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Spontaneous R-parity breaking and left–right symmetry

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ABSTRACT

We propose a simple renormalizable left–right theory where R-parity is spontaneously broken and neutrino masses are generated through the Type I seesaw mechanism and R-parity violation. In this theory R-parity and the gauge symmetry are broken by the sneutrino vacuum expectation values and there is no Majoron problem. The $SU(2)_R$ and R-parity violation scales are determined by the SUSY breaking scale making the model very predictive. We discuss the spectrum and possible tests of the theory through the neutralinos, charginos, Z' and W_R^\pm decays at the Large Hadron Collider.

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1. Introduction

The existence of massive neutrinos, the unknown origin of parity violation in the Standard Model (SM) and the hierarchy problem are some of the main motivations for physics beyond the SM. In the context of the so-called left–right symmetric theories [1] one has the appealing possibility to understand the origin of parity violation and its strong connection to the generation of neutrino masses. The supersymmetric version of these theories can also solve the hierarchy problem, as in the Minimal Supersymmetric Standard Model (MSSM).

Defining a minimal left–right model is a subtle issue since particle content depends on the mechanism generating neutrino masses. In the so-called minimal left–right symmetric theory, neutrino masses are generated through the Type I [2] and Type II [3] seesaw mechanisms. Alternatively, it is possible to have a simple theory [4] where neutrino masses are generated through the Type I [2] and Type III [5] seesaw mechanisms.

Supersymmetric left–right particle content further depends on the status of R-parity, an *ad hoc* discrete symmetry imposed in the MSSM to forbid rapid proton decay. Above the left–right scale, R-parity is automatically conserved due to local $U(1)_{B-L}$. Two situations are possible for the low energy theory: automatic R-parity conservation or spontaneous R-parity violation, which conserves baryon number and therefore does not induce proton decay. The former was discussed in Ref. [6] where the necessary Higgs sector was found to be involved but parity is spontaneously broken. The latter can have a simpler Higgs sector as well as exciting collider predictions, making the origin and impact of R-parity breaking in such models an important issue.

In this Letter we investigate this issue in detail and find that the Higgs sector can be remarkably simplified. This simplification utilizes the right-handed sneutrino which has both $B-L$ and $SU(2)_R$ quantum numbers. Once this field acquires a vacuum expectation value (VEV), both $SU(2)_R \otimes U(1)_{B-L}$ and R-parity are spontaneously broken with the relevant scales determined by the soft SUSY breaking scale. This leads to a simple and predictive model, especially for decays of the neutralinos, charginos, Z' and W_R . Neutrino masses are generated via the Type-I seesaw mechanism and R-parity. The Majoron problem [7] associated with spontaneous lepton number breaking is not present since the Majoron becomes the longitudinal component of Z' . Furthermore, all of this could be accomplished with the same Higgs sector of the MSSM making this the simplest left–right symmetric theory without R-parity. In this theory the left–right discrete symmetry is broken only by the soft terms in order to have a consistent mechanism for R-Parity violation and avoid the domain wall problem.

This Letter is organized as follows: in Section 2 we discuss the theory, while in Section 3 we show the properties of the spectrum, the R-parity violation mechanism, and the mechanism generating neutrino masses are discussed in great detail. The possible tests of the theory are discussed in Section 4.

2. Minimal SUSY left–right theory and R-parity

Left–right symmetric theories are based on the gauge group $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$. Here B and L stand for baryon and lepton number, respectively. In the supersymmetry (SUSY) case, the matter chiral supermultiplets for quarks and leptons are given by

$$\hat{Q} = \begin{pmatrix} \hat{U} \\ \hat{D} \end{pmatrix} \sim (2, 1, 1/3), \quad \hat{Q}^c = \begin{pmatrix} \hat{U}^c \\ \hat{D}^c \end{pmatrix} \sim (1, 2, -1/3), \quad (1)$$

$$\hat{L} = \begin{pmatrix} \hat{N} \\ \hat{E} \end{pmatrix} \sim (2, 1, -1), \quad \text{and} \quad \hat{L}^c = \begin{pmatrix} \hat{N}^c \\ \hat{E}^c \end{pmatrix} \sim (1, 2, 1), \quad (2)$$

