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Neutrino mass patterns, R-parity violating supersymmetry and associated phenomenology

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Abstract. Motivated by the recent super-Kamiokande results on atmospheric neutrinos, we incorporate massive neutrinos, with large angle oscillation between the second and third generations, in a theory with R-parity violating supersymmetry. The general features of such a theory are briefly reviewed. We emphasize its testability through the observation of comparable numbers of muons and taus, produced together with the W-boson, in decays of the lightest neutralino. A distinctly measurable decay gap is another remarkable feature of such a scenario.

Keywords. Neutrino masses; R-parity violation.

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1. Introduction

Although various options beyond the standard model (SM) of electroweak interactions are being investigated with great interest for quite some time now, the standard model has faced practically *no* experimental contradictions in terrestrial experiments so far. In this respect, the observed results on solar and atmospheric neutrinos have a unique role to play, in the sense that their confirmation will require the existence of neutrino masses and mixing, and therefore will take one beyond the jurisdiction of the standard model. It is thus quite natural that the apparent oscillation of the muon neutrinos to another species, inferred with far greater confidence than before from the recent data from the super-Kamiokande (SK) experiment [1], is being enthusiastically examined for traces of some kind non-standard physics answering to a neutrino mass pattern of the suggested type. There are, however, a very large number of possibilities to explore, and the credibility of any one of them will depend not only on how well they explain the neutrino data but also on their other testable consequences. In this regard, one must say that the recent developments in neutrino physics have triggered a lot of incisive thinking on other areas of particle phenomenology as well. Here we propose to discuss some such phenomenological issues in the particular context of supersymmetric theories.

Supersymmetry (SUSY) is perhaps the object of the hottest pursuit in terms of physics beyond the SM [2]. Its usefulness in solving the naturalness problem, its tantalizingly spectacular role in achieving the unification of coupling constants, and its almost invariable presence in theories attempting to unify gravity with the other interactions make it an extremely appealing theoretical option. However, there is no concrete experimental evidence in its favor yet. It is therefore quite natural that the possibilities of generating neutrino masses and mixing in a SUSY scenario should be investigated, especially when evidences for the latter are already knocking at our doors.

Neutrino masses will either necessitate the existence of right-handed neutrinos or require violation of lepton number (L) so that Majorana masses are possible. The former possibility entails an augmentation of the particle content of the minimal SUSY standard model (MSSM). The latter one does not require it, but forces one to go beyond the minimal model again, whereby lepton number violation can be allowed in the theory. However, such a violation is in-built in those SUSY theories where R-parity, defined as $R = (-1)^{3B+L+2S}$, is not a conserved quantity anymore [3]. This is quite consistent with the absence of proton decay so long as baryon number (B) is not violated simultaneously, a situation that again may arise in SUSY where there are scalar leptons and baryons and therefore L-violation and B-conservation does not interfere with the gauge current structure of the theory.

In the next section we present a summary on R-parity violating models, with an emphasis on the type which has a key role in our claims, namely, one with R-parity violation through bilinear terms. In the same section we also discuss the generation of neutrino masses in such theories both at the tree- and one-loop levels. Some distinct accelerator signals, of one viable scenario at least, are mentioned in §3. We conclude in §4.

2. R-parity violation and neutrino mass

The MSSM superpotential is given by

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

where the last three terms give the Yukawa interactions corresponding to the masses of the charged leptons and the down-and up-type quarks, and μ is the Higgsino mass parameter.

When R-parity is violated, the following additional terms can be added to the superpotential:

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

with the λ''-terms causing B-violation, and the remaining ones, L-violation. In order to suppress proton decay, it is customary (though not essential) to have one of the two types of nonconservation at a time. In the rest of this article, we will consider only lepton number violating effects.

The λ- and λ'-terms have been widely studied in connection with phenomenological consequences, enabling one to impose various kinds of limits on them [4]. Their contributions to neutrino masses can be only through loops [5], and their multitude (there are 36 such couplings altogether) makes the necessary adjustments possible for reproducing the requisite values of neutrino masses and mixing angles. We shall come back to these 'trilinear' effects later.

More interesting, however, are the three bilinear terms $\epsilon_i L_i H_2$ [6]. There being only three terms of this type, the model looks simpler and more predictive with them alone as sources of R-parity violation. This is particularly so because the physical effects of the trilinear terms can be generated from the bilinears by going to the appropriate bases. In addition, they have interesting consequences of their own [7,8], since terms of the type

$\epsilon_i L_i H_2$ imply mixing between the Higgsinos and the charged leptons and neutrinos. In this discussion, we shall assume, without any loss of generality, the existence of such terms involving only the second and third families of leptons.

