Upper Bound on the W_R Mass in Automatically R-Conserving Supersymmetric Models

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We show that in automatically R-conserving minimal supersymmetric (SUSY) left-right symmetric models there is a theoretical upper limit on the mass of the right-handed W_R boson given by $M_{W_R} \leq gM_{\mathrm{SUSY}}/f$, where M_{SUSY} is the scale of SUSY breaking, g the weak gauge coupling, and f the Yukawa coupling responsible for generating the right-handed neutrino masses. If M_{W_R} violates the above bound, the ground state of the theory breaks electromagnetism. The only way to avoid this bound while keeping the theory automatically R conserving is to expand the theory to include very specific kinds of additional multiplets.

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There are two interesting extensions of the standard model which are currently the focus of intensive investigation: the minimal supersymmetric standard model (MSSM) [1] and the left-right symmetric model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ [2]. The MSSM extension can resolve several important unanswered questions of the standard model: (i) It explains the stability of the electroweak symmetry breaking scale under radiative corrections from new physics at higher scales such as those due to grand unification or gravity; (ii) local supersymmetry breaking via renormalization group equations can provide a perturbative origin for the scale of electroweak symmetry breaking; and (iii) it may provide a particle physics candidate for the cold dark matter of the Universe. It also connects the standard model with more fundamental theories such as superstrings. On the other hand, the left-right symmetric (LRS) models (i) provide a more satisfactory framework for understanding the origin of parity violation; (ii) restore quark-lepton symmetry to weak interactions; and (iii) if the neutrinos have a mass, the LRS models provide the simplest way to understand the smallness of the neutrino mass via the seesaw mechanism [3].

The next important question is the scale at which these new symmetries manifest themselves. As far as supersymmetry is concerned, the general belief is that its scale M_{SUSY} is below or around a TeV if it has to have the usefulness expected of it. On the other hand, as far as the scale of left-right symmetry (denoted by M_{W_R}) is concerned, in general, it could be anywhere between a few hundred GeV [4] to the grand unified theory scale. The main result of this Letter is that within the theoretical framework that combines both supersymmetry and left-right symmetry there exists a large class of attractive models, where one can derive an upper bound on M_{W_R} related to M_{SUSY}.

In order to introduce the special class of models we discuss, we note that despite its many attractive features, the MSSM extension has a major drawback. While the standard model provides a natural understanding of why baryon (B) and lepton (L) number conservations are obeyed to such a high degree of precision in nature, in MSSM both B and L violation can occur with maximal strength via the so called R-parity violating terms [5]. There is also no cold dark matter (CDM) candidate in the presence of these terms, and the usual practice is to impose an R-parity symmetry [defined as $(-1)^{3B+L+2S}$] on the MSSM to avoid both these problems. There is, however, a less *ad hoc* way to solve the problem of catastrophic B violation as has been noted earlier [6] by extending the gauge group of the supersymmetric model to make it left-right symmetric (to be called SUSYLR) and considering the class of models which implement the seesaw mechanism for small neutrino masses. Such models lead to automatic R-parity conservation prior to symmetry breaking and thus have no problem with B or L violation at all. This model has been studied in several recent papers [7–9]. Specifically, in our earlier paper [7] we pointed out that in the minimal version of this model the requirement of electric charge conservation and low energy parity violation implies that R parity must be spontaneously broken [10]. Therefore, while this model still does not have a CDM candidate, it cures one major drawback of the MSSM; i.e., the baryon number remains an exact symmetry of the model. The model, however, leads to small L-violating terms, which are suppressed and could be tested experimentally by searches for L violation.

In this Letter we report another interesting consequence of this class of minimal SUSYLR models, which is that the mass of the right-handed W_R boson M_{W_R} has an upper limit related to the SUSY breaking scale (i.e., $M_{W_R} \leq gM_{\mathrm{SUSY}}/f$), where g is the weak gauge coupling and f is the Yukawa couplings of right-handed neutrinos. The Yukawa coupling f could *a priori* be of order 1, in which case one gets the most stringent bound on M_{W_R} to be less than a TeV (since M_{SUSY} is expected to be in the TeV range). These results follow from the requirements of electric charge conservation and low energy parity

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violation by the ground state of the theory. The W_R in this class of models (with $f \simeq 1$) then becomes detectable in high energy colliding machines such as the CERN Large Hadron Collider.

