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SUPERSYMMETRIC SIGNALS IN MUON AND TAU DECAYS

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The spectra of the decay leptons produced in μ and τ decays could be significantly different from the standard model predictions. Such changes can be induced by majoron emission processes, characteristic of supersymmetric (SUSY) $SU(2) \otimes U(1)$ models with spontaneously broken R-parity. We analyse the attainable values for the corresponding branching ratios, once all observational constraints have been incorporated, including both those that arise from collider experiments such as LEP, as well as weak interaction constraints, such as the non-observation of neutrinoless double β decay, the limits on the ν_τ mass, the non-observation of neutrino oscillations, etc. We conclude that a new generation of high luminosity experiments such as a τ factory could easily study these branching ratios, even if the ν_τ mass is *below* the attainable limit of sensitivity of the planned facilities.

1. Introduction

The structure of the weak interaction of the τ-lepton is still poorly determined experimentally. From the theoretical point of view the charged leptons could have physical properties substantially different from those predicted by the standard model (for a review see ref. [1]). These properties include non-standard decay parameters, lifetimes, rare lepton and/or CP-violating decay modes, weak universality violating interactions, etc. The good statistics expected at a τ-factory opens up the window to probe such new phenomena [2]. Supersymmetry, both in its conventional realization, as well as in the alternative scenarios without R-parity conservation [3], offers a possible origin for new signals in τ and μ decays, consisting in the emission of very light sneutrinos [4]. It is in fact a feature of

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SU(2) ⊗ U(1) supersymmetric models where the R_p symmetry is broken spontaneously, that one combination of the sneutrinos remains massless. This is so because in this case there must be a physical Nambu–Goldstone boson (called the majoron and denoted by J) that follows from the spontaneous character of the violation of the corresponding global total lepton number symmetry [5]. As a consequence in these models the majoron is the lightest supersymmetric particle and can be kinematically emitted in many weak decays such as [5]

$$\mu \to e + J, \qquad \tau \to e + J, \qquad \tau \to \mu + J. \tag{1}$$

These decays would lead to bumps in the final lepton energy spectrum, at half of the parent mass. These have been searched for experimentally [6] but the limits on their possible existence are still rather poor, especially for the case of τ's. Similarly there may be decays with double majoron emission,

$$\mu \to e + J + J, \qquad \tau \to e + J + J, \qquad \tau \to \mu + J + J. \tag{2}$$

Thus spontaneously broken R_p SUSY theories offer a natural scenario for non-standard μ and τ decay properties. We now come to *which* specific form of R_p breaking is phenomenologically viable. In the minimal SUSY model with broken R-parity [5] the existence of the majoron is accompanied by another light scalar particle, denoted ρ, which receives a mass of order v_L, the scale characterizing the spontaneous violation of R-parity. The value of this scale v_L is severely constrained by the astrophysics of stellar cooling and evolution, leading to a very stringent limit on the relevant vacuum expectation value (vev) [7],

$$v_L < O(30\ \text{keV}). \tag{3}$$

As a result there is a new kinematically possible decay mode for the natural gauge boson,

$$Z^0 \to \rho + J. \tag{4}$$

This leads to an additional contribution to the invisible Z width, which is the equivalent of precisely half neutrino family, i.e. 85 MeV. The recent measurements of the Z^0 width at LEP [8] is sufficient to exclude this model [9].

It is however possible to formulate the R parity breaking model in such a way that the majoron is replaced by an SU(2) ⊗ U(1) *singlet* so that it does not couple to the Z and the decay in eq. (4) is forbidden [10, 11]. The scale characterizing R-parity breaking is now large, i.e.

$$v_R = O(1\ \text{TeV}), \tag{5}$$

while the analogue of eq. (3) is

$$v_L < O(100\,\text{MeV})\,. \tag{6}$$

It was noted in ref. [10] that eq. (6) can be obtained without the need of fine-tuning. The signatures of supersymmetry in these spontaneously broken R-parity models are different from those of the minimal SUSY standard model. For example, SUSY particles may be singly produced and *the missing energy is always carried by neutrinos or the majoron* not by the "photino", which is unstable. In ref. [11] it was shown that these R-parity breaking effects may be large enough to be seen in the decays of the Z at LEP-1.

In the present paper we focus on the study of the processes of single and double majoron emission in the decays of the charged leptons. We summarize the results of a systematic analysis of the constraints on these branching ratios that follow from all existing observational constraints including those from laboratory, astrophysics and cosmology. We conclude that the corresponding signals of this new physics in τ and μ decays, especially single majoron emission processes, *could well be measurable experimentally*.

Upcoming facilities such as a τ factory will be ideally suited to study these new processes and restrict the parameters of these supersymmetric extensions of the standard model. Even a possible improvement on the limits on the τ-neutrino mass would *not* narrow down the possibilities discussed here, to a level that they are rendered undetectable at a τ-factory able to produce 10^7 τ's a year. From this point of view the number of τ's that will be collected at LEP alone, with upgraded luminosity, may already be encouraging.

