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PHYSICS BEYOND STANDARD MODEL IN NEUTRON BETA DECAY*

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Limits from neutron beta decay on parameters describing physics beyond the Standard Model are presented. New Physics is described by the most general Lorentz invariant effective Hamiltonian involving vector, scalar and tensor operators and Standard Model fields only. Two-parameter fits to the decay parameters measured in free neutron beta decay have been done, in some cases indicating rather big dependence of the results on $g_{\rm A}/g_{\rm V}$ ratio of nucleon form factors at zero four-momentum transfer.

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1. Introduction

For many years nuclear β-decays have been exploited as laboratories for testing the Standard Model (SM) in the domain of low energies. Along with developments of intense sources of cold and ultracold neutrons and improvements of experimental techniques, the precision of measurements in the simplest of such systems: the β-decay of a free neutron, is constantly increasing. It opens the way to study the limits on physics beyond SM set solely by the parameters of the neutron β-decay.

We assume that at the quark–lepton level β-decay is described by the general 4-point Hamiltonian [1]

$$\mathcal{H}_\beta = 4 \sum_{k,l=\rm L,R} \left\{ a_{kl} \bar{e} \gamma_\mu P_k \nu^{(k)} \bar{u} \gamma^\mu P_l d + A_{kl} \bar{e} P_k \nu^{(k)} \bar{u} P_l d + \alpha_{kk} \bar{e} \frac{\sigma_{\mu\nu}}{\sqrt{2}} P_k \nu^{(k)} \bar{u} \frac{\sigma^{\mu\nu}}{\sqrt{2}} P_k d \right\} + \text{h.c.}\,, \quad (1)$$

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where u, d are quark fields, e stands for electron field and $P_{\rm L} = \frac{1}{2}(1-\gamma_5)$, $P_{\rm R} = \frac{1}{2}(1+\gamma_5)$, $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$, where our metric and gamma matrices are the same as *e.g.* in [2]. We work in the basis in which mass matrix of charged leptons is diagonal and the left (L) and right (R) neutrino fields are given by

$$\nu^{(\rm L)} = \sum_i U_{ei} P_{\rm L} \nu_i \,, \tag{2a}$$

$$\nu^{(\rm R)} = \sum_i V_{ei} P_{\rm R} \nu_i \,, \tag{2b}$$

where ν_i is the i-th neutrino field with a certain mass, U and V are respectively the Pontecorvo–Maki–Nakagawa–Sakata matrix and similar mixing matrix for right-handed neutrinos. SM is restored when $a_{kl} = A_{kl} = \alpha_{kk} = 0$ for k, $l = \rm L, R$ except $a_{\rm LL} = V_{ud}\, G_{\rm F}/\sqrt{2}$, where $G_{\rm F}$ is the usual Fermi constant and V_{ud} is the element of quark Cabibbo–Kobayashi–Maskawa mixing matrix.

When calculating the amplitudes for neutron beta decay at small four-momentum transfer $q^2 \approx 0$ we have used the relations [1]

$$g_{\rm V} \bar{u}_p \gamma_\mu u_n = \langle p|\bar{u}\gamma_\mu d|n\rangle \,, \tag{3a}$$

$$g_{\rm A} \bar{u}_p \gamma_\mu \gamma_5 u_n = \langle p|\bar{u}\gamma_\mu \gamma_5 d|n\rangle \,, \tag{3b}$$

$$g_{\rm S} \bar{u}_p u_n = \langle p|\bar{u} d|n\rangle \,, \tag{3c}$$

$$g_{\rm T} \bar{u}_p \sigma_{\mu\nu} u_n = \langle p|\bar{u}\sigma_{\mu\nu} d|n\rangle \tag{3d}$$

with $\langle p|$, u_p and $|n\rangle$, u_n being proton and neutron states and bispinors, respectively. From conserved vector current hypothesis one gets $g_{\rm V} = 1$. In the quark model with spherically symmetric wave functions of quarks the following relations have been derived [3]: $g_{\rm S} = -\frac{1}{2} + \frac{9}{10} g_{\rm A}$ and $g_{\rm T} = \frac{5}{3}\left(\frac{1}{2} + \frac{3}{10} g_{\rm A}\right)$. Substituting the SM value for $g_{\rm A} \simeq 1.27$ into the above relations leads to: $g_{\rm S} \simeq 0.64$ and $g_{\rm T} \simeq 1.47$. However, in our derivations and fits we treat $g_{\rm S}$ and $g_{\rm T}$ as free parameters (independent of $g_{\rm A}$).