It is worth pointing out that, while there exist convincing arguments based on analysis of the low energy weak processes which give lower bounds on M_{W_R} in the range of a few hundred GeV, to the best of our knowledge no upper bound on M_{W_R} exists. We further show that the only way to avoid this bound while maintaining the feature of automatic R-parity conservation is to enrich the minimal model by adding a $B - L = 0$ triplet.

Since our arguments suggest that M_{W_R} in this class of models is likely to be in the TeV range, we briefly comment on the existing lower bounds. For a heavy Majorana ν_R, the most stringent lower bounds come from the analysis of the $K_L - K_S$ mass difference [11] and neutrinoless double beta decay [12], which imply $M_{W_R} \gtrsim 1$–2 TeV. These bounds are, however, dependent on assumptions about hadronic matrix elements and nuclear physics details, respectively. Less model dependent limits come from the recent analyses of collider data [13], which provide a lower limit of about 460 GeV for heavy Majorana ν_R. Since the value of M_{SUSY} is expected to be in the TeV range and the value of the coupling parameter f could be less than 1, the above mentioned lower bounds do not rule out the SUSYLR model but reduce the domain of its validity considerably.

We start our discussion by giving the matter content of the minimal SUSYLR model: $Q(2,1,\frac{1}{3})$; $Q^c(1,2,-\frac{1}{3})$; $L(2,1,-1)$; $L^c(1,2,+1)$ denote the quarks and leptons and $\Delta(3,1,+2)$; $\Delta^c(1,3,-2)$; $\overline{\Delta}(3,1,-2)$; $\overline{\Delta^c}(1,3,+2)$; $\Phi(2,2,0)$ denote the Higgs fields [where the numbers in the parentheses represent the representations of the fields under the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$]. Since the weak interaction scale M_W is smaller than M_{SUSY} and M_R, we will initially ignore effects of the order M_W.

For the sake of completeness, we start by presenting the argument of Ref. [7] regarding the inevitability of spontaneous R-parity breaking in the SUSYLR models under consideration if they have to provide a realistic description of nature. Let us write down the relevant part of the superpotential (W). We have included a gauge singlet field (σ) to make the discussion as general as possible [14]:

$$W = if(L^{cT}\tau_2\Delta^c L^c) + M\,\mathrm{Tr}(\Delta^c\overline{\Delta}^c) + h_\sigma \mathrm{Tr}(\Delta^c\overline{\Delta}^c)\sigma + F(\sigma), \tag{1}$$

where $F(\sigma)$ is any analytic function with linear, quadratic, or cubic terms in σ.

The Higgs potential consists of a sum of the F and D terms (V_F and V_D, respectively) and the soft symmetry breaking terms [we have dropped all terms involving Δ and $\overline{\Delta}$ and Φ since their vacuum expectation valves (vev's) are at most of order M_W and will therefore not play any role in our discussion]:

$$V = V_F + V_D + V_S, \tag{2}$$

where

$$\begin{aligned} V_F = {}& |\, 2if\tilde{L}^{cT}\tau_2\Delta^c\,|^2 + \left| h_\sigma \mathrm{Tr}(\Delta^c\overline{\Delta}^c) + \frac{\partial F}{\partial\sigma}\right|^2 \\ &+ \mathrm{Tr}\left| if\tilde{L}^c\tilde{L}^{cT}\tau_2 + M\overline{\Delta}^c + h_\sigma\overline{\Delta}^c\sigma\right|^2 \\ &+ \mathrm{Tr}|M\Delta^c + h_\sigma\Delta^c\sigma|^2, \end{aligned} \tag{3}$$

$$\begin{aligned} V_D = {}& +\frac{g^2}{8}\sum_m |\, L^{c\dagger}\tau_m\tilde{L}^c + \mathrm{Tr}(2\Delta^{c\dagger}\tau_m\Delta^c + 2\overline{\Delta}^{c\dagger}\tau_m\overline{\Delta}^c)\,|^2 \\ &+ \frac{g'^2}{8}\,|\,\tilde{L}^{c\dagger}\tilde{L}^c - 2\,\mathrm{Tr}(\Delta^{c\dagger}\Delta^c - \overline{\Delta}^{c\dagger}\overline{\Delta}^c)\,|^2 \end{aligned} \tag{4}$$

