NEUTRON β-DECAY

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Abstract: The status of neutron β-decay experiments is reviewed, and its implications on the Standard Model of particle physics are discussed.

PACs: 12.15.-y Electroweak interactions; 12.60.-i Models beyond the standard model;
23.40.-s β decay

1. Introduction

There are two main reasons for our interest in precise neutron decay data. First, all semileptonic weak interaction processes (i.e., involving both quarks and leptons) occurring in nature today must be calculated from measured neutron decay parameters. Examples range from proton or neutron weak cross sections needed in cosmology, astrophysics, and particle physics, over pion decay and muon capture, to such mundane problems as precise neutrino detector efficiencies.

Second, in neutron decay many tests on new physics beyond the Standard Model (SM) are possible, relevant both in particle physics and in studies of the very early universe. According to conventional wisdom, the SM and its vector-axialvector (V−A) structure are extremely well tested. However, if one looks closer then one finds that there is still much room for couplings with other symmetries, like scalar S or tensor T couplings, or for additional right-handed V+A couplings, with incomplete parity violation.

Neutron tests beyond the SM are possible because there are many more observables accessible in neutron decay (in principle more than 20) than there are parameters (three) needed to describe neutron decay in the SM, which makes the problem strongly over-determined. When we go beyond the SM there are up to 10 complex coupling constants, allowed in the sense that they obey basic symmetries like Lorentz invariance.

In the language of particle physics, neutron decays are rare events with a low-energy signature in a noisy environment. Therefore the experimental study of neutron decay is challenging, and error margins are easily underestimated. The precision of neutron decay data has dramatically improved over past decades. However, there are still some inconsistencies between various neutron decay data that need to be resolved, but at a much higher level of precision than in the past. There is a high demand for better neutron data for physics both within and beyond the SM, which is the reason why, in recent years, more and more neutron decay “hunters” have joined the party.

The present review is in part based on a 2011 review on the neutron [1], with updates taken mostly from the 2012 release of the Particle Data Group (PDG) [2].

2. Neutron decay parameters in the Standard Model

Neutron β-decay

$$n \to p^+ + e^- + \overline{\nu}_e \tag{1}$$

has a lifetime of about 15 minutes and a β endpoint energy of 782 keV. It is mediated by the exchange of vector bosons $W^\pm$ of mass $m_W \approx 80$ GeV. Exchanged momenta $p << m_W c$ can be neglected in the corresponding propagator, which becomes $\sim 1/m_W^2$ and is very small. The range of the interaction, given by the Compton wavelength $\lambda_\mathrm{C} = h/m_W c$ of the W-boson, is very short.

Neutron decay then is described as a point-like interaction between two charged weak currents. In the V−A electroweak SM, the weak current is composed of a vector part V, which is the same as for the electromagnetic interaction, and an additional axialvector part A of opposite sign. The β-decay matrix element at zero momentum transfer then is

$$\mathcal{M}_\mathrm{neutron} = \frac{G_\mathrm{F}}{\sqrt{2}} V_{ud} [p(\gamma_\mu(1+\lambda\gamma_5) + \frac{\kappa_p - \kappa_n}{2M}\sigma_{\mu\nu} q^\nu)n][e\gamma_\mu(1-\gamma_5)\nu_e]. \tag{2}$$

The strength of the weak interaction is given by the Fermi constant

$$G_\mathrm{F}/(\hbar c)^3 = 1.166\ 378\ 8(7)\times 10^{-5}\ \mathrm{GeV}^{-2}, \tag{3}$$

as determined from the newly measured muon lifetime [3]. The Fermi constant is related to the weak coupling constant $g_\mathrm{w} = e/\sin\theta_\mathrm{w} \approx 0.65$ of the SM as $G_\mathrm{F}/\sqrt{2} = \frac{1}{8} g_\mathrm{w}^2/(m_W c^2)^2$, with the weak angle θ_w, and with the elementary charge $e = (4\pi\alpha)^{1/2} \approx 0.31$ and fine-structure constant α.