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where N^C , the right-handed neutrino, is now required by the gauge group. With this field content, the superpotential is:

$$\mathcal{W} = Y_q \hat{Q}^T i\sigma_2 \hat{\Phi} i\sigma_2 \hat{Q}^C + Y_\nu^D \hat{L}^T i\sigma_2 \hat{\Phi} i\sigma_2 \hat{L}^C + \frac{\mu}{2} \text{Tr}(\hat{\Phi}^T i\sigma_2 \hat{\Phi} i\sigma_2), \quad (3)$$

where the bi-doublet Higgs is defined by

$$\hat{\Phi} = \begin{pmatrix} \hat{H}_D^0 & \hat{H}_U^+ \\ \hat{H}_D^- & \hat{H}_U^0 \end{pmatrix} \sim (2, 2, 0). \quad (4)$$

Typically, in order to have consistent relationships between the quark masses, an extra bi-doublet needs to be introduced or one-loop gluino corrections to the quark masses through trilinear soft breaking terms that are different between the up and down quark sectors must be assumed [8]. Here we see both possibilities as appealing.

So far, it seems like extra superfields are needed to break $SU(2)_R \times U(1)_{B-L}$, since the bi-doublet does not have a $B-L$ quantum number. As mentioned earlier, the choice for these fields depends on whether or not the low energy theory should conserve R-parity (or M-Parity). R-parity is defined as $R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$, where M is M-parity. As it is well known M-parity is -1 for any matter chiral superfield and $+1$ for any Higgs or vector superfield. 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 or higher-dimensional operators as in [6].

In the Letter, we wish to take advantage of the fact that Eq. (3) already contains a scalar field with the correct quantum numbers: the right-handed sneutrino. Once this field acquires a VEV, it spontaneously breaks both the higher gauge symmetry 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 (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 $SU(2)_R \times U(1)_{B-L}$ and R-parity violation with the same Higgs sector as the MSSM.

The kinetic terms in the theory are given by

$$\begin{aligned} \mathcal{L}_{\text{Kin}} = & \int d^4\theta \text{Tr}(\hat{\Phi}^\dagger e^{g_L \hat{V}_L} \hat{\Phi} e^{g_R \hat{V}_R}) \\ & + \int d^4\theta \hat{L}^\dagger e^{g_L \hat{V}_L - \frac{1}{2} g_{BL} \hat{V}_{BL}} \hat{L} \\ & + \int d^4\theta \hat{L}^C \dagger e^{g_R \hat{V}_R^\dagger + \frac{1}{2} g_{BL} \hat{V}_{BL}} \hat{L}^C, \end{aligned} \quad (5)$$

where \hat{V}_L and \hat{V}_R are the vector superfields for the gauge bosons in $SU(2)_L$ and $SU(2)_R$, respectively. Here, we use g_L and g_R for the gauge couplings in left–right sector.

In our notation the soft breaking terms are given by

$$\begin{aligned} V_{\text{soft}} = & M_Q^2 \tilde{Q}^\dagger \tilde{Q} + M_{\tilde{Q}^C}^2 \tilde{Q}^C \dagger \tilde{Q}^C + M_{\tilde{L}}^2 \tilde{L}^\dagger \tilde{L} \\ & + M_{\tilde{L}^C}^2 \tilde{L}^C \dagger \tilde{L}^C + M_\Phi^2 \text{Tr}(\hat{\Phi}^\dagger \hat{\Phi}) \\ & + \left(\frac{1}{2} M_R \text{Tr} \tilde{W}_R \tilde{W}_R + \frac{1}{2} M_L \text{Tr} \tilde{W}_L \tilde{W}_L \right. \\ & + \frac{1}{2} M_{BL} \tilde{B} \tilde{B} + A_q \tilde{Q}^T i\sigma_2 \Phi i\sigma_2 \tilde{Q}^C + A_\nu^D \tilde{L}^T i\sigma_2 \Phi i\sigma_2 \tilde{L}^C \\ & \left. + B \frac{\mu}{2} \text{Tr}(\hat{\Phi}^T i\sigma_2 \hat{\Phi} i\sigma_2) + \text{h.c.} \right). \end{aligned} \quad (6)$$

It is important to mention that under the discrete Left–Right Symmetry one has the transformations: $\hat{Q} \leftrightarrow \hat{Q}^{C*}$, $\hat{L} \leftrightarrow \hat{L}^{C*}$ and $\hat{\Phi} \leftrightarrow$

