SUSY WITHOUT $R$-PARITY:
SYMMETRY BREAKING AND LSP-PHENOMENOLOGY
Ralf Hempfling
Davis Institute for High Energy Physics
Davis, CA 95616, USA
E-mail: hempf@bethe.ucdavis.edu

ABSTRACT
We have studied the predictions for the LSP decay within the framework of a radiatively broken unified supergravity model without $R$-parity. Assuming that Higgs/slepton mixing is the only source of $R$-parity breaking and responsible for the observed neutrino oscillations we obtain predictions for the LSP life-time and branching fractions.

1. Motivation

Supersymmetry is presently the most popular attempt to solve the hierarchy problem of the standard model (SM). Here, the cancellation of quadratic divergences is guaranteed and, hence, any mass scale is stable under radiative corrections. The most economical candidate for a realistic model is the minimal supersymmetric extension of the SM (MSSM). In the SM baryon and lepton number are protected by an accidental symmetry (i.e. there is no gauge and Lorentz invariant term of dimension 4 or less that violates $B$ or $L$ via perturbative effects). This no longer holds in the MSSM due to the existence of superpartners. One way to assure Baryon and Lepton number conservation (and hence the stability of the proton) is to impose by hand a discrete, multiplicative symmetry called $R$-parity, $R_p = (-1)^{2S+3B+L}$, where $S$, $B$ and $L$ are the spin, baryon and lepton numbers, respectively. Aside from the long proton life-time, $R_p$ conserving models have the very attractive feature that the lightest supersymmetric particle (LSP) is stable and a good cold dark matter candidate which can be accounted for if $R_p$ is broken.

In this paper, we will investigate the LSP life-time in a SUSY-GUT scenario where $R_p$ is broken explicitly via dimension 2 terms. We have discussed this model detail in ref. where the emphasis was on neutrino phenomenology in the frame-work of radiative electro-weak spontaneous symmetry breaking (REWSSB). Here, we are particularly interested in the implications for high energy collider phenomenology. We will focus attention of the case that the LSP is a neutralino. This is the most interesting case, since it occurs naturally over most of the SUSY parameter space. Note, however, that in models with broken $R_p$ there is no theoretical/cosmological prejudice concerning the color or electric charge of the LSP. The only requirement is that the LSP life-time is sufficiently short ($\tau_{LSP} \ll 1$ sec) so as not to disturb big
bang nucleosynthesis \( \tau_{\text{LSP}} \gtrsim 10^{24} \text{ sec} / B(\text{LSP} \rightarrow X\nu_\ell) \) so as not to lead to an unacceptable distortion of the cosmic microwave background.

The most general gauge invariant superpotential can be written as

\[ W = \frac{1}{2} y^L_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + y^D_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^c - y^U_{ijk} \hat{H} \hat{Q}_j \hat{U}_k^c - \mu \hat{L}_i \hat{H} + \frac{1}{2} \tilde{y}^D_{ijk} \hat{D}_i^c \hat{D}_j^c \hat{U}_k^c, \]

(1)

where the supermultiplets are denoted by a hat. The left-handed lepton supermultiplets are denoted by \( \hat{L}_i \) \( (i = 1, 2, 3) \) and the Higgs superfield coupling to the down-type quarks is denoted by \( \hat{L}_0 \).

Let us first determine the meaning of the various terms of eq. 1. Here, \( y^L_{ijk}, y^D_{ijk} \) and \( y^U_{ijk} \) denote the lepton, down-type and up-type Yukawa couplings, respectively, and \( \mu_0 \) is the Higgs mass parameter. However, in contrast to the SM the MSSM allows for renormalizable baryon [lepton] number violating interactions \( \tilde{y}^D_{ijk} \) [\( y^L_{ijk} \) and \( \mu_0 \)]. These couplings are constrained from above by experiment. The most model independent constraints can be obtained from collider experiments or neutrino physics. It turns out that the individual lepton and baryon number violating couplings only have to be smaller than \( O(10^{-3} \sim \text{few} \times 10^{-1}) \) with the exception of \( \tilde{y}^D_{121} \lesssim 10^{-7} \) from heavy nuclei decay. Thus, the \( R_p \) violating couplings need not be much more suppressed than the lepton and baryon number preserving Yukawa couplings. (remember that e.g., \( y^D_{011} \simeq 3 \times 10^{-5} / \cos \beta \)). Somewhat stronger but more model dependent constraints can be derived from cosmology.

