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Some aspects of R-parity violating supersymmetry

SOUROV ROY
Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India

Abstract. I briefly review a scenario where R-parity is explicitly broken through a term bilinear in the lepton and Higgs superfields in the superpotential. An immediate consequence of the presence of this term is the generation of a massive neutrino at the tree level. Constraints on the parameter space are discussed in the context of recent super-Kamiokande results on atmospheric neutrinos. The testability of such models is emphasized through the observation of comparable numbers of muons and taus, produced together with the W-boson, in decays of the lightest neutralino. Some other phenomenological implications of such a scenario are also discussed.

Keywords. Supersymmetry; R-parity.

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1. Introduction

Supersymmetry (SUSY) is one of the most attractive options to look for physics beyond the Standard Model (SM) [1]. For the past few decades a lot of efforts have been devoted on theoretical as well as phenomenological studies of SUSY. However, it has not been possible so far to come across any clear experimental indications of SUSY. This has motivated further investigations to explore the possibilities without the assumptions made in the minimal supersymmetric standard model (MSSM), based on which the search strategies are devised. In the MSSM, the lightest supersymmetric particle (LSP) is stable as a consequence of the conservation of a discrete multiplicative quantum number called R-parity.

The R-parity of a particle is defined as $R = (-1)^{L+3B+2S}$, and can be violated if either baryon (B) or lepton (L) number is not conserved in nature [2]. In the SM, it is not possible to write down interactions which violate baryon number (B) or lepton number (L) by one unit because the particles which carry these quantum numbers are fermions. In the SUSY version of the SM, particle spectrum is doubled and baryon number and lepton number are assigned to the supermultiplets, hence $\Delta B = 1$ or $\Delta L = 1$ interactions are allowed.

The most important consequence of R-parity violation is that the LSP can decay now. However, there is no unique way in which R-parity can be violated. It is possible to write down various types of R-parity violating terms and they can lead to different observable predictions.

In the next section we discuss the basic features of the R-parity violating scenario. Section 3 describes the generation of neutrino masses in such models. In §4, constraints on the parameter space are discussed and some distinct collider signatures are mentioned. We conclude in §5.

2. R-parity violation

The R-conserving part of the MSSM superpotential is of the following form in terms of superfields:

$$W_{\rm MSSM} = \mu \hat{H}_1 \hat{H}_2 + h^l_{ij} \hat{L}_i \hat{H}_1 \hat{E}^c_j + h^d_{ij} \hat{Q}_i \hat{H}_1 \hat{D}^c_j + h^u_{ij} \hat{Q}_i \hat{H}_2 \hat{U}^c_j, \tag{1}$$

where μ is the Higgsino mass parameter and the last three terms give all the Yukawa interactions. Here we have suppressed the SU(2) and SU(3) indices.

If now R-breaking interactions are incorporated, the superpotential takes the form

$$W_{\not R} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}^c_k + \epsilon_i \hat{L}_i \hat{H}_2 + \lambda''_{ijk} \hat{U}^c_i \hat{D}^c_j \hat{D}^c_k. \tag{2}$$

The first three terms in eq. (2) violate lepton number whereas the last term is baryon number violating. The λ-type terms are antisymmetric in the first two generational indices and for the λ''-type terms the antisymmetry is there in the last two indices.

In order to suppress the decay of proton one considers either lepton number violating terms or baryon number violating terms at a time in the superpotential though this is not an essential condition. In the rest of this discussion we shall concentrate on the case where only lepton number is violated.

The λ and λ' type terms in W_L have received a lot of attention in recent times and various kinds of limits on their magnitude have been derived from existing experimental data [3]. However, the three bilinear terms $\epsilon_i L_i H_2$ are also very interesting and if they are the only source of R-parity violation then the model becomes more predictive because of the huge reduction in the number of parameters.

The interesting consequences which characterize the presence of LH_2 term in the superpotential are as follows [4]. It can trigger a mixing between charged Higgsinos and charged lepton states as well as between neutral Higgsinos and neutrinos [5]. In addition, the scalar potential in this case contains terms bilinear the slepton and the Higgs fields [6]:

$$\begin{aligned} V_{\rm scal} = {} & m^2_{L_3} \tilde{L}^2_3 \ + \ m^2_{L_2} \tilde{L}^2_2 \ + \ m^2_1 H^2_1 \ + \ m^2_2 H^2_2 \ + \ B\mu H_1 H_2 \\ & + \ B_2 \epsilon_2 \tilde{L}_2 H_2 \ + \ B_3 \epsilon_3 \tilde{L}_3 H_2 \ + \ \cdots, \end{aligned} \tag{3}$$

where m_{L_i} denotes the mass of the *i*-th scalar doublet at the electroweak scale, m_1 and m_2 are the mass parameters corresponding to the Higgs doublets H_1 and H_2 respectively. Other soft SUSY-breaking parameters are denoted by B, B_2 and B_3.

