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New evaluation of neutron lifetime from UCN storage experiments and beam experiments

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Abstract

The analysis of experiments on measuring neutron lifetime has been made. The latest most accurate result of measuring the neutron lifetime [Phys. Lett. B 605, 72 (2005)] 878.5 ± 0.8 s differs from the world average value [Phys. Lett. B 667, 1 (2008)] 885.7 ± 0.8 s by 6.5 standard deviations. In view of this both the analysis and the Monte Carlo simulation of experiments [Phys. Lett. B 483, 15 (2000)] and [Phys. Rev. Lett. 63, 593 (1989)] have been performed. Systematic errors about –6 s have been found in both experiments. The table of results of neutron lifetime measurements is given after corrections and additions have been made. A new world average value of the neutron lifetime of 880.0 ± 0.9 s is given. Here is also presented a separate analysis of experiments on measuring neutron lifetime with UCN and with beam experiments. The average neutron lifetime for experiments with UCN is equal to 879.3(0.6) s, while for beam experiments it is equal to 889.1(2.9) s. The present difference of average values for both groups is 3.3σ and needs consideration. The contribution of beam experiments to the world average is not high, therefore it does not influence our analysis. However, it is an independent problem to be solved. It seems desirable that the precision of beam experiments should be enhanced.

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Keywords: neutron lifetime; ultracold neutrons

A new most accurate result of measuring neutron lifetime [1] 878.5 ± 0.8 s differs from the world average value [2] 885.7 ± 0.8 s by 6.5 standard deviations. The experiment [1] used a gravitational trap of ultracold neutrons (UCN) with covering made of the low-temperature fluorinated oil that has a few advantages over the previous experiments:

1) The coefficient of UCN losses for such a coating makes up only $2{\cdot}10^{-6}$, which leads to the probability of neutron losses in collisions with walls being only 1% of the β-decay probability. In such a way one could observe almost directly the process of neutron decay in the trap.

2) Extrapolation from the best storage time to the neutron lifetime is 5 s. The experimental error is equal to $\pm\ 0.7_{stat} \pm 0.3_{syst}$ s, i.e. the relative accuracy of determining losses at wall collisions is 10%. In such conditions it is practically impossible to get a systematic error of 7 s.

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3) In using a low-temperature fluorinated oil the quasi-elastic scattering of UCN is completely suppressed. The upper constraint on possible corrections concerned with this process is 0.03 s.
4) There is no effect of stationary trajectories of UCN.
5) Owing to high surface properties the surface of traps without coating is less than 10^{-6}. It ensures identity of factor of losses for different traps.
6) The course of the experiment has demonstrated stability and reproducibility of trap coating.

The situation is rather dramatic in estimating the world average value of the neutron lifetime. On the one hand, a new value of the neutron lifetime from the paper [1] cannot be included in the world average value because of the great difference in results. On the other hand, new data with high measurement precision makes doubtful the world average value for the neutron lifetime. In this way the present status is described on the page of the PDG devoted to neutron lifetime [2]. The best way of solving this problem is to conduct new more precise experiments. One could also make a more detailed analysis of earlier experiments and seek for possible systematic errors. We have published such an analysis of previous measurements in [3] and [1,4,5]. In this paper we summarize the obtained results.

Fig. 1 and Table 1 show the dynamics of developing events. Before making the measurements [1] by the “Gravitrap” installation the world average lifetime was mainly determined by the results of paper [8]. At that time there was obtained the non discrepant world average value 885.7 ± 0.8 s. A new precise measurement of neutron lifetime in 2004 [1] gave rise to the discrepancy described above. The discrepancy became more obvious in 2007 after obtaining the results of the measurement by a UCN magnetic trap [6]. It is easy to see that the experiment [8] is one of the most precise experiments in Table 1. It makes the main contribution into the world average value obtained till 2004, it also makes the main contribution into the divergence of data in previous and new measurements.

First of all we have made the analysis of our experiment. We have created the Monte Carlo model and could not find any systematic errors in our measurements which we did not consider. The results of these analyses have been published in paper [1]. A systematic error of 7 s in our measurements, in which extrapolation of the UCN storage time to the neutron lifetime comprises only 5 s, seems to be unlikely. The next stage of our analysis is the analysis of the experiment [8], where the extrapolation is 100-120 s and it is confirmed that it has been done with a systematic uncertainty of 0.4 s. It is this assumption that is quite doubtful. A detailed analysis of the experiment [8], conducted with our Monte Carlo model is made in our paper [4]. We have also made the analysis of the experiment MAMBO I [13] in our paper [5]. In both experiments we have found a negative correction to the neutron lifetime approximately equal to 6 s. The Monte Carlo simulation has been done with the set of programs aimed at the simulation of UCN experiments [24]. Testing the set of programs was done by comparing the calculation of results with that made by GEANT4 modified for UCN [25]. In addition, testing has been made on experimental data in our papers [1] and [5].

