IMPACT OF NEUTRON DECAY EXPERIMENTS ON NON-STANDARD MODEL PHYSICS

G. KONRAD* AND W. HEIL
Institut für Physik, Universität Mainz, Staudingerweg 7
55099 Mainz, Germany
*Email: konradg@uni-mainz.de
www.quantum.physik.uni-mainz.de

S. BAEßLER* AND D. POČANIĆ
Department of Physics, University of Virginia
Charlottesville, VA 22904, USA
*Email: baessler@virginia.edu

F. GLÜCK
IEKP, KIT, 76131 Karlsruhe, Germany
KFKI, RMKI, H-1525 Budapest 114, Hungary
Email: ferenc.glueck@kit.edu

This paper gives a brief overview of the present and expected future limits on physics beyond the Standard Model (SM) from neutron beta decay, which is described by two parameters only within the SM. Since more than two observables are accessible, the problem is over-determined. Thus, precise measurements of correlations in neutron decay can be used to study the SM as well to search for evidence of possible extensions to it. Of particular interest in this context are the search for right-handed currents or for scalar and tensor interactions. Precision measurements of neutron decay observables address important open questions of particle physics and cosmology, and are generally complementary to direct searches for new physics beyond the SM in high-energy physics. Free neutron decay is therefore a very active field, with a number of new measurements underway worldwide. We present the impact of recent developments.

Keywords: Standard Model; Scalar and tensor interactions; Right-handed currents; Neutron beta decay; Neutrino mass; Neutrinoless double beta decay

1. Introduction

Neutron decay, \( n \to p e^- \bar{\nu}_e \), is the simplest nuclear beta decay, well described as a purely left-handed, \( V-A \) interaction within the framework of the Standard Model of elementary particles and fields. Thanks to its highly precise theoretical description,\(^1\) neutron beta decay data can lead to limits on certain extensions to the SM.

Neutron decay experiments provide one of the most sensitive means for determining the weak vector \( (L_V G_F V_{ud}) \) and axial-vector \( (L_A G_F V_{ud}) \) coupling constants,
and the element $V_{ud}$ of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix. Extracted $V_{ud}$, along with $V_{us}$ and $V_{ub}$ from K-meson and B-meson decays, respectively, test the unitarity of the CKM matrix. $G_F$ is the Fermi weak coupling constant, evaluated from the muon lifetime. The value of $L_V$ is important for testing the conserved vector current (CVC) hypothesis. The size of the weak coupling constants is important for applications in cosmology (e.g., primordial nucleosynthesis), astronomy (e.g., solar cycle, neutron star formation), and particle physics (e.g., neutrino detectors, neutrino scattering).

In the SM, the CVC hypothesis requires $L_V = 1$ for zero momentum transfer. Therefore, neutron beta decay is described by two parameters only, $\lambda = L_A/L_V$ and $V_{ud}$. The neutron lifetime $\tau_n$ is inversely proportional to $G_F^2 |V_{ud}|^2 (1 + 3|\lambda|^2)$. Hence, independent measurements of $\tau_n$ and of an observable sensitive to $\lambda$, allow the determination of $V_{ud}$. The value of $\lambda$ can be determined from several independent neutron decay observables, introduced in Sec. 2. Each observable brings a different sensitivity to non-SM physics, such that comparing the various values of $\lambda$ provides an important test of the validity of the SM. Of particular interest is the search for scalar and tensor interactions, discussed in Secs. 4.1 and 4.2. These interactions can be caused, e.g., by leptoquarks or charged Higgs bosons. In Sec. 4.3 we discuss a particular kind of $V+A$ interactions, the manifest left-right symmetric (MLRS) models, with the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge group and right-handed charged current, approximately realized with a minimal Higgs sector.

2. Measurable parameters of neutron decay

The matrix element $M$ describing neutron beta decay can be constructed as a four-fermion interaction composed of hadronic and leptonic matrix elements. Assuming that vector ($V$), axial-vector ($A$), scalar ($S$), and tensor ($T$) currents are involved, the decay matrix element can be written as a sum of left-handed and right-handed matrix elements:

$$M = \frac{2 G_F V_{ud}}{\sqrt{2}} \sum_{j \in \{V, A, S, T\}} L_j \langle p | \Gamma_j | n \rangle \langle e^- | \Gamma_j \frac{1 - \gamma_5}{2} | \nu_e \rangle + R_j \langle p | \Gamma_j | n \rangle \langle e^- | \Gamma_j \frac{1 + \gamma_5}{2} | \nu_e \rangle. \quad (1)$$