However, the experimental exclusion area can be strongly enhanced by imposing theoretical constraints: in the minimal SU(5) SUSY-GUT model, the right-handed leptons, the right-handed up-type quarks and the left-handed quarks are embedded in a 10-dim representation, \( 10_i = E_i^c \oplus U_i^c \oplus Q_i \). The right-handed down-type quarks and the left-handed leptons are embedded in a 5-dim representation, \( 5_i = D_i \oplus L_i \). The two Higgs doublets are embedded together with two proton decay mediating colored triplets, \( T \) and \( D_0 \), in 5-dim representations, \( 5_0 = D_0 \oplus L_0 \) and \( 5 = T \oplus H \). Hence, both the lepton and the baryon number violating interactions arise from the term

\[ W_{\text{GUT}} = \frac{1}{2} y_{ijk} \bar{\Phi}_i \Phi_j \Phi_k, \]

(2)

where the boundary conditions at the GUT-scale, \( M_{\text{GUT}} \), are given by \( y^L_{ijk} = y^D_{ijk} = \tilde{y}^D_{ijk} = y_{ijk} \). These relations, which predict the down-type quark masses correctly to within a factor of 3, are expected to also hold at a comparable level for the \( R_p \) violating couplings. Thus, in general the baryon and lepton number violating couplings are correlated in SUSY GUT models. This leads to very strong constraints on any \( y_{ijk} \) from proton stability which are much stronger than any constraint on individual Yukawa couplings. However, it does not place any constraints on the coefficients of dimension 2 terms, \( \mu_i \), which are the subject of this paper.

The outline of our paper is as follows: in section 2 we present the neutrino and sparticle spectrum obtained from REWSSB including \( \mu_i \). In section 3 we present
the numerical analysis of the LSP life-time, $\tau_{LSP}$, and LSP branching fractions. Our conclusions are presented in section 4.

2. Radiative Electro-Weak Symmetry Breaking

Without any assumptions based on theoretical prejudice there are many models with different SUSY particle spectra and vastly different phenomenology. Thus, it has become standard to derive the low energy particle spectrum from minimal supergravity model with only four independent parameters: the universal scalar mass parameter, $m_0$, the universal gaugino mass parameter, $m_{1/2}$, and the universal $A$ ($B$) parameter multiplying the tri-linear (bi-linear) terms in the superpotential [eq. 1]. This approach is supported by the observation that the absence of FCNC implies a high mass-degeneracy of all scalars with the same gauge quantum numbers (with the possible exceptions of the Higgs mass parameters).

First, we have to minimize the Higgs potential given by

$$V = \left(\mu^2 + m_H^2\right) H^\dagger H + \left(\mu_I\mu_J + m_{L_{1,2}}^2\right) \bar{L}_I^\dagger \bar{L}_J - B_{IJ}\mu_I \left(\bar{L}_J H + H.c.\right)$$

$$+ g^2 + g'^2 \left(\left|H^\dagger H - \bar{L}_J^\dagger \bar{L}_I\right|^2 + \left|H^\dagger \bar{L}_I\right|^2\right),$$

where the low energy soft SUSY breaking parameters are obtained by renormalization group evolution below $M_{GUT}$ in the standard fashion. In order to stay as close to the notation of the MSSM as possible we follow our notation of ref. [4]

$$\bar{v} \equiv \frac{(H^0)}{\sqrt{2}}, \quad v_I \equiv \frac{(\bar{L}_I^0)}{\sqrt{2}}, \quad v \equiv \sqrt{v_I v_I},$$

and we parameterize the VEVs in terms of spherical coordinates

$$\tan \theta'_3 = \frac{v_3}{v_2}, \quad \tan \theta'_2 = \frac{v_2}{v_1 \cos \theta'_3}, \quad \tan \theta'_1 = \frac{v_1}{v_0 \cos \theta'_2}.$$
Analogously, it is convenient to parameterize the $R_p$ breaking mass parameters in terms of three mixing angles

$$
\tan \theta_3 = \frac{\mu_3}{\mu_2}, \quad \tan \theta_2 = \frac{\mu_2}{\mu_1 \cos \theta_3}, \quad \tan \theta_1 = \frac{\mu_1}{\mu_0 \cos \theta_2},
$$

and $\mu \equiv \sqrt{\mu_1 \mu_2}$. The potential in eq. 3 is minimized by an iterative procedure using the analytic solution for $\tan \theta_1 = 0$ as our initial values. This procedure also works surprisingly well for $\tan \theta_1 > 1$. For small $R_p$ violating parameters we can also obtain very reliable analytic expressions in the basis where $y_{ij}^L$ is diagonal by expanding in powers of $\mu_i/\mu_0$.

