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Muonium-antimuonium oscillations and exotic muon decay in broken R-parity SUSY models

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We analyze the process of muonium-antimuonium conversion and the rare decay $\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$ in the class of low energy $N = 1$ supersymmetric theories containing R-parity-breaking terms in the lepton sector. We find that these processes are allowed in those models at the tree level and are controlled by the same combination of coupling strengths. Current experimental constraints on the relevant coupling parameters allow the effective four-fermion couplings for these processes to be as large as $2 \times 10^{-2} G_F$. This is several orders of magnitude larger than many other models allow and just about at the current experimental limits. This result should serve to revitalize experimental searches for these exotic processes.

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It is now well known that low energy supersymmetric models do not share the crucial property of the standard model that baryon (B) and lepton (L) numbers are automatic symmetries of the theory. Indeed, the requirement of SU(3)×SU(2)×U(1) gauge invariance leaves open the possibility of writing renormalizable terms which violate B and L even in the supersymmetric versions which only make use of the minimal content of superfields required to supersymmetrize the standard model. Whether or not L and B are conserved in low energy supersymmetric models depends on some additional discrete symmetry that one is compelled to add to the gauge symmetry and global $N = 1$ supersymmetry in order to prevent too rapid a proton decay. The most popular solution is the imposition of a discrete symmetry known as R parity, which forbids any B- or L-violating term. As safe as this path may appear, it is by no means the only way to achieve a satisfactory level of matter stability. Alternatively, one can impose a B-parity symmetry or an L-parity symmetry which forbids either B- or L-violating terms, respectively. In this Rapid Communication we consider low energy supersymmetry with only B-parity symmetry, which admits L number violation in renormalizable terms of the superpotential. Among several interesting features, this class of models provides a plausible mechanism for generating neutrino masses and flavor mixings [1]. Like many other models that violate the lepton number conservation laws of the standard model, this class of theories may give rise to a variety of exotic processes. Here we focus on the historically rich search for oscillations between muonium ($M = \bar{\mu}e$) and antimuonium ($\bar{M} = \mu\bar{e}$) and on the anomalous decay $\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$. We will show that the present bounds on the R-parity breaking parameters allow for M-$\bar{M}$ oscillations at a rate within reach of the next generation of experiments. Interestingly enough, the same range of R-violating parameters leads to a rate for the anomalous muon decay which may be testable in a newly proposed LAMPF experiment.

Interest in both of these processes was kindled by Pontecorvo [2] and by Feinberg and Weinberg [3] through the observation that this process could distinguish between two types of lepton conservation laws: additive verses multiplicative. The additive law is that of the standard model (separate lepton number conservation for each flavor), while the multiplicative law requires only total lepton number conservation plus preservation of muon parity [defined as $(-1)^{\Sigma L_\mu}$]. The multiplicative law forbids $\Delta L_\mu = \pm 1$ processes, such as $\mu \to e\gamma$, but allows $\Delta L_\mu = \pm 2$ processes that conserve total lepton number, such as $M \to \bar{M}$ and $\mu \to e\nu_e\bar{\nu}_\mu$. The experimental limit of 2% for this last muon decay channel [4] dampens one's enthusiasm for the multiplicative law, which predicts a branching ratio of 50%.

A primary motivation for continued interest in these processes is the recognition that within the framework of gauge theories, a lepton conservation law has no status unless it derives its existence from a local gauge invariance. The simplest departure from the standard model that does not introduce $\Delta L_{\mu,e} = 1$ processes is the introduction of Majorana mass terms without direct flavor mixing. Such models lead to an M-$\bar{M}$ effective coupling constant, $G_{M\bar{M}}$, that is several orders of magnitude below the present experimental limit of $0.16\, G_F$ [5], which has improved by many orders of magnitude since the first measurements were made more than two decades ago [6].

The neutrino Majorana mass mechanism is a one-loop effect (see Fig. 1), but in some models M-$\bar{M}$ conversion may be affected through a one particle exchange mechanism. One such mechanism that has been discussed at great length is derived from models containing a doubly charged Higgs boson (see Fig. 2). Depending upon the precise variant of the model, one finds a value of $G_{M\bar{M}}$ ranging from $10^{-9}\, G_F$ to as high as the current experimental limit [5,7].

