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Disagreement between measurements of the neutron lifetime by the ultracold neutron storage method and the beam technique

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Contents

Abstract. Recent measurements of the neutron lifetime performed using a gravitational trap of ultracold neutrons (UCNs) (Konstantinov Petersburg Nuclear Physics Institute, Russia) and a magnetic UCN trap (LANL, USA) have confirmed PNPI's result of 2005. The results of experiments with stored UCNs agree with each other but differ from those of the beam experiment (NIST, USA) by 3.5σ (corresponding to 1% in the decay probability). This disagreement is currently being discussed in the literature as a 'neutron anomaly'. We analyze possible reasons for that disagreement and test the experimental data for the neutron lifetime and beta-decay asymmetry within the Standard Model. The test is only passed for neutron lifetime values that are obtained using the UCN storage method.

Keywords: neutron lifetime, particle physics, dark matter

1. Introduction. The history of neutron lifetime measurements

The neutron lifetime is one of the most important fundamental quantities for elementary particle physics and cosmology. Of the nonstable elementary particles, the neutron is the most long-lived, its lifetime being ~ 880 s. Precisely the large lifetime of the neutron, i.e., its small decay probability, gives rise to difficulties in determining its lifetime. Thus, for example, in a beam of cold neutrons, only a single neutron out of a million that pass through an experimental device decays along a distance of 1 m. There is, however, an alternative method for measuring the neutron lifetime with the aid of ultracold neutrons (UCNs). The kinetic energy of these neutrons is very low, and they undergo total reflection from the walls of material and magnetic traps with a gradient of the magnetic field at the walls. The idea of the experiment is to keep the neutrons in the trap and to observe their decay. The probability of losses in the trap can be reduced to the level of 1–2% of the neutron decay probability. This is possible in the case of cryogenic material traps [1, 2], and an even lower loss probability can be achieved with magnetic traps [3–6]. Thus, neutrons can be stored in traps and the neutron lifetime can be measured in practically a direct manner, introducing small corrections for UCN losses during storage.

The history of neutron lifetime measurements, presented by the PDG (Particle Data Group), embraces a significant period of time, starting from the first experiments performed in the 1970s with neutron beams [7, 8]. Since then, the measurement precision has been improved by an order of magnitude, and significant progress has been achieved in the application of UCNs. One must, however, recall the pioneering work by A Snell (USA, 1950), J Robson (Canada, 1950), and P E Spivak (USSR, 1955) performed with neutron beams.

Progress in the UCN method was not as unclouded, as it may seem. The first experiments involving UCN storage, performed by V I Morozov's group, were not sufficiently precise, owing to the low UCN density in the traps [9]. The accuracy of the experiments was substantially enhanced after the creation of intense UCN sources in Gatchina [10] and Grenoble [11]. It turned out to be extremely successful to coat the trap walls with a fluorinated oil (fomblin), in which fluorine atoms are substituted for hydrogen atoms [12, 13]. However, the probability of losses in the trap walls in these experiments amounted to, respectively, $\sim 30\%$ [12] and $\sim 13\%$ [13] of the neutron decay probability. The experimental task consisted of extrapolating the UCN storage time to the neutron lifetime. In these experiments, the UCN collision frequency varied owing to changes in the trap shape. The extrapolation distance amounted to ~ 200 s [12] and ~ 100 s [13], so to achieve a precision of ~ 1 s in the neutron lifetime was an extremely difficult task.

Moreover, the effect was revealed of UCN 'low-energy heating' (quasielastic scattering), which resulted in a systema-

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tic uncertainty in neutron lifetime measurements [14–17]. The situation with neutron lifetime measurements with the aid of UCN improved significantly with the use of a cryogenic trap with a gravitational shutter [18]. Owing to low temperatures, the following were suppressed: the effect of inelastic UCN scattering and the 'low-energy heating' effect, while the probability of losses in the trap walls was already reduced to 1–2% of the neutron decay probability. Here, the extrapolation range of the UCN storage time to the neutron lifetime only amounted to 5–10 s. Therefore, achieving a precision ~ 1 s in the neutron lifetime became a reality.