In the above scenario, the scalar potential contains the following terms which are bilinear in the scalar fields:

$$V_{\mathrm{scal}} = m_{L_3}^2 |\tilde{L}_3|^2 + m_{L_2}^2 |\tilde{L}_2|^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + B\mu H_1 H_2 + B_2\epsilon_2 \tilde{L}_2 H_2 + B_3 \epsilon_3 \tilde{L}_3 H_2 + \mu\epsilon_3 \tilde{L}_3^* H_1 + \mu\epsilon_2 \tilde{L}_2^8 H_1 + \cdots, \tag{3}$$

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

An immediate consequence of the additional (L-violating) soft terms in the potential is a set of non-vanishing vacuum expectation values (*vev*) for the sneutrinos [9]. This gives rise to the mixing of the gauginos with neutrinos (and charged leptons) through the sneutrino–neutrino–neutralino (and sneutrino-charged lepton-chargino) interaction terms.

By virtue of both the types of mixing described above, the hitherto massless neutrino states enter into the neutralino mass matrix. This leads to see-saw masses acquired by them via mixing with massive states. The parameters controlling the neutrino sector in particular and R-parity violating effects in general are the bilinear coefficients ϵ_2 , ϵ_3 and the soft parameters B_2, B_3. For our purpose, however, it is more convenient to eliminate the latter in favor of the sneutrino *vev*'s using the conditions of electroweak symmetry breaking [7].

For a better understanding, let us perform a basis rotation [10], removing the R-parity violating bilinear terms via a redefinition of the lepton and Higgs superfields. This, however, does not eliminate the effects of the bilinear terms, since they now take refuge in the scalar potential. The sneutrino *vev*'s in this rotated basis (which are functions of both and the ϵ's and the soft terms in the original basis) are instrumental in triggering neutrino–neutralino mixing. Consequently, the 6×6 neutralino mass matrix in this basis has the following form:

$$\mathcal{M} = \begin{pmatrix} 0 & -\mu & \frac{gv}{\sqrt{2}} & -\frac{g'v}{\sqrt{2}} & 0 & 0 \\ -\mu & 0 & -\frac{gv'}{\sqrt{2}} & \frac{g'v'}{\sqrt{2}} & 0 & 0 \\ \frac{gv}{\sqrt{2}} & -\frac{gv'}{\sqrt{2}} & M & 0 & -\frac{gv_3}{\sqrt{2}} & -\frac{gv_2}{\sqrt{2}} \\ -\frac{g'v}{\sqrt{2}} & \frac{g'v'}{\sqrt{2}} & 0 & M' & \frac{g'v_3}{\sqrt{2}} & \frac{g'v_2}{\sqrt{2}} \\ 0 & 0 & -\frac{gv_3}{\sqrt{2}} & \frac{g'v_3}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -\frac{gv_2}{\sqrt{2}} & \frac{g'v_2}{\sqrt{2}} & 0 & 0 \end{pmatrix}, \tag{4}$$

where the successive rows and columns correspond to $(\tilde{H}_2, \tilde{H}_1, -i\tilde{W}_3, -i\tilde{B}, \nu_\tau, \nu_\mu)$, ν_τ and ν_μ being the neutrino flavour eigenstates in this basis. Also, with the sneutrino *vev*'s denoted by v_2 and v_3,

$$v \ \ (v') = \sqrt{2}\left(\frac{m_Z^2}{\bar{g}^2} - \frac{v_2^2 + v_3^2}{2}\right)^{\frac{1}{2}} \sin\beta \ \ (\cos\beta),$$

M and M' being the SU(2) and U(1) gaugino mass parameters respectively, and $\bar{g} = \sqrt{g^2 + g'^2}$.

Next, one can define two states ν_3 and ν_2, where

$$\nu_3 = \cos\theta\ \nu_\tau + \sin\theta\ \nu_\mu \quad (5)$$

and ν_2 is the orthogonal combination, the neutrino mixing angle being given by

$$\cos\theta = \frac{v_3}{\sqrt{v_2^2 + v_3^2}}. \quad (6)$$

Clearly, the state ν_3 — which alone develops cross-terms with the massive gaugino states — develops a see-saw type mass at the tree-level. The orthogonal combination ν_2 still remains massless.

An approximate expression (neglecting higher order terms in m_z/μ) for the tree-level neutrino mass is

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

where $\bar{g}^2\bar{M} = g^2M' + g'^2M$. The first term is very similar to the usual see-saw formula, with the only difference that couplings between the light and the heavy states is in the present case due to gauge interactions.

The massive state ν_3 can be naturally used to account for atmospheric neutrino oscillations, with $\Delta m^2 = m_{\nu_3}^2$. Large angle mixing between the ν_μ and the ν_τ corresponds to the situation where $v_2 \simeq v_3$.