The four types of currents are defined by the operators:

$$\Gamma_V = \gamma_\mu, \quad \Gamma_A = i \gamma_\mu \gamma_5, \quad \Gamma_S = 1, \quad \text{and} \quad \Gamma_T = \frac{i [\gamma_\mu, \gamma_\nu]}{2\sqrt{2}}. \quad (2)$$

The coupling constants to left-handed (LH) and right-handed (RH) neutrinos are denoted by $L_j$ and $R_j$, respectively. This parametrization was introduced in Ref. 7 in order to highlight the handedness of the neutrino in the participating $V, A, S, T$ currents. The $L_j$ and $R_j$ coupling constants are linear combinations of the coupling constants, $C_j$ and $C'_j$, that were defined in earlier work:

$$C_j = \frac{G_F V_{ud}}{\sqrt{2}} (L_j + R_j), \quad C'_j = \frac{G_F V_{ud}}{\sqrt{2}} (L_j - R_j), \quad \text{for} \quad j = V, A, S, T. \quad (3)$$
We neglect effects of time-reversal violation, i.e., we consider the above 8 couplings to be real.

In neutron decay experiments the outgoing spins are usually not observed. Summing over these spin quantities, and neglecting the neutrino masses, one can evaluate the triple differential decay rate to be:  

$$d^3\Gamma = \frac{1}{(2\pi)^3} \frac{G_F^2 |V_{ud}|^2}{2} p_e E_e (E_0 - E_e)^2 \, dE_0 \, d\Omega_e \, d\Omega_\nu,$$

$$\times \xi \left[ 1 + a \frac{p_e \cdot p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + s_n \left( A \frac{p_e}{E_e} + B \frac{p_\nu}{E_\nu} + \ldots \right) \right],$$  

(4)

where $p_e, p_\nu, E_e,$ and $E_\nu$ are the electron (neutrino) momenta and total energies, respectively, $E_0$ is the maximum electron total energy, $m_e$ the electron mass, $s_n$ the neutron spin, and the $\Omega_i$ denote solid angles. Quantities $a, A, B$ are the angular correlation coefficients, while $b$ is the Fierz interference term. The latter, and the neutrino-electron correlation $a$, are measurable in decays of unpolarized neutrons, while the $A$ and $B$, the beta and neutrino asymmetry parameters, respectively, require polarized neutrons. The dependence of $a, b, A, B$ on the coupling constants $L_j$ and $R_j$ is described in Ref. 7. We mention that in the presence of LH $S$ and $T$ couplings $B$ depends on the electron energy: $B = B_0 + b_\nu \frac{m_e}{E_e}$, where $b_\nu$ is another Fierz-like parameter, similar to $b$.  

We note that $a, A, B, B_0$ are sensitive to non-SM couplings only in second order, while $b$ and $b_\nu$ depend in first order on $L_S$ and $L_T$. A non-zero $b$ would indicate the existence of LH $S$ and $T$ interactions.

Another observable is $C$, the proton asymmetry relative to the neutron spin. Observables related to the proton do not appear in Eq. (4). However, the proton is kinematically coupled to the other decay products. The connection between $C$ and the coupling constants $L_j$ and $R_j$ is given in Refs. 7 and 10.

We also use the ratio of the $\mathcal{F}^{0^+ \rightarrow 0^+}$ values in superallowed Fermi (SAF) decays to the equivalent quantity in neutron decay, $\mathcal{F}^{t^n}$:

$$r_{f^n} = \frac{\mathcal{F}^{t^0 \rightarrow 0^+}}{\mathcal{F}^{t^n}} = \frac{\mathcal{F}^{t^0 \rightarrow 0^+}}{f^n (1 + \delta_R^t)} = \frac{\mathcal{F}^{t^0 \rightarrow 0^+}}{f_R \ln (2) \tau_n},$$  

(5)

where $f^n = 1.6887$ is a statistical phase-space factor.\textsuperscript{1} The”nucleus-dependent (outer) radiative correction $\delta_R^t$, and $O(\alpha^2)$ corrections,\textsuperscript{11–13} change $f^n$ by $\sim 1.5\%$ to $f_R = 1.71385(34)$\textsuperscript{a}. The corrections implicitly assume the validity of the $V-A$ theory.\textsuperscript{15} The dependence of $r_{f^n}$ on coupling constants $L_j$ and $R_j$ is given in Ref. 7.

