The Nature of Neutrinos in Muon Decay and Physics Beyond the Standard Model

Peter Herzeg

The main decay mode of the $\mu^+ \rightarrow e^+ + n + n'$ is the decay into a positron and two neutrinos: $\mu^+ \rightarrow e^+ + n + n'$. In the following we shall refer to these decays as “muon decay”. Studies of muon decay played an important role in the developments that led to the $V - A$ theory of the weak interaction, and ultimately to the formulation of the electroweak component of the Standard Model (SM). Today the main motivation for further investigations of muon decay is to search for deviations from the predictions of the SM. Although there is no definitive experimental evidence at present for physics beyond the SM, for many theoretical reasons, and especially because of the large number of undetermined parameters in the model, the existence of new physics is expected.

In the SM the interaction that mediates muon decay, as well as the nature of the neutrinos $n$ and $n'$, is prescribed. In extensions of the SM new interactions may contribute to the decay mode allowed in the SM, and there may be interactions that give rise to new decay modes of the type $\mu^+ \rightarrow e^+ + n + n'$. In the presence of new interactions the neutrinos are generally massive, and the weak eigenstates and the mass eigenstates of the neutrinos generally do not coincide.

Experiments, such as the KARMEN [2] and LSND [3] experiments, that search for $\nu_e$'s originating from $\mu^-$-decay are sensitive not only to oscillations of neutrinos into $\nu_e$, but also to decays of the type $\mu^+ \rightarrow e^+ + \nu_e + n + n'$, where $n_1$ is a neutrino. The decays $\mu^+ \rightarrow e^+ + \nu_e + n_1$ are forbidden in the SM (they violate the conservation of lepton family numbers, and some of them also the conservation of the total lepton number). In this article we shall review these decays in some extensions of the SM. A question of importance is at what level of sensitivity searches for $\nu_e$-appearance start to provide new information on the $\mu^+ \rightarrow e^+ + \nu_e + n_1$ branching ratios. The results of the LSND experiment brought added interest in this question. Could some of these branching ratios be large enough to account for the observed excess of $e^+$-events?

In any model, the decays $\mu^+ \rightarrow e^+ + \nu_e + n_1$ (and other two-neutrino muon decay modes) are constrained by muon decay data obtained without observing the neutrinos and some also by experimental information on inverse muon decay. In the section below we describe these constraints, and also the experimental information on $\mu^- \rightarrow e^- + \bar{\nu}_e + n_1$ from searches for $\nu_e$-appearance. In the subsequent section we discuss the decays $\mu^- \rightarrow e^- + \bar{\nu}_e + n_1$ in two important extensions of the SM: a class of left-right symmetric models and in the minimal supersymmetric standard model with R-parity violation. The last section is a summary of the main points in the article.

---

a) We discuss for definiteness $\mu^- \rightarrow e^-$. The general conclusions for $\mu^+ \rightarrow e^+$ are the same.

b) Unless otherwise stated, we use here the term “neutrino” for both neutrinos and antineutrinos. Thus, both $\nu$ and $\bar{\nu}$ can be a neutrino or an antineutrino (or a Majorana neutrino). In general $\nu$ can have decay modes into several different pairs (n, n'), where n and n' are not mass eigenstates, then the decay for a given n and n' is into final states $e^+ + \nu_e + n'$, where $n_1$ and $n_2$ are the various mass eigenstates contained in n and n'.

c) The electroweak component of the SM will be understood here to be the minimal version of the $SU(2) \times U(1)$ gauge theory, containing three families of leptons and quarks, one Higgs doublet, and only left-handed neutrinos.

d) We discuss decays $\mu^+ \rightarrow e^+ + \nu_e + n_1$ as the only nonstandard types that can be studied experimentally at the available facilities, since the muons decay predominantly at rest, and therefore the neutrinos are not energetic enough to produce $\mu^+$ or $\nu_e$.

---

Muon Decay in the Standard Model: Comparison with Experiment

In the SM the neutrinos $n_1$ and $n_2$ in muon decay are $n_1 = \nu_e$ and $n_2 = \bar{\nu}_e$, where $\nu_e = (1 - \gamma_e)l/2$ ($l = e, \mu$) are massless left-handed neutrinos (the $\nu_e$ are massless four-component spinors), which accompany the $e^+$ and the $\mu^-$ in the decays $W^+ \rightarrow e^+ + \nu_e$ and $W^- \rightarrow \mu^- + \bar{\nu}_e$. The latter decays result from the interaction

$$\mathcal{L} = \frac{g}{2\sqrt{2}} \left[ (\bar{\nu}_e) \gamma \mu W^+ + (\bar{\nu}_e) \gamma \mu W^- \right] + \text{H.c.},$$