The next parameter V_{ud} in Eq. (2) is the leading element, close to one, of the unitary CKM quark mixing matrix, which rotates the quark mass eigenstates d, s, b in flavor space to the weak-interaction eigenstates d', s', b',

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{sb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{4}$$

The complicated interior of the neutron is taken care of by one free parameter

$$\lambda = |\lambda|\,\mathrm{e}^{\mathrm{i}\varphi}. \tag{5}$$

In the V−A SM, one conventionally writes

$$\lambda = g_\mathrm{A}/g_\mathrm{V}, \tag{6}$$

with the zero-momentum form factors g_A and g_V. Conservation of the weak vector current (CVC) requires that the vector coupling g_V remains unaffected by the intrinsic environment of the nucleon. Partial conservation of the weak axialvector current (PAC) assumes that the axialvector coupling g_A is almost conserved, that is, under V−A, the value of λ should be near one. Under time reversal invariance λ is real and negative, with phase $\varphi = \pi$.

Under CVC, not only the charges but also the higher multipoles of the electroweak hadronic couplings should remain unaffected by the nucleon environment. The "weak magnetism" term in Eq. (2), with nucleon mass *M*, then is determined simply by the difference between proton and neutron anomalous magnetic moments

$$\kappa_p - \kappa_n = 3.706\,. \tag{7}$$

Hence, within the SM, under neglect of *T*-violation, and with G_F from muon decay, the matrix element Eq. (2) has only two free parameters, namely, the first element V_{ud} of the CKM matrix, and the ratio λ of axialvector to vector amplitudes.

There are two further allowed but rare neutron decay channels, radiative β-decay under emission of an inner bremsstrahlung photon $n \to p^+ + e^- + \bar{\nu}_e + \gamma$, and bound β-decay of a neutron into a hydrogen atom $n \to H + \bar{\nu}_e$, but these processes are beyond the scope of this review.

3. The neutron lifetime

With the matrix element of Eq. (2) one arrives at a neutron decay rate

$$\tau_n^{-1} = \frac{c}{2\pi^3}\frac{(m_e c^2)^5}{(\hbar c)^7} G_\mathrm{F}^2\ |V_{ud}|^2 (1+3\lambda^2) f\ , \tag{8}$$

with a phase space factor $f = 1.6887(2)$ from [4]. After corrections for radiative effects and weak magnetism, the lifetime becomes [5]

$$\tau_n = \frac{(4908.7 \pm 1.9)\ \mathrm{s}}{|V_{ud}|^2 (1+3\lambda^2)}\,. \tag{9}$$

The ratio $\lambda = g_\mathrm{A} / g_\mathrm{V}$, on the other hand, can be obtained from the measurements of one of the many neutron-decay correlation coefficients.

We start with the neutron lifetime, which can be measured by two principally different methods, namely, with cold neutrons "in-beam", or with ultracold neutrons (UCN) "in-trap". The in-beam method uses electrons and/or protons emitted from a certain neutron beam volume filled with an average number N_n of neutrons. The charged decay particles are counted in detectors installed near the *n*-beam at a rate of

$$n_e = n_p = N_n / \tau_n\,. \tag{10}$$

To derive τ_n one compares the rate n_e (or n_p) to the rate n_n in a thin neutron detector at the end of the beam. The neutron detection efficiency depends on the neutron cross-section σ_n and the effective thickness of the detector material, which must very precisely be determined.

The UCN in-trap method uses stored ultracold neutrons. In these experiments, one counts the number of UCN that survived in the neutron bottle over successive storage periods of variable durations *T*, with constant initial neutron number $N_n(0)$,

$$N_n(T) = N_n(0)\, \mathrm{e}^{-T/\tau_\mathrm{storage}}\ , \tag{11}$$

with the UCN disappearance rate

$$\frac{1}{\tau_{\text{storage}}} = \frac{1}{\tau_n} + \frac{1}{\tau_{\text{loss}}} . \tag{12}$$