$$\begin{aligned} V_S = {}& m_l^2\tilde{L}^{c\dagger}\tilde{L}^c + M_1^2\,\mathrm{Tr}\Delta^{c\dagger}\Delta^c \\ &+ M_2^2\,\mathrm{Tr}\overline{\Delta}^{c\dagger}\overline{\Delta}^c + Ah_\sigma\,\mathrm{Tr}(\Delta^c\overline{\Delta}^c)\sigma \\ &+ (M'^2\,\mathrm{Tr}\Delta^c\overline{\Delta}^c + ifv\tilde{L}^{cT}\tau_2\Delta^c\tilde{L}^c + \mathrm{H.c.}) + F_1(\sigma). \end{aligned} \tag{5}$$

All the fields in the above equations represent the scalar field of the corresponding superfield. This model will yield the MSSM for scales $\mu \ll \langle\Delta^c\rangle, \langle\overline{\Delta}^c\rangle$; if $\langle\Delta^c\rangle, \langle\overline{\Delta}^c\rangle \neq 0$. R parity will be conserved or broken at this stage, depending on whether $\langle\tilde{\nu}^c\rangle$ is zero or not. We will now show that if $\langle\tilde{\nu}^c\rangle = 0$, either $\langle\Delta^c\rangle = 0$ or if it is nonzero, then the absolute global minimum of V violates electric charge (Q_{em}) conservation.

Note first that since in general $M_1 \neq M_2, \langle\Delta^c\rangle \neq \langle\overline{\Delta}^c\rangle$. In what follows, we will denote the vev's of Δ^c and $\overline{\Delta}^c$ generically by v_R, the right-handed symmetry breaking scale. Consider now the following two vacua: (a) Q_{em} conserving vev

$$\langle\Delta^c\rangle = d\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \qquad \langle\overline{\Delta}^c\rangle = \overline{d}\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \tag{6}$$

(b) Q_{em} breaking vev

$$\langle\Delta^c\rangle = \frac{d}{\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad \langle\overline{\Delta}^c\rangle = \frac{\overline{d}}{\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}. \tag{7}$$

It is easy to see, using properties of the Pauli matrices, that if $\langle\tilde{\nu}^c\rangle = 0$, then the value of the positive definite V_D for the Q_{em} breaking vev is lower than V_D for the Q_{em} conserving vev since $\mathrm{Tr}\Delta^{c\dagger}\tau_m\Delta^c \neq 0$ in case (a), whereas it vanishes for case (b). The value of all other terms of V are the same for both cases. When R parity is broken by giving a nonzero vev $\langle\tilde{\nu}^c\rangle \equiv l'$, there are new contributions to the V, and one can adjust parameters such as f to make the Q_{em} breaking vev have a higher energy than the Q_{em} conserving one. It is, however, important that l' be at least of order M_{SUSY} or the right-handed scale v_R (whichever is lower) to achieve this goal (note that $d \sim \overline{d} \sim v_R$).

Upper bound on v_R.—Let us now proceed to the discussion of this paper. We will now assume that

$$f v_R \gg M_{\rm SUSY}\,, \tag{8}$$

and hence to the lowest order in this approximation, we can neglect the soft supersymmetry breaking terms V_S. Neglecting these terms, the minima are SUSY preserving, and they satisfy the condition $V = 0$. This requires that

$$\tilde{L}^c = 0, \quad M + h_\sigma \sigma = 0,$$
$$\mathrm{Tr}(\Delta^c \overline{\Delta}^c) = -\frac{\partial F}{h_\sigma \partial\sigma}, \quad \mathrm{Tr}\Delta^{c\dagger}\Delta^c = \mathrm{Tr}\overline{\Delta}^{c\dagger}\overline{\Delta}^c. \tag{9}$$

It is interesting to note that at this stage $\tilde{L}^c = 0$ follows from the SUSY preserving condition $V = 0$ and is not put in by hand. In other words, to the extent that supersymmetry is not broken, R parity cannot be spontaneously broken.