$\hat{\Phi}^\dagger$. In this case the Yukawa couplings Y_q and Y_ν^D are hermitian. Notice that in general there is no reason to assume the left–right discrete symmetry in the soft-breaking sector. In the rest of the Letter we will assume that the Left–Right discrete symmetry is only softly broken by the soft terms. In this case one can have a consistent mechanism for R-parity violation and avoid the domain wall problem. Notice that the breaking of the Left–Right symmetry is transmitted only through loop effects to the gauge interactions relevant for β and μ decays. Also we can add non-holomorphic soft terms $A_q^2 \tilde{Q}^T \Phi^* \tilde{Q}^C + A_\nu \tilde{L}^T \Phi^* \tilde{L}^C$ which could help us to correct the relation between the fermion masses at one-loop.

3. Spectrum and R-parity violation

In this theory the gauge boson masses are generated by the vacuum expectation values (VEVs) of sneutrinos ($\langle \tilde{\nu}_i \rangle = v_L^i / \sqrt{2}$ and $\langle \tilde{\nu}_i^C \rangle = v_R^i / \sqrt{2}$) and the bi-doublet ($\langle H_U^0 \rangle = v_u / \sqrt{2}$ and $\langle H_D^0 \rangle = v_d / \sqrt{2}$). The sneutrino VEVs also break R-parity and lepton number eliminating the quantum numbers necessary to distinguish between the lepton, Higgs and gaugino sectors. Therefore the physical charginos and neutralinos, as well as the Higgses will be admixtures of these three sectors. The properties of the full spectrum will be discussed in more detail in a future publication [9]. It is important to mention that in this context there is no Majoron problem since lepton number is part of the gauge symmetry (the Majoron becomes the longitudinal component of Z').

The scalar potential in this theory is given by

$$V = V_F + V_D + V_{\text{soft}}^S, \quad (7)$$

where the relevant terms for V_{soft}^S are given in Eq. (6). Once one generation of sneutrinos, $\tilde{\nu}$ and $\tilde{\nu}^C$, and Φ , acquire a VEV, the potential reads

$$\begin{aligned} \langle V_F \rangle = & \frac{1}{4} (Y_\nu^D)^2 (v_R^2 v_u^2 + v_R^2 v_L^2 + v_L^2 v_u^2) + \frac{1}{2} \mu^2 (v_u^2 + v_d^2) \\ & + \frac{1}{\sqrt{2}} Y_\nu^D \mu v_R v_L v_d, \end{aligned} \quad (8)$$

$$\begin{aligned} \langle V_D \rangle = & \frac{1}{32} [g_R^2 (v_R^2 + v_d^2 - v_u^2)^2 + g_L^2 (v_u^2 - v_d^2 - v_L^2)^2 \\ & + g_{BL}^2 (v_R^2 - v_L^2)^2], \end{aligned} \quad (9)$$

$$\begin{aligned} \langle V_{\text{soft}}^S \rangle = & \frac{1}{2} M_L^2 v_L^2 + \frac{1}{2} M_{\tilde{L}^C}^2 v_R^2 + \frac{1}{2} M_\Phi^2 (v_u^2 + v_d^2) - \text{Re}(B\mu) v_u v_d \\ & - \frac{1}{2\sqrt{2}} (A_\nu^D + (A_\nu^D)^\dagger) v_R v_L v_u \end{aligned} \quad (10)$$

and can be minimized in the usual way. 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):

$$v_R = \sqrt{\frac{-8M_{\tilde{L}^C}^2}{g_R^2 + g_{BL}^2}}, \quad (11)$$

$$v_L = \frac{A_\nu^D v_R v_u}{\sqrt{2(M_L^2 - \frac{1}{8} g_{BL}^2 v_R^2)}}, \quad (12)$$

$$\mu^2 = -\frac{1}{8} (g_R^2 + g_L^2) (v_u^2 + v_d^2) + \frac{M_{H_U}^2 \tan^2 \beta - M_{H_D}^2}{1 - \tan^2 \beta}, \quad (13)$$

$$B\mu = \frac{\sin 2\beta}{2} (2\mu^2 + M_{H_U}^2 + M_{H_D}^2), \quad (14)$$

where Eq. (11) has the same form as the Standard Model minimization condition and demonstrates the need for $M_{\tilde{L}^C}^2 < 0$, while

Eq. (12) indicates that A_ν^D should be small, i.e. $A_\nu^D \ll \frac{\sqrt{2}}{8} g_{BL}^2 \frac{v_R^2}{v_u}$ in

order to have $v_R \gg v_L$. Eqs. (13) and (14) are similar to their MSSM counterparts with $M_{H_U}^2 \equiv M_\phi^2 - \frac{1}{8}g_R^2 v_R^2$ and $M_{H_D}^2 \equiv M_\phi^2 + \frac{1}{8}g_R^2 v_R^2$. Note that the negative contribution to $m_{H_U}^2$ is conducive for electroweak symmetry breaking. Also, even though $M_{L_c}^2$ is negative, a realistic spectrum still exists [9].