The storage vessel in the experiment [8] consists of two coaxial cylinders. The storage of UCN is possible either in the internal cylinder or in the gap between two cylinders. It results either in altering the relationship between the surface and the volume or in altering the relationship between the fraction of neutrons having decayed in the time of flight to that of the neutrons lost in the walls. Later on there is an extrapolation to the neutron lifetime using the rate of counting the neutrons heated inside the vessel and registered by ^{3}He detectors, located around the storage chambers. The analysis made in our paper [4], revealed two large errors. One of them is caused by non-equivalence of UCN registration after storage either in the internal or external vessel. In the case of storage in the internal vessel the valves open inwards of the volume and heat the fraction of neutrons located there. Such an effect does not occur in the external vessel. As result it gives the deficit of counts in UCN detector. But the effect is clearly observed by the detector of the heated neutrons. This effect is observed in raw experimental data as a peak in the count rate diagram of detector counting the heated neutrons from the internal vessel, and is not observed for the external vessel [26]. This effect is not considered in papers [8] and [26]. Our simulation enabled us to make the evaluation of the effect. Insufficient knowledge of the character of the valve movement gives rise to uncertainty as far as the size of this effect is concerned. The second systematic error arises because of unequal detection efficiency for heated neutrons in storing in external and internal vessels. As in the previous case, there is the uncertainty of correction concerned with the uncertainty of effective length of neutron registration by a detector for thermal neutrons. For the claimed precision to be obtained, one needs a detailed calibration of the detectors. Unfortunately in paper [8] this effect had the wrong sign, which requires an additional correction. Due to the above mentioned uncertainties the claimed systematic experimental error of [8] 0.4 s appears to be problematic even after taking into account the mentioned effects. A detailed analysis of systematic errors is given in paper [4]. After accepting a correction and an error from this paper, the result of neutron lifetime from [8] will be 879.9 ± $0.9_{stat.}$ ± 2.4_{syst} s. The corrected result is in agreement with the result 878.5 ± 0.8 s from [1].

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 [6]
878.5 ± 0.7 ± 0.3	A. Serebrov et al. 2005 [1]
886.3 ± 1.2 ± 3.2	M.S. Dewey et al. 2003 [7]
885.4 ± 0.9 ± 0.4	S. Arzumanov et al. 2000 [8]
889.2 ± 3.0 ± 3.8	J. Byrne et al. 1996 [9]
882.6 ± 2.7	W. Mampe et al. 1993 [10]
888.4 ± 3.1 ± 1.1	V. Nesvizhevski et al. 1992 [11]
893.6 ± 3.8 ± 3.7	J. Byrne et al. 1990 [12]
887.6 ± 3.0	W. Mampe et al. 1989 [13]
872 ± 8	A. Kharitonov et al. 1989 [14]
878 ± 27 ± 14	R. Kossakowski et al. 1989 [15]
877 ± 10	W. Paul et al. 1989 [16]
891 ± 9	P. Spivac et al. 1988 [17]
876 ± 10 ± 19	J. Last et al. 1988 [18]
870 ± 17	M. Arnold et al. 1987 [19]
903 ± 13	Y.Y. Kosvintsev et al. 1986 [20]
937 ± 18	J. Byrne et al. 1980 [21]
881 ± 8	L. Bondarenko et al. 1978 [22]
918 ± 14	C.J. Christensen et al. 1972 [23]