In the same experiment, but carried out in 2004 at the Institute Laue-Langevin (ILL) by a collaboration of the B P Konstantinov Petersburg Nuclear Physics Institute of the NRC "Kurchatov Institute" (PNPI NRC KI) and the Joint Institute for Nuclear Research (JINR) [1], the result obtained for the neutron lifetime was $878.5 \pm 0.7\,(\text{stat.}) \pm 0.3\,(\text{syst})$ s. The result of the Gatchina experiment [18] obtained with an identical gravitational trap was substantially surpassed in precision, while their divergence was less than 2σ. In 2006, the neutron lifetime was 885.7 ± 0.8 s, according to the PDG. The divergence between the data obtained in 2005 by the new experiment [1] and the PDG data amounted to 6.5σ, which caused a deep resonance owing to the obvious doubts that such a deviation could be possible. However, already four years later, in the first experiment with a magnetic trap of constant magnets [3], the result was confirmed, namely, the neutron lifetime in this experiment was shown to be 878.2 ± 1.9 s. This result was presented at the VII International Conference, Ultracold and Cold Neutrons. Physics and Sources [4] in 2009, and later it was published [5].

In 2010, the experiment MAMBO II (the abbreviation MAMBO derives from MAMpe BOttle) [19] presented the result 880.7 ± 1.8 s. Then, in 2012, the results of experiments [12, 13] were corrected with fomblin at room temperature: 882.5 ± 2.1 s [20] and 881.6 ± 2.1 s [21]. Finally, in 2015, V I Morozov's group performed a new experiment, in which the result obtained was 880.2 ± 1.2 s [22]. Back in 2010, our group (PNPI NRC KI) thought of making a large gravitational trap and of testing the result of our own experiment of 2005 [23]. This experiment with a large gravitational trap was completed by the PNPI NRC KI–ILL–Rutherford–Appleton (RAL) collaboration in 2017 [2], and it obtained the result $881.5 \pm 0.7 \pm 0.6$ s, so within 2σ both results turned out to be consistent. In the same year of 2017, the result obtained in the experiment at the Los Alamos national laboratory [6] with a UCN magnetic trap was published: $877.7 \pm 0.7 \pm 0.3$ s. Thus, the 2005 result of the measurement involving UCNs was confirmed. The history of measurements starting in 1990 is presented in Fig. 1.

The distribution of neutron lifetime measurements starting in 2005 is shown in Fig. 2. The results of measurements in experiments involving UCN storage in material and magnetic traps is presented in the left-hand part of the figure. Thus, it can be concluded that the results of experiments with UCN storage are consistent within 2σ. But the right-hand part of Fig. 2 shows the result of measurements with a neutron beam and proton trap which is noticeably different [24, 25]. The results with statistical and systematic errors, as well as the total error, calculated as the linear sum of errors, are presented in the Table.

Note that we apply linear summation of systematic and statistical errors, which is more conservative than quadratic summation.

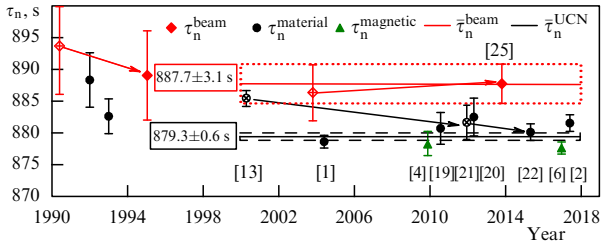

Figure 1. (Color online.) Experimental results for neutron lifetime starting in 1990: difference between data from 2005 [1] and data from 2000 [3], correction of experiments using liquid fomblin [20, 21] and new experiment [22], finally, new results [6] and [2] of 2017. τ_n^{beam} — beam experiments, $\tau_n^{material}$ — material traps, $\tau_n^{magnetic}$ — magnetic traps, $\bar{\tau}_n^{beam}$ — mean for beam experiments, $\bar{\tau}_n^{UCN}$ — mean for UCN storage experiments. The dotted lines show the corridor of errors of the mean value. The shaded symbols indicate experiments, the results of which were subsequently either corrected or revised by the authors.