The tree-level mass here is clearly controlled by the quantity $v' = \sqrt{v_2^2 + v_3^2}$. This quantity, defined as the 'effective' sneutrino *vev* in the basis where the ϵ's are rotated away, can be treated as a basis-independent measure of R-parity violation in such theories. The SK data on atmospheric neutrinos restrict v' to be of the order of a few hundred keV's [11]. However, it should be remembered that v' is a function of ϵ_2 and ϵ_3 both of which can still be as large as on the order of the electroweak scale. It has, for example, been shown [12] that in models based on $N = 1$ supergravity, it is possible to have a very small value of v' starting from large ϵ's, provided that one assumes the R-conserving and R-violating soft terms (as also the slepton and $Y = 1$ Higgs mass parameters) to be the same at the scale of dynamical SUSY breaking at a high energy.

Also, one has to address the question as to whether the treatment of ν_3 and ν_2 as mass eigenstates is proper, from the viewpoint of the charged lepton mass matrix being diagonal in the basis used above. In fact, it can be shown that this is strictly possible when ϵ_2 is much smaller than ϵ_3, failing which one has to give a further basis rotation to define the neutrino mass eigenstates. However, the observable consequences that we describe in the following section are found to be equally valid, with the requirement shifted from the angle θ to the effective mixing angle to be in the neighborhood of maximality.

Furthermore, a close examination of the scalar potential in such a scenario reveals the possibility of additional mixing among the charged sleptons, whereby flavour-changing neutral currents (FCNC) can be enhanced. It has been concluded after a detailed study [13] that the suppression of FCNC requires one to have the ϵ-parameters to be small compared to the MSSM parameter μ (or, in other words, to the electroweak scale) unless there is a hierarchy between ϵ_2 and ϵ_3.

However, one still needs to find a mechanism for mass-splitting between the massless state ν_2 and the electron neutrino, and to explain the solar neutrino puzzle [14]. This is found to follow naturally if one allows for R-parity (L) violating terms of all types in the superpotential. The existence of the various λ and λ'-terms will give rise to loop contributions to the neutrino mass matrix [15].

The generic expression for such loop-induced masses is

$$(m_\nu^{\rm loop})_{ij} \simeq \frac{3}{8\pi^2} m_k^d m_p^d M_{\rm SUSY} \frac{1}{m_{\tilde{q}}^2} \lambda'_{ikp}\lambda'_{jpk} + \frac{1}{8\pi^2} m_k^l m_p^l M_{\rm SUSY} \frac{1}{m_{\tilde{l}}^2} \lambda_{ikp}\lambda_{jpk}, \quad (8)$$

where $m^{d,(l)}$ denote the down-type quark (charged lepton) masses. $m_{\tilde{l}}^2$, $m_{\tilde{q}}^2$ are the slepton and squark mass squared. $M_{\rm SUSY}(\sim \mu)$ is the effective scale of supersymmetry breaking. The mass eigenvalues can be obtained by including the above loop contributions in the mass matrix.

Again, it should be noted that there may be other ways of looking at the problem. For example, it has been shown [17] that, if one assumes *only* trilinear R-violating interactions at a high scale, running of the mass parameters could lead to significant sneutrino *vev*'s at low energy, which might turn out to be principal contributors to the loop-induced masses.

If we want the mass thus induced for the second generation neutrino to be the right one to solve the solar neutrino problem, then one obtains some constraint on the value of the λ's as well as λs. In order to generate a splitting between the two residual massless neutrinos, $\delta m^2 \simeq 5 \times 10^{-6}$ eV^2 (which is suggested for an MSW solution), a SUSY breaking mass of about 500 GeV implies λ' $(\lambda) \sim 10^{-4}$–10^{-5}. The mass-squared difference required for a vacuum oscillation solution to the solar puzzle requires even smaller values of $\lambda'(\lambda)$.

3. Phenomenological consequences

As we have observed before, the SK data imply a constraint on the basis-independent parameter v'. The allowed range of neutrino mass-squared difference from the SK data, combining the fully contained events, partially contained events and upward-going muons, is about $1.5 - 6.0 \times 10^{-3}$ eV^2 at 90% C.L. [18]. For the lightest neutralino mass varying between 50 and 200 GeV, this constrains v' to be in the approximate range 0.0001–0.0003 GeV.

The experimentally observed signals characteristic of the scenario described above should naturally be associated with decays of the lightest neutralino, since that is a process where contributions from R-parity violating effects will not face any competitions from MSSM processes.

In presence of only the trilinear R-violating terms in the superpotential, the lightest neutralino can have various three-body decay modes which can be generically described by $\chi^0 \longrightarrow \nu f \bar{f}$ and $\chi^0 \longrightarrow l f_1 \bar{f}_2$, f, f_1 and f_2 being different quark and lepton flavors that are kinematically allowed in the final state.

