Direct determination of neutron lifetime in β-decay

V.V. Vasiliev

e-mail basil_v@itep.ru

Abstract The neutron lifetime is determined for now most accurately by two methods—the so-called "beam method" and the method of neutron storage in a trap. The goal of this research is to obtain the neutron lifetime with a higher precision by eliminating the traditional systematic errors. A new feature is extracting the neutron lifetime only from the set of electron counting rates with their errors. The newly received neutron lifetime value is \( \tau_{NT} = 883.31 \pm 0.02 \text{(stat.)} \pm 0.02 \text{(sys.)} \) s.

The obtained neutron lifetime is the weighted average of two lifetimes, defined for different subsets of neutrons providing the well-known effect of the asymmetry in the neutron β-decay. Simple calculations predict the values of these lifetimes and show their correspondence to the known asymmetry parameters of neutron decay. The arithmetic mean (central) value for the two newly introduced neutron lifetimes was determined. The resulting weighted value \( \tau_{NT} \) is in a good agreement with the lifetimes in the first and second methods in limits of their double errors, but exceeds them significantly in precision. In addition, estimates of the new lifetimes, which are called here as \( \text{L-neutron lifetime} \) and \( \text{R-neutron lifetime} \), are fulfilled. The estimation results correspond to the known parameters of the neutron decay asymmetry.

Keywords neutron · decay · channel · lifetime · electron · trap

PACS 06.30.-k · 12.90+b · 13.30Ce · 14.20.Dh · 28.20-V · 29.40 Cs

Introduction

Measuring the neutron lifetime is a whole epoch in the history of nuclear physics. This era began in the late 1940s and consists of two periods. In the first period, the results for the neutron lifetime exceeded 900 seconds. The so-called beam method measured a counting rate of protons or electrons from the decay of neutrons \( n \rightarrow p + e^- + \bar{\nu} \) in a neutron beam of a nuclear reactor \([1]\), \([2]\), \([3]\). For the second period, typical neutron lifetimes were less than 900 seconds. During this period, another method of measuring the neutron lifetime becomes the leading one, namely the method of storing ultracold neutrons in a trap until beta-decay. In 2018, this method yielded the neutron lifetime equal to 881.5 ± 0.9 s \([4]\). The most accurate result of the beam method is \( \tau_n = 887.7 \pm 2.2 \) s \([5]\). There were cases of recalculating the results of the experiments and shifting it from the upper range of values to the lower one. Herewith, the shift in the estimates of the lifetime significantly exceeded the indicated experimental errors. In the case of \([1]\) in 1959, the result was 1013 ± 26 seconds and was reduced in 1978 to the value of 877 ± 8 seconds \([6]\) while repeating the basic scheme of the experiment. In the experiment \([3]\) the result of 1980 was 937 ± 18 seconds, but 16 years later, the authors published their result \([7]\) as equal to 889.2 ± 4.8 s. The averaging out all the results for the whole mentioned measurement period without any restriction leads to an average neutron lifetime of about 900 s.

The beam experiments use the differential decay equation:

\[
\frac{dN_d}{dt} = \frac{1}{\tau_n} \cdot \varepsilon \times N,
\]

where \( \frac{dN_d}{dt} \) is the counting rate of the decay electron (or proton) detector, \( \tau_n \) is the neutron lifetime, \( N \) is the number of neutrons at time \( t \) in some region of the neutron beam, \( \varepsilon \) is the total efficiency. The total efficiency includes the ef-
iciency of neutron detection by a neutron detector, the efficiency of collecting electrons (or protons) from the decay region to the electron (proton) detector, and the efficiency of their registration by the detector. The most difficult problem is the exact experimental determination of the number \( N_d = (\varepsilon \times N) \) on the right side of equation (1), i.e. the number of neutrons whose decay is in the field of view for the electron (or proton) detector. The value \( (\varepsilon \times N) \) includes all sources of systematic errors of the beam method.

