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The Problem of the Neutron Lifetime Measurements

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In this paper the analysis of the present situation with the neutron lifetime measurement is made. The problem of experimental data discrepancy has been analyzed and systematic errors of some experiments have been found out. The corrected table of measurements is given and a new world average value of neutron lifetime 879.9 ± 0.9 s is presented.

The recent neutron lifetime experiment [1] has provided the value 878.5 ± 0.8 s. It differs by 6.5 standard deviations from the world average value 885.7 ± 0.8 s quoted by the particle data group (PDG) in 2006 [2]. The experiment employed a gravitational trap with a low-temperature fluorinated oil (fomblin) coating, which provides several advantages with respect to previous experiments. First of all, a small loss factor of only $2\cdot10^{-6}$ per collision of UCN with trap walls results in a low loss probability of only 1% of the probability of neutron β-decay. Therefore the measurement of neutron lifetime was almost direct; the extrapolation from the best storage time to the neutron lifetime was only 5 s. In these conditions it is practically impossible to obtain a systematic error of about 7 s. The quoted systematic error of the experimental result [1] was 0.3 s.

In determination of the world average value of the neutron lifetime there is rather dramatic situation. On the one hand a new value of neutron lifetime from work [1] cannot be included in the world average value because of the big difference of results. On the other hand until this major disagreement is understood the present world average value for the neutron lifetime must be suspect. So the situation on PDG page devoted to the neutron lifetime is formulated [2] in view of this controversy.

The only way out of the present situation is to carry out new more precise experiments. More detailed analysis of the previous experiments and search of possible systematic error is also reasonable.

Table 1 and Fig.1 show dynamics of developing events. Before carrying out measurements [1] using "Gravitrap" installation the world average neutron lifetime was mainly determined by the result of work [5]. At that time the consistent world average value 885.7 ± 0.8 s was obtained. Occurrence of a new precise measurement of neutron lifetime in 2004 led to the described above controversy. It became more obvious in 2007 after obtaining measurements of neutron lifetime with UCN magnetic trap [3]. It is easy to see that the experiment [5] is one of the most precise experiments in Table 1. Not only does it give the main contribution to the world average value obtained until 2004, but it also gives the main contribution to the discrepancy between the results of earlier and new measurements.

Table 1

Progress of neutron lifetime measurements till 2007

τ_n, s	Author(s), year, reference
878.2 ± 1.9	V. Ezhov et al. 2007 [3]
878.5 ± 0.7 ± 0.3	A. Serebrov et al. 2005 [1]
886.3 ± 1.2 ± 3.2	M.S. Dewey et al. 2003 [4]
885.4 ± 0.9 ± 0.4	S. Arzumanov et al. 2000 [5]
889.2 ± 3.0 ± 3.8	J. Byrne et al. 1996 [6]
882.6 ± 2.7	W. Mampe et al. 1993 [7]
888.4 ± 3.1 ± 1.1	V. Nesvizhevski et al. 1992 [8]
893.6 ± 3.8 ± 3.7	J. Byrne et al. 1990 [9]
887.6 ± 3.0	W. Mampe et al. 1989 [10]
872 ± 8	A. Kharitonov et al. 1989 [11]
878 ± 27 ± 14	R. Kossakowski et al. 1989 [12]
877 ± 10	W. Paul et al. 1989 [13]
891 ± 9	P. Spivac et al. 1988 [14]
876 ± 10 ± 19	J. Last et al. 1988 [15]
870 ± 17	M. Arnold et al. 1987 [16]
903 ± 13	Y.Y. Kosvintsev et al. 1986 [17]
937 ± 18	J. Byrne et al. 1980 [18]
881 ± 8	L. Bondarenko et al. 1978 [19]
918 ± 14	C.J. Christensen et al. 1972 [20]

We cannot find by any means an error in 7 s in our measurements [1] where extrapolation of UCN storage time to the neutron lifetime is only 5 s. Therefore we have examined the analysis of the experiment [5] where extrapolation is 100 – 120 s and at the same time it is affirmed that it is done with systematic error 0.4 s. It is this point that causes obvious doubts. A detailed analysis of the experiment [5] performed by means of

