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Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap

V. F. Ezhov[a,b1)], *A. Z. Andreev*[a], *G. Ban*[c], *B. A. Bazarov*[a], *P. Geltenbort*[d], *A. G. Glushkov*[a], *V. A. Knyazkov*[a], *N. A. Kovrizhnykh*[e], *G. B. Krygin*[a], *O. Naviliat-Cuncic*[c,f], *V. L. Ryabov*[a]

[a] *Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Center "Kurchatov Institute", 188300 Gatchina, Russia*

[b] *Saint Petersburg State University, 199034 Saint Petersburg, Russia*

[c] *Université de Caen Normandie, 14032, Caen, France*

[d] *Institut Laue-Langevin, 38042 Grenoble, France*

[e] *D.V. Efremov Scientific Research Institute of Electrophysical Apparatus, 196641 Saint Petersburg, Russia*

[f] *National Superconducting Cyclotron Laboratory Michigan State University, 48824 East Lansing, Michigan, USA*

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Precision measurements of the neutron lifetime enable stringent tests of the standard electroweak model [1] and provide crucial inputs for Big-Bang nucleosynthesis (BBN) calculations [2]. When combined with measurements of decay correlation coefficients [1], the neutron lifetime enables the determination of the V_{ud} element of the Cabbibo-Kobayashi-Maskawa quark mixing matrix, resulting in a complementary unitarity test to that obtained from superallowed Fermi decays [3]. The neutron lifetime is also one of the key parameters for determining the yields of light elements in BBN since the ratio between the free neutron and proton abundances drives the extent of fusion reactions during the first few minutes of the Universe [2].

The present world average value of the neutron lifetime as quoted by the Particle Data Group (PDG), $\tau_n = (880.2 \pm 1.0)$ s [4], is dominated by results obtained using ultra-cold neutrons (UCN) in material bottles. These results, and in particular the most precise of them [5–7], appear to be systematically lower than those obtained using a neutron beam [8]. This difference of more than three standard deviations has been the focus of significant interest [9]. Recent discussions about the observed discrepancy, the experimental methods and their systematic effects can be found in Refs. [10, 11]. The importance of the neutron lifetime in particle physics and cosmology calls for alternative high sensitivity techniques, having other potential sources of systematic effects. We report here a new measurement of the neutron lifetime using UCN stored in a magneto-gravitational trap made of permanent magnets.

1)e-mail: Ezhov_VF@pnpi.nrcki.ru

The repulsive force resulting from the interaction between the neutron magnetic moment and a magnetic field gradient can be used for the confinement of neutrons provided their energies are sufficiently low [12]. This has been incorporated for the measurement of the neutron lifetime in various configurations, the most successful having been a sextupole storage ring [13], leading to $\tau_n = (877 \pm 10)$ s, an Ioffe-Pritchard three dimensional trap leading to a storage time $\tau_S = (833^{+74}_{-63})$ s [14], and an asymmetric Halbach array which recently reported a value of the neutron lifetime with a sub-second uncertainty [6]. We present here a new measurement of the neutron lifetime using permanent magnets in a magneto-gravitational trap. A preliminary result of this experiment has been reported in Ref. [15].

The experimental setup used in the present measurement was operated at one of the beam positions of the PF2 UCN source at the Institut Laue-Langevin (ILL). Technical details about the trap properties and design have been reported elsewhere [16–18].

There are two possible sources of UCN losses in magneto-gravitational traps namely, the losses due to the flip of the neutron magnetic moment relative to the direction of the magnetic field and the losses due to the up-scattering of UCNs by the residual gas in the chamber. Neutrons that got their magnetic moment flipped during storage will reach the magnet walls and be reflected, captured or up-scattered. Those which are reflected on the walls cannot be reflected by the magnetic barrier of the shutter, which is smaller than the barrier of the magnets, and will fall through the bottom aperture towards the detector.

The other source of UCN losses is due to upscattering with the residual gas. In order to estimate this effect, the variation of the number of stored neutrons with the pressure, p, inside the trap volume was measured. In the presence of losses due to the residual gas, the number of trapped UCN as a function of time becomes

$$\dot{N}_T(t) = N_0 e^{-(\lambda_S + \lambda_p p)t}. \tag{1}$$

For a storage time of 2200 s, it was obtained that $\lambda_p = 0.15(4)\,(\mathrm{s}\cdot\mathrm{Torr})^{-1}$. This means that, a relative variation of 10^{-3} on $\lambda_n \approx \lambda_S \approx 1.1\cdot 10^{-3}$ s^{-1} corresponds to a pressure level of 10^{-5} Torr. During the experiments, the pressure in the volume of the magnetic trap was of the order of $1.1\cdot 10^{-6}$ Torr.

As already mentioned, the surfaces of the magnets were covered with Fomblin grease. In a separate measurement, the partial pressure of Fomblin vapor was investigated with a quadruple mass spectrometer [19]. It was shown that, at the pressure used during the measurements, the partial pressure of Fomblin vapor is at the level of $2\cdot 10^{-9}$ Torr and its effect can be neglected at the current level of precision.

In summary, the result from this analysis can be written as

$$\tau_n = (878.3 \pm 1.6_{\mathrm{stat}} \pm 1.0_{\mathrm{sys}})\ \mathrm{s} \tag{2}$$

It should be recalled that the systematic uncertainty in Eq. (2) has in fact a statistical origin so that the uncertainties are to be added in quadrature. The value is consistent with the current PDG average [4], which includes a scale factor of 1.9, and with other results obtained using stored UCNs but is at variance with the result obtained using a neutron beam [8].

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