An electrically charged gauge boson outside the SM is generically denoted $W'$. The most attractive candidate for $W'$ is the $W_R$ gauge boson associated with the left-right symmetric models,\textsuperscript{16,17} which seek to provide a spontaneous origin for parity violation in weak interactions. $W_L$ and $W_R$ may mix due to spontaneous

\textsuperscript{a}The most recently published value of $f_R = 1.71335(15)$\textsuperscript{14} used $f^n = 1.6886$, and did not include the corrections by Marciano and Sirlin.\textsuperscript{12} Applying the Towner and Hardy prescription for splitting the radiative corrections\textsuperscript{13} increases the uncertainty in $f_R$ slightly, to reproduce Eq. (18) in Ref. 12.
symmetry breaking. The physical mass eigenstates are denoted as

\[ W_1 = W_L \cos \zeta + W_R \sin \zeta, \quad \text{and} \quad W_2 = -W_L \sin \zeta + W_R \cos \zeta, \]

(6)

where \( W_1 \) is the familiar \( W \) boson, and \( \zeta \) is the mixing angle between the two mass eigenstates. In the MLRS model, there are only three free parameters, the mass ratio \( \delta = m_1^2/m_2^2 \), \( \zeta \), and \( \lambda' \), while \( m_1, m_2 \) denote the masses of \( W_1, W_2 \), respectively.

3. Experimental Data

We present results of least-squares fits, using recent experimental data as well as target uncertainties for planned experiments on neutron decay. The principle of non-linear \( \chi^2 \) minimization is discussed, e.g., in Ref. 19. Figures 1–6 show the present and expected future limits from neutron decay, respectively. The confidence regions in 2 dimensions, or confidence intervals in 1 dimension, are defined as in Ref. 20.

We first analyze the presently available data on neutron decay. As input for our study we used: \( a = -0.103(4) \) and \( B = 0.9807(30) \) (both from Ref. 2), as well as \( F_{t^0 \rightarrow 0^+} = 3071.81(83) \) s as the average value for SAF decays (from Ref. 21). We used our own averages for \( \tau_n \) and \( A \), as follows.

The most recent result of Serebrov et al.\(^{22}\), \( \tau_n = 878.5(8) \) s, is not included in the PDG 2008 average. We prefer not to exclude this measurement without being convinced that it is wrong, and include it in our average to obtain \( \tau_n = (881.8 \pm 1.4) \) s. Our average includes a scale factor of 2.5, as we obtain \( \chi^2 = 45 \) for 7 degrees of freedom. The statistical probability for such a high \( \chi^2 \) is \( 1.5 \times 10^{-7} \). If our average were the true value of the neutron lifetime \( \tau_n \), both the result of Serebrov et al. and the PDG average would be wrong at the \( 2 - 3 \sigma \) level.

Two beta asymmetry experiments have completed their analyses since the PDG 2008 review. The UCNA collaboration has published \( A = -0.1138(46)(21) \).\(^{23}\) The last PERKEO II run has yielded a preliminary value of \( A = -0.1198(5) \).\(^{24}\) We include these new results in our average, and obtain \( A = -0.1186(9) \), which includes a scale factor of 2.3 based on \( \chi^2 = 28 \) for 5 degrees of freedom. The statistical probability for such a high \( \chi^2 \) is \( 5 \times 10^{-5} \), not much better than in the case of \( \tau_n \).

Hence, we find that the relative errors are about 4% in \( a \), 1% in \( A \), and 0.3% in \( B \). We will not use \( C = -0.2377(26) \)\(^{2} \) in the analysis of present results, since the PERKEO II results for \( B \) and \( C \) are derived from the same data set.\(^{2}\)

\(^2\)We note that a recent experiment\(^{25}\) measured the neutron spin–electron spin correlation \( N \) in neutron decay. \( N \) is the coefficient of an additional term \((+N s_n s_e)\), which appears in Eq. (4) if the electron spin is detected. The \( N \) parameter depends linearly on \( S, T \) couplings. We disregard the result, as it lacks the precision to have an impact on our analysis.
About a dozen new instruments are currently planned or under construction. For recent reviews see Refs. 3, 26. We will discuss a future scenario which assumes the following improvements in precision in a couple of years.