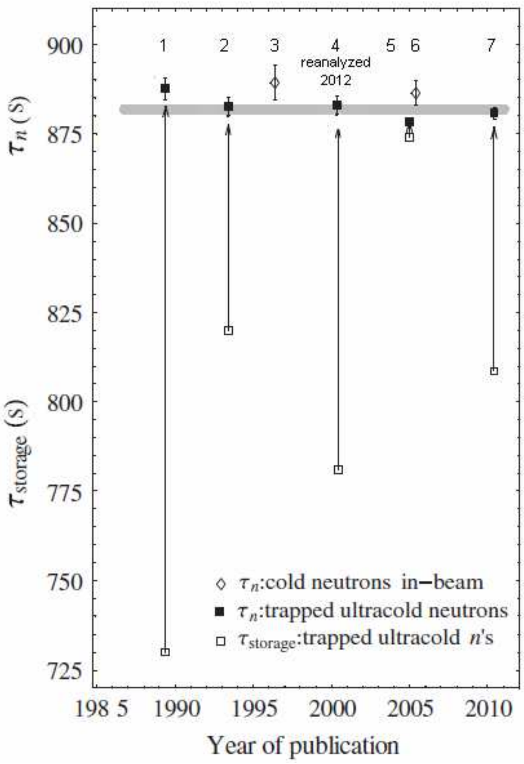
After each such measurement, the neutron trap is emptied and refilled with UCN. The UCN loss rate $1/\tau_{\text{loss}}$ is due to neutron interactions with the walls of the trap, whereas collisions with atoms of the rest gas can usually be neglected. With the trapped-UCN lifetime method, no absolute particle counting is needed, because the mean residence time τ_{storage} can be obtained from a fit to the exponential neutron decay law (11), with $N_n(T)$ measured successively for several different storage times T. The important task is to eliminate τ_{loss} from Eq. (12).

Lifetime experiments both with UCN storage and with cold neutrons in-beam have been done in recent years, often with contradicting results. Though things now seem to clear up. The 2012 PDG average of the neutron lifetime has dropped by six standard deviations as compared to the earlier PDG averages, which had not been updated for about ten years, the new lifetime value being

$$\tau_n = (880.1 \pm 1.1)\ \text{s} , \tag{13}$$

where the error includes a scale factor of S = 1.8. Figure 1 shows the lifetime results that enter the PDG-2012 value. For the UCN storage experiments, the arrows in the figure show the ranges of extrapolation from τ_{storage} to τ_n. Although a larger part of these extrapolations is based on geometric quantities like the length of the trap that were sufficiently well under control, a general aim should be to keep these extrapolation intervals as short as possible. Main changes in the 2012 lifetime average are: the acceptance of data point 5 from [6]; the new data point 7 from [7]; and the revised data point 4 from [8].

Fig. 1 Experimental neutron lifetimes used in the 2012 average of the Particle Data Group. The open diamonds (◊) show the in-beam neutron lifetimes, 3 Byrne *et al.* (1996), and 6 Nico *et al.* (2005). The filled squares (■) show the measurements with trapped UCN, 1 Mampe *et al*. (1989), 2 Mampe *et al*. (1993), 4 Arzumanov *et al*. (2000) (shown is the revised 2012 value); 5 Serebrov *et al*. (2005); 7 Pichlmaier *et al.* (2010). The vertical arrows show the extrapolation from the measured τ_{storage}, open squares (□), to the corrected τ_n (■), see Eq. (12). The grey horizontal bar is the average of these measurements. The overall error, indicated by the width of the bar, includes a scale factor S = 1.8.



4. Neutron decay correlations

The β-decay of slow neutrons involves four vector quantities accessible to experimental investigation: the momenta $\boldsymbol{p}_e$ and $\boldsymbol{p}_p$ of the electron and the proton, and the spins $\boldsymbol{\sigma}_n$ and $\boldsymbol{\sigma}_e$ of the neutron and the electron. The neutrino momentum cannot be measured in experiment, but must be reconstructed as $\boldsymbol{p}_\nu = -(\boldsymbol{p}_e + \boldsymbol{p}_p)$ from the measured electron and proton momenta.