2. An illustrative model

The possibility of generating the spontaneous violation of R-parity and lepton number was illustrated in the model proposed in ref. [10] and further studied in ref. [11]. To set up our notation we recall the basics of the model. First we give the superpotential,

$$h_u u^c Q H_u + h_d d^c Q H_d + h_e e^c l H_d + \left(h_0 H_u H_d - \mu^2\right)\Phi + h_\nu \nu^c l H_u + h \Phi \nu^c S + \text{h.c.} \tag{7}$$

This superpotential conserves *total* lepton number and R-parity. The superfields (Φ, ν_i^c, S_i) are singlets under $SU_2 \otimes U(1)$ and carry a conserved lepton number assigned as $(0, -1, 1)$ respectively. All couplings h_u, h_d, h_e, h_ν, h are described by arbitrary matrices in generation space which explicitly break flavor conservation.

The possible theoretical origin of these additional singlets, e.g. S [12, 13], and some of their possible phenomenological consequences were discussed in refs. [14–16].

In ref. [10] it was also shown how these singlets may drive the spontaneous violation of R-parity and electroweak symmetries leading to the existence of a majoron given by the imaginary part of

$$\frac{v_L^2}{Vv^2}(v_u H_u - v_d H_d) + \frac{v_L}{V}\tilde{\nu}_\tau - \frac{v_R}{V}\tilde{\nu}_\tau^c + \frac{v_S}{V}\tilde{S}_\tau , \tag{8}$$

where the isosinglet vevs

$$v_R = \langle \tilde{\nu}_{R\tau} \rangle , \qquad v_S = \langle \tilde{S}_\tau \rangle \tag{9),(10}$$

with $V = \sqrt{v_R^2 + v_S^2}$ characterize R-parity or lepton number breaking and the isodoublet vevs

$$v_u = \langle H_u \rangle , \qquad v_d = \langle H_d \rangle \tag{11),(12}$$

drive electroweak breaking and the fermion masses. The combination $v^2 = v_u^2 + v_d^2$ is fixed by the W-mass. Finally there is a small seed of R-parity breaking in the doublet sector, i.e.

$$v_L = \langle \tilde{\nu}_{L\tau} \rangle . \tag{13}$$

The magnitudes of the left-handed sneutrino vev $v_L = \langle \tilde{\nu}_{L\tau} \rangle$ is now related to the Yukawa coupling h_ν and vanishes as $h_\nu \to 0$, a possibility which is not available in the minimal model of ref. [5]. Thus one may satisfy the astrophysical limit in a natural way.

In this paper we will concentrate on the consequences of having spontaneously broken R-parity for τ and μ decays. In order to study the phenomenology of these τ and μ decays we need the relevant *chargino* mass matrix. Fortunately the form of this matrix is common to a wide class of SU(2) ⊗ U(1) SUSY models with spontaneously broken R-parity, namely [10]

$$\begin{array}{c|ccc} & e_j^+ & \tilde{H}_u^+ & -i\tilde{W}^+ \\ \hline e_i^- & h_{e\,ij} v_d & -h_{\nu ij} v_{Rj} & \sqrt{2}\, g_2 v_{Li} \\ \tilde{H}_d^- & -h_{e\,ij} v_{Li} & \mu & \sqrt{2}\, g_2 v_d \, . \\ -i\tilde{W}^- & 0 & \sqrt{2}\, g_2 v_u & M_2 \end{array} \tag{14}$$

Similarly, under reasonable approximations, there is an effective 7×7 *neutralino* mass matrix that remains after appropriately removing away any possible heavy isosinglet leptons that may be present. This matrix takes the following form [10]:

$$\begin{array}{c|ccccc} & \nu_i & \tilde{H}_u & \tilde{H}_d & -i\tilde{W}_3 & -i\tilde{B} \\ \hline \nu_i & 0 & h_{\nu ij}v_{Rj} & 0 & g_2 v_{Li} & -g_1 v_{Li} \\ \tilde{H}_u & h_{\nu ij}v_{Rj} & 0 & -\mu & -g_2 v_u & g_1 v_u \\ \tilde{H}_d & 0 & -\mu & 0 & g_2 v_d & -g_1 v_d \\ -i\tilde{W}_3 & g_2 v_{Li} & -g_2 v_u & g_2 v_d & M_2 & 0 \\ -i\tilde{B} & -g_1 v_{Li} & g_1 v_u & -g_1 v_d & 0 & M_1 \end{array} . \qquad (15)$$

In the above two equations $M_{1,2}$ denote the supersymmetry breaking gaugino mass parameters and $g_{1,2}$ are the SU(2) ⊗ U(1) gauge couplings divided by $\sqrt{2}$. We assume the canonical relation $M_1/M_2 = \frac{5}{3}\tan^2\theta w$. In some models, such as the one in ref. [10], the effective higgsino mixing parameter μ may be given as $\mu = h_0\langle\Phi\rangle$, where $\langle\Phi\rangle$ is the VEV of an appropriate singlet scalar.