(1)

where the constant $g$ is the gauge coupling constant associated with the $SU(2)_L$ factor of the SM gauge group. The structure of the interaction (1) is $V - A$, that is, the currents involved are given by the difference of the vector current $\gamma \mu$ and the axial-vector current $\gamma \gamma \mu$. The interaction (1) generates the decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_e$ through the exchange of a $W^+$, as shown in Figure 1. The effective interaction describing the process in Figure 1 is given by

$$H_{\text{SM}} = \frac{g^2}{8m_W^2} \left[ (\bar{\nu}_e) \gamma \mu W^+ + (\bar{\nu}_e) \gamma \mu W^- \right] + \text{H.c.},$$

(2)

where $m_W$ is the mass of the $W$ ($m_W = 80.33 \pm 0.15$ GeV). What is the evidence regarding the description of muon decay in terms of the interaction (2)?

The presence of the $W^+$ exchange contribution is certain: the $W^+$ boson has been seen and studied, and its decays into $e^- + \nu_e$ and $\mu^- + \bar{\nu}_e$ have been detected. A question of interest, which we shall consider now, is the fraction of the total muon-decay rate that can be attributed to this contribution.

The total muon-decay rate (the inverse of the muon lifetime) is given by

$$\Gamma_{\mu\nu} = \frac{G_F^2 m_{\mu}^5}{192 \pi^3}.$$

(3)

In Equation (3) $G_F$ is the Fermi constant. Its value is $G_F = 1.16639(2) \times 10^{-5}$ GeV$^{-2}$/[4] deduced from measurements of the muon lifetime. In the absence of new contributions to muon decay, $G_F$ is given by $G_F = \sqrt{2}g/2m_W^2$. The constant $\sqrt{2}g/2m_W^2$ can be calculated using the experimental values of $g$ and $m_W$. One obtains

$$\sqrt{2}g/2m_W^2 = 0.99 \pm 0.04 G_F.$$

(4)

Equation (4) implies that the observed muon-decay rate can be accounted for by the SM contribution. It also indicates that the SM contribution is the dominant one, unless there is a cancellation in the rate between the SM contribution and some new contributions.

Further information on the interactions involved in muon decay can be obtained from measurements on the positron (energy spectrum, polarizations, and angular distributions) and from the inverse muon decay processes $e^- \rightarrow e^- + \nu_e + \bar{\nu}_e$, where $\nu_e$ is a neutrino, and $\bar{\nu}_e$ is the neutrino emitted in the dominant $\pi^- \rightarrow \mu^- + \bar{\nu}_e$ decay.

If one assumes conservation of lepton family numbers, the only allowed two-neutrino decay mode of the $\mu^-$ is $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e$, where $\nu_e$ and $\bar{\nu}_e$ are in general Dirac neutrinos. The decay of the $\pi^-$ must proceed in this case as $\pi^- \rightarrow \mu^- + \nu_e$ and inverse muon decay as $\nu_e + e^- \rightarrow \mu^- + \bar{\nu}_e$. In such a framework there are ten possible independent four-fermion interactions that can contribute to $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e$. One of these is of the form (2) with $g^2/8m_W^2$ replaced by a general coupling constant $G_{\text{SM}}/\sqrt{2}$, where by the subscripts we have

---

Figure 1.
indicated that the neutrinos in both currents are left-handed. One has \( G^2_{\nu L} = \frac{3 \sqrt{2} \sin \theta_{\nu}}{8 \sin \theta_{\nu}^2} + \ldots \), where the dots stand for the coupling constants of other possible \( V - A \) interactions. The Fermi constant is given now by \( G^2_F = G^2_{\nu L}^2 + |V|^2 \), where \( |V|^2 \) represents the contributions of interactions with structures other than \( V - A \). In this framework one of the conclusions of a combined analysis [5] of muon-decay data (with the neutrinos unobserved) and the inverse muon-decay cross section is that

\[
G_{\nu L}^2 > 0.925 \, G_F^2. \tag{5}
\]

This means that not more than about 10% of the muon-decay rate can originate from interactions other than \( V - A \). In addition, upper bounds have been set on the coupling constants of other possible muon-decay interactions. The best of these is \( -3 < 10^{-3} G_{\nu L}^2 \) [4].

