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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 $n \to p + e^- + \overline{\nu_e}$. 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]

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

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:

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

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:

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

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

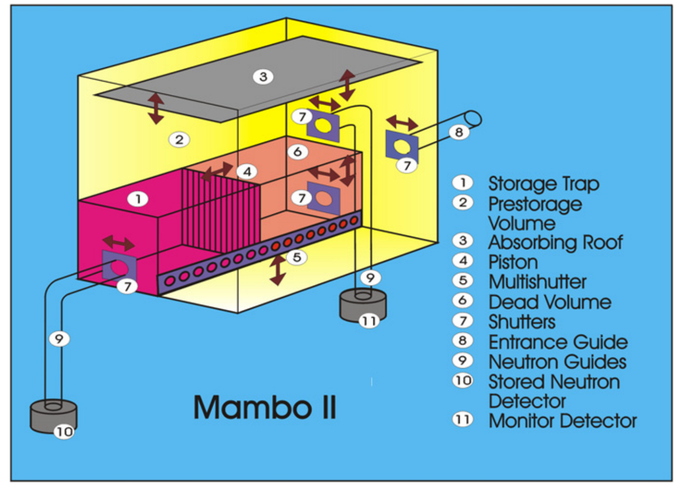

Fig. 1. Schematic view of the MAMBO II installation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

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 in-