The 5×5 (non-symmetric) chargino mass matrix is diagonalized by two matrices U and V, i.e.

$$\chi_i^+ = V_{ij}\psi_j^+ , \qquad \chi_i^- = U_{ij}\psi_j^- , \qquad (16),(17)$$

where the indices i and j run from 1 to 5 and $\psi_j^+ = (e_1^+, e_2^+, e_3^+, \tilde{H}_u^+, -i\tilde{W}^+)$ and $\psi_j^- = (e_1^-, e_2^-, e_3^-, \tilde{H}_d^-, -i\tilde{W}^-)$.

Similarly, the neutralino mass matrix (symmetric, due to the Pauli exclusion principle) is diagonalized by a single 7×7 matrix N, i.e.

$$\chi_i^0 = N_{ij}\psi_j^0 , \qquad (18)$$

where $\psi_j^0 = (\nu_i, \tilde{H}_u, \tilde{H}_d, -i\tilde{W}_3, -i\tilde{B})$, with ν_i denoting weak-eigenstate neutrinos. Here the indices i and j run from 1 to 7. For simplicity we assume CP invariance, which implies that these two matrices are real and, consequently, in an appropriate phase convention, also the corresponding diagonalizing matrices. Using these diagonalizing matrices one can write the electroweak currents in terms of mass-eigenstate fermions. For example, the charged current lagrangian describing the chargino–neutralino weak interaction may be written as

$$\frac{g}{\sqrt{2}} W_\mu \bar{\chi}_i^- \gamma^\mu (K_{Lik}P_L + K_{Rik}P_R)\chi_k^0 + \text{h.c.}, \qquad (19)$$

where $P_{L,R}$ are the two chiral projectors and the 5×7 coupling matrices $K_{L,R}$

may be written as

$$K_{\mathrm{L}ik} = \eta_i \left(-\sqrt{2}\, U_{i5} N_{k6} - U_{i4} N_{k5} - \sum_{m=1}^{3} U_{im} N_{km} \right), \tag{20}$$

$$K_{\mathrm{R}ik} = \epsilon_k \left(-\sqrt{2}\, V_{i5} N_{k6} + V_{i4} N_{k4} \right). \tag{21}$$

The matrix $K_{\mathrm{L}ik}$ is the analogous of the matrix K introduced in ref. [17]. Similarly,. the neutral current lagrangian describing the chargino–chargino and neutralino–neutralino weak interaction may be written as

$$\frac{g}{\cos\theta_{\mathrm{W}}} Z_\mu \{ \bar{\chi}_i^- \gamma^\mu (\eta_i \eta_k O'_{\mathrm{L}ik} P_{\mathrm{L}} + O'_{\mathrm{R}ik} P_{\mathrm{R}}) \chi_k^- + \tfrac{1}{2} \bar{\chi}_i^0 \gamma^\mu (\epsilon_i \epsilon_k O''_{\mathrm{L}ik} P_{\mathrm{L}} + O''_{\mathrm{R}ik} P_{\mathrm{R}}) \chi_k^0 \}, \tag{22}$$

where the 7×7 coupling matrices $O'_{\mathrm{L,R}}$ and $O''_{\mathrm{L,R}}$ are given as

$$O'_{\mathrm{L}ik} = \tfrac{1}{2} U_{i4} U_{k4} + U_{i5} U_{k5} + \tfrac{1}{2} \sum_{m=1}^{3} U_{im} U_{km} - \delta_{ik} \sin^2\theta_{\mathrm{W}}, \tag{23}$$

$$O'_{\mathrm{R}ik} = \tfrac{1}{2} V_{i4} V_{k4} + V_{i5} V_{k5} - \delta_{ik} \sin^2\theta_{\mathrm{W}}, \tag{24}$$

$$O''_{\mathrm{L}ik} = \tfrac{1}{2} \left\{ N_{i4} N_{k4} - N_{i5} N_{k5} - \sum_{m=1}^{3} N_{im} N_{km} \right\} = -O''_{\mathrm{R}ik}. \tag{25}$$

The η_i and ϵ_k factors are sign factors, related with the relative CP parities of these fermions, that follows from the diagonalization of their mass matrices.

As a result of R-parity breaking, the supersymmetric fermions in eqs. (14) and (15) (partners of gauge and Higgs particles) mix with the weak-eigenstate leptons. This mixing implies that the masses of the physical charged leptons, especially the τ are determined in terms of the underlying parameters, such as Yukawa couplings, differently than in the standard model. The corresponding mixing in the neutral sector implies a sizable mass for the ν_τ. For example, in the approximation where we neglect v_{L}, the τ-neutrino mass is given by

$$m_{\nu_\tau} \simeq \frac{\sum_i h_{\nu i \tau}^2 M_0 v_{\mathrm{R}}^2 v_{\mathrm{d}}^2}{h_0 \langle \Phi \rangle (2 v_{\mathrm{u}} v_{\mathrm{d}} M_0 - h_0 \langle \Phi \rangle M_1 M_2)}, \tag{26}$$

where we have set $M_0 = g_1^2 M_2 + g_2^2 M_1$. On the other hand ν_{e} remains massless, while ν_μ acquires a very small mass. For reasonable choices of the parameters, the mass of ν_τ is in conflict with the cosmological limit on stable neutrinos [18].