The analysis mentioned above is not sufficiently general, since the assumption of lepton family number conservation is not justified: there is no reason why possible new contributions to muon decay should respect these conservation laws. A study of muon decay and inverse muon decay in the framework of a general interaction that allows for lepton family number violation and total lepton number violation has been carried out in Reference [6]. The conclusion is that the bounds obtained in the lepton family number conserving case for \( G_{\nu L}^2 \), \( G_{\nu R}^2 \), etc. apply in the general case for sums of the squares of certain combinations of the coupling constants. The sum which replace \( G_{\nu L}^2 \), \( G_{\nu R}^2 \), etc., contain \( G_{\nu L}^2 \), \( G_{\nu R}^2 \), etc., respectively.

The results of the general analysis imply [6] that at least one of the \( \mu^- \) decay modes which involve the neutrino state \( \nu^+_l \) (the neutrino state produced in the dominant \( \pi^- \rightarrow \mu^- + \nu^+_l \) decay) dominates the rate. We note yet that there is some experimental evidence (from pion decays) that \( \nu^+_l \) is not the neutrino state which accompanies the positron on the electron in nuclear beta decay. Some experimental information is available also on the second neutrino in muon decay. This comes from an experiment at LAMPF [7], in which the neutrinos from muon decay were detected for the first time. The detector when filled with heavy water was sensitive to neutrinos \( \nu^+_l \) capable of producing electrons in the reaction \( \nu^+_l + D \rightarrow p + p + e^- \). The good agreement of the measured \( \nu^+_l \) branching ratio and the calculated one in the SM indicates that the total muon decay rate contains a substantial contribution from muon decay into a final state, in which one of the neutrinos is the one accompanying the positron in nuclear decay.

The evidence described above shows that the predictions of the SM for muon decay are consistent with experiment. Nevertheless, the data still leave room for relatively large (of the order of 10 percent) contributions from new physics.

Among the possible new \( \mu^- \) decay modes, the class characterized by the presence of \( \nu^+_l \) among the decay products can be identified by detecting the \( \nu^+_l \)’s through the inverse beta-decay reaction \( \nu^+_l + p \rightarrow p + e^- \). Such experiments search for both \( \nu^+_l \) (where \( \nu^+_l \) is a neutrino), and for \( \nu^+_l \) appearance due to neutrino oscillations. A search for \( \nu^+_l \) originating from muon decay was carried out already in the experiment of Reference [7], where the detector was filled alternately with H2O and D2O. The experiment set an upper limit \( B_{\nu^+_l} < 0.098 \) (90% c.l.) on the sum of the \( \mu^- \rightarrow e^- + \nu^+_l + \bar{\nu}_e \) branching ratios

\[
B_{\nu^+_l} = \frac{2}{\mathcal{F}} \sum_{\nu_i} B(\mu^- \rightarrow e^- + \nu^+_l + \bar{\nu}_e) + \frac{\mathcal{F}}{\mathcal{F}} \sum_{\nu_i} B(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu^+_l) \rightarrow all. \tag{6}
\]

This limit was gradually improved by subsequent experiments [8]. The best present limit is [9]

\[
B_{\nu^+_l} < 2.5 \times 10^{-3} \quad (90\% \, c.l.). \tag{7}
\]

obtained in an experiment at the ISIS facility (Rutherford-Appleton Laboratory, United Kingdom) by the KARMEN collaboration. It should be noticed that the limit (7), as well as all the previous limits, was derived under the assumption that the energy spectrum of the \( \bar{\nu}_e \)’s is the same as the energy spectrum of the \( \nu^+_l \)’s in the SM muon decay. Some other possibilities are under study.

The probability \( P_{\nu^+_l} \) of \( \nu^+_l \) appearance found in the LSND experiment [3] is

\[
P_{\nu^+_l} = (0.31 \pm 0.13) \times 10^{-2}. \tag{8}
\]

If the excess of events found in the experiment is interpreted as due to \( \mu^- \rightarrow e^- + \nu^+_l + \bar{\nu}_e \) decays, \( P_{\nu^+_l} \) is the branching ratio \( B_{\nu^+_l} \) [Equation (6)]. It follows that

\[
10^{-3} < B_{\nu^+_l} < 5 \times 10^{-3} \quad (90\% \, c.l.) \tag{9}
\]

This range is not inconsistent with the upper limit (7). The interpretations of the excess \( e^- \)-events in the SM experiment in terms of \( \mu^- \rightarrow e^- + \nu^+_l + \bar{\nu}_e \) decays and in terms of neutrino oscillations are distinguishable since, unlike the branching ratio (6), the oscillation probability depends on the distance between the neutrino source and the detector and also on the neutrino energy.

The Decays \( \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_1 \) in Extensions of the Standard Model.