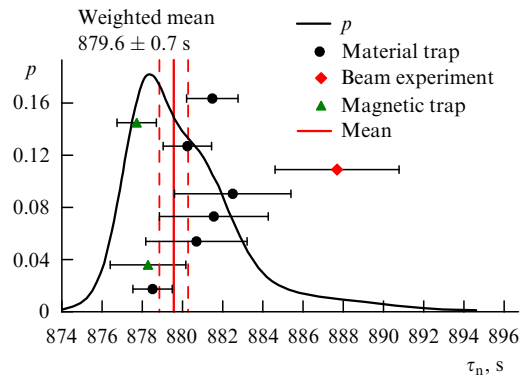

Figure 2. (Color online.) Distribution of results of neutron lifetime τ_n measurements starting from 2005 in experiments involving UCN storage in material and magnetic traps and also in a beam experiment with a trap for protons from decays of neutrons in flight; p — probability density. The uncertainty in the mean value, shown by vertical dashed straight lines, is increased $\sqrt{\chi^2} = 1.4$ times.

Table. Results of measurements of the neutron lifetime τ_n* .

τ_n, s	$(\Delta\tau_n)_{tot}$, s	$(\Delta\tau_n)_{stat}$, s	$(\Delta\tau_n)_{syst}$, s	χ^2	Year	References
881.5	1.3	0.7	0.6	2.1	2017	[2]
877.7	1.0	0.7	0.3	3.6	2017	[6]
880.2	1.2	1.2	—	0.3	2015	[22]
887.7	3.1	1.2	1.9	6.9	2013	[25]
882.5	2.9	1.4	1.5	1.0	2012	[20]
881.6	2.7	0.8	1.9	0.6	2012	[21]
880.7	2.5	1.3	1.2	0.2	2010	[19]
878.3	2.6	1.6	1.0	0.3	2009	[4]
878.5	1.0	0.7	0.3	1.2	2005	[1]

* $(\Delta\tau_n)_{tot}$ — total uncertainty, $(\Delta\tau_n)_{stat}$ — statistical uncertainty, $(\Delta\tau_n)_{syst}$ — systematic uncertainty

The divergence between results of the beam experiment [24, 25] and the UCN experiments amounts to 3.5σ in the case of quadratic summation and to 2.6σ in the case of linear summation. Somehow or other, this difference draws attention [26], and it has already been termed the 'neutron anomaly' [27, 28].

If the results obtained with UCNs alone are averaged, then one obtains $\tau_n = 879.3 \pm 0.6$ s, while the value of χ^2 is reduced from 2 to 1.3.

2. Analysis of the difference between the results of measurements performed in beam experiments and in experiments based on the storage of ultracold neutrons

First of all, one must analyze the essential difference between how beam experiments and experiments with UCN traps are carried out.

A beam experiment is based on the following relationship:

$$\Delta N_p = \lambda N_n \Delta t\,, \tag{1}$$

where ΔN_p is the number of neutron decay products (protons or electrons) registered when the neutron beam crosses the experimental device, N_n is the number of neutrons that cross the device, Δt is the time of flight of neutrons through the device, $\lambda = 1/\tau_n$ is the neutron decay probability, and τ_n is the neutron lifetime. Here, the sole neutron decay channel into p, e, $\tilde{\nu}$ is assumed. The decay probability of a neutron into a hydrogen atom is negligible and estimated to be $3.9 \times 10^{-4}\%$.

The main difficulty of a beam experiment consists of absolute measurements both of quantities present in relationship (1) and of the electron and proton registration efficiencies.