$$
\sin 2\beta = \frac{2B_{00}\mu_0}{m_{L_{00}}^2 + m_H^2 + 2\mu_0^2},
$$

$$
\tan^2 \beta = \frac{m_{L_{00}}^2 + \mu_0^2 + \frac{1}{2}m_2^2}{m_H^2 + \mu_0^2 + \frac{1}{2}m_2^2},
$$

$$
v_i = \frac{\mu_i}{m_{L_{i(i)}} + \frac{1}{2}m_2^2 \cos 2\beta}.
$$

with the convention that indices in braces are not summed over. In general, one fixes the GUT input parameters are $m_0$, $m_{1/2}$ and $A_0$. $B_{00}$ and $\mu$ are obtained by solving
eq. 7 and 8 while keeping $\tan\beta$ and $v$ fixed. Here, we find it convenient to fix the fermionic spectrum given by $\mu$ rather than the scalar spectrum determined by $m_0$.

In fig. 1(a) and (b) we present contours of constant GUT parameters $m_0$ and $B_0$ in the $\tan\beta-m_{1/2}$ plane. and in fig. 1(c) we show how well the approximation works for the minimization of the potential (eq. 9). We see that the deviation of the approximation obtained from eq. 9 denoted by $\sin\theta_1^{\text{app}}$ from the true minimum obtained by numerical methods and denoted by $\sin\theta_1'$ is quite small as long as $\tan\beta = O(1 \sim 10)$. However, it breaks down for $\tan\beta \gtrsim 40$.

### 2.1. Sparticle Spectrum

From LEP experiments we know that there are no charged superpartners with mass below $m_Z/2$. Furthermore, we can deduce a similar constraint on the lightest neutralino which, in our model, is instable. In fig. 2 and 3 we present contours of some relevant scalar and fermionic superpartner masses in the $\tan\beta-m_{1/2}$ plane. We have chosen $A_0 = 0$ and $\mu = 2.5m_{1/2}$. The value of $m_0$ is obtained by imposing REWSSB [see fig. 1(a)]. We see that the only relevant constraint arises from the experimental lower on the lightest neutralino mass denoted by $M_{\text{LSP}}$.

### 2.2. Neutrino Spectrum

The LSP phenomenology of the model under investigation here is governed to a very good approximation by only one parameter, $\tan\theta_1$. This parameter also determines the neutrino masses whose upper limits are given by

$$m_{\nu_e} \leq 4.35\text{ eV}, m_{\nu_\mu} \leq 160\text{ keV}, m_{\nu_\tau} \leq 23\text{ MeV}, \quad \text{Collider-experiment}^{19}$$

$$\sum_{x=e,\mu,\tau} m_{\nu_x} \leq (10 \sim 100)\text{ eV}, \quad \text{Cosmology}^{20} \quad (10)$$
Fig. 4. Contours of constant (a) $m_{\nu_e}^2 - m_{\nu_\tau}^2$ (b) $\sin^2 2\theta_{\tau\nu_\mu}$ in the $\tan \beta - M_{LSP}$ plane. We set $A_0 = 0$ and $\mu = 2.5m_{1/2}$ and $m_{1/2}$ is replaced in favor of $M_{LSP}$.

While there is no direct evidence for non-zero neutrino masses, there is strong experimental evidence for neutrino oscillations which imply that the three neutrinos are non mass-degenerate. In this work, we will take the view that our $R_p$ violating terms are the only source of neutrino masses and, therefore, should account for all the existing neutrino mixing effects. Since not all experimental indication for neutrino oscillations appear compatible with each other or have the same statistical significance a selection has to be taken.$^a$ The solar neutrino puzzle$^2$ may be the most compelling evidence for neutrino mixing. However, the effect appears to involve only the first two neutrino flavors neither of which is likely to be the heaviest neutrino both on theoretical and experimental grounds. Thus, the solar neutrino puzzle is not well suited for a determination of $\tan \theta_1$. Instead we choose to solve the atmospheric neutrino problem.$^3$ This requires that we fix $\tan \theta_1$ such that $m_{\nu_e}^2 - m_{\nu_\mu}^2 = 10^{-2}$ eV$^2$ and we set $\tan \theta_2 = 1$ (we use a small value for $\tan \theta_3 = 0.045$ in order to solve the solar neutrino puzzle via the MSW-effect$^2$; this angle will turn out to be quite irrelevant otherwise). Over most of the parameter space under consideration here this implies $m_{\nu_\mu} \ll m_{\nu_e} \simeq 0.1$ eV. It is then straightforward to obtain lower limits on $\tau_{\nu_\mu}$ from upper limits on $m_{\nu_e}$ [eq. 11] by simple scaling arguments.

