MINIMAL GAUGED $U(1)_{B-L}$ MODEL WITH SPONTANEOUS R-PARITY VIOLATION

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We study the minimal gauged $U(1)_{B-L}$ supersymmetric model and show that it provides an attractive theory for spontaneous R-parity violation. Both $U(1)_{B-L}$ and R-parity are broken by the vacuum expectation value of the right-handed sneutrino (proportional to the soft SUSY masses), thereby linking the $B - L$ and soft SUSY scales. In this context we find a consistent mechanism for generating neutrino masses and a realistic mass spectrum, all without extending the Higgs sector of the minimal supersymmetry standard model. We discuss the most relevant collider signals and the connection between the $Z'$ gauge boson and R-parity violation.

INTRODUCTION

Supersymmetry (SUSY) is one of the most appealing solutions to the hierarchy problem and candidates for physics beyond the Standard Model (SM). It’s most minimal incarnation, the minimal supersymmetric Standard Model (MSSM), contains two major puzzles which have attracted the attention of many experts in the field. The first is the need for a predictive mechanism for SUSY breaking and the second is the existence of baryon and lepton number violating interactions. Pragmatically, the so-called R-parity discrete symmetry is imposed in order to forbid these interactions, which would lead to dimension four contributions to the decay of the proton. As a bonus, once this discrete symmetry is imposed, the lightest supersymmetric particle (LSP) is stable and is a candidate for the cold dark matter in the Universe. Therefore, it is important to investigate the mechanisms for R-parity conservation.

The possible origin of such mechanisms in the MSSM have been studied in detail in Ref. [1]. Furthermore, extensions of the MSSM which contain either a local or global $B - L$ symmetry will preserve R-parity at low energies only if the fields which break that symmetry have even $B - L$ quantum numbers [1]. See Ref. [2] for the study of this issue in $SO(10)$ grand unified theories and left-right models.

There are two simple frameworks where one can understand the origin of the R-parity violating interactions: i) introducing new multiplets having $U(1)_{B-L}$ as a global symmetry [3] but one has to face the Majoron problem [4], ii) the appealing possibility of having a local $U(1)_{B-L}$ symmetry where the Majoron becomes the longitudinal component of the $B - L$ gauge boson and is therefore no longer a problem. Recently, this latter framework was used to construct the simplest supersymmetric left-right theory [5]. In this work we want to study the predictions stemming from the simplest possible scenarios for spontaneous R-parity breaking in light of this second framework.

To do this we follow a simple procedure: postulate the existence of an extra $U(1)_{B-L}$ local gauge symmetry and introduce only the fields necessary for a theoretically consistent theory. These fields are the three generations of right-handed neutrinos required for anomaly cancellation and we will introduce no other fields, i.e the Higgs sector will be the same as in the MSSM. Once the right-handed sneutrino acquires a vacuum expectation value (VEV): $U(1)_{B-L}$ and R-parity are both broken reproducing the MSSM with baryon number conservation but lepton number and R-parity violation and the $B - L$ scale is identified with the soft SUSY mass scale — an interesting prediction. Viable neutrino masses are generated through an extended seesaw mechanism and a realistic spectrum is possible. This scenario leads to interesting phenomenology due to the intimate relationship between the $Z'$ gauge boson and R-parity violation. This is testable through the decays of the $Z'$, and the usual R-parity violating decays of neutralinos and charginos as well as the SUSY induced mass degeneracy between the right-handed sneutrino and the $Z'$ gauge boson.

This work is organized as follows: In Section I we present the model and discuss the basic idea of R-parity violation. In Section II we study the symmetry breaking mechanism showing the conditions on the soft SUSY breaking terms. The full spectrum is discussed in Section III while the possible smoking guns are presented in Section IV.

$U(1)_{B-L}$ EXTENSION OF THE MSSM

It is well known that the MSSM allows for baryon and lepton number violating interactions. Usually, these terms are forbidden by imposing the so-called R-parity. This discrete symmetry is defined as $R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$, where $M$ is the so-called Matter parity. $M = -1$ for any matter superfield and $M = +1$ for the Higgs and Gauge superfields. The MSSM R-parity violating interactions are

$$W_{RPV} = \epsilon_i \hat{L}_i \hat{H}_u + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{Q}_i \hat{L}_j \hat{D}_k^C + \lambda''_{ijk} \hat{U}_i \hat{D}_j^C \hat{D}_k^C$$

(1)

where the first three terms violate the lepton number (L) and the last one violates the baryon number (B). See Ref. [6] for the constraints coming from proton decay and Refs. [7,8] for previous studies.