A new method for the beam experiments has been developed in some years. This method excludes necessitates to measure precisely the number of neutrons in the beam, and eliminates the need to determine the absolute values of the efficiency components.

\[ \text{1 Variation method of neutron decay scale tuning} \]

The method proposed by the author [8] uses a step-wise variation of the initial number of neutrons passing through a region controlled by a detector of electrons. The method is based on a system of differential equations of type (1) for \( k \) steps of neutron numbers:

\[ R_d(i) = \frac{1}{\tau_n} \times N_d(i), \quad (2) \]

where \( R_d(i) \) is the electron count rate from the detector, \( N_d(i) \) is a number of neutrons seen by the electron detector at the \( i \)-th variation step, \( i = 1, 2, 3, \ldots k \). The problem of measuring the number of neutrons is not posed here at all. At each \( i \)-th stage of the neutron number variation the count rate \( R_d(i) \) of the electron detector is measured and, after multiple iterations, the count rate error \( \sigma_d(i) \) at each stage is determined. As a result, an array \( \{R_d(i), \sigma_d(i)\} \) with \( k \) lines is formed. To simplify the notation, it is worth eliminating the indices \( d \) and \( n \) in (2). The next step is to represent an unknown set of neutron numbers \( N_i \) by members of an arithmetic progression \( N_i \approx \frac{1}{\mu} \times m_i \) with \( \frac{1}{\mu} \) as a decimal common difference. The common difference of the required arithmetic progression is the step of the neutron number scale that describes the distribution of counting rates with their errors. The integer \( m_i \) is the number of the scale division corresponding to the neutron number \( N_i \). The parameter \( \mu \), the inverse of the scale step, is called a scale factor or \( \mu \)-factor. Then the system of differential equations of decay has the following form:

\[ \tau \times (R_i \pm \sigma_i) \approx \frac{1}{\mu} \times m_i, \quad (3) \]

where \( i = 1, 2, 3, \ldots k, k \) is the full number of variation steps. The goal is set as follows. It is necessary to choose an optimal scale step to describe in the best way the measured data array of count rates by a certain sample of members of the obtained arithmetic progression of neutron numbers. The

\[ \frac{1}{\mu} \text{ scale step uniquely identifies the set of integers } m_i - \text{ the scale division numbers corresponding to the array of pairs } \{R_i, \sigma_i\} \text{ for a given value of } \tau - \text{trial lifetime. The estimate } \mathbb{K}_i \text{ of neutron number } N_i \text{ is} \]

\[ \mathbb{K}_i = \text{round} \left[ \frac{\text{round} \left[ \frac{\mu \times \tau \times R_i 0}{0} \right]}{\mu} \right] \cdot p. \quad (4) \]

The operator \( \text{round}[C, p] \) rounds to the nearest number with \( p \) significant digits. The operator \( \text{round}[C, 0] \) means rounding to the nearest integer. The following error functional is constructed for the required range of \( \tau \) for different \( p \):

\[ F_{\mu, p}(\tau) = \sum_{i=1}^{k} \frac{(R_i - \frac{1}{\mu} \times \mathbb{K}_i(p, \mu, \tau))^2}{\sigma_i^2}. \quad (5) \]

The scale factor \( \mu_0 \) is to be selected for the best approximation by the estimate \( \mathbb{K}_i(p, \mu_0, \tau) \) for any \( p \). The neutron lifetime \( \tau_0 \) is determined from the equation

\[ \frac{dF_{\mu_0, p}(\tau)}{d\tau} = 0. \quad (6) \]