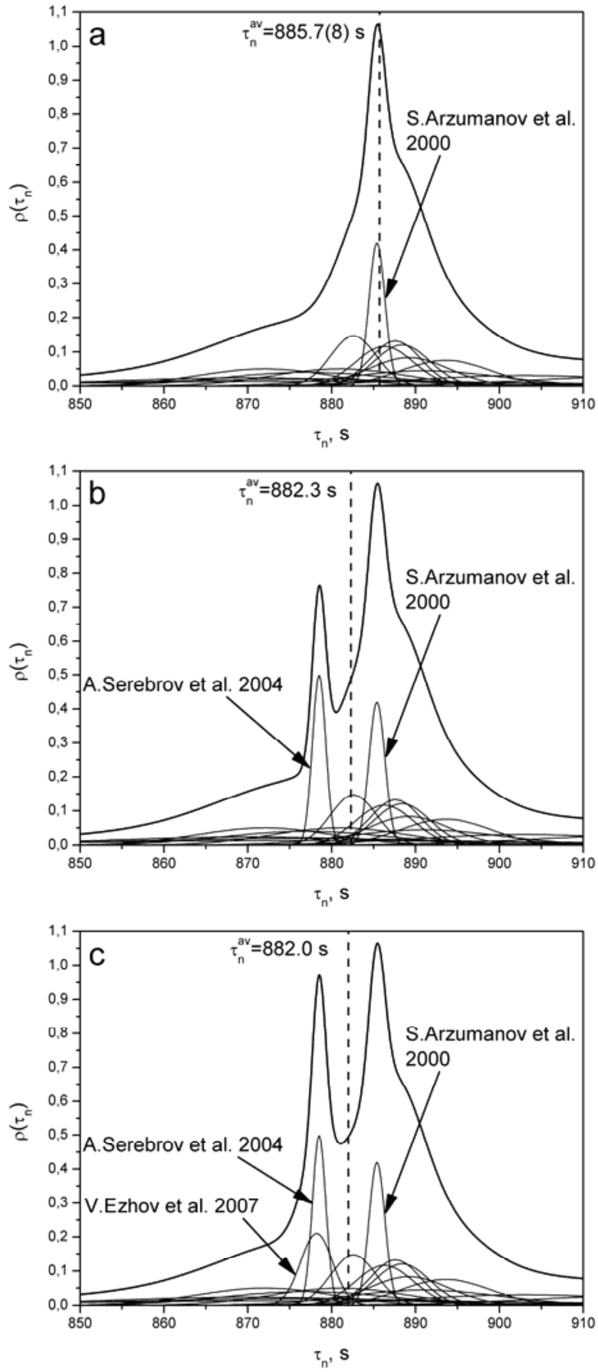

Figure 1. Progress of the neutron lifetime measurements. a: before "Gravitrap" measurement in 2003; b: after "Gravitrap" measurement in 2004; c: after magnetic trap measurement in 2007.

The next stage of our analysis was the experiment [13]. Since after completing the experiment [13] one discovered the effect of quasi-elastic scattering of UCN on the surface of the liquid fomblin, we created a Monte Carlo model taking this process into consideration. As a result two systematic effects were found. One of them is concerned with long storage of above-barrier neutrons while the other one is caused by quasi-elastic scattering of UCN on the surface of the liquid fomblin. A detailed analysis of these effects is available in our paper [5]. The discovered correction resulting from the effects of above-barrier neutrons and quasi-elastic scattering is –6.0 ± 1.6 s. The systematic experimental error [13] is about 3 s. It can substantially cover for the lack of information on experiment details. The corrected result is in agreement with the result 878.5 ± 0.8 s [1].

Now one should give a new table (Table 2, Fig. 2) of data on neutron lifetime measurements with corrections from papers [8] and [4] as well as from papers [13] and [5]. We also added the experimental result MAMBO II [27] to the table, which is the continuation of the experiment MAMBO I. MAMBO II used the spectrum without above-barrier neutrons. Therefore the systematic of the experiment MAMBO I was suppressed.

Table 2. 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 [28] *
878.2 ± 1.9	V. Ezhov et al. 2007 [6] *
878.5 ± 0.7 ± 0.3	A. Serebrov et al. 2005 [1] *
886.3 ± 1.2 ± 3.2	M.S. Dewey et al. 2003 [7]
879.9 ± 0.9 ± 2.4	S. Arzumanov et al. 2000 [8,4] *
880.7 ± 1.8	A. Pichlmaier et al. 2010 [27] *
889.2 ± 3.0 ± 3.8	J. Byrne et al. 1996 [9]
882.6 ± 2.7	W. Mampe et al. 1993 [10] *
893.6 ± 3.8 ± 3.7	J. Byrne et al. 1990 [12]
881.6 ± 3.0	W. Mampe et al. 1989 [13,5] *
872 ± 8	A. Kharitonov et al. 1989 [14] *
878 ± 27 ± 14	R. Kossakowski et al. 1989 [15]
877 ± 10	W. Paul et al. 1989 [16] *
891 ± 9	P. Spivac et al. 1988 [17]
876 ± 10 ± 19	J. Last et al. 1988 [18]
870 ± 17	M. Arnold et al. 1987 [19]
903 ± 13	Y.Y. Kosvintsev et al. 1986 [20] *
937 ± 18	J. Byrne et al. 1980 [21]
881 ± 8	L. Bondarenko et al. 1978 [22]
918 ± 14	C.J. Christensen et al. 1972 [23]