However, forbidding all the terms in Eq. (1) is not necessary for a viable model. In this work we want to understand the origin of the non-harmful R-parity violating interactions in the simple extension of the MSSM by a local $U(1)_{B-L}$ symmetry. The full gauge group is
then $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$. The matter chiral supermultiplets for quarks and leptons and their $(SU(2)_L, U(1)_Y, U(1)_{B-L})$ quantum numbers are given by

$$
\hat{Q} = \left( \begin{array}{c} \tilde{U} \\ \tilde{D} \end{array} \right) \sim (2, 1/3, 1/3), \quad \hat{L} = \left( \begin{array}{c} \tilde{N} \\ \tilde{E} \end{array} \right) \sim (2, -1, -1),
$$

$$
\hat{U}^C \sim (1, -4/3, -1/3), \quad \hat{D}^C \sim (1, 2/3, -1/3), \quad \hat{E}^C \sim (1, 2, 1),
$$

and in order to cancel the anomalies one introduces three chiral superfields for the right-handed neutrinos: \( \hat{N}^C \sim (1, 0, 1) \). With this matter content, the superpotential reads as

$$
W_{BL} = W_{MSSM} + Y^D \hat{L}^T i\sigma_2 \hat{H}_u \hat{N}^C, \quad (2)
$$

where

$$
W_{MSSM} = Y_u \hat{Q}^T i\sigma_2 \hat{H}_u \hat{U}^C + Y_d \hat{Q}^T i\sigma_2 \hat{H}_d \hat{D}^C + Y_e \hat{L}^T i\sigma_2 \hat{H}_d \hat{E}^C + \mu \hat{H}_u^0 i\sigma_2 \hat{H}_d. \quad (3)
$$

The two MSSM doublet Higgses are defined by

$$
\hat{H}_u = \left( \begin{array}{c} \hat{H}^0_u \\ \tilde{H}^0_u \end{array} \right) \sim (2, 1, 0), \quad \hat{H}_d = \left( \begin{array}{c} \hat{H}^0_d \\ \tilde{H}^0_d \end{array} \right) \sim (2, -1, 0).
$$

So far, it seems like extra superfields are needed to break $U(1)_{B-L}$, since the Higgs doublets do not have $B-L$ quantum numbers. As mentioned earlier, the choice for these fields depends on whether or not the low energy theory should conserve R-parity (or M-Parity). Therefore, R-parity conservation requires Higgs fields with an even value of $B-L$. Typically, this is achieved by introducing several extra Higgs chiral superfields.

In this work, we wish to take advantage of the fact that the model already contains scalar fields with the correct quantum numbers: the right-handed neutrinos. Once one of these fields acquires a VEV, it spontaneously breaks both the extra gauge symmetry, $U(1)_{B-L}$, as well as R-parity and forces left-handed sneutrino, through mixing terms, to acquire a VEV. Since lepton number is part of the gauge symmetry the Majoron $\varepsilon$ (the Goldstone boson associated with spontaneous breaking of lepton number) becomes the longitudinal component of the $Z'$ and does not pose a problem. Therefore, in this context one can have a simple and consistent TeV scale theory for spontaneous $U(1)_{B-L}$ and R-parity violation with the same Higgs sector as the MSSM.

In addition to the superpotential, the model is also specified by the soft terms:

$$
V_{soft} = m^2_{\hat{N}^C} |\hat{N}^C|^2 + M^2_{\hat{L}} |\hat{L}|^2 + M^2_{\hat{E}^C} |\hat{E}^C|^2 + m^2_{\hat{H}^0_u} |\hat{H}_u^0|^2 + m^2_{\hat{H}^0_d} |\hat{H}_d^0|^2 + \left( \frac{1}{2} M_{BL} \tilde{B} \tilde{B}' \right) + \left[ A^D_\nu \hat{L}^T i\sigma_2 \hat{H}_u \hat{N}^C + B \mu \hat{H}_u^0 i\sigma_2 \hat{H}_d + \text{h.c.} \right] + \ldots \quad (5)
$$

where the terms not shown here correspond to terms in the soft MSSM potential. Now, we are ready to investigate the possible predictions coming from spontaneous R-parity violation.

**SYMMETRY BREAKING AND R-PARITY VIOLATION**

In this theory the gauge boson masses are generated by the vacuum expectation values (VEVS) of sneutrinos ($\langle \hat{\nu} \rangle = v_\nu/\sqrt{2}$ and $\langle \hat{\nu}^C \rangle = v_\nu/\sqrt{2}$), and the Higgs doublets ($\langle H^0_u \rangle = v_u/\sqrt{2}$ and $\langle H^0_d \rangle = v_d/\sqrt{2}$). The sneutrino VEVs also break R-parity and lepton number eliminating the quantum numbers necessary to distinguish between the lepton, Higgsino and gaugino sectors. Therefore the physical charginos and neutralinos, as well as the Higgses will be admixtures of these three sectors.