An experiment based on UCN storage is based on measurement of the following dependence upon time:

$$N_n(t) = N_n(0)\exp\left(-\frac{t}{\tau_{\text{storage}}}\right), \tag{2}$$

where $N_n(t)$ is the number of neutrons in the trap at time moment t, which can be measured with the aid of a neutron detector in certain intervals of time, and $\tau_{\text{storage}}^{-1}$ is the UCN storage probability in the trap,

$$\tau_{\text{storage}}^{-1} = \tau_n^{-1} + \tau_{\text{loss}}^{-1}\,. \tag{3}$$

The main difficulty in a UCN experiment is accurate measurement of UCN losses in the trap — τ_{loss}^{-1}. Losses in the trap are determined by the collision frequency with its walls and the interaction of UCNs with residual gas in the trap:

$$\tau_{\text{loss}}^{-1} = \eta\gamma(E) + \tau_{\text{vac}}^{-1}\,, \tag{4}$$

where η is a loss factor, which is independent of the UCN energy, $\gamma(E)$ is the effective collision frequency depending upon the UCN energy and the trap dimensions, and τ_{vac}^{-1} is the probability of UCN losses during interaction with molecules of the residual gas.

In experiments [1, 2, 9, 12, 18–20], measurement is performed of the dependence of τ_{loss}^{-1} upon the collision frequency, and extrapolation of $\tau_{\text{storage}}^{-1}$ to τ_n^{-1} is applied.

In experiments [13, 21, 22], the collision frequency is measured by the registration of neutrons after inelastic interaction with the trap walls with the aid of ^{3}He detectors of thermal neutrons, installed outside the trap.

In experiments [1, 2, 18] with a gravitational UCN trap at low (~ 100 K) temperatures, the loss factor is quite small, so a precision of ± 1 s in extrapolation can be justified.

Finally, in experiments with UCN storage in magnetic traps [4, 6], UCN losses during storage should be equal to zero in the absence of UCN depolarization in strong magnetic fields. The results of two independent experiments [4, 6] are in good agreement.

On the whole, a situation of consistency is observed in the case of eight UCN storage experiments, and agreement exists between the results of experiments based on UCN storage in material and magnetic traps. Apparently, the result for the neutron lifetime (879.3 ± 0.6 s), obtained from a set of eight experiments based on different techniques, must be considered quite reliable.

Beam experiment [25] is actually the only sufficiently precise beam experiment, since its accuracy exceeds that of the preceding beam experiments. It is too early to call the disagreement between the result of a sole beam experiment and the results of a whole series of UCN storage experiments a 'neutron anomaly', since, at least, experiment [25] must be repeated and independent beam experiments must be performed.

Naturally, from the point of view of modern searches for new physics, the present situation concerning this discrepancy problem is quite understandable. Any discrepancy beyond the limits of 3σ is considered a reason for discussion. Therefore, we shall present ideas that were earlier put forward and are presently voiced as a possible explanation for the discrepancy between the results of measurements. Most assumptions are, naturally, related to the existence of possible losses unaccounted for in UCN storage experiments.

(1) One of the most popular hypotheses concerns so-called small heating in the case of UCN storage in traps. In a recent study [29], even the influence of Earth's rotation on UCN storage in traps is considered. Indeed, owing to rotation of the trap and to the interaction of a UCN with its walls, the spectrum of the neutrons stored will slowly spread out (will undergo heating and cooling). A neutron may leave the trap if its energy increases. The authors of Ref. [29] propose to take this effect into account in UCN storage experiments, when a precision of better than 1% is involved. In this connection, it must be noted that the 'heating' effect of UCNs stored in a trap is under control in the experiment with a large gravitational trap. The 'heated' neutrons would leap out of the trap and would be revealed by the detector during the long storage time interval (1600 s). The experimental estimate of the upper time limit of such an effect is less than 1 s. Moreover, this effect is compensated in the course of extrapolation to the zero collision frequency, i.e., to the lifetime of the neutron.

(2) When the result $878.5 \pm 0.7 \pm 0.3$ s with a deviation of 6.5σ from the PDG data was announced in 2005, one of the proposals involved a discussion of oscillations $n \to n'$ (neutron $\to$ mirror neutron) [30]. The idea of this proposal must be clarified.