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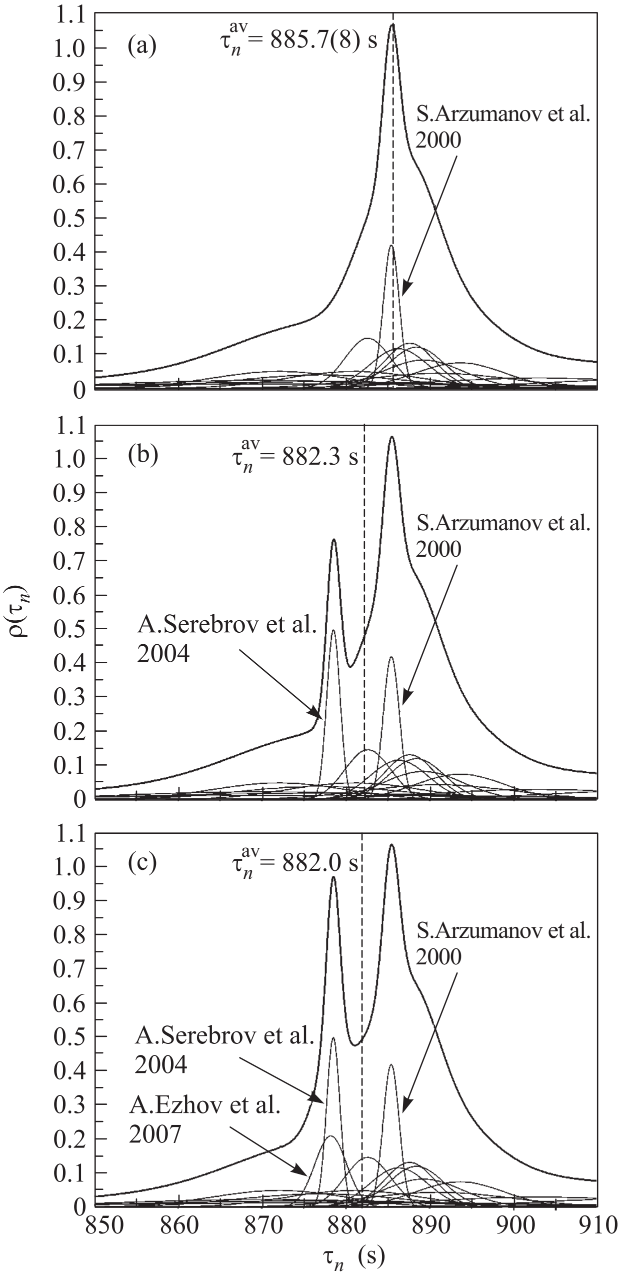

Fig.1. Progress of the neutron lifetime measurements. (a) before "Gravitrap" measurement in 2003; (b) after "Gravitrap" measurement in 2004; (c) after magnetic trap measurement in 2007

Monte Carlo simulation is made in our work [21]. The analysis of experiment MAMBO I [10] is given in our work [22]. In both experiments there has been found a negative correction to the neutron lifetime equal to about 6 s. MC simulations were performed using a code written by A.K. Fomin especially for simulations with UCN [23]. This code was tested with GEANT4 code adapted to include the influence of gravity on neutrons [24]. Also its benchmark tests with experimental data are shown in our works [1] and [22].

The storage vessel in the experiment [5] consists of two coaxial cylinders. Storage of ultracold neutrons might occur either in the inner cylinder or in the gap between two cylinders. Thus one can observe alteration of ratio of the surface and the volume or of those neutrons that decayed during the flight to the neutrons lost in the walls. Later on one makes extrapolation to the neutron lifetime using the counting rate of neutrons heated inside the vessel and registered by ^{3}He detectors located around the storage vessels. The analysis made in our paper [21] has found out two considerable errors. One of them is due to non-equivalence of registration of ultracold neutrons after storage in the inner or annular vessel. In case of storage in the inner vessel the valves open into the volume and heat some neutrons inside it. For the annular vessel such an effect does not occur. The second systematic error arises because of unequal efficiency of the detector of heated neutrons during storage in inner and annular vessels. A detailed analysis of systematic errors is given in work [21]. Here we quote only the resulting table of systematic errors.

The summary table of corrections is shown in Table 2. We assume that after taking into account MC correction and uncertainty the result of work [5] for neutron lifetime could be $879.9 \pm 0.9_{\rm stat} \pm 2.4_{\rm syst}$ s. The resulting corrected value for the neutron lifetime is in agreement with the result 878.5 ± 0.8 s of the work [1].

The experiment [10] has been analysed and its Monte-Carlo model has been created, as after completing the experiment [10] the quasi-elastic scattering effect of ultracold neutrons on the surface of liquid fomblin was found. As a result, two systematic effects have been discovered. One of them is related to a long storage of above-barrier neutrons, the other one is concerned with quasi-elastic scattering of ultracold neutrons on the surface of liquid fomblin. A detailed analysis of these effects is available in our work [22]. Here we quote a comparative table of corrections from work [10] and from our work [22].