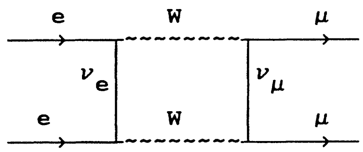

FIG. 1. Conversion through double Majorana neutrino exchange.

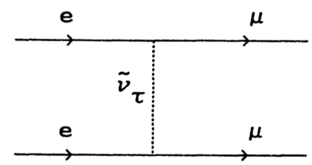

FIG. 3. Conversion through τ sneutrino exchange.

A distinctly different tree-level mechanism for M-$\bar{M}$ conversion is found in supersymmetric models containing R-parity breaking terms. This has been pointed out previously by Mohapatra [8]. However, in the implementation of this idea, it was assumed that only one R-breaking parameter was nonvanishing, and in that case the amplitude for M-$\bar{M}$ conversion is proportional to the difference of the squared masses of the two components of the complex scalar neutrino field. In our approach, we avoid any assumption about the sneutrino mass spectrum and realize a mechanism which at the same time leads to the rare muon decay. Hence, we consider the most general L-violating but supersymmetric invariant superpotential, and we attribute the simultaneous presence of M-$\bar{M}$ and $\mu \to e^+\bar{\nu}_e\nu_\mu$ to the existence of two R-parity violating couplings of this superpotential. Indeed, in models with B-parity there exist three-flavor couplings involving a complex scalar neutrino, i.e., $e\mu\tilde{\nu}_\tau$, and the conversion process can occur through the exchange of a single $\tilde{\nu}_\tau$. The L-violating couplings in the leptonic sector of the model are due to the $L_iL_jE^c_k$ terms in the superpotential, where L and E^c denote the superfields containing the usual fermionic left-handed isodoublet and the positron isosinglet fields, respectively. In components, these terms give rise to the following L-violating fermion-fermion-scalar couplings:

$$\mathcal{L}_{\text{int}} = \lambda_{ijk}\left[\tilde{\nu}^i_L\bar{l}^k_R l^j_L + \tilde{l}^j_L\bar{l}^k_R\nu^i_L + \tilde{l}^{k*}_R\nu^{ic}_R l^j_L - (i \to j)\right] + \text{H.c.}, \qquad (1)$$

where $\tilde{\nu}^i_L$ and $\tilde{l}^i_L$ are, respectively, the scalar neutrino and the left-handed scalar lepton fields of generation i, and the charge conjugate fields are defined through $\nu^{ic}_R = C\bar{\nu}^{iT}_L$, where C is the charge conjugation operator. The coupling λ_{ijk} is antisymmetric in the first two indices and is real if CP is a good symmetry. In this model, M-$\bar{M}$ conversion proceeds through $\tilde{\nu}_\tau$ exchange as shown in Fig. 3, and the effective Hamiltonian is given by

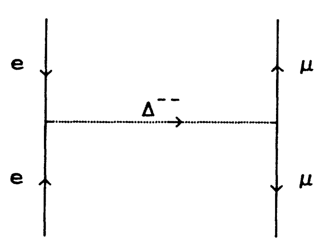

FIG. 2. Conversion through doubly charged scalar exchange.

$$\mathcal{H}_{M\bar{M}} = -\left[4\lambda_{312}\lambda^*_{321}/m^2(\tilde{\nu}_\tau)\right]\bar{\mu}_R e_L\bar{\mu}_L e_R + \text{H.c.} \qquad (2)$$

An effective interaction parameter $G_{M\bar{M}}$ is conventionally defined through the four-fermion interaction introduced by Feinberg and Weinberg [3] for this process

$$\mathcal{H}_{\text{FW}} = (4G_{M\bar{M}}/\sqrt{2})\mu_L\gamma_\beta\bar{e}_L\mu^\beta_L\gamma e_L + \text{H.c.} \qquad (3)$$

For practical purposes, the effects of the interactions (2) and (3) will be equivalent in M-$\bar{M}$ oscillations if their matrix elements are equal for the $1S, j = 0$ configuration. Equating these matrix elements yields

$$|G_{M\bar{M}}|/\sqrt{2} = \frac{3}{4}|\lambda_{312}\lambda^*_{321}|/m^2(\tilde{\nu}_\tau). \qquad (4)$$

Constraints on the couplings in this model imply $|\lambda_{312}\lambda^*_{321}| < (2\text{–}3)\times 10^{-3}$ for a sneutrino mass of 100 GeV [9]. Therefore

$$|G_{M\bar{M}}| < 2 \times 10^{-2}G_F[100\,\text{GeV}/m^2(\tilde{\nu}_\tau)] \qquad (5)$$

This is within reach of the muonium experiment now underway at PSI [10].