3.1. Neutrino masses

Let us discuss how the neutrino masses are generated in this context. Once the symmetry is broken the neutralinos $\tilde{\chi}^0$ are defined as a linear combination of \tilde{B} , \tilde{W}_R^0 , \tilde{H}_D^0 , \tilde{H}_U^0 and \tilde{W}_L^0 and their mass matrix is given by

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_{BL} & 0 & 0 & 0 & 0 \\ 0 & M_R & -\frac{1}{2}g_R v_d & \frac{1}{2}g_R v_u & 0 \\ 0 & -\frac{1}{2}g_R v_d & 0 & -\mu & \frac{1}{2}g_2 v_d \\ 0 & \frac{1}{2}g_R v_u & -\mu & 0 & -\frac{1}{2}g_2 v_u \\ 0 & 0 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & M_2 \end{pmatrix}. \quad (15)$$

Working in the basis where the neutralino mass matrix is diagonal one finds that the matrix which define the mixings between the neutrinos and neutralinos in the basis $(\nu_i, \nu_j^c, \tilde{\chi}^0)$ is defined by

$$\mathcal{M}_{\nu\chi} = \begin{pmatrix} 0 & M_\nu^D & \Gamma \\ (M_\nu^D)^T & 0 & G \\ \Gamma^T & G^T & M_{\tilde{\chi}^0} \end{pmatrix}, \quad (16)$$

where

$$\Gamma^{\alpha i} = -\frac{g_{BL}}{2} v_L^\alpha N_{1i} - \frac{v_R^\beta}{\sqrt{2}} (Y_\nu^D)^{\alpha\beta} N_{4i} + g_2 v_L^\alpha N_{5i}, \quad (17)$$

and

$$G^{\beta i} = \frac{g_{BL}}{2} v_R^\beta N_{1i} - \frac{v_L^\alpha}{\sqrt{2}} (Y_\nu^D)^{\beta\alpha} N_{4i} - g_R v_R^\beta N_{2i}. \quad (18)$$

In the above equations, N is the matrix which diagonalizes the neutralino mass matrix. Now, assuming that $G, \Gamma \ll M_{\tilde{\chi}^0}$ integrating out the neutralinos and the right-handed neutrinos one finds the neutrino mass matrix

$$M_\nu = M_\nu^R + M_\nu^I \quad (19)$$

with

$$M_\nu^R = -(M_\nu^D (\Gamma G^{-1})^T + (\Gamma G^{-1}) (M_\nu^D)^T), \quad (20)$$

$$M_\nu^I = M_\nu^D (M_{\nu c})^{-1} (M_\nu^D)^T, \quad (21)$$

and

$$M_{\nu c} = G (M_{\tilde{\chi}^0})^{-1} G^T. \quad (22)$$

In the above equations M_ν^I is the usual Type I seesaw contribution generated when the right-handed neutrinos are integrated out, but the mass matrix for ν^c is generated by R-parity violation. Therefore, in this case neutrino masses are generated through the double seesaw mechanism. The second contribution, M_ν^R , is generated by pure R-parity violation. Therefore, we see that in this theory, with a mechanism for spontaneous R-parity violation, it is possible to generate neutrino masses in a consistent way. It is important to emphasize that the matrix Γ in Eq. (17) and G in Eq. (18) can be small and one can have a mini-seesaw mechanism where the seesaw scale is TeV. In the above equations $M_\nu^D = Y_\nu^D v_u$, which is, in principle, a free matrix since the charged lepton masses can be generated through SUSY loop effects due to the chargino and neutralino corrections. This is similar to the solution presented in [8] for the quark sector. See Ref. [10] for models with similar neutrino mass matrix.