Fortunately, the structure of the SUSY fermion mass matrices, eqs. (14) and (15), and of the corresponding majoron couplings implies that there are new decay modes for the leptons (as well as the SUSY fermions) involving majoron emission. For the case of neutrinos these models naturally realize the possibility of having a new mode of neutrino decay involving majoron emission [19, 20],

$$\nu_\tau \to \nu + \mathrm{J}\,. \tag{27}$$

These two-body decay lifetimes are much faster than required by cosmology so as to efficiently suppress the relic ν_τ contribution, for a wide range of values of the parameters. Moreover, these decays are *invisible* and therefore of the type that is allowed by astrophysics [1]. As a result, in all of these models m_{ν_τ} can be as large as allowed by laboratory experiments. This enables the effects upon μ and τ decays to be correspondingly enhanced. It is precisely the study of the corresponding non-standard decay properties of the charged leptons that is the subject of our present work. First we summarize the observational constraints relevant in our analysis.

3. Experimental constraints

There are important restrictions on the parameters of any supersymmetric extension of the standard model, such as the spontaneously broken R parity models. These follow from several collider experiments, such as the recent LEP data on Z decays and $\bar{\mathrm{p}}\mathrm{p}$ collider data, e.g. on $\mathrm{W}^\pm, \mathrm{Z}^0$ and gluino production. In addition to these constraints, there are important restrictions, characteristic of broken R-parity models, related to weak interactions and neutrino mass considerations. These follow from laboratory, astrophysics and cosmology. This second group of constraints plays a very important role for our present analysis, since they are found to exclude many parameter choices that are allowed by the collider constraints, while the converse is not true. We now give the list of the relevant constraints in the first group used in our present analysis:

(1) The heavy sector of the matrix (14) leads to two heavy *charginos* (i.e. charged supersymmetric partners of gauge and Higgs bosons). The lightest of these charginos, denoted $\chi^\pm$, has not yet been produced in Z^0 decays in LEP [8], leading to the mass limit

$$m_{\chi^\pm} \geqslant 45\ \mathrm{GeV}\,. \tag{28}$$

(2) The recent measurements of the Z widths at LEP give [8]

$$\Gamma_{\mathrm{Z}}^{\mathrm{total}} \lesssim 2522\ \mathrm{MeV} \quad (95\%\ \mathrm{C.L})\,. \tag{29}$$

These measurements restrict the additional decay channels of the Z involving charginos and neutralinos, present in any SUSY model, such as our broken R-parity model.

(3) LEP limits on the invisible Z width [8]

$$\Gamma_Z^{\rm inv} = 482 \pm 16 \text{ MeV} \Rightarrow \Gamma_Z^{\rm inv} \lesssim 510 \text{ MeV} \quad (95\% \text{ C.L.}) . \tag{30}$$

These measurements restrict the additional contributions involving invisibly decaying neutralinos, present in the R-parity broken models.

(4) The CDF lower limit on the gluino mass $m_{\tilde{g}}$ [21] restricts the soft supersymmetry breaking electroweak gaugino mass parameter,

$$M_2 > 20 \text{ GeV} . \tag{31}$$

(5) $p\bar{p}$ collider limits on the ratio $R = \sigma_{W^\pm} \text{Br}(W^\pm \to e^\pm \nu)/\sigma_Z \text{Br}(Z \to e^+e^-)$ imply [22]

$$0.825 \leqslant \frac{R}{R_{\rm SM}} \leqslant 1.091 , \tag{32}$$

while in SUSY models there are additional possible contributions involving charginos and neutralinos, produced in virtual W or Z decays.

(6) LEP constraints on the hadronic peak cross section [8]

$$\sigma_0^{\rm had,T} \simeq 3.88 \times 10^5 \frac{12\pi}{M_Z^2} \Gamma_{ee} \frac{\Gamma_{\rm had}}{(\Gamma^{\rm total})^2} \text{ (nb)} \tag{33}$$

versus total Z width are given as an allowed ellipsis $(\sigma_0^{\rm had}, \Gamma_Z^{\rm total})$. In a SUSY model, such as ours, the Z hadronic width in principle receives contributions from hadronically decaying neutralinos.

The constraints in the second group relevant for our analysis are given below:

(1) In spontaneously broken R-parity models, total lepton number is necessarily violated. Even though the seed of this violation lies in the τ-sector, i.e. mostly τ-number is violated, in general lepton mixing effects exist and transfer L-breaking effects also to the L_e sector, where it is very well tested. The non-observation of neutrinoless double β-decay then implies a very stringent constraint, i.e.

$$\langle m \rangle = \sum_i K_{Lei}^2 m_i \leqslant 3 \text{ eV} , \tag{34}$$

where we neglect the induced right-handed current interaction arising from R-parity breaking (see eq. (19)). In practice in our model the sum in eq. (34) has really just one dominant term, namely the heavy τ-neutrino contribution. For large masses of the ν_τ we have modified eq. (34) in order to take into account the effects of the two-nucleon correlation function, as in ref. [23].

