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

Peter Herczeg

The main decay mode of the μ^+ [a] is the decay into a positron and two neutrinos: $\mu^+ \to e^+ + n + n'$ [b]. 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) [c]. Today the main motivation for further investigations of muon decay is to search for deviations from the predictions of the SM [1]. 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 $\mu^+ \to e^+ + n + n'$. 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 $\bar\nu_e$'s originating from μ^+-decay are sensitive not only to oscillations of neutrinos into $\bar\nu_e$, but also to decays of the type $\mu^+ \to e^+ + \bar\nu_e, + n_x$, [d] where n_x is a neutrino. The decays $\mu^+ \to e^+ + \bar\nu_e + n_x$ 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 $\bar\nu_e$-appearance start to provide new information on the $\mu^+ \to e^+ + \bar\nu_e + n_x$ 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 $\mu^+ \to e^+ + \bar\nu_e + n_x$ (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 $\mu^+ \to e^+ + \bar\nu_e + n_x$ from searches for $\bar\nu_e$-appearance. In the subsequent section we discuss the decays $\mu^+ \to e^+ + \bar\nu_e + n_x$ in two important extensions of the SM: in 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 μ^+-decay. The general conclusions for μ^--decay are the same.
b) Unless otherwise stated, we use here the term "neutrino" for both neutrinos and antineutrinos. Thus, both n and n' can be a neutrino or an antineutrino (or a Majorana neutrino). In general μ^+ can have decay modes into several different pairs (n, n'). If n and/or n' are not mass eigenstates, then the decay for a given n and n' is into final states $e^+ + n_i + n_j'$, where n_i and n_j' 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 $SU(2)_L \times U(1)$ gauge theory, containing three families of leptons and quarks, one Higgs doublet, and only left-handed neutrinos.
d) The decays $\mu^+ \to e^+ + \bar\nu_e + n_x$ are the only nonstandard types that can be studied experimentally at the available facilities, since the muons decay predominately at rest, and therefore the neutrinos are not energetic enough to produce μ's and τ's.

Muon Decay in the Standard Model: Comparison with Experiment

In the SM the neutrinos n and n' in muon decay are $n = \nu_{eL}$ and $n = \bar\nu_{\mu L}$, where $\nu_{lL} = (1 - \gamma_5)\nu_l/2$ $(l = e,\mu)$ are massless left-handed neutrinos (the ν_l are massless four-component spinors), which accompany the e^+ and the μ^+ in the decays $W^+ \to e^+ + \nu_{eL}$ and $W^+ \to \mu^+ + \nu_{\mu L}$. The latter decays result from the interaction

$$\mathcal{L} = \frac{g}{2\sqrt{2}}\left(\bar\nu_e\gamma_\lambda(1-\gamma_5)e + \bar\nu_\mu\gamma_\lambda(1-\gamma_5)\mu\right)W^\lambda + \text{H.c.}, \qquad (1)$$

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 $\bar\nu_l\gamma_\lambda l$ and the axial-vector current $\bar\nu_l\gamma_\lambda\gamma_5 l$. The interaction (1) generates the decay $\mu^+ \to e^+ + \nu_{eL} + \bar\nu_{\mu L}$ through the exchange of a W, as shown in Figure 1. The effective interaction describing the process in Figure 1 is given by

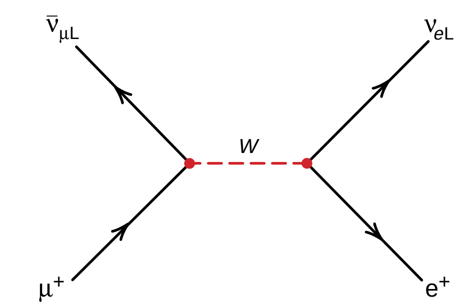

Figure 1.

$$H_{SM} = \frac{g^2}{8m_W^2}\left(\bar\mu\gamma_\lambda(1-\gamma_5)\nu_\mu\right)\left(\bar\nu_e\gamma_\lambda(1-\gamma_5)e\right) + \text{H.c.}, \qquad (2)$$

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 $\mu^+ + \nu_\mu$ 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

$$\Gamma^{(\mu)} \simeq \frac{G_F^2 m_\mu^5}{192\pi^3} \ . \qquad (3)$$

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 $G_F \simeq \sqrt{2}g^2/8m_W^2$. The constant $\sqrt{2}g^2/8m_W^2$ can be calculated using the experimental values of g and m_W. One obtains

$$\left(\frac{\sqrt{2}\,g^2}{8m_W^2}\right)^2 = (0.99 \pm 0.04)G_F^2 \ . \qquad (4)$$

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 $n_\pi + e^- \to \mu^- + n_a$, where n_a is a neutrino, and n_π is the neutrino emitted in the dominant $\pi^+ \to \mu^+ + neutrino$ decay.