Fig. 1 illustrates the method in the case of integer neutron numbers. The figure shows the best correspondence of count rates to the set of neutron numbers 1, 2, 3, 5 by the straight line L1. The path AB-BC-CD-DE-EF describes the action of the operator (4) in the case of the count rate R2 for the line L2. At the counting rate R3 the operator implements the trajectory GH-HK-KD-DE-EF. The description of the line L2 in integers leads to an increase in the error functional by the deviations FA and GF. Hence a deviation from the optimal line (from L1 to L2) leads to an increase in the approximation error while processing in the same neutron number scale. The main requirement for obtaining an accurate result is a high accuracy of counting rate measurements.
2 Experimental data

The experimental data of background measurement in the last ITEP experiment on the magnetic storage of ultra-cold neutrons (UCN) was used. The background consisted of electrons generated in the vacuum chamber of the magnetic trap by the decay of neutrons. Electrons were transported from the trap to the UCN detector \([9]\). The proportional gas chamber of the UCN detector operated as an electron detector of high efficiency. The vertical and horizontal channels of the reactor with open shutters were sources of thermal, intermediate and fast neutrons of the neutron background. The set of those neutrons penetrating through the walls of the trap was the generator of decay electrons.

To measure the electron background, a separate long experiment was performed. The low pressure gas detector was specially optimized for counting electrons emanating from the magnetic trap. A special absorber was installed into the trap chamber for eliminating the ultracold neutrons. A virtually complete storage cycle for electrons collected in the trap from background neutrons was carried out. The electron counts in the intervals with the magnetic shutter on and in the drain intervals with the magnetic shutter off were measured. The counting of the electron background from the neutron flux through the magnetic trap was an analogue of the beam experiment. The count of electrons flowing to the detector from the magnetic trap changed cyclically with the changes in the set of simultaneously operating neutron channels of the reactor. The data on background measurements in the readout intervals of the outgoing electrons were processed and shown in the order of growth in Fig. 2–Fig. 4. The full series of 152 count rates is divided into two series. There are seventy-one values (“series 71”, S-71) in the first series (Fig. 2). The most accurate among these values is \( R = 6.6667 \cdot 10^{-3} \pm 6 \cdot 10^{-7} \text{ s}^{-1} \). In addition, eighty-one values formed the second series (“series 81”, S-81) Fig. 3 –Fig. 4. Out of 81 measurements, for reasons of scale, two points are not shown:

point number 146 : \( R = 1.355 \cdot 10^{-2} \pm 6 \cdot 10^{-5} \text{ s}^{-1} \)

and

point number 152 : \( R = 3.738 \cdot 10^{-2} \pm 4 \cdot 10^{-4} \text{ s}^{-1} \).

There are several steps of the background electrons in Fig. 2 – Fig. 4. Fig. 4 shows the count of electrons flowing out of the magnetic trap after opening the magnetic shutter. All results for different reading-out intervals were received over a period of more than 100 days. The paper \([9]\) described the scheme and description of the experimental set-up in more details.
3 Decay asymmetry and neutron lifetime

The well-known phenomenon of electron-spin asymmetry of the neutron beta decay \( n \rightarrow p + e^- + \bar{\nu} \) reveals itself in the fact that neutron decays with an electron emitting in the direction of the neutron spin occur less frequently than neutron decays with an electron emitting against the neutron spin direction. The neutron decay probability [10] modified for decay electrons emitting is

\[
dW(E_e, \Theta_e) = W_0 dE_e d\Theta_e \left( 1 + A \cdot \frac{v_e}{c} \cdot \cos \Theta_e \right),
\]