The presence of these L-violating soft terms in the scalar potential leads to non-vanishing vacuum expectation values (VEV) of the sneutrinos in general. This gives rise to the neutrino (charged lepton)-gaugino mixing through sneutrino-neutrino-Bino/neutral Wino (sneutrino-charged lepton-charged Wino) interaction terms [7]. Due to the presence of these two kinds of mixing mentioned above, neutralino mass matrix gets enlarged and the neutrino acquires a see-saw type mass at the tree level [8]. The non-zero VEV of the sneutrino can also lead to mixing between the charged Higgs and sleptons and neutral scalar (pseudoscalar) Higgs and sneutrinos.

Furthermore, the physical effects of the trilinear terms can be generated from the bilinear terms by going to the approriate basis. In this context it must be mentioned that although it may seem possible to rotate away the LH_2 term from the superpotential by a redefinition of the lepton and Higgs superfields, their effects can be seen in general in the scalar sector of the theory. At the same time trilinear interaction terms are generated in the superpotential.

3. Generation of neutrino mass

Let us now turn our attention to the discussion of the neutrino mass generation at the tree level keeping in mind that we want to explain the results from super-Kamiokande (SK) experiments on atmospheric neutrinos [9], namely, 1.5×10^{-3} $\mathrm{eV}^2 < \Delta m^2_{32} < 6 \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.82$.

In the rotated basis the sneutrino VEV $< \tilde{\nu}'_\tau >$ (for the time being consider one generation case) determines the mass of the neutrino and in order to generate a small mass this parameter should be kept small. This actually boils down to the fact that $\Delta m^2 \equiv m_1^2 - m_{L_3}^2$ and $\Delta B \equiv B - B_3$ must be small. It has been shown that in an R-parity violating theory embeded in supergravity, the universality of these soft parameters at a very high scale ($\sim 10^{16}$ GeV) imply very small differences of the above kinds [10]. However, it does not necessarily mean that the parameters ϵ and $< \tilde{\nu}_\tau >$ defined in the original basis are small.

Since our goal is to explain the SK results, we assume that the bilinear terms in the superpotential are dominant for the second and third generations only and then rotate away these terms by field redefinition. The sneutrino VEV's in the rotated basis (v'_μ and v'_τ) enter into the neutralino mass matrix which takes the form

$$\mathcal{M}_\chi = \begin{pmatrix} 0 & -\mu' & \frac{gv_2}{\sqrt{2}} & -\frac{g'v_2}{\sqrt{2}} & 0 & 0 \\ -\mu' & 0 & -\frac{gv'_1}{\sqrt{2}} & \frac{g'v'_1}{\sqrt{2}} & 0 & 0 \\ \frac{gv_2}{\sqrt{2}} & -\frac{gv'_1}{\sqrt{2}} & M_2 & 0 & -\frac{gv'_\tau}{\sqrt{2}} & -\frac{gv'_\mu}{\sqrt{2}} \\ -\frac{g'v_2}{\sqrt{2}} & \frac{g'v'_1}{\sqrt{2}} & 0 & M_1 & \frac{g'v'_\tau}{\sqrt{2}} & \frac{g'v'_\mu}{\sqrt{2}} \\ 0 & 0 & -\frac{gv'_\tau}{\sqrt{2}} & \frac{g'v'_\tau}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -\frac{gv'_\mu}{\sqrt{2}} & \frac{g'v'_\mu}{\sqrt{2}} & 0 & 0 \end{pmatrix}, \tag{4}$$

where the successive rows and columns correspond to $(\tilde{H}_2, \tilde{H}'_1, -i\tilde{W}_3, -i\tilde{B}, \nu'_\tau, \nu'_\mu)$. Here M_2 and M_1 are the $\mathrm{SU}(2)$ and $\mathrm{U}(1)$ gaugino mass parameters respectively, μ' is the Higgsino mass parameter ($\mu' = \sqrt{\mu^2 + \epsilon_2^2 + \epsilon_3^2}$) and $v'_1 =< H'_1 >$. The *primed* quantities denote the rotated basis.

This leads to *one* non-vanishing tree-level neutrino mass eigenvalue. The root of this can be traced to the fact that one linear combination of ν'_μ and ν'_τ, given by

$$\nu_3 = \nu'_\tau \cos\theta + \nu'_\mu \sin\theta \tag{5}$$

enters into cross-terms with the $\tilde{B}$ and $\tilde{W}_3$, while its orthogonal state ν_2 decouples from the mass matrix and therefore remains massless. The angle θ is given by

$$\cos\theta \;\; = \;\; v'_\tau / v' \tag{6}$$

with $v' = \sqrt{{v'}_{\mu}^{2} + {v'}_{\tau}^{2}}$. The quantity v', which is a kind of 'effective' sneutrino vev in a basis where the bilinear terms are rotated away from the superpotential, is a basis-independent measure of R-parity violation, which directly controls the tree-level neutrino mass acquired in the process. An approximate expression for the mass of the neutrino at the tree level is given by

$$m_{\nu_3} \approx -\frac{\bar{g}^2(v_2^2 + v_3^2)}{2\,\bar{M}} \times \frac{\bar{M}^2}{M_2 M_1 - m_Z^2\ \bar{M}/\mu\ \sin 2\beta}, \tag{7}$$

where we introduced $\bar{g}^2 \bar{M} = g^2 M_1 + {g'}^2 M_2$.