$^a$It has recently been suggested that three neutrino flavor are enough to accommodate all three indication for neutrino oscillation$^2$. However, for the sake of generality we will be more conservative.
In fig. 4 we present contours of constant values for \(m^2_{\nu_\mu} - m^2_{\nu_e}\) and \(\sin^2 2\theta_{\mu\nu}\). We fix \(\mu = \pm 2.5m_{1/2}\) and \(A_0 = 0\). We see that for positive values of \(\mu\) the mass difference \(m^2_{\nu_\mu} - m^2_{\nu_e} = O(10^{-9} \text{ eV}^2)\) is very small and quite compatible with long wave oscillation (LWO) solution to the solar neutrino problem [fig. 4 does not change if we set \(\tan \theta_3 = O(1)\)]. For \(\mu < 0\) there is a sizable region where \(m^2_{\nu_\mu} - m^2_{\nu_e} = O(10^{-5} \text{ eV}^2)\) as required by the MSW explanation of the solar neutrino deficiency\(^4\). These results were first presented in ref. 7. \(^3\)

### 3. LSP Phenomenology

In this section, we will discuss the decay properties of the LSP. The main interest from the point of view of collider phenomenology is the question whether the LSP decays inside the detector (else the analysis is equivalent to the case of unbroken \(R_p\)).

Since the magnitude of \(R_p\) violation is parameterized by an a priori free parameter \(\tan \theta_1\), we cannot determine \(\tau_{\text{LSP}}\). The situation changes if we relate \(\tan \theta_1\) to the neutrino masses. In the first part of this section we will present the prediction for \(\tau_{\text{LSP}}\) assuming the atmospheric neutrino puzzle is a result of \(R_p\) violation. [This prediction can be turned into a lower limit by imposing any of the upper limits on \(m_{\nu_e}\) of eq. (11).] In the second part of this section, we will discuss the branching fractions of the LSP which is independent of \(\tan \theta_1\) and, hence, also of any assumption about neutrino masses.

#### 3.1. LSP life-time

As pointed out in ref. \(^8\) in models without \(R_p\) the neutrinos and neutralinos are

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\(^3\)Note that fig. 7(a), fig. 8(a) and fig. 9 are mislabeled in ref. \(^7\). The region with \(\mu > 0\) and the region with \(\mu < 0\) should be interchanged.
indistinguishable. As a result, the formulae for the neutralino radiative decay in the MSSM\(^2\) and the decay into three fermions\(^2\) can be directly generalized to our model. However, we do have to include the effects of Yukawa couplings which were neglected for \(R_p\) preserving three-body decays\(^3\). Our complete set of formulae will be presented elsewhere\(^2\). Here, we simply present our numerical results.

In fig. 5 we have plotted \(\Gamma_{LSP} vs. \tan \theta_1\). We find that there are simple scaling relations if \(R_p\) violation is sufficiently small (say \(\tan \theta_1 \lesssim 0.1\)):

\[
\Gamma_{LSP}, m_{\nu_x} \propto \tan^2 \theta_1 \quad (x = e, \mu, \tau). \tag{11}
\]

The parameters \(\tan \theta_2\) and \(\tan \theta_3\) which govern the neutrino oscillations have only a small impact on the LSP properties. In fig. 6 we present contours of \(\tan \theta_1\) (fixed by imposing \(m_{\nu_x}^2 - m_{\nu_x}^2 = 10^{-2} \text{ eV}^2\)) and constant \(m_{LSP}\) in the \(\tan \beta - M_{LSP}\) plane for \(\mu = \pm 2.5 m_1/2\). We find that that required range of the \(R_p\) violation is \(\tan \theta_1 = 10^{-x}\) \((x = 2 \sim 5)\) with the upper (lower) limit corresponding to small (large) values of \(\tan \beta\). The corresponding range of the LSP life-time is \(c \tau_{LSP} = 1 \text{ m } \sim 0.1 \text{ mm}\) (for \(M_{LSP} = 40 \sim 160 \text{ GeV}\)) and can easily be determined at forthcoming collider experiments. Furthermore, we need larger \(R_p\) violation (for fixed \(m_{\nu_e}\)) for \(\mu < 0\) due to cancellation among tree-level and one-loop contributions. For \(\tan \beta > 30 \sim 40\) the one-loop contribution even dominates over the tree-level result. For \(M_{LSP} \gtrsim m_z\) the