2. Decay parameters

From Eq. (1) the five-fold differential decay width for polarized neutron without measurement of final electron and proton polarization is given by (in analogy to [4])

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e E_\nu^2 \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{\lambda}_n \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \right\}, \tag{4}$$

where $\vec{\lambda}_n$ is the neutron polarization vector, m_e, $p_e = |\vec{p}_e|$, E_e are, respectively, the mass, momentum and total energy of electron, E_0 is the maximum value of E_e, $|\vec{p}_\nu| = E_\nu = E_0 - E_e$ is the antineutrino energy[1]. The Ω_e, Ω_ν denotes the solid angles of electron and antineutrino emission. We have worked at tree-level (except: calculation of $\langle E_e^{-1}\rangle$ — see below) and with approximations such that terms proportional to $\bar{u}_p\gamma_5 u_n$ are not present in (4). Furthermore, we will consider only cases when: $g_{\rm V}$, $g_{\rm A}$, $g_{\rm S}$, $g_{\rm T}$, as well as a_{kl}, A_{kl}, α_{kk} for k, $l = $ L, R are real — then $D \equiv 0$ and time reversal symmetry is preserved, that is well motivated experimentally (PDG average [5]: $D = (-4 \pm 6) \times 10^{-4}$).

We express the decay parameters a, b, A, B, where B has the form of $B = B_0 + b_\nu\, m_e/E_e$, in terms of the ratio $g_{\rm A}/g_{\rm V}$ and the following parameters (see also [1]) for k, $l = $ L, R

$$V_{kl} = \frac{a_{kl}}{a_{\rm LL}}\kappa_k\,, \qquad S_{kl} = \frac{A_{kl}}{a_{\rm LL}}\frac{g_{\rm S}}{g_{\rm V}}\kappa_k\,, \qquad T_{kl} = \frac{\alpha_{kl}}{a_{\rm LL}}\frac{g_{\rm T}}{g_{\rm V}}\kappa_k\,, \tag{5}$$

where

$$\kappa_{\rm L} = 1\,, \qquad \kappa_{\rm R} = \left(\frac{\sum_i' |V_{ei}|^2}{\sum_i' |U_{ei}|^2}\right)^{1/2} \tag{6}$$

with summation $\sum_i'$ running only over kinematically allowed antineutrino states. In SM and for some cases of physics beyond SM $b = 0$ and $b_\nu = 0$. As a result of the applied approximations formulas for a, b, A, B_0, b_ν depend in general case only on two combinations

$$s_{\rm L} = S_{\rm LL} + S_{\rm LR}\,, \tag{7a}$$

$$s_{\rm R} = S_{\rm RR} + S_{\rm RL}\,. \tag{7b}$$

Next, following the approach applied in [6, 7, 8], we define

$$\bar{a}\left(\langle W^{-1}\rangle\right) = \frac{a}{1 + b\,\langle W^{-1}\rangle}\,, \tag{8a}$$

$$\bar{A}\left(\langle W^{-1}\rangle\right) = \frac{A}{1 + b\,\langle W^{-1}\rangle}\,, \tag{8b}$$

$$\bar{B}\left(\langle W^{-1}\rangle\right) = \frac{B_0 + b_\nu\,\langle W^{-1}\rangle}{1 + b\,\langle W^{-1}\rangle}\,, \tag{8c}$$

where $\langle W^{-1}\rangle = m_e\langle E_e^{-1}\rangle$, and apply these quantities in the fits to the experimental data. The χ^2, which we will minimize with the fit procedure,

[1] The effect of nonzero neutrino masses enters only trough presence of mixing matrices U and V.

is of the form

$$\chi^2 = \sum_i \left[\frac{a_i - \bar{a}\Big(\langle W^{-1} \rangle_i \Big)}{\delta a_i} \right]^2 + \sum_j \left[\frac{A_j - \bar{A}\Big(\langle W^{-1} \rangle_j \Big)}{\delta A_j} \right]^2 + \sum_k \left[\frac{B_k - \bar{B}\Big(\langle W^{-1} \rangle_k \Big)}{\delta B_k} \right]^2 , \tag{9}$$

where the selected data are presented in Table I: a_i, A_j, B_k and δa_i, δA_j, δB_k denote the central value and the error of the respective decay parameter in a certain experiment. We calculate the particular value of $\langle W^{-1} \rangle_i = m_e \langle E_e^{-1} \rangle_i$