The mass implied by the atmospheric ν_μ-deficit in the SK data requires v' to be in the range (1–3) $\times 10^{-4}$ GeV approximately.

However, the explanation for the solar neutrino puzzle requires a mass-splitting between the remaining two massless neutrino states. This can be achieved at the one-loop level in the presence of λ and λ' type terms in the superpotential [11].

4. Constraints and phenomenology

As we have already mentioned, the quantity v' is constrained by the allowed range of $\Delta m_{\mu\tau}^2$ coming from the SK data. Next, the value of the angle θ (defined in the previous section) should determine v'_μ and v'_τ completely, once v' is fixed. Modulo the very small neutrino-neutralino mixing, the angle θ can be identified with the neutrino vacuum mixing angle (θ_0) if the *charged lepton mass matrix is diagonal* in the basis where bilinear terms are rotated away from the superpotential. In this case, the large angle mixing will require $v'_\mu \approx v'_\tau$. In general, the actual neutrino mixing matrix is given by

$$V_l = V_\theta U^T, \tag{8}$$

where V_θ is the 2×2 orthogonal matrix corresponding to the rotation angle θ, and U is the matrix that diagonalises $\mathcal{M}_l \mathcal{M}_l^\dagger$ ($\mathcal{M}_l$ is charged lepton mass matrix in the rotated basis).

It is the matrix V_l which should correspond to a rotation angle of $\pi/4$ for maximal mixing, and to a range approximately between 32 and 58 degrees for $\sin^2 2\theta_0 > 0.82$, θ_0 being the neutrino mixing angle. This will in turn determine the allowed ranges of v'_μ and v'_τ for each value of the ratio ϵ_2/ϵ_3 and $\theta \approx \theta_0$ if $\epsilon_2/\epsilon_3 \ll m_\mu/m_\tau$. Corresponding to these allowed values of v'_μ and v'_τ, the L-violating soft parameters B_2 and B_3 also get constrained.

In the scalar sector, there are mixings between $\tilde{\tau}$ and $\tilde{\mu}$ as well as between $\tilde{\nu}_\tau$ and $\tilde{\nu}_\mu$ states. This leads to flavor changing neutral currents (FCNC) because simultaneous diagonalisation is not possible for charged lepton and scalar mass matrices. It has been shown that in order to suppress FCNC one needs either $\epsilon_2 \ll \epsilon_3$ ($\epsilon_3 \ll \epsilon_2$) or $\epsilon_{2,3} \ll \mu$ [12].

Next question arises that what could be the collider signatures of such a scenario. Because of the mixing between neutrinos and neutralinos as well as charged leptons and charginos, additional decay channels for the lightest neutralino open up, namely, $\tilde{\chi}_1^0 \to lW$ and $\tilde{\chi}_1^0 \to \nu Z$ which dominate over the three body decay modes over a large region of the parameter space. Now the large angle mixing implies that the massive neutrino field, which has a cross-term with Bino, couples to the muons and taus with comparable strengths.

Thus, near equal number of muons and taus should be produced along with W-boson from the decay of $\tilde{\chi}_1^0$ [13].

A recent study shows that at the Fermilab Tevatron with upgraded energy and luminosity, this should lead to like-sign dimuons or ditaus, together with a real W [14]. The other important consequence is a measurable decay length for the lightest neutralino. For further details, the reader is referred to [13]. There can also be radiative decays of $\tilde{\chi}_1^0$ in the form $\tilde{\chi}_1^0 \to \nu\gamma$ with branching ratio $\sim$ 10% [15].

In the scalar sector of the theory, there are new decay modes of the type $h \to \tilde{\chi}_1^0\nu$, $\tilde{\nu} \to b\bar{b}, \tau^+\tau^-, \nu\nu$ which are dominant in some region of the parameter space [16]. In the charged scalar sector, $H^+ \to \tilde{\chi}_1^0\tau, \tilde{\chi}_1^+\nu_\tau$, $\tilde{\tau}^+ \to \nu_\tau\tau^+, c\bar{s}$ decay modes are available now and it has been shown that $H^+ \to \tilde{\chi}_1^0\tau$ can be dominant for small $\tan\beta$. Associated production $e^+e^- \to H^\pm\tilde{\tau}_1^\mp$ is also possible with $\sigma \sim$ 0.12 pb at $\sqrt{s}$ = 192 GeV [17].

5. Conclusions

We have demonstrated that R-parity violation through bilinear term generates neutrino mass at the tree level and at the same time a large angle mixing between the second and third generation is also possible. This leads to a pattern which is required by the SK data in order to explain the observed deficiency in atmospheric muon neutrinos. Mixings in the fermionic and the scalar sector of the theory offer very rich phenomenology which can be tested in the present and future colliders.

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