Table 3 quotes data from the work [10] with our additional corrections due to above-barrier neutrons and quasi-elastic scattering effects. In this table we use the data for long holding time intervals which bring the main contribution and do not depend on entry conditions (the form of initial spectrum, diffusion of a covering). As a total correction we find -6.0 ± 1.6 s. Our correction is a negative one and roughly compensates corrections from [10]. The systematic uncertainty in [10] is estimated to be about 3 s. It can cover substantially a lack of the information on experiment details. The resulting

Table 2

MC correction on the neutron lifetime result of the experiment [5] from work [21]

	Correction, s	Uncertainty, s
Not full emptying of the inner vessel during cleaning while working with the annular vessel	0	1
Effect of heating of neutrons by the shutters	−2.8	2
Effect of not equal thermal neutron detection efficiencies for different vessels	−2.1	1
Effect of not equal thermal neutron detection efficiencies for different vessels (correction in the experiment is +0.6 s)	−0.6	
Total	−5.5	2.4

Table 3

Results for neutron lifetime obtained from different holding intervals: τ_n is the result from work [10], $\Delta\tau$ [10] is the correction from [10], $\Delta\tau$ [22] is the correction due to above-barrier neutrons and quasi-elastic scattering calculated in work [22], and $\tau'_n = \tau_n$ (corrected [10]) + $\Delta\tau$ [22]

Holding interval, s	τ_n, s (uncorrected [10])	$\Delta\tau$, s [10]	τ_n, s (corrected [10])	$\Delta\tau$, s [22]	τ'_n, s
112.5–225	893(10)	~ -2	891(10)		
225–450	885.0(4)	+3.5	888.5(4)		
450–900	881.2(2.5)	+8	889.2(2.5)	−7.84 (0.87)	881.36 (2.65)
900–1800	878.0(1.5)	+9	887.0(1.5)	−5.29 (0.70)	881.71 (1.65)
1800–3600	878.5(2.6)	+8.6	887.1(2.6)	−5.54 (0.87)	881.56 (2.74)
			$\tau_n = 887.6(1.1)$		$\tau'_n = 881.6(1.2)$

corrected value for the neutron lifetime would agree with the result 878.5 ± 0.8 s of the work [1].

Now it is necessary to show a new table of results of the neutron lifetime measurements taking into account the correction of works [5] and [21], and also works [10] and [22]. We also included in the table the result of the experiment MAMBO II [25] based on the experiment MAMBO I. It uses UCN spectrum with a cutoff below the Fomblin critical energy. Because of this the systematic error of MAMBO I experiment was suppressed. Work [8] can be withdrawn from the list since a new much more accurate result has been obtained on this installation using low-temperature Fomblin rather than solid oxygen. The difference between an earlier result and a new one is 2.9 standard deviations. It is reasonable to withdraw the previous result due to obtaining a new more accurate result with 4 times higher accuracy. At last, it is necessary to include a new result of V. Morozov's group [26].

Finally, after corrections and additions the table of experimental results for neutron lifetime looks as follows (Table 4, Fig.2). The standard error of average value from Table 4 is 0.6 s, but the standard deviation of experimental results is 0.9 s. Thus, it will be expedient to accept 879.9 ± 0.9 s as the world average value for the neutron lifetime.

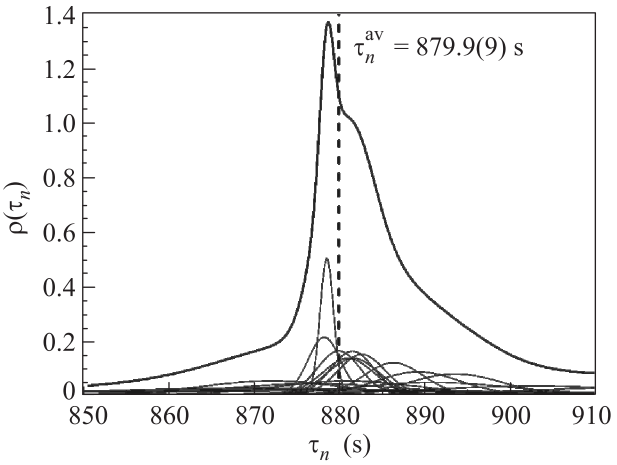

Fig.2. Distribution of results of measurements for the neutron lifetime after corrections and additions, giving average value of 879.9 ± 0.9 s

Table 4

The table of the experimental results for the neutron lifetime after corrections and additions