(2) Neutrino oscillation data and direct searches for anomalous peaks on the energy distribution of the electrons and muons coming from the decays such as $\pi, K \to e\nu$ and $\pi, K \to \mu\nu$ lead to constraints on the mixing matrix elements K_{Lei} and $K_{L\mu i}$ $(i = 3)$ [24].

(3) The ARGUS limit on the τ-neutrino mass,

$$m_{\nu_\tau} \leqslant 35 \text{ MeV}, \tag{35}$$

is a restrictive constraint on spontaneously broken R-parity models since, as seen above, in these models the τ-neutrino may acquire a large mass from the mixing with the heavy neutralinos. Moreover, if it were stable, the ν_τ would easily violate the standard cosmological limit.

(4) The limits on the μ and τ lifetimes impose severe restrictions on the parameters of these models, especially in connection with the search for possible distortions in their decay spectra associated with double majoron emission processes.

(5) The existence of fermion states that cannot be kinematically produced in low-energy weak decays changes the relative rates of various such processes, for instance β- or μ-decays, leading to universality violations. The resulting constraints were discussed in ref. [1] and have been implemented.

(6) The cosmological limit on the ν_τ decay lifetime implies

$$\tau \lesssim 1.5 \times 10^7 \text{ yr} \left(\frac{m_{\nu_\tau}}{\text{keV}} \right)^{-2} \tag{36}$$

for $m_{\nu_\tau} \lesssim$ few MeV. For larger ν_τ-masses the limit is weaker, due to the Boltzmann suppression. This constraint is normally easy to satisfy in this model due to the invisible decay mode $\nu_\tau \to \nu + J$, where J is the majoron [20].

(7) The limits on lepton flavour violating processes such as $\mu \to e + \gamma$ and $\mu \to 3e$ and the corresonding τ-decay processes [24]. In this model the $\mu \to e + \gamma$ decay process occurs only at one-loop level, while the three-lepton decays can arise at the tree level due to the existence of flavour changing couplings of the Z^0 to charged leptons.

(8) The limits on lepton flavour violating decays with single majoron emission. The present experimental limit from TRIUMF on $\mu \to e + J$ is $\text{Br}(\mu \to e + J) \leqslant 2.6 \times 10^{-6}$, while the MARK-III τ-decay limits are $\text{Br}(\tau \to e + J) \leqslant 7.12 \times 10^{-3}$ and $\text{Br}(\tau \to \mu + J) \leqslant 2.25 \times 10^{-2}$ [6].

This list expands those constraints that are relevant for the analysis of purely supersymmetric signatures previously studied in refs. [1, 11, 25] in that it is now crucial to also include constraints on flavour and/or total-lepton-number-violating processes such as those arising from the non-observation of neutrino oscillations, neutrinoless double β decay, etc.

4. Majoron emission in μ and τ decays

We now focus on the general study of the decay properties of the charged leptons in spontaneously broken R parity models of the type considered in sect. 2. The spectrum of the charged lepton decays could in principle be modified both by single and double majoron emission processes, as shown in fig. 1. To determine these deviations we use the mass eigenstates obtained by diagonalizing eq. (14), given in eq. (17). In terms of the chargino diagonalizing matrices U and V introduced earlier the effective lagrangian interaction of the majoron with charged fermions may be given as

$$\frac{i}{\sqrt{2}} J\bar{\chi}_j\{\eta_k P_{\mathrm{L}} A_{kj} - \eta_j P_{\mathrm{R}} A_{jk}\}\chi_k \,, \tag{37}$$

where χ_i^- are negatively charged Dirac spinors composed out of the two 2-component mass eigenstate fermions obtained, for each value of i, from diagonalizing their mass matrix, eq. (17). From eq. (37) we can derive the amplitudes for the decay rates of μ and τ with single as well as double majoron emission. For example, single majoron emission in μ decay is determined when $k \to \mu$ and $j \to \mathrm{e}$. Similarly for the case of single majoron emission in τ-decays the possible assignments are $k \to \tau$ and $j \to \mathrm{e}, \mu$. The matrix A may be obtained, in a good approximation, from the matrices U and V as follows:

$$A_{jk} = \sum_{i=1}^{3} h_{\nu i3} U_{ji} V_{k4} \frac{v_{\mathrm{R}}}{V} \,. \tag{38}$$

The corresponding charged lepton decay width is given as

$$\Gamma(e_k \to e_j + \mathrm{J}) = \frac{m_k}{32\pi}\left[A_{kj}^2 + A_{jk}^2\right] \tag{39}$$

and from this the single majoron emission branching ratio is easily determined.