Our world is left-handed with respect to the weak interaction, and the issue of global symmetry restoration has been discussed for a long time [31]. In order to restore global symmetry, one can assume the world of dark matter to be right-handed with respect to inversion in space. In the simplest scheme, involving a 'mirror Standard Model', the mirror neutron n′ is a dark matter particle of the same mass as the neutron n, but with an opposite magnetic moment and, naturally, with a very small interaction constant with ordinary matter, but with the same gravitational interaction. Then, $n \to n'$ transitions are possible in the absence of magnetic fields (both ordinary magnetic fields and dark matter mirror magnetic fields). Upon realizing such transi-

tions, the mirror neutron leaves the trap, since it barely interacts with ordinary matter. Then, the lifetime in UCN storage experiments will be underestimated. The proposal concerning the possibility of $n \to n'$ oscillations was put forward in Ref. [30] in 2006. Experimental studies of $n \to n'$ oscillations were carried out in Refs [32–35]. The most accurate restriction was imposed on $n \to n'$ oscillations in Ref. [33], where it was shown that the period of oscillations exceeds 414 s (with a 90% CL (confidence level)), or that the oscillation probability in the absence of a magnetic field is less than 2.4×10^{-3} s^{-1}. In 2009, the upper limit of the period of $n \to n'$ oscillations was improved in this experiment to 448 s (90% CL) [34]. Thus, $n \to n'$ oscillations were not revealed. All these studies are certainly interesting. However, it is important to note that with the aid of neutron oscillations it is not possible to explain the difference between the results of the beam experiment and those of the UCN experiment.

The point is that $n \to n'$ oscillations (if they exist) are already significantly suppressed in Earth's magnetic field. Moreover, the effect of UCN escaping due to the appearance of a mirror component is proportional to the number of collisions in the trap, and it is excluded in extrapolation to zero collision frequency. Thus, the idea of $n \to n'$ oscillations cannot explain the divergence between the two methods (beam and UCN) of measuring the neutron lifetime by underestimating the result in the UCN storage method.

(3) In the standard neutron decay scheme, three decay modes are considered, although practically everything is determined by the decay producing a proton, and only 1% of events are accompanied by the production of a γ-quantum together with the proton:

$n \to p + e^- + \bar{\nu}_e$ — 100 %,
$n \to p + e^- + \bar{\nu}_e + \gamma$ — $(9.2 \pm 0.7) \times 10^{-3}$ [36],
$n \to H + \bar{\nu}_e$ — 3.9×10^{-6} [37].

The emission process of a γ-quantum represents the decay electron bremsstrahlung that depends on the electron energy as E_β^{-1}. The relative probability of this process is approximately 1%, but this process is automatically taken into account in the experiment in Ref. [25], since there is a proton in the final state.

The most suitable process involving decay into a neutral hydrogen atom that is not kept in the magnetoelectric trap of experiment [25] can be realized with a very low relative decay probability: 3.9×10^{-4} % [37]. A quantitative explanation of the 'neutron anomaly' would require a relative decay probability of 1%. However, it must be noted that it is interesting to calculate the correction to the formation probability of a hydrogen atom, when the neutron decay occurs in quite a strong magnetic field (4.6 T). Naturally, such a strong magnetic field cannot affect the total neutron decay probability, but the possibility of the magnetic field influencing the formation of the hydrogen atom in the final state must be estimated. This estimation, carried out by Ye G Druckaryov (PNPI NRC KI), revealed that the magnetic field changes the formation probability of a hydrogen atom negligibly.

(4) An interesting explanation for the neutron decay anomaly was recently presented in Ref. [28]. It reduces to the introduction of an additional decay channel into dark matter in the final state. The assumption is that, if these particles are stable in the final state, they can be dark matter particles with a mass close to the neutron mass. From the point of view of previously discussed ideas, this represents a transition to dark matter very similar to the transition into a dark matter mirror neutron of a mass differing from that of an ordinary neutron, but very close to it. It is important to note that here dark matter is assumed to interact with baryonic matter. Within such a scenario, the departure is expected of a monochromatic photon in the energy range of 0.782–1.664 MeV with a relative probability of 1% [28]. This is important, since an experimental test becomes possible. Such a test was performed in [38] practically right after the publication of Ref. [28]. No monochromatic γ-quanta were revealed at a reliability level of 4σ.

