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LEPTON-FLAVOUR-VIOLATION IN SUSY MODELS WITH AND WITHOUT R-PARITY [a]

KAZUHIRO TOBE

CERN, Theory Division, CH-1211, Geneva 23, Switzerland
E-mail: kazuhiro.tobe@cern.ch

We discuss Lepton-Flavour-Violating phenomena such as $\mu \to e\gamma$, $\mu \to eee$, and $\mu \to e$ conversion in nuclei in SUSY models with and without R-parity. We stress that experimental searches for all the LFV processes are important to distinguish between the different models.

Recently, the atmospheric neutrino experiment SuperKamiokande has announced evidence for non-zero neutrino mass, which indicates the existence of physics beyond the Standard Model (SM). Generally in models that accommodate neutrino oscillations, lepton-flavour-violating phenomena (LFV) can occur not only in the neutrino, but also in the charged-lepton sector. In this paper, we will discuss LFV in processes such as $\mu \to e\gamma$, $\mu \to eee$, and $\mu \to e$ conversion in nuclei in two models, which are extensions of the minimal SUSY SM (MSSM): one is the MSSM with right-handed neutrinos (without R-parity violation),[1] the other is the MSSM with R-parity violation.[2] Especially the latter model can also be tested by the HERA experiments;[3] however, the low energy muon-decay experiments provide very stringent bounds on some of the couplings, which are not constrained by HERA. We will also discuss the different features of LFV in these two models.

1 LFV in the MSSM with right-handed neutrinos

In this section, we consider the MSSM with right-handed neutrinos. The superpotential in the lepton sector is given by

$$W = f_e^i H_1 E_i^c L_i + f_\nu^i V_{ij} H_2 N_i^c L_j + \frac{M_R}{2} N_i^c N_i^c, \tag{1}$$

where for simplicity we assumed that the right-handed neutrino mass matrix is proportional to the unit matrix. In this framework, the small neutrino masses arise through the seesaw mechanism; if the right-handed neutrino mass scale M_R is much larger than the electroweak scale, we can obtain very tiny neutrino masses: $m_{\nu i} = (m_{\nu i}^D)^2/M_R$, $\nu_{\rm mass}^i = V_{ij}\nu_{\rm flavor}^j$, where m_ν^D is a Dirac neutrino mass ($m_{\nu i}^D = \frac{f_\nu^i v \sin\beta}{2}$), and the mass eigenstates ($\nu_{\rm mass}$) of neutrinos are related to the flavour eigenstates ($\nu_{\rm flavor}$) via the mixing matrix V. An important

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point is that,because of the LFV mixing V, LFV is induced in the slepton mass terms even if we assume universal scalar mass (m_0) at the gravitational scale $M = 2 \times 10^{18}$GeV. We can calculate the LFV in slepton masses by solving the renormalization group equations numerically. The approximate solution is given by $(\Delta m^2_{\tilde{L}})_{ij} \simeq -\frac{|f_\nu^k|^2 V_{ki} V_{kj}}{16\pi^2}(6 + 2a_0^2) m_0^2 \log(M/M_R)$. Note that large neutrino Yukawa couplings and large mixing V induce large flavour-violating masses. The LFV masses $(\Delta m^2_{\tilde{L}})_{ij}$ generate LFV processes, e.g. $(\Delta m^2_{\tilde{L}})_{23}$ induces $\tau \to \mu\gamma$, and $(\Delta m^2_{\tilde{L}})_{12}$ generates $\mu \to e$ flavour violation. The atmospheric neutrino experiments indicate large mixing V_{32}. This large mixing can induce large branching ratio for $\tau \to \mu\gamma$ [1,4]. Moreover, some of the solar neutrino solutions suggest large V_{21}, which can induce large $\mu \to e$ flavour violation.[4] In Fig. 1, we present the branching ratios of $\mu \to e\gamma$ and $\mu \to e$ conversion in Ti assuming that

$$V = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{-1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad m_{\nu i} = (0,\ 0.006,\ 0.055)_i \text{ eV}, \tag{2}$$

which provides a solution to the atmospheric neutrino problem, as well as a large-angle MSW solution to the solar neutrino problem.[b] We also checked that Br($\mu \to$ eee)/Br($\mu \to$ eγ) $\simeq 6 \times 10^{-3}$. Therefore the present and future experiments with a sensitivity of 10^{-14} for the $\mu \to e\gamma$ rate [5] and 10^{-16} for the $\mu \to e$ conversion rate in Al [6][c]can probe the LFV in a large region of the parameter space of this model.