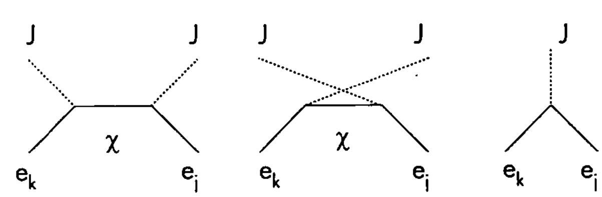

Fig. 1. Feynman diagrams for single and double majoron emission processes

The double majoron emission process of fig. 1 could in principle lead to spectral changes in μ- and τ-decays, such as in the Michel parameter. The corresponding amplitude is given by

$$M = M_1 + M_2 = i\bar{u}_j(p) m_k P_R u_k(q) \sum_{\alpha=4}^{5} \frac{O_{j\alpha} O_{k\alpha}}{M_\alpha^2}, \tag{40}$$

where we have set $O_{j\alpha} = \eta_j A_{j\alpha}$. In eq. (40) we only included the heavy chargino exchange and neglected the final lepton mass. This gives an extra contribution to the charged lepton differential decay rate, given by

$$\mathrm{d}\Gamma_{\mathrm{SUSY}}(e_k \to e_j + \mathrm{J} + \mathrm{J}) = \frac{m_k^5}{(2\pi)^4 2^7} \left| \sum_\alpha \frac{O_{j\alpha} O_{3\alpha}}{M_\alpha^2} \right|^2 x^2 \,\mathrm{d}x \,\mathrm{d}\Omega, \tag{41}$$

leading to

$$\Gamma_{\mathrm{SUSY}}(e_k \to e_j + \mathrm{J} + \mathrm{J}) = \frac{G_\mathrm{F}^2 m_k^5}{192\pi^3} \epsilon, \tag{42}$$

where ϵ is defined as

$$\epsilon = \tfrac{1}{8} \left| \sum_\alpha \frac{O_{j\alpha} O_{k\alpha}}{G_F M_\alpha^2} \right|^2. \tag{43}$$

As a result their effect upon the μ Michel parameter

$$\Delta\rho = \frac{\epsilon/2}{1+\epsilon} \tag{44}$$

is negligibly small in view of the stringent constraints on the μ-lifetime. For the case of τ-decays this could in principle give rise to a sizable change in ρ. However, this is found not to be allowed in the model, once the phenomenological restrictions are consistently implemented (see sect. 5).

Lepton exchange and chargino–lepton interference contributions could also give rise to different decay spectra, not parametrizable as in eq. (44). However, here we expect their magnitudes to be doubly and singly suppressed, respectively, with respect to eq. (41), since they explicitly involve R-parity violating couplings.

5. Results and discussion

With all the constraints discussed in sect. 3 we have determined the regions in parameter space allowed by experiment. A specially important role is played in our analysis by constraints related to flavour and/or total-lepton-number-violating processes such as those arising from the non-observation of neutrino oscillations, neutrinoless double β decay, etc. Our global study of the constraints presented here updates the earlier results of ref. [11] also by the inclusion of the more recent data, e.g. from LEP, although the results basically agree in this respect. The presently allowed region of the parameters in spontaneously broken R parity models is the relevant one for the study of anomalous μ and τ decays.

We now present a summary of our study of the phenomenological implications of the spontaneously broken R parity models for μ and τ decays. The rates for anomalous decays have been determined as a function of the relevant parameters such as the SUSY parameters μ and M_2 in the range given by*

$$20 \leqslant \frac{M_2}{\text{GeV}} \leqslant 250, \qquad -250 \leqslant \frac{\mu}{\text{GeV}} \leqslant 250. \tag{45),(46}$$

For definiteness we assume $v_R = v_S$ and fix the values $v_R = 1$ TeV and $v_L = 100$ MeV. We also fix a characteristic value for

$$\tan\beta = \frac{v_u}{v_d}, \tag{47}$$

such as $\tan\beta = 4$, $\tan\beta = 6$, $\tan\beta = 10$, $\tan\beta = 20$ and $\tan\beta = 40$. The rates for anomalous τ decays are controlled by the parameter h_ν which also determines the neutrino mass, eq. (26). These are varied randomly in the interesting range given by

$$10^{-10} \leqslant h_{\nu 13}, h_{\nu 23} \leqslant 10^{-1}, \qquad 10^{-4} \leqslant h_{\nu 33} \leqslant 10^{-1}. \tag{48),(49}$$

We have performed a careful sampling of the points in our parameter space that are allowed by all the constraints discussed above, in order to evaluate the attainable magnitudes of the modifications in the μ and τ decay spectra that can arise from majoron emission processes.

First we studied the effects of double majoron emission. We calculated the values of these double majoron emission rate arising from chargino exchanges, eq. (41). We found it to be too small, relative to the normal μ and τ decay rates, if the parameters lie in the region allowed by experiment. We also verified explicitly that our intuition regarding the relative importance of lepton and lepton–chargino interference contributions is correct, i.e. that these rates are even smaller than pure chargino exchange contribution. As a result these double majoron emission processes can not produce any measurable spectral distortion effects in a way that is consistent with observation. This situation contrasts sharply with that in the

* It is always possible, if CP is conserved in this sector, to choose $M_2 > 0$, while μ may have either sign.