If one assumes conservation of lepton family numbers, the only allowed two-neutrino decay mode of the μ^+ is $\mu^+ \to e^+ + \nu_e + \bar\nu_\mu$, where ν_e and ν_μ are in general Dirac neutrinos. The decay of the π^+ must proceed in this case as $\pi^+ \to \mu^+ + \nu_\mu$, and inverse muon decay as $\nu_\mu + e^- \to \mu^- + \nu_e$. In such a framework there are ten possible independent four-fermion interactions that can contribute to $\mu^+ \to e^+ + \nu_e + \bar\nu_\mu$. One of these is of the form (2) with $g^2/8m_W^2$ replaced by a general coupling constant $G_{LL}^V/\sqrt{2}$, where by the subscripts we have indicated that the neutrinos in both currents are left-handed. One has $G_{LL}^{V}/\sqrt{2} = (g^2/8m_W^2) + ...$, where the dots stand for the coupling constants of other possible $V - A$ interactions. The Fermi constant is given now by $G_F^2 = |G_{LL}^{V}|^2 + |x|^2$, where $|x|^2$ 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

$$|G_{LL}^{V}|^2 > 0.925\ G_F^2\ . \quad (5)$$

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 $\sim 3 \times 10^{-2} G_F$ [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 $|G_{LL}^{V}|^2$, $|G_{LL}^{S}|^2$,... apply in the general case for sums of the squares of certain combinations of the coupling constants. The sums which replace $|G_{LL}^{V}|^2$, $|G_{LL}^{S}|^2$, etc., contain G_{LL}^{V}, G_{LL}^{S}, etc., respectively.

The results of the general analysis imply [6] that at least one of the μ^+-decay modes which involve the neutrino state $\bar{n}_\pi$ (the neutrino state produced in the dominant $\pi^- \rightarrow \mu^- + neutrino$ decay) dominates the rate. We note yet that there is some experimental evidence (from pion decays) that n_π is not the neutrino state which accompanies the positron or 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 n_e capable of producing electrons in the reaction $n_e + D \rightarrow p + p + e^-$. The good agreement of the measured $n_e + D \rightarrow p + p + e^-$ cross section 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 beta 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 in the rate) contributions from new physics.

Among the possible new μ^+-decay modes, the class characterized by the presence of $\bar{\nu}_e$ among the decay products can be identified by detecting the $\bar{\nu}_e$'s through the inverse beta-decay reaction $\bar{\nu}_e + p \rightarrow n + e^+$. Such experiments search for both $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ decays (where n_x is a neutrino), and for $\bar{\nu}_e$-appearance due to neutrino oscillations. A search for $\bar{\nu}_e$ originating from muon decay was carried out already in the experiment of Reference [7], where the detector was filled alternately with H_2O and D_2O. The experiment set an upper limit $B_{(\bar{\nu}_e)} < 0.098$ (90% c.l.) on the sum of the $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ branching ratios

$$B_{(\bar{\nu}_e)} \equiv \sum_{n_x} B(\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x) = \sum_{n_x} \Gamma(\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x)/\Gamma(\mu^+ \rightarrow \mathrm{all}). \quad (6)$$

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

$$B_{(\bar{\nu}_e)} < 2.5 \times 10^{-3} \qquad (90\%\ \mathrm{c.l.}), \quad (7)$$

obtained in an experiment at the ISIS facility (Rutherford-Appleton Laboratory, United Kingdom) by the KARMEN collaboration. It should be noted 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 $\bar{\nu}_\mu$'s in the SM muon decay. Some other possibilities are under study.