**Symmetry Breaking:** The scalar potential in this theory is given by

$$
V = V_F + V_D + V_{soft},
$$

where the relevant terms for $V_{soft}$ are given in Eq. (5). Once one generation of sneutrinos, $\hat{\nu}$ and $\hat{\nu}^C$, $\hat{H}_u$ and $\hat{H}_d$, acquire a VEV, the scalar potential reads

$$
\langle V_F \rangle = \frac{1}{4} (Y^D_\nu)^2 (v_R^2 + v_L^2 + v_u^2 + v_e^2) + \frac{1}{2} \mu^2 (v_u^2 + v_\nu^2)
$$

$$
\langle V_D \rangle = \frac{1}{32} \left[ g_1^2 (v_u^2 - v_d^2 - v_L^2)^2 + g_2^2 (v_u^2 - v_d^2 - v_L^2)^2 + g_{BL}^2 (v_R^2 - v_L^2)^2 \right],
$$

$$
\langle V_{soft} \rangle = \frac{1}{2} M_{L, u, e}^2 v_R^2 + \frac{1}{2} M_{H, u}^2 v_u^2 + \frac{1}{2} M_{H, d}^2 v_d^2 - \text{Re} (B \mu) v_u v_d + \frac{1}{2\sqrt{2}} \left( A^D_\nu + (A^D_\nu)^\dagger \right) v_R v_L v_u,
$$

where $g_1$, $g_2$ and $g_{BL}$ are the gauge couplings for $U(1)_Y$, $SU(2)_L$ and $U(1)_{B-L}$, respectively. This can be minimized in the usual way but illuminating results can be found for the case $v_R \gg v_u, v_d \gg v_L$. (a reasonable assumption given the phenomenologically necessary hierarchy between the left-and right-handed scales):

$$
v_R = \sqrt{-8M_{\tilde{N}_u}^2 g_{BL}^2}, \quad v_L = \frac{B_\nu v_R}{M_L^2 - \frac{1}{8} g_{BL}^2 v_R^2},
$$

with $B_\nu = \frac{1}{\sqrt{2}} (Y^D_\nu \mu v_d - A^D_\nu v_u)$. The first part of Eq. (10) has the same form as the Standard Model minimization condition and demonstrates the need for $M_{\tilde{N}_u}^2 < 0$, while the second part indicates that $B_\nu$ should be small, i.e. $B_\nu \ll M_L^2 - \frac{1}{8} g_{BL}^2 v_R^2$ in order to have $v_R \gg v_L$. The $v_u$ and $v_d$ minimization conditions are equivalent to the MSSM ones in this limit.

**R-Parity Violation:** R-parity violating bilinear terms, which mix leptons with Higgsinos and gauginos, will be generated from Yukawa couplings, after symmetry breaking and are given in Table I. The first term on the left is new and is the only term not suppressed by neutrino masses. The first term
the right corresponds to the so-called $\epsilon$ term, and the last three terms on the left are small but important for the decay of neutralinos and charginos.

Trilinear R-parity violating interactions follow once the neutralinos are integrated out. These will depend on the Yukawa couplings: $Y_e$ and $Y_d$. The general form for $\lambda$- and $\lambda'$-type interactions is: $Y_{e}/M_{\tilde{e}}$ and $Y_{d}/M_{\tilde{d}}$. For realistic neutrino masses, these interactions are small enough to evade experimental bounds. For further discussion on effective trilinear terms in bilinear R-parity violation see [8].

\section*{MASS SPECTRUM}

The purpose of this section is to check that a realistic spectrum exists.

\textbf{Gauge Bosons:} The gauge sector consists of the SM gauge bosons and an extra neutral gauge boson, the $Z'$. In the case $v_R \gg v_u, v_d \gg v_L$, the extra gauge boson has the mass $M^2_{Z'} = g^2_{BL} v^2_R/4$. The most conservative bounds from LEP2 and CDF are $M_{Z'}/g_{BL} > (5-10)$ TeV [9]. See Ref [10] for a recent study of the $Z'$ at the LHC and Ref [11] for a review.

