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Neutron β-decay, Standard Model and cosmology

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Abstract

The precise value of the neutron lifetime is of fundamental importance to particle physics and cosmology. The neutron lifetime recently obtained, $878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{sys}}$ s, is the most accurate one to date. The new result for the neutron lifetime differs from the world average value by 6.5σ. The impact of the new result on testing of Standard Model and on data analysis for the primordial nucleosynthesis model is scrutinized.

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Keywords: Neutron lifetime; CKM unitarity; Cosmology

1. Introduction, present status of neutron β-decay studies

The problem of precise measurements of the neutron lifetime is important for elementary particle physics and cosmology. The decay of a free neutron into a proton, an electron, and an antineutrino is determined by the weak interaction comprising the transition of a d-quark into a u-quark.

In the Standard Model of elementary particles, the quark mixing is described by the Cabibbo–Kobayashi–Maskawa (CKM) matrix which must be unitary. The values of the individual matrix elements are determined by the weak decays of the respective quarks. In particular, the matrix element V_{ud} can be determined from the data on nuclear β-decay and neutron β-decay. The extraction of V_{ud} from the data on neutron β-decay is extremely tempting due to the theoretical simplicity of describing the neutron decay compared to the description of nuclear decay. Unfortunately, the experimental procedure is a very complicated one, since it requires precise measurements of the neutron lifetime τ_n and the β-decay asymmetry A_0.

The general formula for calculating $|V_{\text{ud}}|^2$ is based on the neutron β-decay data τ_n and A_0 [1]

$$|V_{\text{ud}}|^2 = \frac{(4908.7 \pm 1.9)}{\tau_n(1+3\lambda^2)}, \tag{1}$$

$$f\tau_n(1+\delta'_R) = \frac{K}{|V_{\text{ud}}|^2 G_F^2 (1+3\lambda^2)(1+\Delta_R)}, \tag{2}$$

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

where f is the phase space factor, δ'_R is a model-independent external radiative correction, Δ_R is a model-dependent internal radiative correction, λ is the ratio of the axial-vector weak coupling constant to the vector coupling constant, G_F is the Fermi weak coupling constant determined from the μ-decay, and $K = \hbar 2\pi^3(\hbar c)^6/(m_e c^2)^5$.

The formula (1) takes into account accuracy of calculation of radiative correction [1]. Thus, the required relative accuracy of measuring the neutron lifetime τ_n must be higher than 10^{-3} and than 2×10^{-3} for A_0.

The accuracy of determination of neutron lifetime (τ_n) and asymmetry (A_0) of neutron β-decay have been increased during the last 30 years about 20 times. Fig. 1 shows results of experimental data from 70s of the previous century up to the present time. The most precise measurement of A_0 has been reached

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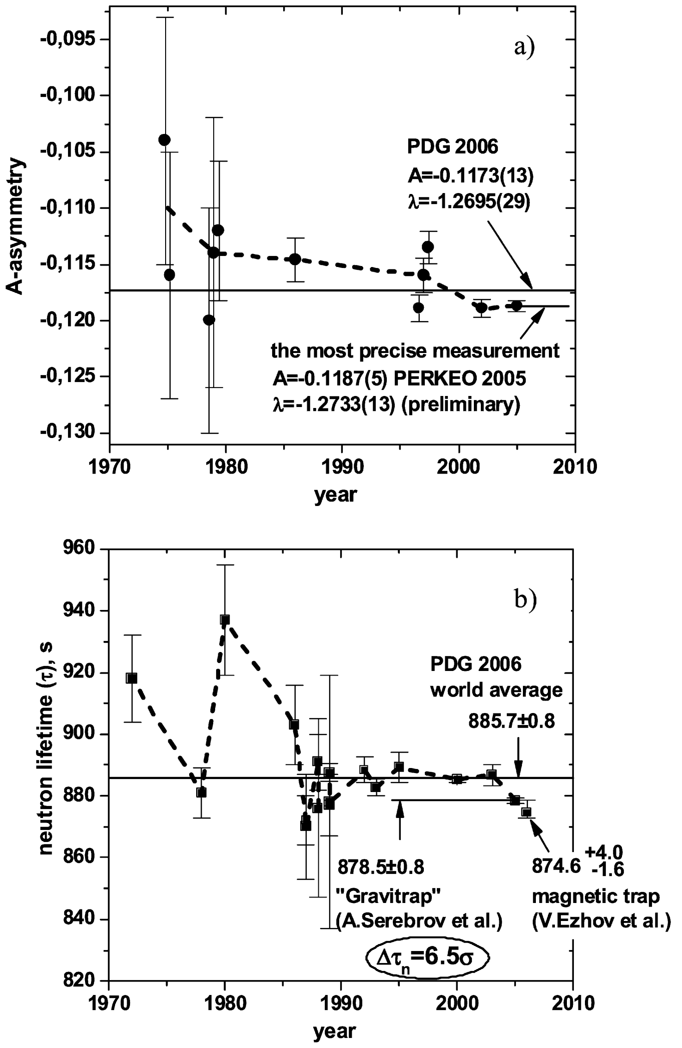

Fig. 1. The progress in experimental accuracy of neutron β-decay data: (a) A-asymmetry, (b) neutron lifetime.

by group of D. Dubbers from Heidelberg University. They announced a preliminary result: $A = -0.1187(5)$ [2,3]. The corresponding G_A/G_V ratio is $\lambda = -1.2733(13)$. The most precise result for A_0 is in reasonable agreement with the value of PDG (2006) $A = -0.1173(13)$ and $\lambda = -1.2695(29)$.