The other more important thing to note is that the solutions to Eq. (9) give rise to degenerate minima. The solutions are

$$\langle\Delta^c\rangle = d\begin{pmatrix} 0 & \sin\theta \\ \cos\theta & 0 \end{pmatrix}, \qquad \langle\overline{\Delta}^c\rangle = \overline{d}\begin{pmatrix} 0 & \cos\theta \\ \sin\theta & 0 \end{pmatrix}, \tag{10}$$

and

$$\langle\sigma\rangle = -M/h_\sigma, \quad \langle\tilde{L}^c\rangle = 0\,, \tag{11}$$

with

$$\overline{d}^2 = d^2 = -\partial F/h_\sigma \partial\sigma\,. \tag{12}$$

In Eq. (10), θ can be any angle, and this corresponds to the degeneracy of the vacua.

In order to lift the degeneracy, and see which of the above vacua is the true minimum, we turn on the most general soft supersymmetry breaking terms (V_S) as a perturbation. V_S is given by Eq. (5) where m_l, v, M_1, M_2, M' are all at most of the order $M_{\rm SUSY} \ll v_R$.

Note that as already mentioned, since $M_W < M_{\rm SUSY}$, we will continue to set $\langle\Phi\rangle = \langle\tilde{L}\rangle = M_W = 0$ as we turn on V_S as a perturbation. *A priori,* $\langle\tilde{L}^c\rangle$ can be order $M_{\rm SUSY}$. However, we will show in the following that this cannot be the case, and that in fact $\tilde{L}^c = 0$ to the first order in $M_{\rm SUSY}$.

To see if $\tilde{L}^c$ picks up a vev, let us use Eq. (10) with $\theta = 0$ and $d \sim \overline{d} \sim v_R$, and examine the $\tilde{L}^c$ terms. Substituting for $\Delta^c, \overline{\Delta}^c$, and l' into Eqs. (3)–(5), we have the following quadratic terms in l':

$$|2if\tilde{L}^{cT}\tau_2\Delta^c|^2 \sim |f|^2 v_R^2 l'^2, \quad \mathrm{Tr}|if\tilde{L}^c\tilde{L}^{cT}\tau_2 + (M + h_\sigma\sigma)\overline{\Delta}^c|^2 \sim f v_R M_{\rm SUSY} l'^2,$$
$$f v \tilde{L}^{cT}\tau_2\Delta^c\tilde{L}^c \sim f M_{\rm SUSY} v_R l'^2, \quad m_{lc}^2 \tilde{L}^{c\dagger}\tilde{L}^c \sim M_{\rm SUSY}^2 l'^2,$$
$$\frac{g'^2}{8}\,|\,\tilde{L}^{c\dagger}\tilde{L}^c + 2\,\mathrm{Tr}(\overline{\Delta}^{c\dagger}\overline{\Delta}^c - \Delta^{c\dagger}\Delta^c)\,|^2 \sim (g'^2 \text{ or } g^2) M_{\rm SUSY}^2 l'^2. \tag{13}$$

It is important to note that there are no linear or cubic terms in $\tilde{L}^c$, and the rest are all quartic terms. Thus assuming inequality (8), we have the following relation from the above equations:

$$V_{\tilde{L}^c} \approx |f v_R|^2\,|l'|^2 \pm \mu^2|l'|^2 + \mathrm{const} \times |l'|^4, \tag{14}$$

where μ^2 denotes masses of the order of $M_{\rm SUSY}^2$ or $f v_R M_{\rm SUSY}$. By the assumption of inequality (8), it follows that μ^2 is small compared to the positive definite leading term in Eq. (14). Therefore, at the minimum, $l' = 0$ or $\tilde{L}^c = 0$. This means that there cannot be any spontaneous R-parity violation if inequality (8) is true. But from our result given earlier, this means that electromagnetism is spontaneously broken. Hence inequality (8) must be false, and we have the bound

$$v_R \le M_{\rm SUSY}/f\,, \tag{15}$$

which implies a bound on $M_{W_R} \le g M_{\rm SUSY}/f$.