\textbf{Neutralinos and Neutrinos:} Once R-parity is broken the neutralinos and charginos will occur in the charged and neutral sectors, $\nu, \nu^c, B, B^c, W^0, H^0, H^0_u$. In order to understand the neutrino masses we focus on the simple case $v_L \rightarrow 0$ and $Y_{\nu}^D$ small:

$$M_\nu = M^I_\nu + M^R_\nu,$$

where $M^I_\nu$ is the type I seesaw contribution [12] and $M^R_\nu$ is due to R-parity violation. These contributions are given by

$$M^I_\nu = \frac{1}{2} Y_{\nu}^D M_{\nu_c}^{-1} (Y_{\nu}^T)^T v^2_u,$$

$$M^R_\nu = m M_{\tilde{\nu}^0} m^T,$$

where

$$M_{\nu_c} \simeq \left( M_{BL} + \sqrt{4 M^2_{Z'}/2 + M^2_{BL}} \right) / 2$$

$$m = \text{diag}(0, 0, 0, 0, Y_{\nu}^D v_R/\sqrt{2}),$$

and $M_{\tilde{\nu}^0}$ is the neutralino mass matrix in the MSSM. Therefore, it is possible to simply reproduce the light neutrino masses.

\textbf{Bosonic Spectrum:}

Defining the basis $\sqrt{2} \text{Im} (\tilde{\nu}, \tilde{\nu}^c, H^0_u, H^0_d)$ for CP-odd scalars, $\sqrt{2} \text{Re} (\tilde{\nu}, \tilde{\nu}^c, H^0_u, H^0_d)$ for CP-even scalars and for the charged scalars $(\tilde{e}^c, \tilde{e}^c, H^+_L, H^-_d)$ we have computed the mass matrices. It is important to show that the spectrum of the theory is realistic and the expected Goldstone bosons exist. Here, we analyze the spectrum in the very illustrative limit of zero mixing between the left- and right-handed sleptinos, i.e. $Y_{\nu}^D, A^D_{\nu} \rightarrow 0$. In this limit, Eq. (10) indicates that $v_L \rightarrow 0$ as well and $B_\nu \rightarrow 0$, by definition. Applying this limit to the bosonic mass matrices shows that they decouple into three values: two eigenvalues representing the left- and right-handed slepton masses and the MSSM two-by-two mass matrix for the up- and down-type Higgs. We will focus on the former since the latter only reproduces the results of the MSSM.

One of the eigenvalues for the CP-odd sleptons corresponds to the Goldstone boson eaten by $Z'$ (the Majoron) and is completely made up of the imaginary part of the right-handed sneutrino, Im $\tilde{\nu}^c$. The second eigenvalue is the mass of the physical complex left-handed sneutrino (note that this is the physical state in this limit, as opposed to the real and imaginary parts of the left-handed sneutrino):

$$m^2_{\tilde{\nu}^c} = M^2_L - \frac{1}{8} g^2_{BL} v^2_R - \frac{1}{8} (g_1^2 + g_2^2) (v_u^2 - v_d^2).$$

(16)

Note that this mass implies that $M^2_L > \frac{1}{2} g_{BL} v^2_R$. This mass is also an eigenvalue of the CP-even mass matrix. The other CP-even eigenvalue is the mass for the CP-even piece of the right-handed sneutrino, Re $\tilde{\nu}^c$:

$$m^2_{\text{Re}\tilde{\nu}^c} = g^2_{BL} v^2_R/4,$$

(17)

which is positive and is degenerate with the $Z'$ mass. Finally, the masses of the charged sleptons are:

$$m^2_{\tilde{e}^c_L} = M^2_L - \frac{1}{8} g^2_{BL} v^2_R + \frac{1}{8} (g_2^2 - g_1^2) (v_u^2 - v_d^2) + \frac{1}{2} v^2_e v^2_d,$$

$$m^2_{\tilde{e}^c_R} = M^2_L + \frac{1}{8} g^2_{BL} v^2_R + \frac{1}{4} g_1^2 (v_u^2 - v_d^2) + \frac{1}{2} v^2_e v^2_d.$$ (18)

A closer examination of Eqs.(16,18) for the MSSM fields indicates that these values are the MSSM mass values modified appropriately by $B - L$ D-term contributions. All of these masses are realistic given $M^2_L > \frac{1}{2} g_{BL} v^2_R$. Of further interest is the prediction of the degeneracy between the $Z'$ gauge boson and the physical right-handed sneutrino. This degeneracy also extends to the right-handed neutrino when $g_{BL} v_R \gg M_{BL}$. Corrections to the approximate masses presented here would be of the order $Y_{\nu}^D v_L v_R$ or $A^D_{\nu} v_L \tilde{\nu}^0_{\nu}$. All of these terms are highly suppressed due to neutrino masses, making this discussion relevant even in the non-limit case.