- $\Delta a/a = 0.1\%$: Measurements of the neutrino-electron correlation coefficient $a$ with the aSPECT$^{27,28}$, aCORN$^{29}$, Nab$^{30}$, and PERC experiments are projected or underway.
- $\Delta b = 3 \times 10^{-3}$: The first ever measurement of the Fierz interference term $b$ in neutron decay is planned by the Nab collaboration$^{30}$. In addition, the UCNb$^{31}$ and PERC collaborations are exploring measurements of $b$.
- $\Delta A/A = 3 \times 10^{-4}$: Measurements of the beta asymmetry parameter $A$ with PERKEO III$^{32}$, UCNA$^{33}$, abBA$^{34}$, and PERC$^{35}$ are either planned or underway.
- $\Delta C/C = 0\%$: The abBA$^{34}$ and UCNB$^{36}$ collaborations intend to measure the neutrino asymmetry parameter $C$. PERC is also exploring a measurement of $C$.
- $\Delta \nu_n = 0.8\text{ s}$: Measurements of the neutron lifetime $\nu_n$ with beam experiments$^{39,40}$, material bottles$^{41,42}$, and magnetic storage experiments$^{43-47}$ are planned or underway.

Our assumptions about future uncertainties for $a, A, B, C$ reflect the goal accuracies in the proposals, while for $\nu_n$ we only assume the present discrepancy to be resolved. Our assumed $\Delta \nu_n$ corresponds to the best uncertainty claimed in a previous experiment.$^{22}$

Our scenario “future limits” assumes that the SM holds and connects the different observables. We used $a = -0.10588$, $b = 0$, $B = 0.98728$, $C = -0.23875$, and $\nu_n = 882.2\text{ s}$ derived from $A = -0.1186$ and $F^{0^+\to0^+} = 3071.81\text{ s}$. These values agree with the present measurements within $2\sigma$.

4. Searches for physics beyond the Standard Model

Our fits are not conclusive if all 8 coupling constants $L_j$ and $R_j$, for $j = V, A, S, T$, are treated as free parameters. We are more interested in restricted analyses presented below. Experiments quote $a, A, B, C$ after applying (small) theoretical corrections for recoil and radiative effects; we neglect any dependence on non-SM physics in these corrections.

4.1. Left-handed $S, T$ currents

Addition of LH $S, T$ currents to the SM leaves $L_V^\nu = 1, L_A = \lambda, L_S, L_T$ as the non-vanishing parameters. Non-zero Fierz interference terms $b$ and $b_\nu$ appear in this model; the direct determination of $b$ through beta spectrum shape measurement is the most sensitive way to constrain the size of the non-SM currents. The experiments discussed above measure the correlation coefficients from the electron spectra and asymmetries, respectively. The published results on $a, A, B, C$ assume $b = b_\nu = $
0. To make use of measured values of \( a \) in a scenario involving a non-zero value for the Fierz term \( b \), we rewrite Eq. (4) for unpolarized neutron decay:

\[
d^3\Gamma \propto \left(1 + a \frac{\mathbf{P}_e \cdot \mathbf{P}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e}\right) \left(1 + \frac{a}{1 + bm_e \langle E_e^{-1}\rangle} \frac{\mathbf{P}_e \cdot \mathbf{P}_\nu}{E_e E_\nu}\right).
\]

The value quoted for \( a \) is then taken as a measurement of \( \bar{a} \), defined through

\[
\bar{a} = \frac{a}{1 + bm_e \langle E_e^{-1}\rangle},
\]

where \( \langle \cdot \rangle \) denotes the weighted average over the part of the beta spectrum observed in the particular experiment. This procedure has been also applied in Refs. 7, 21, 48. Reported experimental values of \( A, B, \) and \( C \) are interpreted as measurements of

\[
\bar{A} = \frac{A}{1 + bm_e \langle E_e^{-1}\rangle}, \quad \bar{B} = \frac{B_0 + b_v m_e \langle E_e^{-1}\rangle}{1 + bm_e \langle E_e^{-1}\rangle}, \quad \bar{C} = -\frac{x_C (A + B_0) - x'_C b_v m_e}{1 + bm_e \langle E_e^{-1}\rangle},
\]