4. Possible signals at the LHC

As it is well known in supersymmetric scenarios where R-parity is broken the neutralinos are unstable and new decay channels become available for the charginos. For a recent analysis of the signals of R-parity violation see [11]. In this theory the chargino mass matrix is given by

$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_R & 0 & -\frac{g_R}{\sqrt{2}} v_d \\ 0 & M_2 & \frac{g_2}{2} v_u \\ -g_R \frac{v_u}{\sqrt{2}} & \frac{g_2}{\sqrt{2}} v_d & \mu \end{pmatrix} \quad (23)$$

when we work in the basis $\tilde{\chi}^+ = (\tilde{W}_R^+, \tilde{W}_L^+, \tilde{H}_U^+)$ and $\tilde{\chi}^- = (\tilde{W}_R^-, \tilde{W}_L^-, \tilde{H}_D^-)$. Now, the matrix that defines the mixing between charged leptons and charginos reads as

$$\mathcal{M}_{\pm} = \begin{pmatrix} M_{\tilde{\chi}^\pm} & \Gamma^+ \\ \Gamma^- & M_E \end{pmatrix}, \quad (24)$$

where

$$\Gamma_{\alpha i}^+ = \frac{1}{\sqrt{2}} g_2 v_{L\alpha} C_{2i}^+ + \frac{1}{\sqrt{2}} (Y_\nu^D)_{\alpha\beta} v_R^\beta C_{3i}^+, \quad (25)$$

$$\Gamma_{\beta i}^- = -\frac{1}{\sqrt{2}} g_R v_{R\beta} C_{1i}^- + \frac{1}{\sqrt{2}} (Y_\nu^D)_{\alpha\beta} v_L^\alpha C_{3i}^-. \quad (26)$$

Here, C^\pm are the matrices which diagonalize the chargino mass matrix. The generic predictions coming from R-parity scenarios are the decays of neutralinos and the new decays for the charginos. In our case we have three charginos, $\tilde{\chi}^\pm$, which will have the following decay channels: $\tilde{\chi}_i^\pm \rightarrow e_j^\pm Z, \nu W^\pm$ through the coupling Γ^\pm , and the neutralinos decays $\tilde{\chi}_i^0 \rightarrow \nu Z, e_j^\pm W^\mp$ through the coupling Γ and G , respectively. Therefore, once we take into account the neutrino mass constraints one can predict these decays [9].

It is important to mention that once the charginos are integrated out one can generate mass for one charged lepton. In this case:

$$(M_E)_{\alpha\beta} = \Gamma_{\alpha i}^+ M_{\tilde{\chi}_i^+}^{-1} \Gamma_{\beta i}^-. \quad (27)$$

And, neglecting the terms proportional to Y_ν^D :

$$(M_E)_{\alpha\beta} \approx -\frac{g_2 g_R}{2} v_{L\alpha} v_{R\beta} \frac{C_{2i}^+ C_{1i}^-}{M_{\tilde{\chi}_i^+}}. \quad (28)$$

Therefore, one could generate one of the charged lepton masses once the charginos are integrated out. There are some new novel decays in this theory. For example the decays $\tilde{\nu} \rightarrow e_i^- e_j^+$, $Z' \rightarrow e_i^\pm \tilde{\chi}_j^\mp$ and $W_R^\pm \rightarrow e_i^\pm \tilde{\chi}_j^0$ which could help test this theory. Before finishing this section, we would like to emphasize that in this case the R-parity violating decays of the neutralinos and charginos are not highly suppressed by neutrino masses since they are proportional to the couplings Γ , G and Γ^\pm . This is an important difference between the usual R-parity violating scenarios and this one. We will study these issues in great detail in a future publication [9].

5. Summary and outlook

We have investigated the connection between R-parity and the possibility of finding the simplest supersymmetric left–right symmetric theory. We found a simple theory where R-parity is spontaneously broken and neutrino masses are generated through Type I seesaw and R-parity violation. In this theory R-parity and the $SU(2)_R$ symmetry are broken by the vacuum expectation value of the sneutrinos, which are related to the SUSY breaking scale. The Higgs sector of the theory is quite simple since could be composed

of the MSSM Higgses or only two bidoublets. We have discussed the spectrum of the theory, and the possible tests at the Large Hadron Collider though the decays of neutralinos, charginos, Z' and W_R^\pm . Furthermore, neutralinos and charginos decays are not highly suppressed by neutrino masses because of the double seesaw mechanism. The phenomenological and cosmological aspects of this theory will be investigated in detail in a future publication.

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