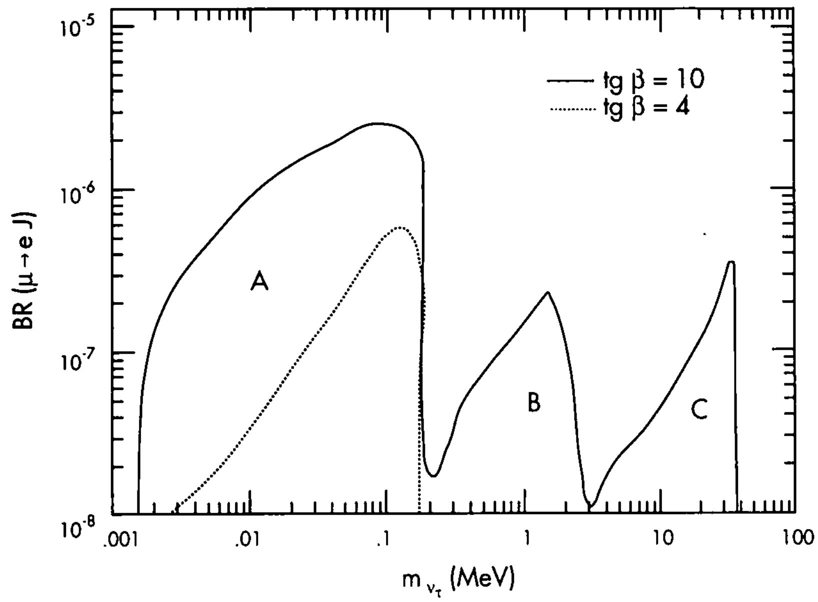

Fig. 2. Range of ν_τ mass values for which the single majoron emission μ- decay branching ratio is in the interesting range $10^{-8} \leqslant \mathrm{Br}(\mu \to \mathrm{e} + \mathrm{J}) \leqslant 2.6 \times 10^{-6}$. The value $\mathrm{Br}(\mu \to \mathrm{e} + \mathrm{J}) \leqslant 2.6 \times 10^{-6}$ is the present experimental limit from TRIUMF [6]. The points in the region delimited by the solid contours correspond to $\tan\beta = 10$ while those inside the dashed contours correspond to $\tan\beta = 4$. All of the observational constraints of sect. 3 have been imposed.

model of ref. [5], that manifestly violates the present experimental limit on the Z invisible width from LEP.

We now move to single majoron emission processes. In fig. 2 we display the attainable values of the single majoron emission muon decay branching ratios as a function of the τ-neutrino mass. The figure shows the range of ν_τ mass values for which the single majoron emission muon decay branching ratio is in the interesting ranges $10^{-8} \leqslant \mathrm{Br}(\mu \to \mathrm{e} + \mathrm{J}) \leqslant 2.6 \times 10^{-6}$. The points inside the solid contours obey all the observational constraints of sect. 3 including the present experimental limit from TRIUMF $\mathrm{Br}(\mu \to \mathrm{e} + \mathrm{J}) \leqslant 2.6 \times 10^{-6}$ [6]. They correspond to $\tan\beta = 10$. We also found that about one half of the allowed points with $\mathrm{Br}(\mu \to \mathrm{e} + \mathrm{J}) \geqslant 10^{-8}$ fall inside the region B, about one third inside region C and less than 20% inside region A. Similarly the inner dashed contour gives the same information for the case $\tan\beta = 4$. We verified explicitly that the results are more favorable for larger $\tan\beta$ values.

In fig. 3 we display the range of ν_τ mass values for which the single majoron emission τ-decay branching ratio is in the interesting ranges $10^{-6} \leqslant \mathrm{Br}(\tau \to \mu + \mathrm{J}) \leqslant 2.25 \times 10^{-2}$. The value $\mathrm{Br}(\tau \to \mu + \mathrm{J}) \leqslant 2.25 \times 10^{-2}$ is the present experimental limit from MARK-III [6] while the other values fall well within the sensitivities of