The probability $P_{\bar{\nu}_e}$ of $\bar{\nu}_e$ appearance found in the LSND experiment [3] is

$$P_{\bar{\nu}_e} = (0.31 \pm 0.13) \times 10^{-2}\ . \quad (8)$$

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

$$10^{-3} < B_{(\bar{\nu}_e)} < 5 \times 10^{-3} \qquad (90\%\ \mathrm{c.l.})\ . \quad (9)$$

This range is not inconsistent with the upper limit (7). The interpretations of the excess e^+-events in the LSND experiment in terms of $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ 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 $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ in Extensions of the Standard Model

The decays $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ 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 supersymmetric 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 is introduced 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 (LRSM) 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_L) is associated with $SU(2)_L$, while the $SU(2)_R$ group accommodates a second (hitherto undetected) charged gauge boson, the W_R, which couples only to right-handed currents (i.e., currents involving the right-handed components of the fermion fields). The model requires the existence of right-handed neutrinos ν'_{lR} ($l = e,\mu,\tau$), which are the partners of the right-handed components of the charged lepton l_R^- in doublets of $SU(2)_R$. Thus, the right-handed neutrinos are not sterile, but participate in the right-handed interactions. Also, the neutrinos are expected to have nonzero masses.

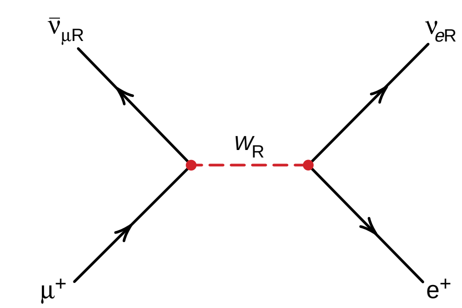

Figure 2.

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 $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ (see Figure 2), [e] which is of the $V + A$ form

e) For simplicity we are taking for this argument the neutrinos to be Dirac particles, and neglecting neutrino mixing.

$$H_{W_R} = \frac{g_R^2}{8m_{W_R}^2}\left(\bar{\mu}\gamma_\lambda\,(1+\gamma_5)\nu_\mu\right)\left(\bar{\nu}_e\gamma_\lambda\,(1-\gamma_5)e\right) + \text{H.c.}\,. \tag{10}$$

In Equation (10) g_R is the coupling constant associated with $SU(2)_R$; the coupling constant associated with $SU(2)_L$ is denoted now by g_L; m_{W_R} is the mass of W_R. If $g_R = g_L$, then in the limit when the masses of the W_L and W_R 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_R heavier than the W_L. 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_{W_R}. The present experimental lower bound on m_{W_R} 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, $\vec{\Delta}_R \equiv \left(\Delta_R^{++}, \Delta_R^{+}, \Delta_R^0\right)$ and $\vec{\Delta}_L \equiv \left(\Delta_L^{++}, \Delta_L^{+}, \Delta_L^0\right)$, 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, $m_{\nu_l} \propto m_l^2/m_{W_R}$ for the neutrino masses. In this version of LRSM the right-handed neutrinos are heavy, with masses of the order of m_{W_R}.

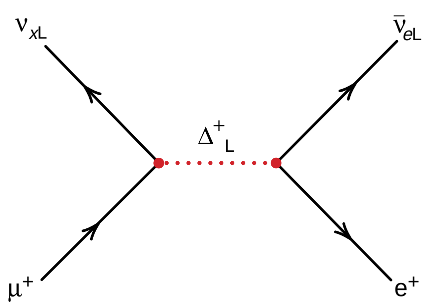

Figure 3.

In the above version of $SU(2)_L \times SU(2)_R \times U(1)$ models in addition to the usual muon-decay mode $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ the lepton family number violating decays $\mu^+ \to e^+ + \bar{\nu}_e + \nu_x$ $(x = e,\mu,\tau)$ also occur [11]. They are mediated by the singly charged component of the $\vec{\Delta}_L$, as shown in Figure 3.

We shall assume in the following that mixing in the leptonic sector can be neglected. Then the decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ f) 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

$$H_\Delta = \frac{G'}{\sqrt{2}}\left(\bar{\mu}(1+\gamma_5)\nu_\mu^{\,c}\right)\left(\overline{\nu_e^{\,c}}(1-\gamma_5)e\right) + \text{H.c.}, \tag{11}$$

where $G' = -\sqrt{2} f_{ee}\, f^*_{\mu\mu}/2m_+^2$, f_{ee} and $f_{\mu\mu}$ are $\vec{\Delta}_L$-lepton coupling constants, and m_+ is the mass of the Δ_L^+; the field $\nu_l^{\,c}$ ($l = e,\mu$) describes the right-handed antiparticle of ν_l. The branching ratio $B\left(\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu\right) \simeq B_{(\bar{\nu}_e)}$ is given by

$$B\left(\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu\right) \simeq \frac{1}{4}\left|\frac{G'}{G_F}\right|^2 . \tag{12}$$