The decays \( \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_1 \) occur in many extensions of the SM [10–13]. They can be mediated at the tree level by new gauge bosons, nonstandard Higgs bosons, and by the supersymmetric partners of the leptons. Here we shall consider these decays in a class of left-right symmetric models and in the minimal super-symmetric standard model with R-parity violation.

Left-Right Symmetric Models. These models [14] are attractive extensions of the electroweak sector of the SM. They provide a framework for the understanding of parity violation in the weak interaction. The SM parity violation appears in an ad hoc manner, by arranging (following experiment) that the W-boson couples only to currents involving the left-handed components of the fermion fields. These couplings have a form analogous to those in Equation (1). The question of why nature appears to select fermions of only one handedness to participate in the weak interaction is in the context of the SM unanswered. In left-right symmetric models (LRS) parity violation appears in a new light. The gauge group of the simplest LRSM is \( SU(2)_L \times SU(2)_R \times U(1) \), which is larger than the gauge group of the SM by the \( SU(2)_R \) factor. The observed W-boson (called here \( W_R \)) is associated with \( SU(2)_R \), while the \( SU(2)_L \) group accommodates a second (hitherto undetected) charged gauge boson, the \( W_L \), which couples only to right-handed currents (i.e., contains the right-handed neutrinos as partners of the right-handed components of the fermion fields). The model requires the existence of right-handed neutrinos \( e^+_R = (\ell = e, \mu, \tau) \) which are the partners of the right-handed components of the charged lepton \( e^+_L \) in doublets of \( SU(2)_L \). Thus, the right-handed neutrinos are not sterile, but participate in the right-handed interactions. Also, the neutrinos are expected to have nonzero masses.

The general effect of the \( W_R \) can be illustrated on the example of muon decay. The exchange of the \( W_R \) gives a second contribution to \( \mu^- \rightarrow e^- + \nu^+_l + \bar{\nu}_e \) (see Figure 2), which is of the \( V - A \) form

\[\text{(1)}\]
In Equation (10) $\gamma_3$ is the coupling constant associated with SU(2)$_L$; the coupling constant associated with SU(2)$_R$ is denoted now by $g_3$; $m_{\nu_0}$ is the mass of the W. If $g_3 = g_1$, then in the limit when the masses of the W and $m_{\nu_0}$ are equal, the sum of the effective interactions (2) and (10) conserves parity. The observed parity violation arises through spontaneous symmetry breaking (the same mechanism which generates the mass of the W in the SM). This can make the W heavier than the W$\nu$. The left-handed interactions then dominate, but parity violation is no longer maximal, since the right-handed interactions also participate.

The strength of the right-handed interactions depends on the size of $m_{\nu_0}$. The present experimental lower bound on $m_{\nu_0}$ is at least 300 GeV, and in most versions of SU(2)$_L \times SU(2)_R \times U(1)$ models larger. This means that the right-handed interactions must be weaker than the usual weak interactions by at least an order of magnitude.

The Higgs sector of SU(2)$_L \times SU(2)_R \times U(1)$ models is richer than that of the SM, in part because the gauge symmetry, which has to be broken to electromagnetic gauge invariance only, is larger. An attractive choice for implementing the symmetry breaking is a Higgs sector that includes two triplets of Higgs bosons, $\Delta^+ \equiv \Delta_{+}^U, \Delta_{+}^D$ and $\Delta^- \equiv \Delta_{-}^U, \Delta_{-}^D$, which couple to the right-handed and the left-handed leptons, respectively. With this choice, and with some additional assumptions, the model predicts a seesaw relation of the form, $m_{\nu_{\mu}} \approx m_{\nu_{\mu}} m_{\psi_{\mu}}$, for the neutrino masses. This version of LRSM the right-handed neutrinos are heavy, with masses of the order of $m_{\psi_{\mu}}$.

In the above version of SU(2)$_L \times SU(2)_R \times U(1)$ models in addition to the usual muon-decay mode $\mu^- \to e^- + \nu_1 + \bar{\nu}_1$, the lepton family number violating decays $\mu^- \to e^- + \bar{\nu}_2 + \nu_1$ will be the dominant one, since it is the only one which survives in the absence of family mixing. The effective interaction responsible for this decay is given by

$$H_\Delta = \frac{G'}{\sqrt{2}} \left[ \bar{\mu} \gamma_1 (1 + \gamma_5) \nu_1 \right] \gamma_1 (1 - \gamma_5) \nu_1 + H.c.,$$