(5) The development of the idea of mirror dark matter led to the consideration in Ref. [39] of a scheme, according to which the mass of the mirror neutron is inferior to the standard neutron mass. The article presents an attempt to relate the 'neutron anomaly' and the so-called reactor antineutrino anomaly, which signifies a deficit in the measured antineutrino flux from the reactor with respect to the calculated value. The problem is actively being discussed at neutrino conferences, and experiments are being carried out in search of a sterile neutrino, i.e., a transition to dark matter in the neutrino sector. Two such so-called anomalies were discussed in Ref. [39]: the neutron and reactor anomalies. Each of them is at a reliability level of $\sim 3\sigma$ (the 'antineutrino deficit' amounts to 6.6 ± 2.4%, while the 'neutron anomaly' amounts to 1.0 ± 0.3%). The peculiarity of the proposal in Ref. [39] consists of the fact that both anomalies can be explained by the sole phenomenon of $n \to n'$ oscillations in the baryonic sector between the neutron n and the dark matter neutron n' of mass $m_{n'}$, somewhat inferior to the mass m_n of the ordinary neutron. The mass difference $m_n - m_{n'}$ can be compensated by the binding energy in the nucleus, while $n \to n'$ transitions will be strengthened. Calculations within the proposed model require a single free parameter: the mass difference $m_n - m_{n'}$. If the probability of $n \to n'$ oscillations for a free neutron is normalized to the 'neutron anomaly' (1%), then, upon achieving in calculations an explanation of the 'neutrino anomaly' (6.6%), one can determine the mass difference $m_n - m_{n'}$ and, thus, find the mass of the dark matter neutron. Preliminary estimates reveal a suitable mass difference $m_n - m_{n'} \approx 3$ MeV. However, an analysis was performed of the cumulative yields of isotopes in fission products that did not confirm the possible existence of an additional decay channel in which dark matter neutrons are produced with a mass difference $m_n - m_{n'} \approx 3$ MeV. The conclusion of the analysis performed is that for mirror neutrons the range of mass differences $m_n - m_{n'} \geqslant 3$ MeV is closed.

(6) In a recent publication [40], the mirror dark matter scheme is considered for the case of $m_n - m_{n'} \approx 10^{-7}$ eV. The assumption is then made that, when the neutron passes through the magnetic field of the solenoid in the experiment [24, 25], compensation occurs of the mass difference $m_n - m_{n'}$ owing to the binding energy in the magnetic field due to the neutron magnetic moment. Transitions $n \to n'$ are intensified, while the proportion of standard decays involving the production of a proton decreases by 1%. Such an assumption can be investigated in the experiment in Ref. [25] by varying the magnetic field and also in the new beam experiment [41] with a magnetic field that is one fifth as strong, which is presently under preparation.

(7) In attempts to reveal the difference in performance between the beam experiment and UCN storage experiments, it can be noted that the neutron decay in the beam experiment