2 LFV in SUSY models with R-parity violation

Subsequently, we consider the MSSM with R-parity violation in which the small R-parity violation can potentially explain small neutrino masses. The superpotential is

$$W = f_e^i H_1 E_i^c L_i + \frac{f_{ijk}}{2} L_i L_j E_k^c + f'_{ijk} L_i Q_j D_k^c. \tag{3}$$

Here we assume that the baryon-number-violating terms $U^c D^c D^c$ are forbidden by baryon parity in order to avoid rapid proton decay.[d]The Yukawa couplings f and f' violate lepton flavour number as well as lepton number. The LFV

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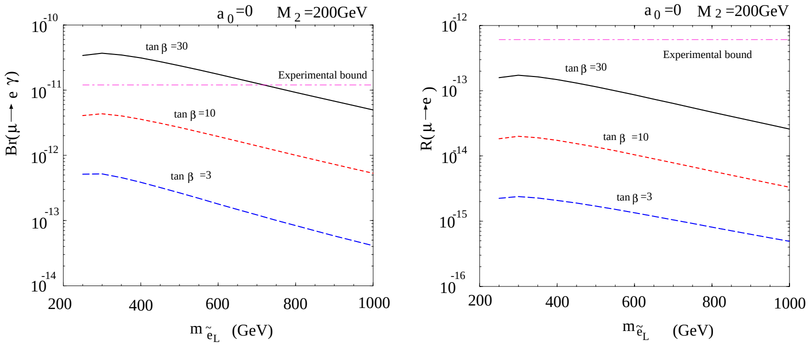
[b] In the case with other solar neutrino solutions, see Ref.[4]

[c] We numerically checked that the $R(\mu \to e \text{ in Al}) \simeq 0.6 R(\mu \to e \text{ in Ti})$.

[d] We neglect R-parity violation in soft SUSY-breaking terms. This could be important for neutrino masses. Here we do not consider any particular models for neutrino masses.



(a) (b)

Figure 1: Event rates for (a) $\mu \to e\gamma$ (b) $\mu \to e$ conversion in Ti as a function of the left-handed selectron mass. We fixed the right-handed neutrino mass to $M_R = 10^{13}$ GeV.

experiments put the most stringent bounds on certain combinations of the Yukawa couplings f and f'.[7,8] We list the bounds in Table 1. To understand an interesting feature of the LFV in this model, let us consider some simple examples. If only f_{131} and f_{231} are non-zero, the ratios of the event rates between the LFV processes are given by

$$\frac{\mathrm{Br}(\mu \to e\gamma)}{\mathrm{Br}(\mu \to eee)} = 1 \times 10^{-4}, \quad \frac{R(\mu \to e \text{ in Ti (Al)})}{\mathrm{Br}(\mu \to eee)} = 2 \times 10^{-3} \ (1 \times 10^{-3}), \quad (4)$$

where we took all $m_{\tilde{l}}$ to be 100 GeV. The rate of $\mu \to eee$ is much larger than those of the other LFV processes. This is because $\mu \to eee$ is generated at tree level, while the rest of the LFV processes are induced at the one-loop level. If only f_{132} and f_{232} are non-zero, the event rates are given by

$$\frac{\mathrm{Br}(\mu \to e\gamma)}{\mathrm{Br}(\mu \to eee)} = 1.2, \quad \frac{R(\mu \to e \text{ in Ti (Al)})}{\mathrm{Br}(\mu \to eee)} = 18 \ (11), \qquad (5)$$

where we took $m_{\tilde{l}} = 100$ GeV. Even though all processes are induced at the one-loop level in this case, the branching ratio of $\mu \to eee$ is still comparable to that of $\mu \to e\gamma$, and the rate of $\mu \to e$ conversion is even much larger because of a log-enhancement in the off-shell photon penguin contributions.[8] Therefore $\mu \to eee$ and $\mu \to e$ conversion are important in this model. The interesting point is that the relations in Eqs.(4), (5) are quite different from those of the MSSM with right-handed neutrinos discussed in the previous section. Therefore, in order to distinguish between the different models, the study of all the LFV processes can be important. Note that at present the future proposal for