Note that if $f v_R \le M_{\rm SUSY}$, then the first two terms in Eq. (14) would be of the same order and could lead to a net negative value for the (mass)^2 term for the field l', and thereby give a nonzero vev for l' (causing R-parity violation and therefore a $Q_{\rm em}$ conserving and parity violating low energy theory).

A way of understanding the role played by V_S in preferring the electromagnetism violating vacuum (if there is no R-parity violation) is to note that, because in general $M_1 \ne M_2$ in Eq. (5), the magnitude of the vev's of Δ^c and $\overline{\Delta}^c$ are slightly different. Now the degenerate vacua of Eq. (10) will be slightly split. Substituting Eqs. (10) and (12) into Eqs. (3)–(5), it is easy to see that the minimum value is obtained for $\theta = 45°$ since $d \ne \overline{d}$. This vacuum violates electromagnetism (the electromagnetism conserving case $\theta = 0$ is not even a local minimum and is in fact a saddle point).

The upper bound in Eq. (15) implies that $v_R \le M_{\rm SUSY}$ if the Yukawa couplings in the right-handed sector are of the order 1. This is the main result of our paper. Since the bound on v_R depends on the unknown Yukawa coupling f, it gets weaker as f becomes much smaller than 1.

So far we have ignored M_W and hence have not considered the effect of the vev of the bidoublet. We will now show that turning on $\langle\Phi\rangle \sim M_W$ and $\langle\tilde{L}\rangle \le M_W$

does not change any of our conclusions. Because of terms such as $|h\tilde{L}^T\tau_2\phi\tau_2 + 2if\tilde{L}^{cT}\tau_2\Delta^c|^2$, Eq. (14) will be modified to

$$V_{\tilde{L}^c} \approx fM_W^2 v_R l' + |fv_R|^2|l'|^2 \pm \mu^2|l'|^2 + \text{const} \times |l'|^4. \quad (16)$$

Note that in this case the effective $(\text{mass})^2$ term for the l' is still positive. At the minimum, $l' \sim M_W(M_W/fv_R) \ll M_W$ if $fv_R > M_{\text{SUSY}}$. This value of $\langle l' \rangle$ is much too small to stabilize the electromagnetism conserving vacuum, and therefore the bound $fv_R < M_{\text{SUSY}}$ holds even after electroweak effects are taken into account. In fact, the splitting in the magnitudes of Δ^c and $\overline{\Delta}^c$ caused by this tiny nonzero l' causes the theory to prefer the electromagnetism violating vacuum if the bound is violated.

Let us now discuss what one has to do to avoid the above bound on M_{W_R} while at the same time maintaining automatic R-parity conservation in the theory both before and after symmetry breaking. The simplest way is to enrich the minimal models by adding a $B - L = 0$ triplet denoted by ω. The relevant part of the superpotential is given by

$$W = M\,\text{Tr}(\Delta^c\overline{\Delta}^c) + a\,\text{Tr}(\Delta^c\omega\overline{\Delta}^c) + c\,\text{Tr}\omega^2 + h_\sigma\,\text{Tr}(\Delta^c\overline{\Delta}^c)\sigma + h_\omega\,\text{Tr}\omega^2\sigma + F(\sigma). \quad (17)$$

Using $SU(2)_R$ invariance, we can always choose a basis such that ω acquires the electromagnetism preserving vacuum expectation value of the form

$$\langle\omega\rangle = w\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (18)$$

By substituting vacuum expectation values for Δ^c and $\overline{\Delta}^c$ from Eq. (10) into Eq. (17) and using Eq. (18), we see that the superpotential W has a nontrivial θ dependence due to the trilinear terms involving the three triplet fields. Since the soft-supersymmetry breaking terms will have exactly the same form as the superpotential, the value of the Higgs potential will have nontrivial θ dependence even if R parity is not spontaneously broken. Thus there is no problem of degenerate vacua, and these trilinear couplings can have signs so that the electromagnetism conserving vacuum with $\theta = 0$ is an absolute minimum even without R-parity violation.

In conclusion, we have studied the low energy implications of the class of SUSY left-right models that lead to automatic R-parity conservation. The most important result of our investigation is that in the minimal version of this model, there is an upper bound on M_{W_R}, which, for allowed values of parameters in the theory, can be as small as a TeV, making it possible to rule out the model in this parameter range.

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