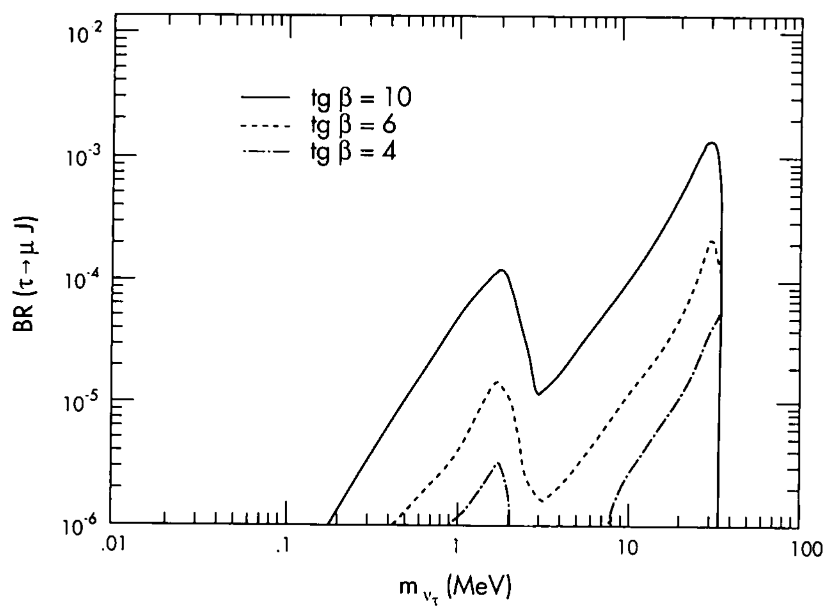

Fig. 3. Range of ν_τ mass values for which the single majoron emission τ-decay branching ratio is in the interesting range $10^{-6} \leqslant \mathrm{Br}(\tau \to \mu + \mathrm{J}) \leqslant 2.25 \times 10^{-2}$. The value $\mathrm{Br}(\tau \to \mu + \mathrm{J}) \leqslant 2.25 \times 10^{-2}$ is the present experimental limit from MARK-III [6]. The points in the region delimited by the solid contours correspond to $\tan\beta = 10$ while those inside the dashed contour correspond to $\tan\beta = 6$ and those inside the dot-dashed contour correspond to $\tan\beta = 4$. All of the observational constraints of sect. 3 have been imposed.

the proposed τ factories [2]. The points contained inside the region delimited by the solid contour correspond to $\tan\beta = 10$ while those inside the dashed contour correspond to $\tan\beta = 6$ and the dot-dashed are for $\tan\beta = 4$. Again the observational constraints of sect. 3 make the enhanced branching ratios more likely for larger $\tan\beta$ values.

Finally, fig. 4 gives the corresponding information of fig. 3 for the case of the decay $\tau \to \mathrm{e} + \mathrm{J}$. Here contours are plotted for $\tan\beta = 10$, $\tan\beta = 20$ and $\tan\beta = 40$.

Our results indicate that the flavour-violating μ and τ decay processes with single majoron emission could lead to observable effects for a wide range of the allowed parameters, even at a level similar to the present sensitivities of μ decay experiments [6]. Particularly encouraging from this point of view are the prospects for physics at a τ factory and at LEP. In contrast, we find that the flavour-violating μ and τ decay processes with double majoron emission *cannot* appreciably modify the μ or τ decay spectra, without conflicting with observation.

In summary, we showed that the μ and τ decay properties may be substantially modified with respect to the standard model predictions. These effects are all consistent with the existing constraints that follow from neutrino physics, astro-

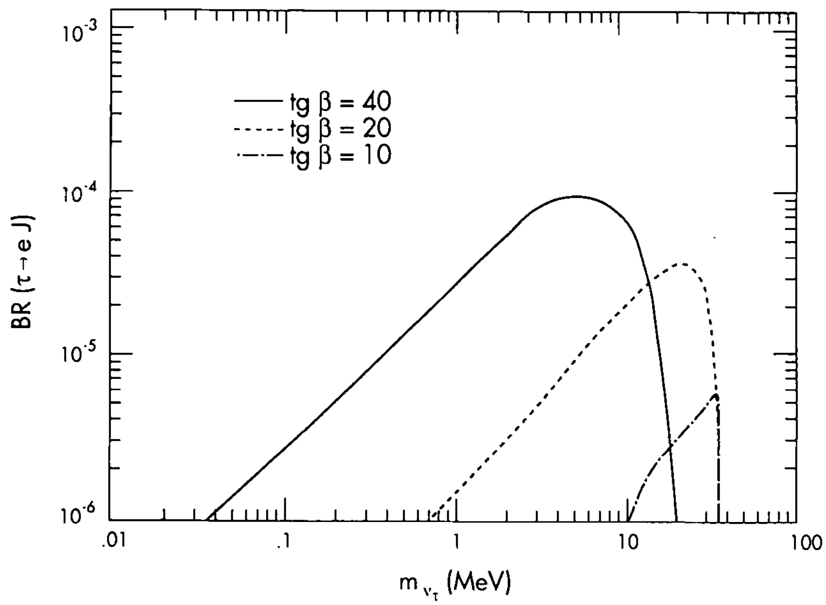

Fig. 4. Same as fig. 3 for the case of the decay $\tau \to e + J$. In this case the attainable branching ratios are in the range $10^{-6} \leqslant Br(\tau \to e + J) \leqslant$ few $\times 10^{-4}$, as β varies between $\tan\beta = 10$ and $\tan\beta = 40$. This is to be contrasted with the experimental limit $Br(\tau \to e + J) \leqslant 7.12 \times 10^{-3}$. The points in the region delimited by the solid contours correspond to $\tan\beta = 40$ while those inside the dashed and dot-dashed ones correspond to $\tan\beta = 20$ and $\tan\beta = 10$, respectively. All of the observational constraints of sect. 3 have been imposed.

physics and cosmology. In particular they are perfectly consistent with the present limit on the ν_τ mass. By tightening this limit one expects that a τ factory would also limit the new possibilities discussed here. Our figures show, however, that our anomalous decays can be sizable even for values of the τ-neutrino mass *below* the values ~ 5 MeV that can be probed at a τ factory [2]. This further highlights the physics case for building a high luminosity source of τ-leptons, and stresses the complementarity of the physics discussed here with the direct searches for ν_τ mass effects.

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