was observed in the case of cold neutrons, but not in the UCN experiment. It is not possible to point to any physical reason following from the above. However, an actual difference exists in the time interval of decay observation. In a beam of cold neutrons, the decay process is observed within an interval of 10^{-3} s after the last neutron interaction (collision with the wall of the neutron guide). In the experiment with UCNs, the mean flight time between collisions is 0.3 s, while the interval for measuring the decay exponential is actually $\sim 10^3$ s. In comparing these intervals, the issue can be raised of how rigorously the exponential law is satisfied in neutron decay. Deviation from the exponential law in neutron decay can arise if different levels exist in the initial state or if there are several decay modes [42]. Finally, one can recall the Zeno quantum paradox [43], according to which all nonstable states freeze at $t = 0$, and also the Zeno quantum effect consisting of the fact that the decay probability can vary if measurements are performed frequently in order to establish whether a decay really took place. Measurements with the beam can be related to the Zeno paradox, since $t = 10^{-3}$ s, while the neutron lifetime is six orders of magnitude larger. Measurements with UCNs can be related to the quantum Zeno effect, since frequent collisions of a neutron with the trap walls correspond to measurement acts of the neutron stability at each moment of time. The number of such measurements is of the order of 10^4. It is still to be clarified whether the quantum Zeno paradox and the quantum Zeno effect are somehow related to the problem at hand. According to estimates presented in Refs [42, 44], the time scale at which the decay law of nonstable particles can possibly differ from the potential law is far from the characteristic times dealt with in experiments to measure the neutron lifetime.

On the whole, the conclusion can be made that there still exists no clear physical idea to explain the observed divergence. It is possible that the most probable answer is determined precisely by the systematic error in the beam experiment.

3. Measurement of the neutron decay asymmetry and a test for verifying the Standard Model

Let us now consider in greater detail the investigation of neutron decay, including measurement of the decay asymmetry and a test for verifying the Standard Model. As is well known, the matrix element $V_{\rm ud}$ of the Cabibbo–Kobayashi–Maskawa (CKM) matrix,

$$\begin{pmatrix} \mathrm{d}' \\ \mathrm{s}' \\ \mathrm{b}' \end{pmatrix} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix}, \tag{5}$$

can be determined from the neutron decay owing to measurements of the lifetime and of the decay asymmetry, and it can be compared with the value of $V_{\rm ud}$ determined by other methods. The formula relating the half-decay period ($\tau_{1/2}$) of the neutron and the element $V_{\rm ud}$ has the form

$$f\tau_{1/2}(1+\delta'_{\rm R})(1+\Delta_{\rm R}) = \frac{K}{|V_{\rm ud}|^2\, G_{\rm F}^2(1+3\lambda^2)}\,, \tag{6}$$

where $f = 1.6886$ is a phase space factor, $\delta'_{\rm R} = 1.466 \times 10^{-2}$ is a model-independent radiative correction, calculated with a precision of 9×10^{-5}, $\Delta_{\rm R} = 2.40 \times 10^{-2}$ is a model-dependent internal radiative correction calculated with a precision of 8×10^{-4}, $G_{\rm F}$ is the Fermi weak interaction coupling constant determined from the μ-decay, $K = \hbar(2\pi^3 \ln 2)(\hbar c)^6/(m_{\rm e}c^2)^5$, and $\lambda = G_{\rm A}/G_{\rm V}$ is the ratio of the axial-vector and vector weak interaction coupling constants, determined experimentally from measurements of angular correlation coefficients in the neutron β-decay (Fig. 3). The following quantity is determined in the experiment to measure the beta-decay asymmetry:

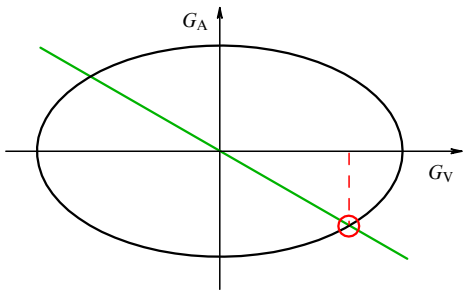

Figure 3. Determination of the matrix element $V_{\rm ud}$ from neutron decay data.

$$A_0 = -2\,\frac{\lambda(\lambda+1)}{1+3\lambda^2}\,. \tag{7}$$

With account of $G_{\rm V} = V_{\rm ud}G_{\rm F}$ in Fig. 3, from equation (6) we obtain an ellipse, and from equation (7) the curve that crosses it, and the intersection point permits us to determine the element $V_{\rm ud}$.