τ_n, s	Author(s), year, reference
881.5 ± 2.5	S. Arzumanov et al. 2009 [26]
878.2 ± 1.9	V. Ezhov et al. 2007 [3]
$878.5 \pm 0.7 \pm 0.3$	A. Serebrov et al. 2005 [1]
$886.3 \pm 1.2 \pm 3.2$	M.S. Dewey et al. 2003 [4]
$879.9 \pm 0.9 \pm 2.4$	S. Arzumanov et al. 2000 [5,21]
881.0 ± 3	A. Pichlmaier et al. 2000 [25]
$889.2 \pm 3.0 \pm 3.8$	J. Byrne et al. 1996 [6]
882.6 ± 2.7	W. Mampe et al. 1993 [7]
$893.6 \pm 3.8 \pm 3.7$	J. Byrne et al. 1990 [9]
881.6 ± 3.0	W. Mampe et al. 1989 [10,22]
872 ± 8	A. Kharitonov et al. 1989 [11]
$878 \pm 27 \pm 14$	R. Kossakowski et al. 1989 [12]
877 ± 10	W. Paul et al. 1989 [13]
891 ± 9	P. Spivac et al. 1988 [14]
$876 \pm 10 \pm 19$	J. Last et al. 1988 [15]
870 ± 17	M. Arnold et al. 1987 [16]
903 ± 13	Y.Y. Kosvintsev et al. 1986 [17]
937 ± 18	J. Byrne et al. 1980 [18]
881 ± 8	L. Bondarenko et al. 1978 [19]
918 ± 14	C.J. Christensen et al. 1972 [20]

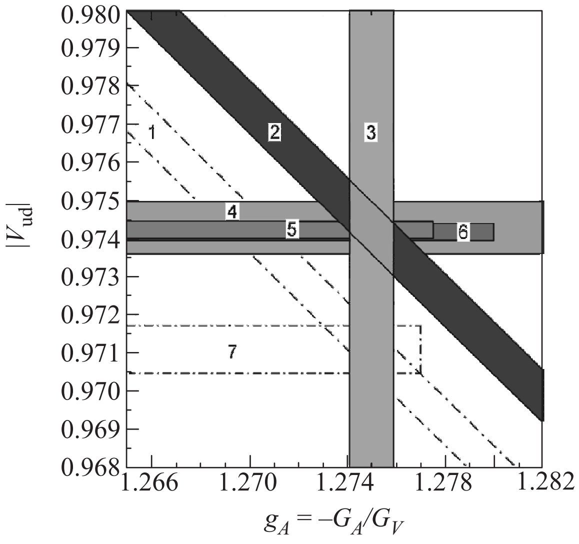

Fig.3. The dependence of the CKM matrix element $|V_{\rm ud}|$ on the values of the neutron lifetime and the axial coupling constant g_A. *1* – neutron lifetime, PDG 2006; *2* – neutron lifetime, this article; *3* – neutron β-asymmetry, Perkeo 2007; *4* – neutron β- decay, this article + Perkeo 2007; *5* – unitarity; *6* – $0^+ \to 0^+$ nuclear transitions; *7* – neutron β-decay, PDG 2006 + Perkeo 2007

To conclude, we have to mention that the analysis of neutron β-decay with a new world average neutron lifetime demonstrates reasonable agreement in frame of Standard Model. Fig.3 shows this analysis which is discussed in detail in [27, 28]. Fig.3 shows dependence of the CKM matrix element on the values of the neutron lifetime and the axial coupling constant g_A. The value $|V_{\rm ud}| = 0.9743(7)$, calculated for the new world average value for the neutron lifetime 879.9(9) s and $g_A = 1.2750(9)$ [29], agrees with both $|V_{\rm ud}| = 0.97419(22)$ from the unitarity of the CKM matrix elements [2] and $|V_{\rm ud}| = 0.97425(22)$, measured from the superallowed $0^+ \to 0^+$ nuclear β-decays, caused by pure Fermi transitions only [29, 30].

One can see that the value $|V_{\rm ud}| = 0.9711(6)$, calculated for the old world average value for the neutron lifetime 885.7(8) s, is ruled out by the experimental values $|V_{\rm ud}| = 0.97419(22)$ and $|V_{\rm ud}| = 0.97425(22)$.

Besides, it should be mentioned that detailed analysis of the nucleosynthesis process in the early stages of the formation of the Universe was made [31]. They analyzed the effect of the new value of the neutron lifetime on the consistency of data on the initial abundances of D and ^{4}He isotopes and the data on baryon asymmetry η_{10}. The use of the new value of the neutron lifetime improves the agreement between the data on the initial abundances of deuterium and helium, and those on baryon asymmetry. Although the accuracy of the cosmological data is much lower than that of measurements of the neutron lifetime, the shift of τ_n from the world average value to the new value has a certain effect on the verification of the nucleosynthesis model in the early stages of the formation of the Universe.

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