From the experimental limit (7) one obtains

f) The decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ was first considered [15] before the advent of gauge theories, in connection with the question regarding the nature of the suspected conservation law, which was supposed to account for the apparent absence of processes like $\mu \to e\gamma$. The decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ 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 $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ 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 $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ is not the weak interaction, the existence of a conserved multiplicative quantum number cannot be ruled out by the absence of $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ at a certain level.

$$\left|G'\right| < 10^{-1} G_F\,. \tag{13}$$

A bound on G' follows also from a new experimental limit on muonium to antimuonium conversion [16]. Muonium (antimuonium) is a bound state of $\mu+$ and e^- $(\mu^-$ and $e^+)$. In the model we are considering, muonium to antimuonium conversion is mediated by the doubly charged component of $\vec{\Delta}_L$ [17]. The coupling constant $G_{M\bar{M}}$ of the corresponding interaction is related to G' as $G' \simeq -4G_{M\bar{M}}\, m_{++}^2/m_+^2$, where m_{++} is the mass of the Δ_L^{++}. Assuming that the mixing of $\vec{\Delta}_L$ with other Higgs fields can be neglected, one has the relation $m_+^2 = (m_{++}^2 + m_0^2)/2$ [18] among the masses of the Δ_L^{++}, Δ_L^{+}, and Δ_L^0. This relation and the experimental limit $\left|G_{M\bar{M}}\right| < 3 \times 10^{-3}$ (90% c.l.) [16] imply

$$\left|G'\right| < 2.4 \times 10^{-2} G_F\,, \tag{14}$$

and therefore

$$B\left(\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu\right) < 1.5 \times 10^{-4}\,, \tag{15}$$

which is too small to account for the LSND result. The consequences of mixing among the Higgs fields and in the leptonic sector are under study.

In $SU(2)_L \times SU(2)_R \times U(1)$ models the decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$, and muonium to antimuonium conversion, can give important information on the values of the ν_μ-mass allowed in these models [11]. As in the SM, the neutrino masses in $SU(2)_L \times SU(2)_R \times U(1)$ models are undetermined. In any model, the masses and lifetimes of the neutrinos are constrained by the requirement that in the present universe the energy density of the neutrinos does not exceed the upper limit on the total energy density of the universe. This can be shown to imply that neutrinos of masses between ~35 eV and ~3 GeV have to be unstable. For such neutrinos there is a relation between their masses and lifetimes. The heavier the neutrino, the faster it has to decay. An issue of interest is then whether in a given model there is a decay mode which allows a given neutrino to decay fast enough. For ν_μ in $SU(2)_L \times SU(2)_R \times U(1)$ models the only such decay mode turns out to be $\nu_\mu \to \nu_e + \nu_e + \bar{\nu}_e$, and this only for ν_μ's with masses in the range

$$40 \text{ keV} \leqslant m_{\nu_\mu} < 170 \text{ keV}. \tag{16}$$

The upper limit in Equation (16) is the present experimental limit on m_{ν_μ}. Can the ν_μ have a mass in the range of (16)? The special role of the decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ and of muonium to antimuonium conversion in $SU(2)_L \times SU(2)_R \times U(1)$ models is that they can probe this question. The dominant mechanism for the decay $\nu_\mu \to \nu_e + \nu_e + \bar{\nu}_e$ is the exchange of the neutral component of the $\vec{\Delta}_L$. For the decay rate to be sufficiently large, Δ_L^0 cannot be arbitrarily heavy. As follows from some further considerations, this implies that the constant G' has a lower bound for m_{ν_μ}'s in the range (16). This lower bound is $\left|G'\right| \gtrsim 7 \times 10^{-4}$, to be compared with the bound (14). It can be shown that as the experimental limit on the $B\left(\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu\right)$ becomes more and more stringent than the bound (15), the lower bound for the possible values of m_{ν_μ} in Equation (16) will become increasingly larger.

The Minimal Supersymmetric Standard Model with R-parity Violation. Supersymmetry is an extension of the known space-time symmetries (the invariance with respect to the inhomogeneous Lorentz transformations) [19]. Supersymmetry transforms bosons (fermions) into fermions (bosons). The supersymmetric version of the SM, the minimal supersymmetric standard model (MSSM) contains not only the SM fields, but also their superpartners. The superpartners of the leptons and the quarks, for example, are spin-zero particles, called the sleptons and the squarks, respectively. 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.