TABLE I

We have followed the PDG [5] data selection but took only the most precise data (the error in measurements of a is less than 6% of central value, for A and B — it is less than 2%). When experiment reports statistic and systematic error separately we add these two errors in quadrature. In the case of asymmetric errors, we have taken the larger of the reported errors. Most of presented values of the $\langle W^{-1} \rangle$ have been taken from [7]. We have used all 11 "data points" in the table below in every fit presented in this paper. Because of unsolved experimental ambiguity of neutron lifetime measurements (see [5]) we have not included this quantity in our analyzes.

Par.	Value	Error	$\langle W^{-1} \rangle$	Paper ID (PDG)		
a	−0.1054	0.0055	0.655	Byrne	02	[12]
	−0.1017	0.0051	0.655	Stratowa	78	[13]
A	−0.11966	0.00166	0.557	Liu	10	[14]
	−0.1189	0.0007	0.534	Abele	02	[15]
	−0.1160	0.0015	0.582	Liaud	97	[16]
	−0.1135	0.0014	0.558	Yerozolimsky	97	[17]
	−0.1146	0.0019	0.581	Bopp	86	[18]
B	0.980	0.005	0.599	Schumann	07	[19]
	0.967	0.012	0.600	Kreuz	05	[20]
	0.9801	0.0046	0.594	Serebrov	98	[21]
	0.9894	0.0083	0.554	Kuznetsov	95	[22]

from

$$\langle E_e^{-1}\rangle_i = \int\limits_{E_i^{\min}}^{E_i^{\max}} dE_e \frac{d\Gamma}{dE_e} E_e^{-1} \Bigg/ \int\limits_{E_i^{\min}}^{E_i^{\max}} dE_e \frac{d\Gamma}{dE_e}\,, \tag{10}$$

where $E_i^{\min}$ and $E_i^{\max}$ in general are different for different experiments. At this stage of calculation, Fermi function $F(E_e)$ (that is a leading order QED correction) [9, 10, 11] has been incorporated and SM was assumed

$$\frac{d\Gamma}{dE_e} = \left(g_{\rm V}^2 + 3g_A^2\right) \frac{G_{\rm F}^2|V_{ud}|^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 F(E_e)\,, \tag{11}$$

$$F(E_e) = \frac{2\pi\alpha\, E_e/p_e}{1 - e^{-2\pi\alpha\, E_e/p_e}}\,. \tag{12}$$

3. Results

In SM the formulas derived for decay parameters depend on $\lambda = g_{\rm A}/g_{\rm V}$ alone and simplify to

$$a = \frac{1-\lambda^2}{3\lambda^2+1}\,, \qquad A = \frac{2\lambda(1-\lambda)}{3\lambda^2+1}\,, \qquad B = \frac{2\lambda(\lambda+1)}{3\lambda^2+1}\,. \tag{13}$$

In this case, the one-parameter fit is performed, which results in $\chi^2_{\min} = 25.42$ with

$$\begin{aligned} & \pm\ 0.0014\ (\,68.27\%\ \text{C.L.}\,) && \text{(14a)}\\ \lambda\ =\ 1.2703\ & \pm\ 0.0023\ (\,90\%\ \text{C.L.}\,) && \text{(14b)}\\ & \pm\ 0.0028\ (\,95.45\%\ \text{C.L.}\,) && \text{(14c)} \end{aligned}$$

that is in a good agreement with the PDG average [5]: $\lambda = 1.2701 \pm 0.0025$ (error scaled by PDG by 1.9).

The above results (14a)–(14c) apply also when: $V_{kl} = S_{kl} = T_{kk} = 0$ for k, $l = $ L, R except $V_{\rm LR}$ (and $V_{\rm LL} = 1$ by definition — see Eqs. (5) and (6)). In this case the formulas (13) hold for modified λ

$$\lambda = \frac{g_{\rm A}}{g_{\rm V}} \frac{1 - V_{\rm LR}}{1 + V_{\rm LR}}\,. \tag{15}$$

In the next step one of the parameters: $V_{{\rm R}k}$, s_k, T_{kk} for $k =$ L, R is nonzero and fitted together with the ratio $g_{\rm A}/g_{\rm V}$. Among these cases only when the nonzero parameter is $s_{\rm L}$ or $T_{\rm LL}$ we have $b \neq 0$ and $b_\nu \neq 0$. The results of such two-parameter fits are presented in Fig. 1.