* UCN experiments

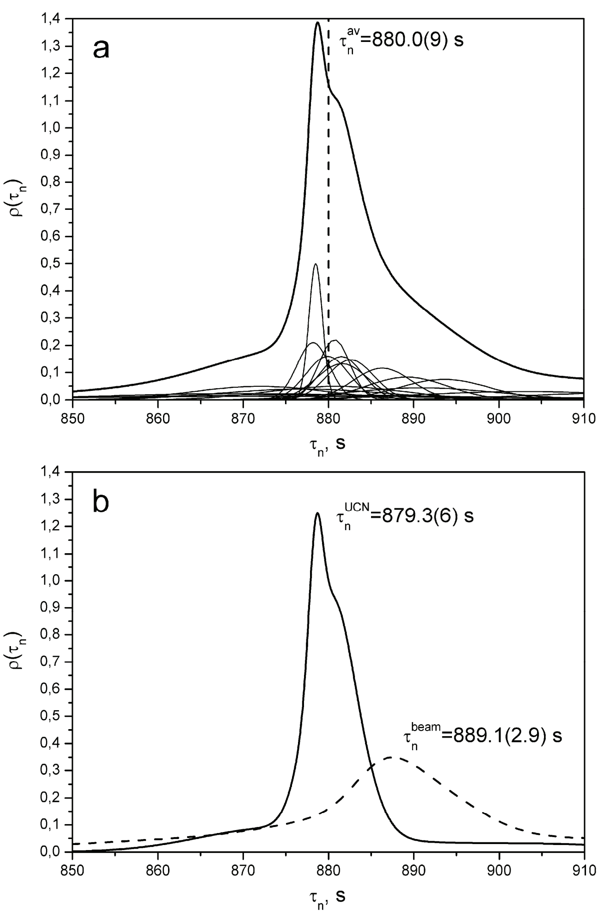

Figure 2. a) Distribution of results of measurements for the neutron lifetime after corrections and additions, giving the average value of 880.0 ± 0.9 s. b) Distribution of two groups of data: experiments on neutron lifetime with UCN and beam experiments.

The value from paper [11] can be withdrawn from the list, since much more accurate data have been obtained by this installation using low-temperature fomblin rather than solid oxygen. The difference between earlier and new data is 2.9 standard deviations. We assume that coating made of solid oxygen is not so reliable and that the coating of a narrow trap is more problematic. The observed difference of 2.9 standard deviations can be caused by this circumstance.

Finally the table should contain new data obtained by V.I. Morozov's group [28], reported at the conference. Then after corrections and additions the table of experimental data on neutron lifetime looks the following way (Table 2, Fig. 2). The standard error of the average value of the neutron lifetime according to Table 2 is 0.6 s, while the standard deviation is 0.9 s because of $\chi^2 = 2.3$. Thus we think it is reasonable to accept 880.0 ± 0.9 s as the world average value for the neutron lifetime.

To summarize, one should note that the analysis of neutron β-decay with a new world average value for the neutron lifetime is in agreement with the Standard Model. This analysis is shown in Fig.3 and described in detail in papers [29,30]. Fig. 3 shows the dependence of the matrix element of quark mixing $|V_{ud}|$ on the axial coupling constant g_A at different values of the neutron lifetime. The value $|V_{ud}|$ = 0.9743(7), calculated for a new world average value of the neutron lifetime of 880.0(9) s and g_A = 1.2750(9) [31], agrees with $|V_{ud}|$ = 0.97419(22), calculated from unitarity of the quark mixing matrix [2] and $|V_{ud}|$ = 0.97425(22), measured from nuclear β-decay [31,32]. One can see that the value $|V_{ud}|$ = 0.9711(6), obtained from an earlier world average value of the neutron lifetime 885.7(8) s, does not coincide with experimental data $|V_{ud}|$ = 0.97419(22) and $|V_{ud}|$ = 0.97425(22).