	$\mu \to e\gamma$	$\mu \to 3e$	$\mu \to e$ in nuclei
$\lvert f_{131} f_{231} \rvert$	2×10^{-4} (7×10^{-6})	7×10^{-7}	1×10^{-5} (2×10^{-7})
$\lvert f_{132} f_{232} \rvert$	2×10^{-4} (7×10^{-6})	7×10^{-5}	1×10^{-5} (2×10^{-7})
$\lvert f_{133} f_{233} \rvert$	2×10^{-4} (7×10^{-6})	1×10^{-4}	2×10^{-5} (4×10^{-7})
$\lvert f_{121} f_{122} \rvert$	8×10^{-5} (2×10^{-6})	7×10^{-7}	6×10^{-6} (1×10^{-7})
$\lvert f_{131} f_{132} \rvert$	8×10^{-5} (2×10^{-6})	7×10^{-7}	7×10^{-6} (1×10^{-7})
$\lvert f_{231} f_{232} \rvert$	8×10^{-4} (2×10^{-6})	4×10^{-5}	8×10^{-6} (1×10^{-7})
$\lvert f'_{111} f'_{211} \rvert$	7×10^{-4} (2×10^{-5})	1×10^{-4}	5×10^{-6} (2×10^{-7})
$\lvert f'_{112} f'_{212} \rvert$	7×10^{-4} (2×10^{-5})	1×10^{-4}	4×10^{-7} (7×10^{-9})
$\lvert f'_{113} f'_{213} \rvert$	7×10^{-4} (2×10^{-5})	2×10^{-4}	4×10^{-7} (7×10^{-9})
$\lvert f'_{121} f'_{221} \rvert$	7×10^{-4} (2×10^{-5})	2×10^{-4}	4×10^{-7} (6×10^{-9})
$\lvert f'_{122} f'_{222} \rvert$	7×10^{-4} (2×10^{-5})	2×10^{-4}	4×10^{-5} (7×10^{-7})
$\lvert f'_{123} f'_{223} \rvert$	7×10^{-4} (2×10^{-5})	3×10^{-4}	5×10^{-5} (9×10^{-7})
$\lvert f'_{131} f'_{231} \rvert$	2×10^{-3} (6×10^{-5})	4×10^{-4}	4×10^{-7} (6×10^{-9})
$\lvert f'_{132} f'_{232} \rvert$	2×10^{-3} (6×10^{-5})	5×10^{-4}	9×10^{-5} (2×10^{-6})
$\lvert f'_{133} f'_{233} \rvert$	2×10^{-3} (6×10^{-5})	9×10^{-4}	2×10^{-4} (3×10^{-6})

Table 1: Present (Future) constraints on R-parity-violating couplings from LFV processes. The present limits (future expectations) on the event rates are given by Br($\mu \to e\gamma$) $< 1.2 \times 10^{-11}$ (10^{-14}), Br($\mu \to 3e$) $< 1.0 \times 10^{-12}$, and R($\mu \to e$ in Ti (Al)) $< 6.1 \times 10^{-13}$ (10^{-16}). We took $m_{\tilde{\nu}} = m_{\tilde{l}_R} = 100$ GeV and $m_{\tilde{q}} = 300$ GeV.

$\mu \to eee$ is missing. Furthermore, we should stress here that not only low-energy muon probes but also other experiments[3] should be encouraged in order to investigate the R-parity-violating SUSY since this theory is well-motivated from the recent neutrino data.

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