We have already seen that an important consequence of the bilinears is a mixing between neutrinos and neutralinos as also between charged leptons and charginos. This opens up additional decay channels for the lightest neutralino, namely, $\chi^0 \longrightarrow lW$ and $\chi^0 \longrightarrow \nu Z$.

When the neutralino is heavier than at least the W, these two-body channels dominate over the three-body ones over a large region of the parameter space, the effect of which can be observed in colliders such as the upgraded Tevatron, the LHC and the projected high-energy electron–positron collider. Different observables related to these decays have been studied in recent times [19].

Here we would like to stress upon one distinctive feature of the scenario that purportedly explains the SK results with the help of bilinear R-parity violating terms. It has been found that over almost the entire allowed range of the parameter space in this connection, the lightest neutralino is dominated by the Bino. A glance at the neutralino mass matrix reveals that decays of the neutralino ($\simeq$ Bino) in such a case should be determined by the coupling of different candidate fermionic fields in the final state with the massive neutrino field ν_3 which has a cross-term with the Bino. Large angle neutrino mixing, on the the hand, implies that ν_3 should have comparable strengths of coupling with the muon and the tau. Thus, a necessary consequence of the above type of explanation of the SK results should be comparable numbers of muons and taus emerging from decays of the lightest neutralino, together with a W-boson in each case [10]. Such signals, particularly those in the form of muons from two-body decays of the lightest neutralino, should distinguish such a scenario. For further details including plots of the branching ratios, the reader is referred to [10].

Of course, the event rates in the channel mentioned above will depend on whether the two-body decays mentioned above indeed dominate over the three-body decays. The latter are controlled by the size of the λ- and λ'-parameters. It has been found that if in this case these parameters have to be of the right orders of magnitude to explain the mass-splitting required by the solar neutrino deficit, then, even for the MSW case, the decay widths driven by the trilinear term are smaller than those for the two-body decays by at least an order of magnitude. For vacuum oscillation, the three body decays turn out to be even smaller. Thus the prediction of comparable numbers of muons and taus seem to be quite robust so long as the two-body neutralino decays are kinematically allowed.

The other important consequence [10] of this picture is a large decay length for the lightest neutralino. We have already mentioned that the atmospheric neutrino results restrict the basis-independent R-violating parameter v' to the rather small value of a few hundred keV's. This value affects the mixing angle involved in calculating the decay width of the neutralino, which in turn is given by the formula

$$L = \frac{\hbar}{\Gamma} \times \frac{p}{M(\tilde{\chi}_1^0)}, \tag{9}$$

where Γ is the decay width of the lightest neutralino and p, its momentum. As can be seen from figure 2 in ref. [10], the decay length decreases for higher neutrino masses, as a result of the enhanced probability of the flip between the Bino and a neutrino, when the LSP is dominated by the Bino. Also, a relatively massive neutralino decays faster and hence has a smaller decay length. The interesting fact here is that even for a neutralino as massive as 250 GeV, the decay length is as large as about 0.1 to 10 millimeters. This clearly will leave a measurable decay gap, which unmistakably characterizes the theoretical construction under investigation here [20].

If the lightest neutralino can have two-body charged current decays, then the Majorana character of the latter also leads to the possibility of like-sign dimuons and ditaus from pair-produced neutralinos. Modulo the efficiency of simultaneous identification of W-

pairs, these like-sign dileptons can also be quite useful in verifying the type of theory discussed here.

4. Summary and conclusions

We have demonstrated that it is possible to explain both the atmospheric and solar neutrino deficits in a SUSY model with R-parity violation is in-built in it. An important role is played by the bilinear R-violating terms in the superpotential, whereby a tree-level mass for one neutrino can be generated via mixing with neutralinos. The mass-squared difference expected from the atmospheric muon neutrino deficiency (for $\nu_\mu - \nu_\tau$ oscillation) constrains the basis-independent parameter characterizing R-parity violation in the neutrino–neutralino and lepton–chargino sectors. Side by side, the existence of trilinear lepton number violating terms in the superpotential can give rise to a mass-splitting between the two remaining neutrinos and thus account for the solar neutrino deficit. The values of the trilinear parameters required for this imply that the lightest neutralino should dominantly decay in two-body channels if it is heavier than the W-boson. Maximal mixing, as required by the super-Kamiokande data, implies that comparable numbers of muons and taus should be seen in charged current decays of the neutralino when the two-body decays are kinematically allowed. In addition, the magnitudes of the R-parity violating parameters required by the atmospheric neutrino data causes the neutralinos to have large decay lengths, and therefore leads to displaced vertices in SUSY search experiments. Thus R-parity violating SUSY lends itself as a viable mechanism for generating the expected neutrino masses and mixing patterns, with verifiable (or falsifiable) consequences in collider experiments.

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