To appreciate the generality of the bound in Eq. (5), it is important to notice that $\tilde{\nu}_\tau$ exchange is the only way to give rise to M-$\bar{M}$ conversion at the tree level in models with broken R-parity. Indeed, there exist only two operators in the superpotential with $\Delta L = 1$. One involves two colored superfields, so that it cannot produce M-$\bar{M}$ oscillations at tree level. The other operator gives rise to the terms in Eq. (1). Given the antisymmetry of the λ_{ijk} couplings in the first two indices, $\tilde{\nu}_\tau$ represents the only choice for the scalar in the two vertices with $\mu_R e_L$and $\mu_L e_R$. Hence the M-$\bar{M}$ conversion process is proportional to the product of R-parity-violating couplings $\lambda_{132}\lambda^*_{231}$. This product does not enter into other neutral current flavor-changing processes such as $\mu \to e\gamma$ at the one-loop level and is therefore not constrained by the tight experimental bounds on these processes.

We turn now to the exotic muon decay $\mu^+ \to e^+\bar{\nu}_e\nu_\mu$ whose rate in models with good B-parity is proportional to the product of the same R-violating couplings which occur in the M-$\bar{M}$ transition. Indeed, this muon decay rate is readily obtained by replacing $\tilde{\nu}_\tau$ by τ in the diagram of Fig. 3 with the attendant change of the charged isodoublet leptons by their neutral partners in the external legs. The corresponding effective Hamiltonian is

$$\mathcal{H}_{\mu e} = \frac{\bar{G}^{(e)}_\mu}{\sqrt{2}}\left[\bar{\mu}\gamma_\alpha(1+\gamma_5)e\right]\left[\bar{\nu}_\mu\gamma^\alpha(1-\gamma_5)\nu_e\right] \qquad (6)$$

where

$$\bar{G}^{(e)}_\mu m^2(\tilde{\tau}) = \left(\sqrt{2}\lambda_{312}\lambda^*_{321}\right). \qquad (7)$$

The effective decay constant for this rare mode, $G_\mu^{(e)}$, is conventionally defined through an interaction such as Eq. (3) in which the electron field has a left-handed projection rather than the right-handed projection appearing in Eq. (6). This difference is of no consequence in the total decay rate for this mode, so that $\bar{G}_\mu^{(e)}$ and $G_\mu^{(e)}$ are equivalent for our purposes here. The prediction of left-right models is different in this regard [13], and in principle, electron polarization experiments can distinguish between the two underlying theories. Taking $m(\tilde{\tau}) = 100$ GeV and given the bound $\mid \lambda_{312} \mid \mid \lambda_{321} \mid < (2\text{–}3) \times 10^{-3}$ [9], we obtain

$$\bar{G}_\mu^{(e)} < 2 \times 10^{-2} G_F, \quad (8)$$

a result similar to the previous bound on $G_{M\bar{M}}$. The recent LAMPF proposal [11] to search for $\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$ in order to improve the present upper limit on $G_\mu^{(e)}$ of $0.14 G_F$ [12] to a value of the order $10^{-2} G_F$ would test the process in the range of R-violating parameters which also allows for a test in M-$\bar{M}$ transitions. Hence, our result also provides incentive for the LAMPF experiment to go forward beyond that provided in a recent analysis of these processes in left-right-symmetric models [13].

In conclusion, we have shown that in supersymmetric models with R-parity broken in the leptonic sector there exists a range of parameters leading simultaneously to M-$\bar{M}$ conversion and to $\mu^+ \to e^+ \bar{\nu}_e \nu_\mu$ at rates which are testable in the current muonium experiment at PSI and the newly proposed muon decay experiment at LAMPF.

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