The simplest such correlations are given by the scalar products of type $A\,\boldsymbol{p}_e \cdot \boldsymbol{\sigma}_n$, $a\,\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu$, etc., of any two of these four vectors. This gives the six correlation coefficients arranged in a self-explaining way in Fig. 2.

In the SM, all these coefficients depend solely on the value of $\lambda = g_\mathrm{A} / g_\mathrm{V}$. The PDG 2012 average $\lambda = -1.2701 \pm 0.0025$ with scale factor $S = 1.9$ is derived from six different measurements of the neutron β-decay asymmetry A. When therein we replace the Abele 2002 value by the A value reported in 2012 [9] we obtain

$$\lambda = -1.2724 \pm 0.0029 \text{ (neutron)}, \qquad (14)$$

with $S = 2.3$. While earlier β-asymmetry measurements needed large corrections of 15% and more, the new measurement with the PERKEO instrument requires only a 3×10^{-3} correction that is smaller than the quoted error.

Fig. 3 shows the values of λ derived from all available measurements. Besides the six β-asymmetry values that enter Eq. (14), the figure shows the (not yet significant) values of λ derived from the correlations a, B, and the newly measured proton asymmetry $C \propto A + B$. We further show the value of λ derived from the neutron lifetime, Eq. (13), using Eq. (9) with $|V_{ud}|$ taken from nuclear $0^+ \rightarrow 0^+$ super-

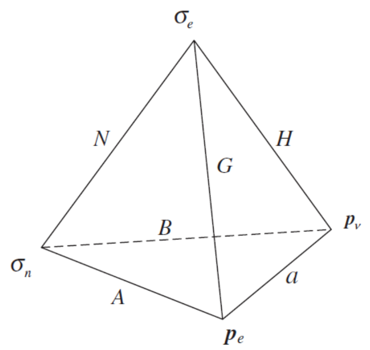


Fig. 2 Schematic arrangement of twofold correlations between momenta $\boldsymbol{p}$ and/or spins $\boldsymbol{\sigma}$ in the β-decay of slow neutrons, with: β-asymmetry A, neutrino-asymmetry B, electron-antineutrino correlation a, electron helicity G, and spin-spin and spin-momentum coefficients N and H.

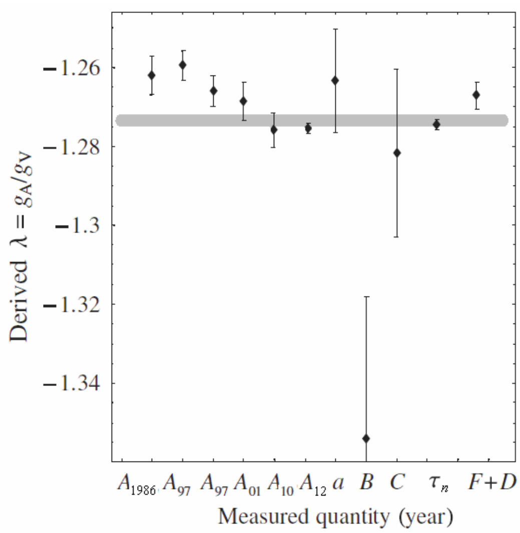


Fig. 3 The ratio λ of axial vector to vector coupling constants as derived from: neutron β-asymmetry A_{1986} to A_{2012}; neutrino asymmetry B; proton-asymmetry C; electron-neutrino correlation a; neutron lifetime τ_n ($|V_{ud}|$ derived from nuclear β-decays); hyperon correlations $F + D$. Horizontal grey bar: average and overall error with $S = 3$.