\textbf{Charginos and Charged Leptons:} Mixing between the charged leptons and the charginos will occur in the charged fermion sector, $(\tilde{e}^c, W^0_L, H^+_L)$ and $(\tilde{e}^c, W^0_L, H^-_d)$. Since the mixing between the MSSM charginos and the charged leptons is proportional to $v_L$ and $Y_{\nu}^D$ small corrections to the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{TABLE I: Bilinear R-parity violating terms from: the gauge sector (left column) and the superpotential (right column).} & \\
\hline
$\frac{1}{2} g_{BL} v_R (\nu^c B)$ & $\frac{1}{2} Y_{\nu}^D v_R (\nu^c \sigma_2 H_u)$ \\
$\frac{1}{2} g_2 v_L (\nu W^0)$ & $\frac{1}{2} Y_{\nu}^D v_L (\tilde{H}_u^0 \nu^c)$ \\
$\frac{1}{2} g_2 v_L (\nu W^+) & $\frac{1}{2} Y_{e} v_L (\tilde{H}_d^0 e^c)$ \\
$\frac{1}{2} g_{1} v_L (\nu B) & \\
\hline
\end{tabular}
\end{table}
charged lepton masses can exist once the charginos are integrated out. However, this contribution is always small once we impose the neutrino constraints.

COLLIDER SIGNALS

As a consequence of $R$-parity violation, the lightest neutralino will be unstable and will decay via lepton number violating interactions. These type of interactions will also exist for the charginos and the new gauge boson:

Sleptons decays: It is important to emphasize the importance of the lepton number violating decays of sleptons. Here one has the decays $\tilde{\chi}^0_i \rightarrow \nu_j \tilde{e}^c$ or $e_j \nu_k$, $\tilde{\nu}^c_i \rightarrow \tilde{e}^c_j \nu_k$ and $\tilde{\nu}^c_i \rightarrow \tilde{e}^c_j \nu_k$. These decays are proportional to $\nu_{\nu}$ or $Y_{\nu}^D v_R$ and are crucial for the test of the model.

$Z'$ decays: The $Z'$ will decay mainly into ($\ell$)leptons since its coupling to ($\ell$)quarks is suppressed by the corresponding $B - L = 1/3$. In addition to the typical $Z'$ decays, new lepton number violating decays will be possible. These include $Z' \rightarrow \tilde{\chi}^0_j \tilde{\chi}^\mp_j$ which are suppressed by $v_{\nu}$. Also possible are the very interesting decays $Z' \rightarrow \nu^C \nu^C$, where the right-handed neutrinos can decay mainly to an electron and a selectron. These decays are lepton number violating and proportional to $v_R$. In particular very exciting signals are possible if the selectron is long-lived.

Neutralino decays: These will include $\tilde{\chi}^0_i \rightarrow Z^0 \tilde{\nu}$ and $\tilde{\chi}^0_i \rightarrow W^\pm e^\mp$ as usual. In the case when the neutralino is the up-like Higgsino, these decays are proportional to $v_{\nu}$, while in the rest of the cases are suppressed by $v_{\nu}$. L-violating Higgs decays: The Higgses now could have lepton number violating decay channels open such as MSSM-like Higgs into a slepton and a $W$ or $Z$ if kinematically allowed.

Chargino decays: In this case new decays into charged sleptons and a $Z$ or $W$ exist. All these decays are suppressed by $v_{\nu}$ or $Y_{\nu}^D$ once we impose the constraints coming from neutrino masses. The properties of all decays mentioned above will be studied in a future publication. See Ref. [13] for a recent study of $R$-parity violating decays at the LHC.

SUMMARY AND OUTLOOK

We proposed and studied a mechanism for spontaneous $R$-parity violation in the minimal $U(1)_{B-L}$ extension of the MSSM. The symmetry breaking is achieved through the VEV of the right-handed sneutrino so no new Higgs fields are needed. Because the sneutrino VEV is proportional to the soft SUSY mass scale, the $B - L$ breaking scale will be connected to the soft SUSY mass scale. The generation of viable neutrino masses, properties of the spectrum, the generation of R-parity breaking terms and the possible signals at future colliders experiments have been discussed and the mass degeneracy between the $Z'$ and the right-handed sneutrino has been noted. The fact that such a rich model is a product of simply extending the MSSM by local $U(1)_{B-L}$ and provides an understanding of spontaneous breaking of $R$-parity is very appealing to us and we plan to study further it’s phenomenology in a future publication.

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