has a rather weak dependence on $\mu(E)$ and we consider it to be more reliable. The detailed description of the methods of size and energy extrapolation as well

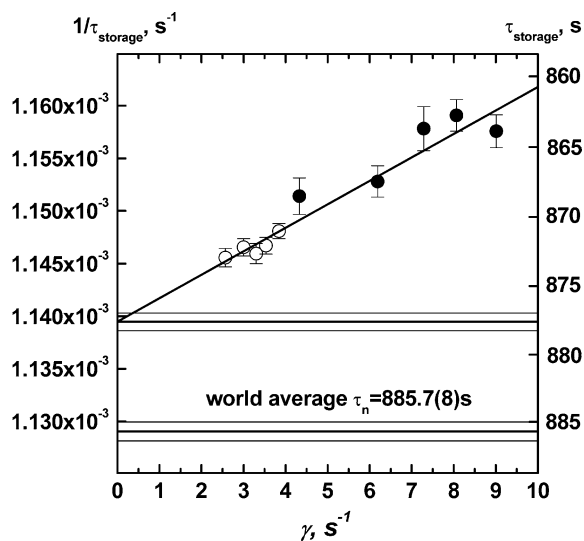


Fig. 3. Result of extrapolation to the neutron lifetime using joint energy and the size extrapolation method. Measurements made with a spherical (open circles) and cylindrical (filled circles) traps.

as the comparison of its advantages and disadvantages are presented in our work [7]. The experimental studies of the problem of UCN losses during storage in material traps are presented in our work [8].

5. Monte Carlo simulation of the experiment and systematic errors

To both estimate the accuracy of and to check the reliability of the size extrapolation method using the calculated γ -function, we have used a Monte Carlo (MC) simulation of the experiment.

In the MC-simulations the behaviour of neutrons has been described taking into account the gravitational field, the form of the storage traps, losses in the trap $\eta = 2 \times 10^{-6}$, the geometry of the secondary vessel and the UCN guide for transporting the UCN to the detector. As a result we can simulate directly the measurements and obtain the time diagram as shown in Fig. 2. The UCN storage times in the traps have been calculated in the same way as done in the experiment, and the extrapolation to the neutron lifetime using the calculated γ -function made as well. The single free parameter in the MC-simulation is the coefficient of diffuse scattering at the interaction with the trap surface.

A comparison between the results of MC simulations with various values for the diffuse scattering probability and the experimental results in Fig. 2, allows us to conclude that the probability of diffuse scattering of UCN on the LTF coating is 10% or more. The final simulation of the experiment was done using probabilities of diffuse reflection of 10% and 1%. To simplify the MC calculations we used a cylinder rather than the quasi-spherical form for the wide trap. The final analysis of the simulated measurements reproduced the neutron lifetime value assumed in the calculation with an accuracy of ± 0.236 s. This accuracy is limited by the statistical accuracy of the MC calculation. That is, the systematic uncertainty of the size extrapolation method using the calculated γ -function is ± 0.236 s.

6. The influence of the residual gas for UCN storage

On the level of accuracy for neutron lifetime measurements of about 1 s, the influence of residual gas at a pressure of 5×10^{-6} mbar is already important. This correction cannot be measured directly, for instance by improving the vacuum by one order of magnitude, because the expected effect is less than the statistical uncertainty. Instead, we increased the residual gas pressure to 8×10^{-4} mbar, making the $(p\tau)$ -parameter for residual gas 9.5 mbar s and obtained a calculated correction to the storage time of 0.4 ± 0.02 s. It does not depend on UCN energy, so this correction can be used for the neutron lifetime result.

7. Final result for the neutron lifetime and the list of systematic corrections and uncertainties

Values of systematic effects with their uncertainties are shown in Table 1. The main contribution to uncertainty we have is due to measurement statistics. The next largest is the uncertainty in the calculation of the function γ . The contributions due to influence of the shape of the $\mu(E)$ -function and uncertainty of UCN spectrum are considerably less; these were estimated by means of variation of their parameters within the uncertainty allowed by the experimental data. Thus the total systematic correction is 0.4 ± 0.3 s and the final

Table 1
The systematic effects and their uncertainties

Systematic effect	Value, s	Uncertainty, s
Method of γ values calculation	0	0.236
Influence of $\mu(E)$ function shape	0	0.144
Spectrum uncertainties	0	0.104
Uncertainties of traps sizes (1 mm)	0	0.058
Influence of the residual gas	0.4	0.024
Uncertainty of LTF critical energy (20 neV)	0	0.004
Total systematic effect	0.4	0.3

result for the neutron lifetime from our experiment is $878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}}$.