where \( A \) is the correlation coefficient of the electron emission with the direction of the neutron spin, \( \Theta_e \) is a solid angle of electron emission, \( W_0 \) is a constant. From numerous experiments [11] it is known that the coefficient \( A = -0.1173 \pm 0.0013 \). Thus, neutron decays with electron emission in the direction of the neutron spin and against the spin differ qualitatively and quantitatively. The decay asymmetry in case of a transversely polarized neutron beam is the relative difference of the electrons emitted in the direction of the neutron spin and against the neutron spin. However, the fact that even with a completely depolarized ensemble of neutrons, the asymmetry of decay leads to two different frequencies of electron generation in the decay region remains unnoticed. Nevertheless, the asymmetry of neutron decay is a phenomenon of existence of two \( \beta \)-decay constants, i.e. two reduced decay frequencies defined at different subsets of neutrons. The total set \( T \) of neutrons is a sum of two subsets. Those are the subset of \( L \)-neutrons with decays by an electron emission against the direction of the neutron spin \((L\text{-channel})\) and the subset of \( R \)-neutrons, decaying with the emission of an electron in the direction of the neutron spin \((R\text{-channel})\). Hence \( T = L \cup R \) and the number of neutrons \( N_T \) in the total set \( T \) is the sum of \( L \)-neutrons \( (L\text{-subset}) \) and \( R \)-neutrons \( (R\text{-subset}) \): \( N_T = N_L + N_R \). Without loss of generality the decay constants for these neutron sets are equal to

\[
\lambda_T = \lambda_L \cdot W_L + \lambda_R \cdot W_R.
\]

Here the total decay constant \( \lambda_T \) has the form of a weighted average of the partial constants \( \lambda_L \) and \( \lambda_R \). The weights \( W_L \) and \( W_R \), when use the parallel decay rule [12, p. 344] as \( \frac{N_L}{N_T} = \frac{\lambda_L}{\lambda_L + \lambda_R} \) are the following relations

\[
W_L = \frac{N_L}{N_L + N_R} = \frac{\lambda_L}{\lambda_L + \lambda_R}, \quad W_R = \frac{N_R}{N_L + N_R} = \frac{\lambda_R}{\lambda_L + \lambda_R}.
\]

The lifetime of neutrons in every \( S \)-set is \( \tau_{NS} = \frac{1}{\lambda_S} \) and the total lifetime on the full set \( T \) is equal to \( \tau_{NT} = \frac{1}{\lambda_T} \). Therefore, a record for the total lifetime follows from (9) in the form of a weighted average value, namely:

\[
\tau_{NT} = \tau_{NL} \cdot W_{TL} + \tau_{NR} \cdot W_{TR},
\]

where the weights for the partial lifetimes receive the following forms:

\[
W_{TL} = \frac{\tau_{NL}^2}{\tau_{NL}^2 + \tau_{NR}^2}, \quad W_{TR} = \frac{\tau_{NR}^2}{\tau_{NL}^2 + \tau_{NR}^2}.
\]

The introduced partial decay constants receive the following dependence on the asymmetry parameter \( \Delta \)

\[
\lambda_L = \lambda_0 \cdot (1 + \Delta), \quad \lambda_R = \lambda_0 \cdot (1 - \Delta),
\]

where \( \lambda_0 \) is the arithmetic mean of the introduced constants, \( \Delta = \frac{\lambda_L - \lambda_R}{\lambda_L + \lambda_R} \), which is the average helicity of electrons emitted during neutron decay. The average helicity of electrons can be calculated from the electronic neutron decay spectrum, for example, from the results of [13]. The partial lifetimes are

\[
\tau_{NL} = \tau_{NCenter} \cdot (1 - \Delta), \quad \tau_{NR} = \tau_{NCenter} \cdot (1 + \Delta),
\]

where \( \tau_{NCenter} \) is a central neutron life time, i.e. the central point between values of \( \tau_{NL} \) and \( \tau_{NR} \). The weighted average decay constant \( \lambda_T \) is related to the average decay constant \( \lambda_0 \) as follows:

\[
\lambda_T = \lambda_0 \cdot (1 + \Delta^2).
\]

The total neutron lifetime \( \tau_{NT} \) vs \( \Delta \) is

\[
\tau_{NT} = \tau_{NCenter} \cdot \frac{1 - 2 \cdot \Delta^2}{1 + \Delta^2}.
\]