where \( x_C = 0.27484 \) and \( x'_C = 0.1978 \) are kinematical factors, assuming integration over all electrons.\(^\text{e}\) This procedure is not perfect. The presence of a Fierz term \( b \) might influence systematic uncertainties. For example, the background estimate in PERKEO II assumes the SM dependence of the measured count rate asymmetry on \( E_e \). The term \( m_e \langle E_e^{-1}\rangle \) depends on the part of the electron spectrum used in each experiment. We have used the following values in our study: \( m_e \langle E_e^{-1}\rangle = 0.5393 \) for \( \bar{A} \), dominated by PERKEO II\(^\text{19} \), \( m_e \langle E_e^{-1}\rangle = 0.6108 \) for \( \bar{B} \), dominated by Serebrov \textit{et al.}\(^\text{50,51} \) and PERKEO II\(^\text{12} \), and the mean value \( m_e \langle E_e^{-1}\rangle = 0.6556 \), taken over the whole beta spectrum, for \( \bar{a} \) and \( \bar{C} \).

Figure 1 shows the current limits from neutron decay. Free parameters \( \lambda, L_S/L_V \), and \( L_T/L_A \) were fitted to the observables \( a, b, A, B, \) and \( C \). Unlike Secs. 4.2 and 4.3, here we omit the neutron lifetime \( \tau_n \), since otherwise we would have to determine the possible influence of the Fierz term in Fermi decays, \( b_F \), on the \( F^0 \to \pi^0 \) values. A combined analysis of neutron and SAF beta decays will be published soon.

Figure 2 presents the impact of projected measurements in our future scenario. For comparison, a recent combined analysis of nuclear and neutron physics data (see Ref. 48) finds \( L_S/L_V = 0.0013(13) \) and \( L_T/L_A = 0.0036(33) \), with 1 \( \sigma \) statistical errors. It includes the determination of the Fierz term \( b_F \) from superallowed beta decays, updated in Ref. 21, which sets a limit on \( L_S \) that is hard to improve with neutron decay alone. As in the recent survey of Severijns \textit{et al.}\(^\text{38} \) we do not include the limits on tensor couplings obtained\(^\text{53} \) from a measurement of the Fierz term \( b_{GT} \) in the forbidden Gamow-Teller decay of \( ^{22}\text{Na} \), due to its large log \( ft(=7.5) \) value. Neutron decay has the potential to improve the best remaining nuclear limit on \( L_T \) as provided by a measurement of the longitudinal polarization of positrons emitted

\(^\text{e}\) Note that we define \( C \) with the opposite sign compared to Ref. 7 to adhere to the convention that a positive asymmetry indicates that more particles are emitted in the direction of spin.
Fig. 1. Present limits from neutron decay (only $a$, $A$, and $B$). The SM values are at the origin of the plot. Analogous limits extracted from muon decays are indicated. Other limits are discussed in the text. All bars correspond to single parameter limits.

Fig. 2. Future limits from neutron decay, assuming improved and independent measurements of $a$, $b$, $A$, $B$, and $C$. Analogous limits extracted from muon decays are not indicated since they exceed the scale of the plot.

by polarized $^{107}$In nuclei ($\log ft = 5.6$).\textsuperscript{54,55} Limits from neutron decay are independent of nuclear structure. The stringent limit on $L_T$ in Ref. 48 stems mainly from measurements of $\tau_n$ and $B$ in neutron decay. New neutron decay experiments alone could lead to an accuracy of $\Delta(L_T/L_A) = 0.0023$, competitive with the combined analysis of neutron and nuclear physics data,\textsuperscript{48} and $\Delta(L_S/L_V) = 0.0083$, both at the 1$\sigma$ confidence level. Supersymmetric (SUSY) contributions to the SM can be discovered at this level of precision, as discussed in Ref. 56.

4.2. Right-handed $S$, $T$ currents

Adding the RH $S$ and $T$ currents to the SM yields $L_V = 1$, $L_A = \lambda$, $R_S$, and $R_T$ as the remaining non-zero parameters. The observables depend only quadratically on $R_S$ and $R_T$, i.e., the possible limits are less sensitive than those obtained for LH $S$, $T$ currents. Figure 3 shows the present limits from neutron decay. A similar analysis of this scenario was recently published in Ref. 57.

Free parameters $\lambda$, $R_S/L_V$, and $R_T/L_A$ were fitted to the observables $a$, $A$, $B$, $C$, and $\tau_n$. Additionally, to take into account uncertainties in the $\mathcal{F}t$ values and in radiative corrections, we fitted $\mathcal{F}_{\beta^0\to0^+}$ and $\mathcal{F}_{\beta^0\to0^+}$ to ‘data points’ 3071.81(83) s and 1.71385(34), respectively.