Formula (6) for element $V_{\rm ud}$ can be represented in the form [45]

$$|V_{\rm ud}|^2 = \frac{4908.7 \pm 1.9\mathrm{c}}{\tau_{\rm n}(1+3\lambda^2)}\,. \tag{8}$$

In Fig. 4, the results are presented of a test of data on the neutron β-decay in order to determine the matrix element $V_{\rm ud}$ making use of the ratio of the axial and vector weak interaction coupling constants, ($G_{\rm A}/G_{\rm V} = \lambda$), based on the most precise measurements of the electron decay asymmetry [46].

The intersection of data for $\tau_{\rm n}$ and $\lambda = G_{\rm A}/G_{\rm V}$ yields a value of $V_{\rm ud}$ from the neutron decay that can be compared with the value of $V_{\rm ud}$ based on super-allowed $0^+ \to 0^+$ nuclear transitions and with the value of $V_{\rm ud}$ from the unitarity of the CKM matrix ($V_{\rm ud}^2 + V_{\rm us}^2 + V_{\rm ub}^2 = 1$).

As seen from Fig. 4, the test of the Standard Model is passed successfully only if the neutron lifetime data used come from UCN storage experiments.

Thus, in problems of elementary particle physics, astrophysics, cosmology, and neutrino physics, it is preferable to make use of the value 879.3 ± 0.6 s from UCN experiments, while the beam experiments must be amended.

In addition, we note that at present the accuracy of UCN experiments in measuring the neutron lifetime has reached the level of 7×10^{-4}. The PERKEO II experiment achieved a precision in the electron decay asymmetry of 4.2×10^{-3} [46]. The accuracy of results obtained in the PERKEO III experiment and presented to the Workshop on Particle Physics at Neutron Sources (PPNS-2018) was 2.5 times better and was in agreement with the result of PERKEO II. Thus, measurements of the decay asymmetry exhibit quite decisive agreement. On the whole, one can conclude that the accuracy of experiments is already approaching the theore-

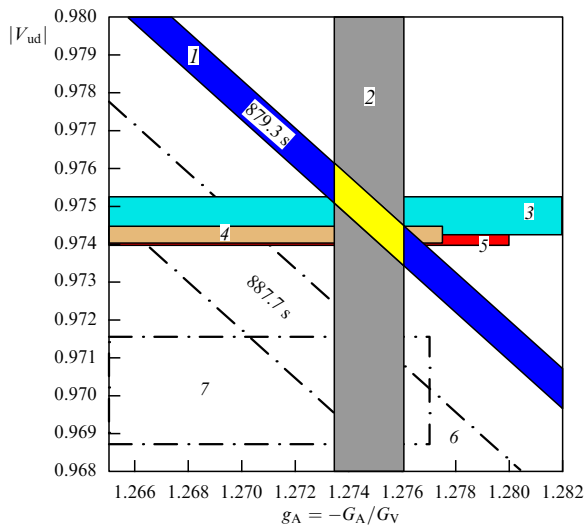

Figure 4. (Color online.) Dependence of matrix element $|V_{ud}|$ on the neutron lifetime and the axial coupling constant g_A. *1* — neutron lifetime measured with the aid of UCN (879.3 ± 0.6 s); *2* — neutron decay asymmetry (PERKEO II experiment); *3* — neutron β-decay (UCN experiments + PERKEO II); *4* — unitarity; *5* — nuclear $0^+ \to 0^+$ transitions; *6* — neutron lifetime [25] (887.7 ± 2.2 s); *7* — neutron β-decay (experiment [25] + PERKEO II).

tical accuracy related to the calculation of radiative corrections.

4. Conclusion

The impression has been created that the most probable cause of the divergence discussed lies in the experimental errors of the beam method. It would, naturally, be quite desirable to see the result of the experiment repeated in the neutron beam with a proton trap, as well as the result of an independent experiment in a neutron beam involving the registration of protons and electrons produced in neutron decays. It is important to note that repetition of the experiment with a proton trap is planned, and that a new experiment is to be carried out using a neutron beam [41]. Maybe they will clarify the neutron anomaly problem or confirm it more definitely.

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