8. Conclusion

In the present experiment the storage time is very close to the neutron lifetime. The difference between the best-measured storage time and the neutron lifetime is about 5 s only. This gives confidence in the reliability of the result obtained.

It should be mentioned that our new result differs by 2.9 standard deviations from the result of our old experiment with solid oxygen coating, where accuracy of measurements was 4 times worse [10]. New oil coating gives more guaranties for identity of coating for wide and narrow traps than solid oxygen. (It is clear from experiments with Ti sublayer.) If this deviation was not random we could not exclude the case that narrow trap was coated by solid oxygen a little bit worse because its shape is more complicated for coating than the spherical one. Therefore we favour the new result of neutron lifetime measurement with LTF coating not only due to high statistical accuracy.

The new result for the neutron lifetime (878.5 ± 0.8 s) can be used for the unitarity test of Cabibbo–Kobayashi–Maskawa (CKM) matrix. Fig. 4 shows a plot of V_{ud} versus $-G_A/G_V$ from [3] with the new result for the neutron lifetime. The authors of work [3] favour result $A_0 = -0.1189(7)$ [2] for β -asymmetry in comparison with the world average value $A_0 = -0.1173(13)$ [9]. (In earlier experiments the large corrections had to be made for neutron polarization, electron magnetic mirror effects and background, which were all in the 15% to 30% range.) We follow recom-

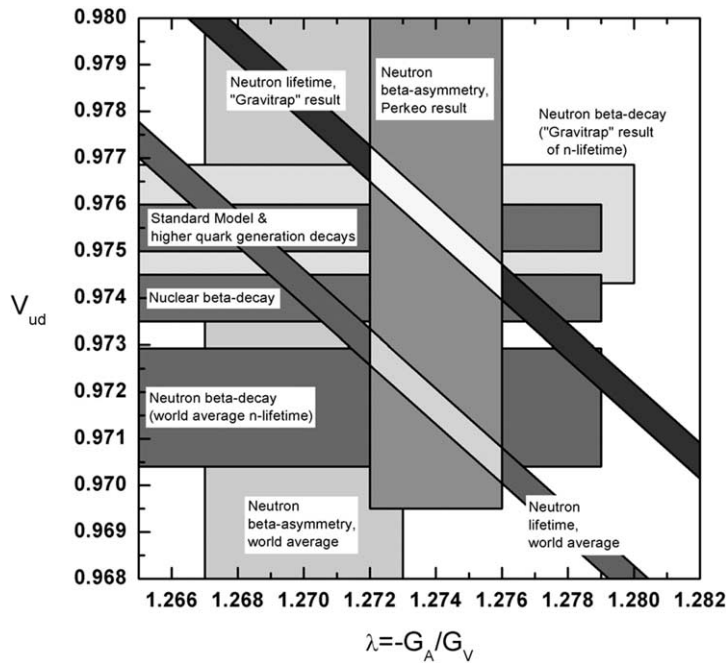


Fig. 4. $|V_{ud}|$ versus $-G_A/G_V$. $|V_{ud}|$ was derived from higher quark generation decays via $|V_{ud}| = \sqrt{1 - |V_{us}|^2 - |V_{ub}|^2}$ predicted from unitarity, from Ft values of nuclear-decays, and neutron β -decay.

recommendations of work [3] but the G_A/G_V -value from the world average value A_0 is shown in Fig. 4 also.

The new lifetime result is different from the world average value (885.7 ± 0.8 s [9]) by 6.5 standard deviations, and by 5.6 standard deviations from the previous most precise result [1]. However, the new result for the neutron lifetime together with the current value for the β -asymmetry in neutron decay ($A_0 = -0.1189(7)$ [2]) is in a good agreement with the Standard Model.

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