The Fierz interference terms $b$ and $b_\nu$ are zero in this model. Hence, measurements of $b$ (or $b_\nu$ in SAF beta decays) can invalidate the model, but not determine its parameters. Figure 4 shows the projected improvement in our future scenario. The grey ellipse stems from a recent survey of the state of the art in nuclear and neutron beta decays.\textsuperscript{48} New neutron decay experiments alone could considerably improve the limits on RH $S$ and $T$ currents, to $\Delta(R_S/L_V) = 0.0275$ and $\Delta(R_T/L_A) = 0.0173$. 
4.3. Right-handed W bosons

Adding RH $V$ and $A$ currents to the SM leaves $\delta$, $\zeta$, and $\lambda'$ as the non-vanishing parameters. Figure 5 shows the current limits from neutron decay. The fit parameters $\delta$, $\zeta$, $\lambda'$, $\mathcal{F}_{\nu^0 \to \nu^+}$, and $f_R$, were fitted to the observables discussed in Sec. 4.2.
Measurements of the polarized observables, i.e., the electron, neutrino, or proton asymmetries, lead to important restrictions, but are at present inferior to limits on the mixing angle $\zeta$ from $\mu$ decays. They are also inferior to limits on the mass $m_2$ from direct searches for extra $W$ bosons. Comparison of beta decay limits with high energy data is possible in our minimal MLRS model. For example, the comparison with $W'$ searches at Tevatron assumes a RH CKM matrix identical to the LH one and identical couplings. In more general scenarios the limits are complementary to each other since they probe different combinations of the RH parameters.

Figure 6 shows the improvement from planned measurements in our future scenario. The $\chi^2$ minimization converges to a single minimum at mass $m_2 = \infty$; with $\chi^2 = 0$, i.e., the mixing angle $\zeta$ is not defined at this minimum. The 68.3% C.L. is $\delta < 0.0196$ which yields $m_2 > 574$ GeV. In the mass range $>1$ TeV, not excluded by collider experiments, we would improve the limit on $\zeta$ from $\mu$ decays slightly.

We emphasize that all presented RH coupling limits ($R_S$, $R_T$, $\delta$, and $\zeta$) assume that the RH (Majorana) neutrinos are light ($m \ll 1$ MeV). The RH interactions are kinematically weakened by the masses of the predominantly RH neutrinos, if these masses are not much smaller than the electron endpoint energy in neutron decay (782 keV). If both the $W$ boson and neutrino left-right mixing angles were zero, and if the RH neutrino masses were above 782 keV, RH corrections to neutron decay observables would be completely absent.

In summary, new physics may be within reach of precision measurements in neutron beta decay in the near future.

5. Limits from other measurements

5.1. Constraints from muon and pion decays

Muon decay provides arguably the theoretically cleanest limits on non-$\left(V-A\right)$ weak interaction couplings. Muon decay involves operators that are different from the ones encountered in neutron, and generally hadronic, decays. However, in certain models (e.g., the SUSY extensions discussed in Ref. 56, or in the MLRS), the muon and neutron decay derived limits become comparable. In order to illustrate the relative sensitivities of the muon and neutron sectors, we have attempted to translate the muon limits from Refs. 2 and 63 into corresponding neutron observables such as $L_S/L_V$, $L_T/L_A$, and $R_T/R_A$. In doing so we neglected possible differences in SUSY contributions to muon and quark decays, making the comparison merely illustrative. These limits are plotted in Figs. 1–6, as appropriate, showing that neutron decay measurements at their current and projected future sensitivity are not only complementary, but also competitive to the muon sector.

Limits similar to the ones discussed in Sec. 5 can be extracted from pion decays (added complexity of heavier meson decays limits their sensitivity). The presence of a tensor interaction would manifest itself in both the Fierz interference term in beta decays (e.g., of the neutron) and in a non-zero value of the tensor form factor for the pion. The latter was hinted at for well over a decade, but was recently
found to be constrained to $-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}$ with 90% C.L. While values for $b$ in neutron decay and for the pion $F_T$ are not directly comparable, in certain simple scenarios they would be of the same order. Thus, finding a non-zero value for $b$ in neutron decay at the level of $O(10^{-3})$ would be extremely interesting. Similarly, the $\pi \rightarrow e \nu$ decay ($\pi e_2$) offers a very sensitive means to study non-$(V-A)$ weak couplings, primarily through a pseudoscalar term in the amplitude. Alternatively, $\pi e_2$ decay provides the most sensitive test of lepton universality. Thus, new measurements in neutron decay would complement the results of precision experiments in the pion sector, such as PIBETA and PEN.