allowed β-decays. Finally, we show the value $\lambda = F + D$ derived from weak hyperon decays that take place within the same baryon flavour-SU(3) octet as does neutron decay, and which are becoming competitive. The hyperon weak decays are linked to each other and to neutron decay by current algebra. The grey horizontal bar shows the overall average

$$\lambda = -1.2738 \pm 0.0018 \text{ (all data, } S = 2.0\text{)}. \tag{15}$$

Next, from any three different vectors out of $\boldsymbol{p}_e$, $\boldsymbol{p}_\nu$, $\boldsymbol{\sigma}_n$, and $\boldsymbol{\sigma}_e$ one can form four triple products, all T violating, namely

$$D\boldsymbol{\sigma}_n \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu),\ L\boldsymbol{\sigma}_e \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu),\ R\boldsymbol{\sigma}_e \cdot (\boldsymbol{\sigma}_n \times \boldsymbol{p}_e),\ V\boldsymbol{\sigma}_n \cdot (\boldsymbol{\sigma}_e \times \boldsymbol{p}_\nu)\,. \tag{16}$$

Limits on these quantities exist for D and R. The present limit $D = (-1.2 \pm 2.0) \times 10^{-4}$ translates into a phase between g_A and g_V of

$$\varphi = -180.018° \pm 0.026°, \tag{17}$$

which means that, within error, λ is real and T is conserved. With $R = 0.008 \pm 0.015\text{(stat)} \pm 0.005\text{(syst)}$, the first correlation coefficient involving electron spin was measured. The newest publications on D and R are in Refs. [10] and [11], respectively. There are five more neutron decay quantities that involve four and fivefold products, but these are probably not worthwhile pursuing.

Several new neutron decay instruments are under construction or in the test phase, for details see [1]. Such new experiments are highly welcome in order to corroborate the existing neutron decay data.

Summing up, experimental results exist on ten of the more than 20 neutron decay parameters that are accessible experimentally, namely, on τ_n, a, A, B, C, N, D, R, b, b'. For the Fierz amplitudes b and b', vanishing in the SM, only upper limits have been derived. The quality of the neutron data (except for the lifetime) is well comparable to the quality of muon decay data, as is discussed in [1].

5. Tests of the Standard Model with neutron decay

Neutron decay data test the Standard Model in various ways. We mentioned good agreement of $\lambda = g_A/g_V$ derived from neutron and from hyperon decay, in support of current algebra. Another test is the good agreement between the CKM matrix elements derived from neutron decay,

$$|V_{ud}| = 0.9742 \pm 0.0012 \text{ (neutron)}, \tag{18}$$

with the values derived from pion decay ($|V_{ud}| = 0.9728 \pm 0.0030$) and from superallowed nuclear $0^+ \rightarrow 0^+$ β-decays ($|V_{ud}| = 0.97425 \pm 0.00022$). The measured values of $|V_{ud}|^2$ can be used to test the unitarity of the first row of the CKM matrix $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. With $|V_{ud}|$ from neutron decay, Eq. (18), and the other elements from high-energy physics, this gives

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000 \pm 0.0026 \text{ (neutron)}. \tag{19}$$

For unitarity tests of the other rows and columns of the CKM matrix, see Ref. [1].

We next turn to the question whether the basic symmetry of the electroweak interaction is really V−A. The most general Lorentz-invariant weak Hamiltonian can be constructed from five types of scalar products, namely, Scalar×Scalar (S), Vector×Vector (V), Tensor×Tensor (T), Axialvector×Axialvector (A), Pseudoscalar×Pseudoscalar (P), with 10 complex coupling constants. Neutron decay is not sensitive to pseudoscalar P amplitudes, due to its low energy release, so we limit discussion to possible S and T amplitudes. In fact, no one knows why nature seems to have chosen the V−A variety, and, contrary to common belief, tests excluding S and T amplitudes are not very stringent.