Therefore, the dependence of the error functional (5) on the trial lifetime is symmetrical with respect to the point \( \tau_{NCenter} \). Then the weighted average lifetime according to (16) is to the left of the center of symmetry. The goal of this study, therefore, turned out to be two-fold. Firstly, it is a direct determination of an experimental value for the observed neutron lifetime, i.e. the weighted average neutron lifetime. On the other hand, it became necessary to determine the value of the “central” neutron lifetime. In the case of a convincing correspondence between a determined displacement value and a calculated value (16), it is advisable to introduce new physical quantities into the physical dictionary – the lifetimes of \( L \)-neutrons and \( R \)-neutrons and to estimate their numerical values using formulas (14.1) and (14.2).
4 Direct determination of the neutron lifetime from the experimental data

The interval of the trial lifetime from 860 seconds to 940 seconds is quite informative for solving the given problem. This interval includes the results of measurements of the lifetime of the last three decades. To determine the neutron lifetime, it is necessary to find the minimum value of the scale-factor \( \mu \), providing the condition of “reduction-to-one”. This condition means that the minimum point of the error functional is the closest to the unity for any data series in the considered range of the lifetime. The “reduction-to-one” is applied to the data shown in Fig. 2–Fig. 4 for various values of the scale step in the indicated range of the trial neutron lifetime \( \tau \). The results of the data processing are illustrated by Fig. 5–Fig. 7.

Fig. 5 shows the result of the reduction-to-one for the S-152 series with \( p = 3 \). The closest to the unity is the value of the functional minimum equal to 1.074, corresponding to the lifetime of 883.305 s for the scale-factor \( \mu = 72 \). At the same scale-factor \( \mu \), minimums of the functional of the second, third and fourth orders of accuracy reached a good agreement. The value for the neutron lifetime is \( \tau_{NT} = (529983 \pm 10) \cdot \frac{1}{10} \cdot 10^{-2} \) s after using the half-width of the parabola of the third order functional at height \( \chi^2 = 1.2 \).

Fig. 6 shows the results of the reduction-to-one for the S-71 (1) and S-81 (2) series separately. The dependence of the average weighted functional over two series on the lifetime gives the result for the neutron lifetime \( \tau_{NT} = (264992 \pm 7) \cdot \frac{1}{10} \cdot 10^{-2} \) s. Thus, the complete result for the neutron lifetime is \( \tau_{NT} = 883.31 \pm 0.02 \) s, 95%, CL.

All these facts prove the following:

a) both independent data series S-71 and S-81 are qualitatively homogeneous and describe electrons from the decay of neutrons without admixture of an additional background;

b) the results of independent data series S-71 and S-81 are compatible within statistical errors, reasonably processed together and do not require an additional introduction of a systematic error to describe the consolidated result.

Therefore, the applied method has reached its goal of eliminating known systematic errors for higher accuracy in the experimental determination of the neutron lifetime.

Additional studies were made to prove the existence of a common center of symmetry of the error functional on the trial lifetime interval from 895 to 905 seconds for all orders of accuracy \( p = 0, 1, 2, \cdots \).

Fig. 7 shows results for the scale-factor \( \mu = 72 \) by dependencies (1)-(3) of error functional \( F_{\mu,p}(\tau) \): (1) integers \( p = 0 \); (2) \( p = 1 \); (3) \( p = 2 \). The coincidence of the minimums of all three orders of the functional on the \( \tau \)-scale at the point of 899.975 s, with symmetry of the left and right wings of the functional shows that this point is the center of symmetry and confirms the result of [9]. This value can
serve as an estimate of the so-called “central” neutron lifetime. The symmetry of the coordinates of the jumps of the functional (3) with respect to this \( \tau_{\text{Center}} = 899.975 \) s point also confirms its central position. The dependence of the functional on the trial lifetime allows determining the value of the central neutron lifetime with a completely moderate error \( \tau_{\text{NCent}} = (179995 \pm 4) \cdot 5 \cdot 10^{-3} \) s. It is important to emphasize that the error functional in the range of the trial lifetime of 750-1050 s has only one specified center of symmetry for all accuracy level \( p \).