5.2. RH coupling constraints from $0\nu$ double $\beta$ decay, and $m_\nu$

The most natural mechanism of neutrinoless ($0\nu$) double beta decay is through virtual electron neutrino exchange between the two neutron decay vertices. The LH and RH $\nu_e$ may mix with mass eigenstate Majorana neutrinos $N_i$:

$$\nu_{eL} = \sum_{i=1}^{6} U_{ei} \frac{1 - \gamma_5}{2} N_i,$$
$$\nu_{eR} = \sum_{i=1}^{6} V_{ei} \frac{1 + \gamma_5}{2} N_i,$$  \hspace{1cm} (10)

where $U_{ei}$ and $V_{ei}$ denote elements of the LH and RH mixing matrices, respectively.

The neutrinoless double beta decay amplitude with the virtual neutrino propagator has two parts. If the SM LH $V-A$ coupling combines with LH coupling terms (LL interference), the amplitude contribution is proportional to the Majorana neutrino masses (weighted with the $U_{ei}^2$ factors). Since from neutrino oscillations we have rather small lower limits for these masses ($40\text{ meV}$ for the heaviest LH neutrino), we get only weak constraints for the non-SM LH couplings. On the other hand, if the SM LH $V-A$ coupling combines with RH non-SM terms (LR interference), the amplitude is proportional to the virtual neutrino momentum (instead of the neutrino mass); since the momentum can be quite large we get constraints for the RH non-SM couplings. The latter part of the $0\nu$ double beta decay amplitude is proportional to the effective RH couplings $\tilde{R}_j = R_j \varepsilon$, for $j = V, A, S, T$, where:

$$\varepsilon = \sum_{i=1}^{6} (\text{light}) U_{ei} V_{ei},$$ \hspace{1cm} (11)

According to Ref. 69 there are three different scenarios:

D: all neutrinos are light Dirac particles $\Rightarrow$ no constraints for non-SM couplings because $\varepsilon = 0$.

M-I: all neutrinos are light ($< 1\text{ MeV}$) Majorana particles $\Rightarrow$ no constraints for non-SM couplings, because $\varepsilon = 0$ from orthogonality condition.

M-II: both light ($< \text{MeV}$) and heavy ($> \text{GeV}$) Majorana neutrinos exist $\Rightarrow$ constraints for non-SM couplings: $\varepsilon \neq 0$, because heavy neutrinos are missing from the sum; $\varepsilon$ is on the order of the unknown, likely small, mixing angle $\theta_{LR}$ between LH and RH neutrinos.
In the M-II scenario there are stringent constraints for the effective RH $V, A, S, T$ couplings: $|\tilde{R}_j| < 10^{-8}$. These effective couplings are proportional to $\varepsilon \sim \theta_{LR}$. Since $\varepsilon$ depends on specific neutrino mixing models, it is not possible to give model independent limits for the $R_j$ couplings based on $0\nu$ double $\beta$ decay data. We have already mentioned in Sec. 4.3 that for the heavy RH (Majorana) neutrinos the RH observables in neutron decay are kinematically weakened or for special cases completely suppressed.

Assuming 1 TeV effective RH neutrino mass scale within M-II, one obtains $|\zeta| < 4.7 \times 10^{-3}$ and $m_2 > 1.1 \text{ TeV}$. For a larger RH neutrino mass scale these constraints become weaker.

In Ref. 73 it is argued that neutrinoless double beta decay occurs in nature. If further experiments confirm this observation, one can be sure that the neutrinos are Majorana particles.

The RH couplings can contribute to neutrino mass through loop effects, leading to constraints on the RH coupling constants from neutrino mass limits. Using the absolute neutrino mass limit $m(\nu_e) < 2.2 \text{ eV}$ from the Troitsk and Mainz tritium decay experiments, one obtains the 1 $\sigma$ limits: $|R_S| < 0.01$, $|R_T| < 0.1$, and $|R_V - R_A| < 0.1$. With the $m(\nu_e) < 0.22 \text{ eV}$ model dependent limit from cosmology (similar neutrino mass limit is expected from the KATRIN experiment), the above coupling constant limits become 10 times more restrictive. An intermediate neutrino mass upper limit of order $0.5 - 0.6 \text{ eV}$ comes from neutrinoless double beta decay and from other cosmology analysis.