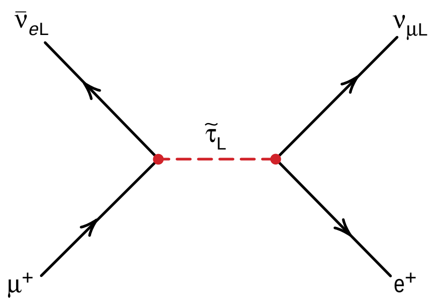

Figure 4.

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

$$H_{\tilde{\tau}} = \frac{G''}{\sqrt{2}}\left(\bar{\mu}(1-\gamma_5)\nu_e\right)\left(\bar{\nu}_\mu(1+\gamma_5)e\right) + \text{H.c.}\,, \qquad (17)$$

where $G''/\sqrt{2} = \lambda_{132}\,\lambda^*_{231}/4m_{\tilde{\tau}}^{\,2}$, $m_{\tilde{\tau}}$ is the mass of the $\tilde{\tau}_L$, and the λ's are coupling constants; the subscripts on the λ's are family indices. The product of the λ's in Equation (17) turns out to govern also muonium to antimuonium conversion [12]. The latter process is mediated by $\tilde{\nu}_\tau$ the superpartner of the ν_τ. From the experimental limit [16] on muonium to antimuonium conversion we obtain the bound [g)]

$$B\left(\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu\right) \lesssim 10^{-4}\,, \qquad (18)$$

which is much below the LSND range (9).

In addition to $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$, other decays of the type $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ also occur. An analysis [21] shows that under the assumption that lepton and slepton mixing is small, the sum of their branching ratios is $B_{(\bar{\nu}_e)} \lesssim 2 \times 10^{-4}$. The effects of mixings are being investigated.

Summary

In this article we discussed two-neutrino decays of the muon of the type $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$, where n_x is a neutrino. Such decays are experimentally accessible through the detection of $\bar{\nu}_e$'s using the inverse beta-decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The decays $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ are of considerable importance, since they probe leptonic interactions that are not present in the Standard Model. A new issue of interest is whether such decays could be fast enough to be potential sources of the observed excess of 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 $\nu_\mu \rightarrow \nu_e$ oscillations support the interpretation of the result of their previous experiment in terms of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

We reviewed the decays $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ in two important extensions of the Standard Model: in a class of left-right symmetric models and in the minimal supersymmetric standard model with R-parity violation. In the version of left-right symmetric models where the smallness of the masses of the usual neutrinos is related to the large size of the scale of the right-handed interactions, the decay $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ (which is expected to dominate among $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$) is mediated by the singly charged component of a triplet of Higgs bosons $\vec{\Delta}_L$. Assuming that the mixing of $\vec{\Delta}_L$ with other Higgs fields can be neglected, the upper limit on the $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ branching ratio turns out to be $\sim 10^{-4}$ (implied by the present limit on muonium to antimuonium conversion). This is an order of magnitude below the range required to account for the LSND result. In the minimal supersymmetric standard model with R-parity violation the upper limit on the sum of the $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ branching ratios is $\sim 2 \times 10^{-4}$, assuming that lepton and slepton mixing is small. A further study of $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ decays in the above models, and also in other extensions of the standard model is in progress.

To improve the sensitivity of experiments searching for $\mu^+ \rightarrow e^+ + \bar{\nu}_e + n_x$ decays remains important. In the case of left-right symmetric models improved limits on the $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ branching ratio would also provide information on the mass of the muon neutrino in these models. ■

g) We used $m_{\tilde{\tau}}^{\,2} - m_{\nu_{\tilde{\tau}}}^{\,2} \lesssim 0.8\, m_Z^2$ (see P. Nath et al., Reference [19]) and $m_{\tilde{\tau}} \simeq 45$ GeV (the experimental lower bound on $m_{\tilde{\tau}}$ see Reference [4]).

Peter Herczeg received his M.S. from the Czech Technical University in Prague, Czech Republic, and his Ph.D. from the University of Sussex, England. During 1962–1965 he was a staff member at the Institute of Physics of the Czechoslovak Academy of Sciences in Prague. Subsequently he held research associate positions at the Niels Bohr Institute (Copenhagen), University of Sussex, California Institute of Technology, and at Carnegie-Mellon University. In 1973 he joined the Medium Energy Physics Group (T-5) of the Theoretical Division at Los Alamos. His research has been mainly in the areas of the weak interactions and the phenomenology of extensions of the Standard Model of the fundamental interactions. It has included subjects in the fields of CP violation, rare decays, and time reversal violation in low-energy processes. For his contributions to these fields he was elected in 1993 a Fellow of the American Physical Society.

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