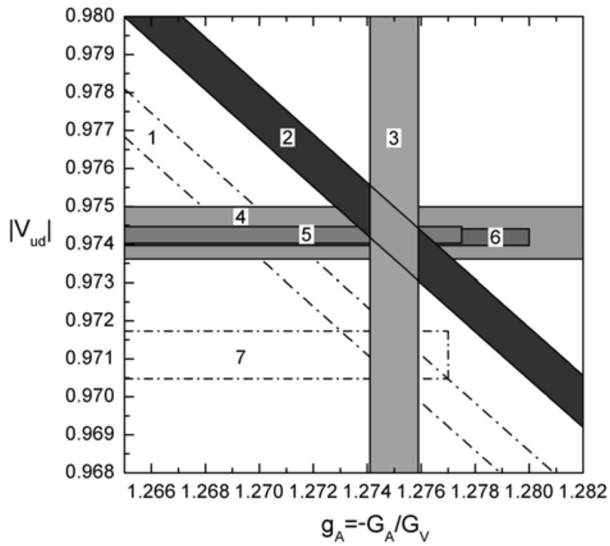

Figure 3. The dependence of the CKM matrix element $|V_{ud}|$ on the values of the neutron lifetime and the axial coupling constant g_A. (1) neutron lifetime, PDG 2006; (2) neutron lifetime, this article; (3) neutron β-asymmetry, Perkeo 2007; (4) neutron β-decay, this article + Perkeo 2007; (5) unitarity;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

Besides it is to be noted, that a comprehensive analysis has been made of original nuclear synthesis at the early stage of the Universe [33]. There has been analyzed the influence of the new value for the neutron lifetime on the agreement of data on original abundance of D and ^{4}He with the observed baryon asymmetry η_{10}. The new neutron lifetime value improves the data agreement between original abundance of D, ^{4}He and baryon asymmetry. Although the accuracy of cosmological data is much lower than that of neutron lifetime measurements, the shift between the earlier world average and the new one undoubtedly affects the predictions of nuclear synthesis models at the early stage of the Universe.

Before completing the paper we would like to make a separate analysis of experiments on neutron lifetime with stored UCN and beam experiments. The average neutron lifetime measured with UCN is equal to 879.3(0.6) s, while for beam experiments it is 889.1(2.9) s. Fig. 2b illustrates the distribution of the two groups of data. Fig. 4 shows the two groups of data in the historical order.

The observed difference between the average values of the two groups is 3.3σ and needs consideration. The contribution of beam experiments into the world average value is not high, therefore it does not affect the analysis made above. However it is an independent problem that must be solved. It is highly desirable that the precision of beam experiments should be enhanced.

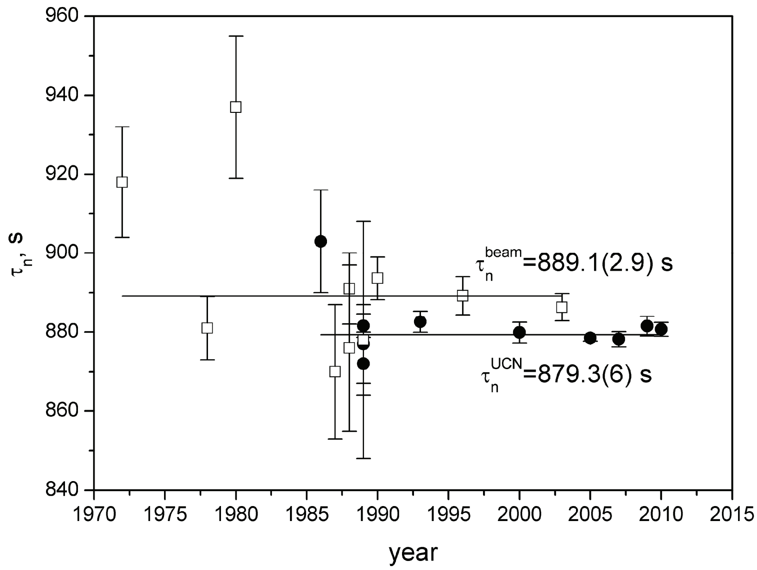

Figure 4. Two groups of data in the historical order: ● – experiments on neutron lifetime with UCN, □ – beam experiments.