5 Upper limit of a systematic error

As a source of systematic error, a hypothetical difference between the electrons flowing through the closed magnetic shutter and the electrons flowing onto the detector through the open magnetic shutter may appear. If only the electrons of the first type are presented in the first S-71 series, then in the second S-81 series there is a fraction of electrons of the second type providing the maximum values of the counting rate. The result indicated in Fig. 6 confirms complete coincidence. Moreover, the minimums of the functional for S-152, \( \mu = 72 \) at \( p = 2, p = 3 \) and \( p = 4 \) coincide in those limits altogether.

Nevertheless, the fact that the minimums at the accuracy \( p = 4 \) shift from 883.29 s for S-71 to 883.33 s for S-81 gives a reason to interpret it due to some unaccounted factors and to introduce on this basis a systematic error equal to the half of the bias value. Thus, the estimate of the systematic error is 0.02 s, and the result for the neutron lifetime as a weighted average is \( \tau_{\text{NT}} = 883.31 \pm 0.02 \) s, 95%CL. The obtained value \( \tau_{\text{NT}} \) is in a good agreement with the result shown in Fig. 5.

The weighted average lifetime is connected with the central lifetime as

\[
\tau_{\text{NT}} = \tau_{\text{NCenter}} \cdot \left( 1 - \frac{2 \cdot \delta}{1 + \delta} \right).
\]

From (16) \( \delta \) is interpreted as \( \delta = \Delta^2 \). The obtained value for \( \Delta = \frac{1}{\sqrt{107}} \) is in a good agreement with \( A = -0.1173 \pm 0.001 \) and \( \frac{\Delta}{\bar{A}} = 0.824 \). This value for the average helicity is confirmed by the spectrum of electrons from the neutron decay [13].

Thus, the displacement of the weighted average neutron lifetime relative to the so-called central lifetime is a consequence of the electron-spin asymmetry of neutron decay. The main purpose of this research is the direct determination of the observed neutron lifetime. Nevertheless, it is easy to predict from the displacement the numerical values for the lifetime of L-neutrons \( \tau_{\text{NL}} \) (14.1) and the lifetime of R-neutrons \( \tau_{\text{NR}} \) (14.2). They are the following:

\[
\tau_{\text{NL}} = (2 \cdot 3 \cdot 5)^2 \cdot \left( 1 - \frac{1}{\sqrt{107}} \right) \text{ s},
\]

\[
\tau_{\text{NR}} = (2 \cdot 3 \cdot 5)^2 \cdot \left( 1 + \frac{1}{\sqrt{107}} \right) \text{ s}.
\]
The errors of the indicated values are estimated not exceeding 0.08 s. A direct determination of these parameters of the neutron $\beta$-decay will make it possible in the future to indicate their values more accurately.

Now it is worth noticing that the weighted average of the mentioned above values of $\tau_{NL}$ and $\tau_{NR}$ is in a good agreement with the neutron lifetime obtained in this research from the experimental data. This can be easily verified using numerical expressions for the lifetime weights of (12.1) and (12.2), namely:

\[
W_{\ell} = \frac{1}{2} + \frac{\sqrt{107}}{108}.
\]

\[
W_{R} = \frac{1}{2} - \frac{\sqrt{107}}{108}.
\]

The calculation result by formula (11) gives 883.33 s that coincides with the experimental result of this work within ±0.01 s.

7 Conclusion

Using the proposed method, the neutron lifetime is determined with the accuracy of 0.02 s. The system of differential equations of decay with a step-wise variation of the number of neutrons turned out to be a sufficient tool for determining the neutron lifetime by the modified least-squares method. Traditional sources of systematic errors inherent in the beam method of measuring the neutron lifetime are successfully excluded. As a result, the accuracy of the neutron lifetime is significantly improved. The observed (weighted average) neutron lifetime obtained in this work is expressed in primes as

\[
\tau_{NT} = 2 \cdot 5^{2} \cdot \frac{53}{3} \text{ s}
\]

within no more than 0.03 s (taking into account the introduced systematic error).