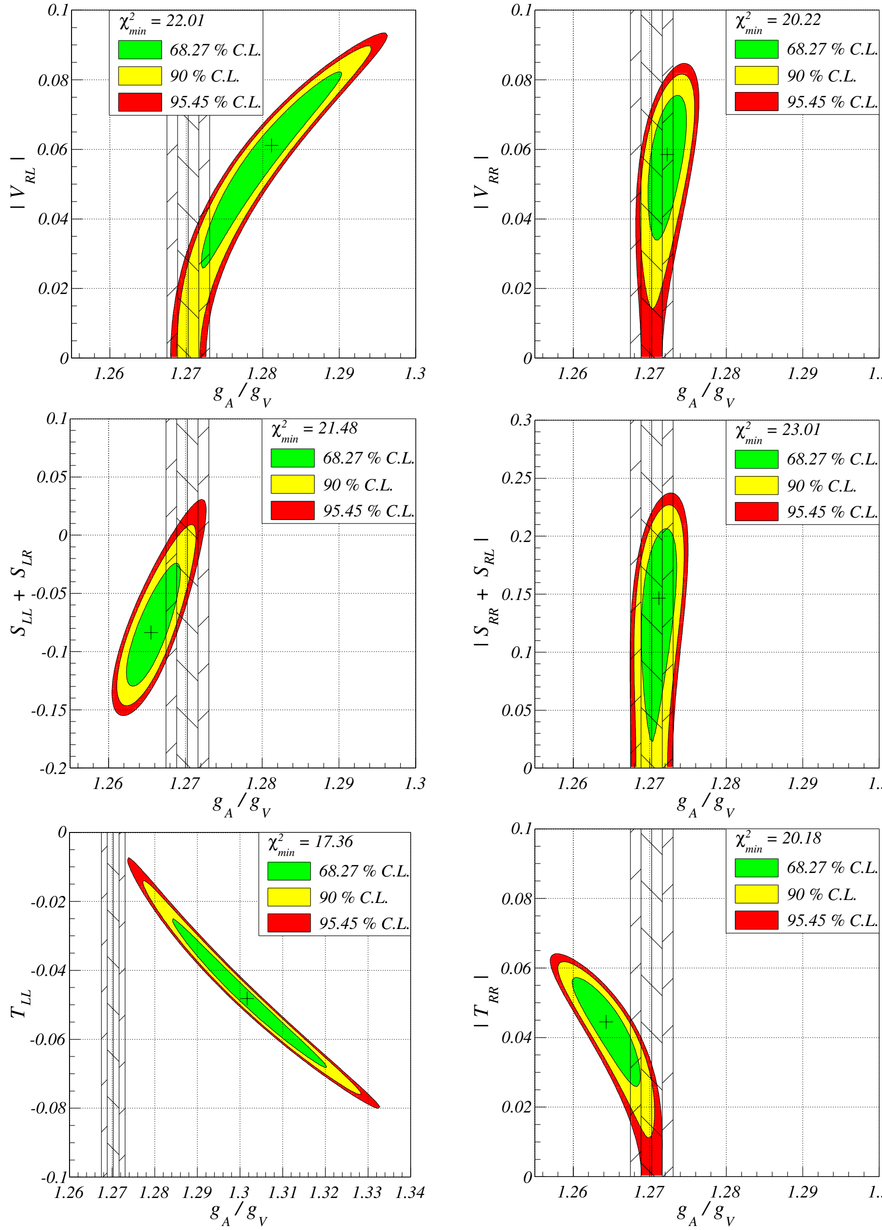

Fig. 1. Results of the two-parameter fits (the cross denote the position of $\chi^2_{\rm min}$ in each case). The line — marked areas correspond to the $\lambda = g_{\rm A}/g_{\rm V}$ intervals: (14a) — the narrow one and (14c) — the wider one. Note that $|\cdot|$ is the absolute value — not the module of a complex number, as all parameters are real.

In conclusion, Standard Model describes the neutron beta decay very well. The fits are minimally better if New Physics is included, especially if tensor terms are present. In some cases there is rather big dependence of the results on $g_{\rm A}/g_{\rm V}$ ratio.

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