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References

[1] A. Serebrov, V. Varlamov, A. Kharitonov et al., Phys. Lett. B **605**, 72 (2005);
A.P. Serebrov, V. Varlamov, A. Kharitonov et al., Phys. Rev. C **78**, 035505 (2008).
[2] C. Amsler, M. Doser, M. Antonelli et al. (Particle Data Group), Phys. Lett. B **667**, 1 (2008) and 2009 partial update for the 2010 edition (URL: http://pdg.lbl.gov).
[3] A.P. Serebrov, A.K. Fomin, Phys. Rev. C **82**, 035501 (2010).
[4] A.K. Fomin, A.P. Serebrov, Pis'ma v ZhETF **92**, 16 (2010) [JETP Lett. **92**, 40 (2010)].
[5] A.P. Serebrov, A.K. Fomin, Pis'ma v ZhETF **90**, 607 (2009) [JETP Lett. **90**, 555 (2009)].
[6] V. Ezhov in Proceedings of "The Seventh UCN Workshop", St. Petersburg, Russia, 2009 (URL: http://cns.pnpi.spb.ru/ucn/articles/Ezhov1.pdf).
[7] M.S. Dewey, D. M. Gilliam, J. S. Nico et al., Phys. Rev. Lett. **91**, 152302 (2003).
[8] S. Arzumanov, L. Bondarenko, S. Chernyavsky et al., Phys. Lett. B **483**, 15 (2000).
[9] J. Byrne, P.G. Dawber, C.G. Habeck et al., Europhys. Lett. **33**, 187 (1996).
[10] W. Mampe, L. Bondarenko, V.I. Morozov et al., Pis'ma Zh. Eksp. Teor. Fiz. **57**, 77 (1993) [JETP Lett. **57**, 82 (1993)].
[11] V.V. Nesvizhevskii, A.P. Serebrov, R.R. Tal′daev et al., Zh. Eksp. Teor. Fiz. **102**, 740 (1992) [JETP **75**, 405 (1992)].
[12] J. Byrne, P.G. Dawber, J.A. Spain et al., Phys. Rev. Lett. **65**, 289 (1990).

[13] W. Mampe, P. Ageron, C. Bates et al., Phys. Rev. Lett. **63**, 593 (1989).
[14] A.G. Kharitonov, V.V. Nesvizhevsky, A.P. Serebrov et al., Nucl. Instrum. Meth. A **284**, 98 (1989).
[15] R. Kossakowski, P. Grivot, P. Liaud et al., Nucl. Phys. A **503**, 473 (1989).
[16] W. Paul, F. Anton, L. Paul et al., Z. Phys. C **45**, 25 (1989).
[17] P.E. Spivak, Zh. Eksp. Teor. Fiz. **94**, 1 (1988) [JETP **67**, 1735 (1988)].
[18] J. Last, M. Arnold, J. Döhner et al., Phys. Rev. Lett. **60**, 995 (1988).
[19] M. Arnold ”Messung der Lebensdauer freier Neutronen”, Dissertation (Heidelberg: Univ. of Heidelberg, 1987).
[20] Yu.Yu. Kosvintsev, V.I. Morozov, G.I. Terekhov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 444 (1986) [JETP Lett. **44**, 571 (1986)].
[21] J. Byrne, J. Morse, K.F. Smith et al., Phys. Lett. B **92**, 274 (1980).
[22] L.N. Bondarenko, V.V. Kurguzov, Yu.A. Prokof'ev et al., Pis'ma Zh. Eksp. Teor. Fiz. **28**, 329 (1978) [JETP Lett. **28**, 303 (1978)].
[23] C.J. Christensen, A. Nielsen, A. Bahnsen et al., Phys. Rev. D **5**, 1628 (1972).
[24] A.K. Fomin, PhD Thesis, PNPI, Gatchina, 2006.
[25] F. Atchison, T. Bryś, M. Daum et al., Nucl. Instr. and Meth. in Phys. Res. A **552**, 513 (2005).
[26] A.I. Fomin, PhD Thesis, Kurchatov Institute, Moscow, 2000.
[27] A. Pichlmaier, V. Varlamov, K. Schreckenbach et al., Phys. Lett. B **693**, 221 (2010).
[28] P. Geltenbort in Proceedings of “The Seventh UCN Workshop”, St. Petersburg, Russia, 2009 (URL: http://cns.pnpi.spb.ru/ucn/articles/Geltenbort.pdf).
[29] A.P. Serebrov, Phys. Lett. B **650**, 321 (2007).
[30] M. Faber, A.N. Ivanov, V.A. Ivanova et al., Phys. Rev. C **80**, 035503 (2009).
[31] H. Abele, Prog. Part. Nucl. Phys. **60**, 1 (2008).
[32] J. C. Hardy, I.S. Towner, Phys. Rev. C **79**, 055502 (2009).
[33] G.J. Mathews, T. Kajino, T. Shima, Phys. Rev. D **71**, 021302(R) (2005).