where $G' = -\sqrt{2} f_\Delta f_{\nu_1} f_{\nu_2} 2m_\mu^2 f_\psi f_{\nu_1} f_{\nu_2}$ and $f_{\nu_1}$ are the $\Delta_\nu$-lepton coupling constants, and $m_{\psi_1}$ is the mass of the $\psi_1$. The branching ratio $B(\mu^- \to e^- + \bar{\nu}_2 + \nu_1)$ in LRSM is given by

$$B(\mu^- \to e^- + \bar{\nu}_2 + \nu_1) = \frac{1}{4} \frac{G'^2}{G^2}.$$ 

From the experimental limit (7) one obtains

$\gamma_3$ was first considered in [15] before the advent of gauge theories, in connection with the question reflecting the nature of the expected conservation law, which was supposed to account for the apparent absence of processes like $\mu \to e \gamma$. The decay $\mu^- \to e^- + \bar{\nu}_2 + \nu_1$ would be allowed if the absence of $\mu \to e \gamma$ is due to the conservation of a particular multiplicative quantum number ("muon parity"), while both $\mu^- \to e^- + \bar{\nu}_2 + \nu_1$ and $\mu \to e \gamma$ are forbidden by the conservation of the additive "muon number" (which is identical to the muon family number). We note that since an interaction responsible for $\mu^- \to e^- + \bar{\nu}_2 + \nu_1$ is not the weak interaction, the existence of a conserved multiplicative quantum number cannot be ruled out by the absence of $\mu \to e \gamma$.

The Nature of Neutrinos in Muon Decay and Physics Beyond the Standard Model

The Nature of Neutrinos in Muon Decay and Physics Beyond the Standard Model
the quarks, for example, are spin-zero particles, called the squarks and the sleptons. Supersymmetric models can solve some of the theoretical problems of the SM and allow the unification of the interactions of the SM with gravity.

Unlike in the SM, in the MSSM the conservation of lepton (L) and baryon (B) numbers is not automatic: the Lagrangian can contain L- and B-violating gauge-invariant supersymmetric terms. To eliminate B-violation, which would have to be extremely weak to prevent too rapid proton decay, a discrete symmetry, called R-parity symmetry, is usually imposed [20]. R-parity is a multiplicative quantum number, whose value is +1 for the SM particles, and −1 for the superpartners. The requirement of R-parity invariance eliminates not only the B-violating terms, but also the L-violating ones. Alternatively, with a different choice of the discrete symmetry, it is possible to arrange that the L-violating terms remain.

The presence of R-parity-violating terms in the Lagrangian has rich phenomenological consequences. One of these is that they allow the production of single superpartners (in R-parity-conserving models the superpartners have to be produced in pairs). Another is that they give rise to some new processes that are forbidden in the SM. Among these are new two-neutrino decays of the muon.

The decay \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \) has been considered in this model in Reference [12]. It is mediated by the superpartner \( \tilde{\nu} \) of the left-handed component of the \( \nu \), as shown in Figure 4. The corresponding interaction is of the form

\[
H_L = \frac{G_F}{\sqrt{2}} \left( \bar{\nu}_1 (1 - \gamma_5) \nu_1 + \gamma_5 \nu_1 \right) + H.c. ,
\]

where \( G_F/N_\chi^2 = 1/132 A_{\chi^2}/4m^2 \). \( m_\chi \) is the mass of the \( \tilde{\nu} \), and the \( \lambda \)'s are coupling constants; the subscripts on the \( \lambda \)'s are family indices. The product of the \( \lambda \)'s in Equation (17) turns out to govern also muonium to antimuonium conversion in this model [16].

The latter process is mediated by the \( \tilde{\nu} \) superpartner of the \( \nu \). From the experimental limit [16] on muonium to antimuonium conversion we obtain the bound\(^ g \)

\[
B(\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e) \ll 10^{-8} ,
\]

which is much below the LSND range (9). In addition to \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \), other decays of the type \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \) also occur. An analysis [21] shows that under the assumption that lepton and slepton mixing is small, the sum of their branching ratios is \( B(\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e) \ll 10^{-4} \).

The effects of mixings are being investigated.

Summary

In this article we discussed two-neutrino decays of the muon of the type \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \), where \( \nu_e \) is a neutrino. Such decays are experimentally accessible through the detection of \( \tilde{\nu} \)'s using the inverse beta-decay reaction \( \nu_e + p \rightarrow e^- + \bar{\nu}_e + n \). The decays \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \) are of considerable importance, since they probe leptonic interactions that are not present in the SM. A new issue of interest is whether such decays could be fast enough to be potential sources of the observed excess of \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e \) events in the LSND experiment. In this connection it should be noted that the data from a recent experiment [22] of the LSND collaboration on

\[\text{References}\]