One mode of access to S and T amplitudes is given by the Fierz interference amplitude b in β-decay. The Fierz term enters unpolarized energy spectra as $\mathrm{d}\Gamma \propto 1+[m_e/(E_e+m_e)]b$, with electron kinetic energy E_e. It describes g_S-g_V and g_T-g_A interference, i.e., b is linear in both g_S and g_T. For a purely left-handed weak interaction, $b = 2(S+3\lambda^2 T)/(1+3\lambda^2)$, with $S = g_\mathrm{S}/g_\mathrm{V}$ and $T = g_\mathrm{T}/g_\mathrm{A}$. It is difficult to determine b from the shape of unpolarized β-spectra, but Fierz interference terms necessarily enter all measured decay correlations, too. The neutrino asymmetry B, for instance, contains two Fierz terms b and b', with $b' = 2\lambda(2\lambda T - S - T)/(1+3\lambda^2)$. From a joint evaluation of the coefficients A, B, and C, we find the limits $-0.3 < b, b' < 0.5$ at 95% confidence. If one includes the ratio of neutron and nuclear superallowed ft-values $\mathcal{F}t_n/\mathcal{F}t_{0\to 0}$, this 95% C.L. limit on the Fierz amplitudes improves considerably to

$$|b| < 0.03,\ |b'| < 0.02. \tag{20}$$

From this we derive the 95% C.L. limits on the amplitudes g_S, g_T for a left-handed S-T sector

$$-0.23 < g_S/g_V < 0.08,\ -0.02 < g_T/g_A < 0.05 \text{ (left-handed).} \tag{21}$$

S and T couplings could as well be right-handed, in which case the Fierz terms b and b' vanish. Right-handed S and T amplitudes enter the correlation coefficients only quadratically, with 95% limits

$$|g_\mathrm{S}/g_\mathrm{V}| < 0.15,\ |g_\mathrm{T}/g_\mathrm{A}| < 0.10 \text{ (right-handed).} \tag{22}$$

Today, many models beyond the SM start with a left-right symmetric universe, and the left-handedness of the electroweak interaction arises as an "emergent property" due to a spontaneous symmetry breaking in the course of a phase transitions of the vacuum in the early universe. This should lead to a mass splitting of the corresponding gauge boson, namely, the left-handed W_1 and the right-handed W_2, with masses m_L, m_R, and $\delta = (m_\mathrm{L}/m_\mathrm{R})^2 << 1$. If the mass eigenstates W_1 and W_2 do not coincide with the electroweak eigenstates W_L and W_R, then

$$W_\mathrm{L} = W_1 \cos\zeta + W_2 \sin\zeta,\ W_\mathrm{R} = -W_1 \sin\zeta + W_2 \cos\zeta, \tag{23}$$

with left-right mixing angle ζ. The neutron decay parameters then depend not only on $|V_{ud}|$ and λ, but also on δ and ζ. Using all correlation and lifetime measurements, we obtain the exclusion plot of Fig. 4, in good agreement with the SM expectation $\delta = \zeta = 0$. The 95% limits on the mass m_R of the right-handed W_R and the mixing angle ζ are derived as

$$m_{\mathrm{R}} > 250\ \mathrm{GeV},\ -0.23 < \zeta < 0.06. \quad (24)$$

which is becoming competitive with limits from high-energy searches, for details see Ref. [1].

In summary, there are many observables in neutron decay, which permit important tests of the Standard Model, and there are many upcoming experiments that will sharpen these tests.

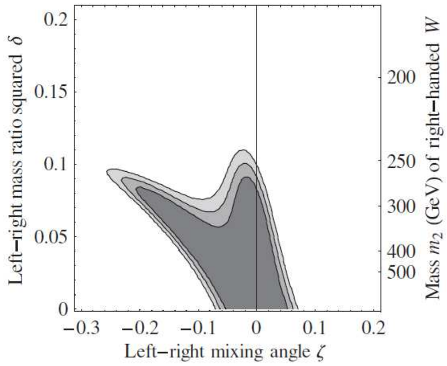


Fig. 4 Exclusion plot for the parameters of the manifest left-right symmetric model: mass ratio squared $\delta = (m_{\mathrm{R}} / m_{\mathrm{L}})^2$ of left and right-handed W bosons and their relative phase ζ. The exclusion contours are for 1σ (dark grey), 2σ (grey), and 3σ (light grey). The Standard Model predicts $\delta = \zeta = 0$.

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