Acknowledgements

This work was supported by the German Federal Ministry of Education and Research under Contract No. 06MZ989I, 06MZ170, the European Commission under Contract No. 506065, the Universität Mainz, and the National Science Foundation Grants PHY-0653356, -0855610, and -0970013.

References

1. A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. D 70, p. 093006 (2004).
2. C. Amsler et al., Phys. Lett. B 667, p. 1 (2008), and 2009 partial update for the 2010 edition (URL: http://pdg.lbl.gov).
3. H. Abele, Prog. Part. Nucl. Phys. 60, p. 1 (2008).
4. J. S. Nico and W. M. Snow, Annu. Rev. Nucl. Part. Sci. 55, p. 60 (2005).
5. D. Dubbers, Prog. Part. Nucl. Phys. 26, p. 173 (1991).
6. P. Herczeg, Prog. Part. Nucl. Phys. 46, p. 413 (2001).
7. F. Glück, J. Joó and J. Last, Nucl. Phys. A 593, p. 125 (1995).
8. T. D. Lee and C. N. Yang, Phys. Rev. 104, p. 254 (1956).
9. J. D. Jackson, S. B. Treiman and H. W. Wyld, Phys. Rev. 106, p. 517 (1957).
10. F. Glück, Phys. Lett. B 376, p. 25 (1996).
11. D. H. Wilkinson, Nucl. Phys. A 377, p. 474 (1982).
12. W. J. Marciano and A. Sirlin, Phys. Rev. Lett. 96, p. 032002 (2006).
13. I. S. Towner and J. C. Hardy, Phys. Rev. C 77, p. 025501 (2008).
14. H. Abele et al., Eur. Phys. J. C 33, p. 1 (2004).
15. A. Sirlin, Phys. Rev. 164, p. 1767 (1967).
16. J. Pati and A. Salam, Phys. Rev. D 10, p. 275 (1974).
17. R. Mohapatra and J. Pati, Phys. Rev. D 11, p. 566 (1975).
18. M. A. Bég, Phys. Rev. Lett. 38, p. 1252 (1977).
19. W. T. Eadie et al., Statistical Methods in Experimental Physics (North-Holland Publishing Co., 1971).
20. W. H. Press et al., Numerical Recipes: The Art of Scientific Computing, 3rd edn. (Cambridge University Press, 2007). Sec. 15.6.
59. R. P. MacDonald et al., Phys. Rev. D 78, p. 032010 (2008).
60. M. Czakon, J. Gluza and M. Zralek, Phys. Lett. B 458, p. 355 (1999).
61. V. M. Abazov et al., Phys. Rev. Lett. 100, p. 031804 (2008).
62. N. Severijns et al., Nucl. Phys. A 629, p. 429c (1998).
63. C. A. Gagliardi, R. Tribble and N. J. Williams, Phys. Rev. D 72, p. 073002 (2005).
64. V. Cirigliano, private communication (2009).
65. M. Bychkov et al., Phys. Rev. Lett. 103, p. 051802 (2009).
66. P. Herczeg, private communication (2004).
67. http://pibeta.phys.virginia.edu/.
68. http://pen.phys.virginia.edu/.
69. M. Doi, T. Kotani and E. Takasugi, Prog. Theor. Phys. Suppl. 83, p. 1 (1985).
70. H. Päs et al., Phys. Lett. B 453, p. 194 (1999).
71. R. Mohapatra and A. Y. Smirnov, Annu. Rev. Nucl. Part. Sci. 56, p. 569 (2006).
72. J. Hirsch, H. V. Klapdor-Kleingrothaus and O. Panella, Phys. Lett. B 374, p. 7 (1996).
73. H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Modern Phys. Lett. A 21, p. 1547 (2006).
74. T. M. Ito and G. Prezeau, Phys. Rev. Lett. 94, p. 161802 (2005).
75. V. M. Lobashev et al., Nucl. Phys. A 719, p. C153 (2003).
76. C. Kraus et al., Eur. Phys. J. C 40, p. 447 (2005).
77. E. Komatsu et al., Astrophys. J. Suppl. Ser. 180, p. 330 (2009).
78. J. Angrik et al., FZKA Scientific Report 7090 (2004), http://bibliothek.fzk.de/zb/berichte/FZKA7090.pdf.
79. M. Tegmark et al., Phys. Rev. D 69, p. 103501 (2004).