In addition to the main result, estimates of the effect of splitting the neutron lifetime are obtained. It is indicated that neutron decay can be described by two lifetimes: $L$-neutron lifetime and $R$-neutron lifetime, differing in the sign of the scalar product of the electron momentum and the neutron spin. The estimation results correspond to the known parameters of the electron-spin asymmetry of the neutron decay. This fact provides the grounds for introducing new quantities - $L$-neutron lifetime and the $R$-neutron lifetime into the neutron $\beta$-decay physics. The obtained interval of neutron lifetimes from $\tau_{NL} = 813 \text{ s}$ to $\tau_{NR} = 987 \text{ s}$ gives an explanation of the range of experimental values obtained over the 70-year history of of the neutron lifetime measurements.

This method opens up the prospect of reducing the neutron lifetime errors to thousandths of a second.

Acknowledgements

The author is deeply grateful to V.V. Vladimirsky for his personal support. The author is grateful to the staff of the UCN-ITEP group - V. F. Belkin, A. A. Belonozhenko, N. I. Kozlov, E. N. Mospan, A. Yu. Karpov, I. B. Rozhinin, A.M. Salomatkin, V.G. Frankovskaya, and also and especially G.M. Kukavadze and S.P. Boroblev for the creation and operation of the KENTAVR set-up at the ITEP HWR reactor.

References

1. Sosnovskii A.N., Spivak P.E., Prokof’ev Yu. A., et al. Measurement of the Neutron Half-life. JETP, vol. 9, Num. 4, p. 717, (1959).
2. Christensen C.J., Nielsen A., Bahnsen A., et al. Free-Neutron Beta-Decay Half-Life. Phys. Rev., D5, Num. 7, p. 1628, (1972).
3. Byrne J., Morse J., Smith K. F., et al. A new measurement of the neutron lifetime. Physics Letters B, Vol. 92, rel: 3-4, p. 274-278, (1980).
4. Serebrov A.P., Kolomensky E.A., Fomin A.K., et al. Neutron lifetime measurements with a large gravitational trap for ultracold neutrons. Physical Review C, Vol. 97, rel: 5, Num. 055503, (2018).
5. Yue T. Y. Dewey M. S., Gilliam D. M., et al. Determination of the Neutron Lifetime. Phys. Rev. Lett., 111, 222501, (2013).
6. Bondarenko L.N., Kurguzov V.V., Prokof’ev Yu. A., et al. Measurement of the neutron half-life period, JETP Letters, vol.28, rel. 5, pp. 329-333, (1978).
7. Byrne J., Dawber P.G., Habec C.G., et al. A revised value for the neutron lifetime measured using Penning trap, Europhysical Letters, 33 (3), pp.187-192, (1996).
8. Vasiliev V.V., A method for measuring radioactive decay constant. Bulletin of inventions Num. 36, 2009. RF patent of invention Num. 2377599, G01T 1/30.
9. Vasiliev V.V., Neutron Lifetime and the Background Structure in a Neutron Magnetic Trap, JETP Letters, vol.77, Num. 5, pp. 207-2011, (2003).
10. Jackson J.D., Treiman S.B. and H.D. Wyld, Jr., Possible Tests of Time Reversal Invariance in Beta-Decay, Physical Review, vol.106, Num. 3, p.517-521, (1957).
11. K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021, p.10 , (2010).
12. Blatt J.M., Weisskopf V.F., Theoretical nuclear physics, John Wiley & Sons, New York (1952).
13. Robson V.V., The Radioactive Decay of the Neutron, Physical Review, vol.83, rel. 2, p.349-358 (1951).