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**Fig. 6.** Contours of constant \(\tan \theta_1\) and \(\tau(\chi_1^0)\) in the \(\tan \beta - M_{LSP}\) plane for \(\mu = \pm 2.5 m_1/2\). The other SUGRA parameters are as in fig. 4.
Fig. 7. A comparison of the total LSP-width with the LSP-width due to two-body decays. In (a) we show both sets of curves as a function of $M_{\text{LSP}}$. In (b) we show the difference of total width minus two-body decays normalized to $\Gamma_{\text{LSP}}$.

two-body decays dominate and differ from the full width only by a few % [fig. 7].

(A partial analysis of the two-body decays has been performed previously\textsuperscript{10}).

So far we have assumed exact universality at $M_{\text{GUT}}$. However, it has been pointed out in ref. \textsuperscript{27} that the evolution from the Planck scale $M_P$ to $M_{\text{GUT}}$ can already have a significant impact on the sparticle spectrum. This is particularly important in $\text{SO}(10)$ based models were the Higgs and slepton universality is violated via gaugino effects, since the Higgs (slepton) fields belongs to a 10-dim (16-dim) representation (remember: below $M_{\text{GUT}}$ non-universal effects arise only from Yukawa couplings while the non-universal effects above $M_{\text{GUT}}$ arise from the gauge couplings).
Fig. 9. Different LSP-branching fractions as functions of $M_{\text{LSP}}$ for five values of $\tan \beta$. We set $A_0 = 0$ and $\mu = 2.5 m_{1/2}$.

can accommodate this effect by modifying the boundary conditions at $M_{\text{GUT}}$

$$m_H^2(M_{\text{GUT}}) = m_{L_0}^2(M_{\text{GUT}}) = m_0^2 + R_H m_{1/2}^2,$$

where we typically expect $R_H = 9 \alpha_{\text{GUT}}/(4\pi) \ln(M_{\text{GUT}}/M_{\text{P}}) \simeq -0.1$.

In fig. 8 we see that the effect of non-universal terms is very significant (small) for small (large) values of $\tan \beta$ were the down-typ Yukawa couplings are small (large).

3.2. LSP Branching Fraction

So far we have used results from neutrino physics in order to eliminate the $R_p$ breaking parameters $\tan \theta_i$ ($i = 1, 2, 3$). However, to a good approximation this dependence drops out if we consider the branching fractions. In fig. 9 we present the branching fractions as a function of $M_{\text{LSP}}$ for eight different channels. The dominant decay mode is into quarks [(a) and (b) are first two generations only; (e) is the third generation] with a strong enhancement into $b\bar{b}$ (e) for small $\tan \beta$. Invisible decay modes (c) are typically below 10% and the radiative decay (d) is insignificant. The leptonic decays into $\tau^+\tau^-$ (f), $\ell^+\ell^-$ ($\ell = e, \mu$) (g) and $\ell^+\tau^\mp$ (h) is typically O(10%). For $M_{\text{LSP}} \gtrsim 100$ GeV the situation becomes much more transparent by considering the two-body decays [fig. 10]. Here, there are only three relevant channels with $B(LSP \to W^{\pm}\tau^\mp) \simeq 0.5$ and $B(LSP \to Z^0\nu), B(LSP \to h^0\nu) \simeq 0.25$. 
4. Conclusions

We have investigated the LSP phenomenology in supersymmetric models without lepton number conservation. In any model of this kind, lepton number is violated spontaneously via sneutrino VEVs as well as explicitly. Both effects are of the same order and have to be studied consistently. Assuming that Higgs-sneutrino mixing is responsible for the observed neutrino oscillations we find that the LSP decays inside the detector. The life-time can be determined over a large region of the SUSY parameter space. The branching fractions for all relevant decay modes are we presented.

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6. References

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