The most precise measurement of neutron lifetime have been carried out by PNPI group with collaborators from JINR and ILL [4]. New experiment of neutron lifetime gives the value: 878.5 ± 0.8 s, which differs from the PDG (2006) value (885.7 ± 0.8 s) by 7.2 s or 6.5 standard deviations. In this experiment the method of storage of ultracold neutrons (UCN) in the trap was used, just as in the most previous experiments. However the probability of losses in experiment [4] was about 1% only of the probability of neutron β-decay. In previous experiments the loss factor was by 30 times higher. The extrapolation from the best storage time to neutron lifetime in new experiment was 5 s only, therefore it is very improbable to obtain systematic error about 7 s. The estimated systematic error in the new experiment was 0.3 s. Recently the measurement of neutron lifetime by means of continuous storage of UCN in magnetic trap has been carried out [5]. The result of measurement gives $\tau_n = (874.6^{+4.0}_{-1.6})$ s. This value did not also confirm the world average value and is closer to the result of the experiment [4].

The next sections will be devoted to the analysis of the new result for neutron lifetime [4] and the most precise result of A_0 [2,3] for Standard Model and cosmology.

2. Standard Model with the most precision data of neutron β-decay

The main aim of precision measurements of neutron β-decay is to find deviations from the Standard Model assumptions as possible indications of new physics. V_{ud} mixing matrix element obtained from neutron β-decay (${}^{n}V_{ud}$) can be compared with the matrix element obtained from $f\tau$ values for the nuclear superallowed $0^+ \to 0^+$ transitions (${}^{00}V_{ud}$). The superallowed $0^+ \to 0^+$ transitions are the pure Fermi transitions, and only G_V coupling constant is involved in the process. The neutron decay proceeds through a mixed Fermi/Gamov–Teller transition and the both coupling constant G_A and G_V are involved in the process. In the case of pure $V-A$ variant of interaction the both V_{ud} values have to be equal to each other. Therefore the equation ${}^{n}V_{ud} = {}^{00}V_{ud}$ is the $V-A$ test of Standard Model. Any other types of interaction can destroy this equation.

Another test of Standard Model is the unitarity test. V_{ud} matrix element have to be equal to $(1 - V_{us}^2 - V_{ub}^2)^{1/2}$, where V_{us} and V_{ub} are determined from the transitions with s- and b-quarks. Thus, we have to check two equations:

$$ {}^{n}V_{ud} = {}^{00}V_{ud} \quad (V-A \text{ test}), $$

$$ {}^{n}V_{ud} = \left(1 - V_{us}^2 - V_{ub}^2\right)^{1/2} \quad (\text{unitarity test}). $$

Fig. 2 shows analysis for both tests with data from PDG (2006). We can see very good agreement for ${}^{n}V_{ud}$, ${}^{00}V_{ud}$ and $(1 - V_{us}^2 - V_{ub}^2)^{1/2}$. Unfortunately the accuracy of λ-value from PDG (2006) is not so good to do precise conclusions for these tests. It would be more interesting to use the most precision last data.

Fig. 3 shows analysis for both tests with the most precision data of neutron β-decay. For this analysis the most precise data was used: the new value of $\tau_n = 878.5 \pm 0.8$ [4] and the new value of $A_0 = -0.1187(5)$ [2,3] or $\lambda = -1.2733(13)$. The inclined line demonstrates dependence of ${}^{n}V_{ud}$ from λ, which corresponds to Eq. (1). The vertical line is λ-value from [2,3]. The crossing of these lines gives ${}^{n}V_{ud}$ value determined from neutron β-decay. We can compare ${}^{n}V_{ud}$ with ${}^{00}V_{ud}$ and with $(1 - V_{us}^2 - V_{ub}^2)^{1/2}$.

For $V-A$ test we have the following result: ${}^{n}V_{ud} - {}^{00}V_{ud} = (2.4 \pm 1.0) \times 10^{-3}$ or 2.4σ.

As far as unitarity test is concerned the following equation can be written:

$$ |{}^{n}V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0038(28), \quad \Delta = -1.5\sigma. $$

In these calculation we use $V_{us} = 0.2257(21)$ from PDG (2006).

At last we can analyze the situation with new value of A_0 and value of τ_n from PDG (2006) 885.7 ± 0.8 s. This dependence of