Natural Suppression of Proton Decay in Supersymmetric Type III Seesaw Models

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Abstract

Supersymmetric standard model (MSSM) has two sources of rapid proton decay: (i) R-parity breaking terms and (ii) higher dimensional Planck induced B-violating terms; its extensions to include neutrino masses via the type I seesaw mechanism need not have the first of these problems due to the existence of B-L as a gauge symmetry but for sure always have the second one. If instead, neutrino masses are explained in a type III seesaw extension of standard model, an anomaly free gauge symmetry different from B-L is known to exist. In this note, it is shown that a realistic supersymmetric versions of this model can be constructed (MSSM as well as SUSY left-right with type III seesaw) which eliminate R-parity violating couplings and suppress Planck scale contributions to proton decay. The degree of suppression of the latter depends on the weak gauge group. For the left-right case, the suppression to the desired level is easily achieved.
I. INTRODUCTION

Supersymmetry provides a very attractive way to solve the gauge hierarchy problem of the standard model. This and the fact that it also provides a natural candidate for the dark matter of the universe has made supersymmetric extensions of the standard model (MSSM) a prime focus of theoretical and experimental research in the past two decades. Despite these attractive features, MSSM as a complete theory is not satisfactory since it takes a step backward from standard model as far as our understanding of proton decay is concerned. There are two new sources of rapid proton decay in MSSM, which arise from the fact that the theory has supersymmetry: (i) renormalizable R-parity breaking interactions, a combination of two of which, $QLd^c$ and $u^c d^c d^c$, lead to extremely rapid p-decay and secondly (ii) Planck scale induced higher dimensional operators of the form $QQQL/M_{Pl}$ and $u^c u^c d^c e^c/M_{Pl}$, which also do the same. Current lower limits on the proton lifetime can be used to set limits on the product of the two couplings in case (i) $\lambda'\lambda'' < 10^{-24}$ and the individual couplings in case (ii) $\lambda < 10^{-7}$ [1]. These are extremely stringent bounds and before supersymmetric models can be accepted as good descriptions of nature, one must find a satisfactory way to either eliminate or suppress these interactions in a natural manner.

It was pointed out many years ago that extending MSSM to incorporate neutrino masses via type I seesaw mechanism (i.e. include three right handed neutrinos into MSSM) automatically extends the local symmetry to $SU(2)_L \times U(1)_{A_R} \times U(1)_{B-L}$ which when broken by $B - L = 2$ Higgs fields automatically eliminates the undesirable R-parity breaking terms [2]. However they do not eliminate the Planck scale induced terms and usually, one invokes additional gauged discrete symmetries to achieve that goal [3]. While B-L symmetry is physically quite well motivated, symmetries [3] used to eliminate the $QQQL$ type operators are often quite adhoc. We explore this question in the context of type I II seesaw models [4].

In several papers [5, 7], it has been pointed out that nonsupersymmetric type III seesaw models admit an extra $U(1)_X$ gauge symmetry. The presence of this additional gauge symmetry provides a natural way to understand why the seesaw scale (in this case the Majorana mass of the triplet fermions of the type III seesaw model), is much less than the its natural value, the Planck scale in much the same way that the B-L symmetry provides an explanation does the same for the type I seesaw case. However as already noted, in the type I seesaw case, B-L symmetry while forbidding the R-parity breaking terms still allows the
Planck scale operators of type $QQQL$ and $u^c u^c d^c e^e$. In this brief note we point out that the type III seesaw case is very different: the same symmetry that explains the smallness seesaw scale compared to the Planck scale also automatically forbids both the R-parity breaking as well as the Planck induced proton decay operators in the symmetry limit. When the gauge symmetry is broken, the resulting higher dimensional B-violating operators are suppressed with the degree of suppression depending on the nature of the electroweak gauge group: for instance we find that the required suppression is more easily achieved for left-right gauge group than the SM case.

This paper is organized as follows: in sec. 2, we discuss the extension of MSSM with type III seesaw (called MSSM$_{III}$); in sec. 3, we discuss the left-right extension and in sec. 4, we conclude with some comments and a summary.

II. MSSM$_{III}$: MSSM EXTENDED WITH TYPE III SEESAW

The basic idea of the type III seesaw model is to add three hypercharge neutral triplet fermions to the standard model\cite{4}. We denote the triplets as:

$$\Sigma = \begin{pmatrix} t^+ \\ t^0 \\ t^- \end{pmatrix}$$  \hspace{1cm} (1)

In order to find the extra gauge symmetry of the model, one looks at the constraints on $U(1)_X$ charges of the various fields from the requirement of vanishing of the following anomalies involving the $U(1)_X$ symmetry: (i) $U(1)_X[SU(2)_L]^2$, (ii) $U(1)_X[SU(3)_C]^2$ (iii) $U(1)_X[U(1)_Y]^2$ (iv) $U(1)_Y[U(1)_X]^2$ and $U(1)_X[Gravity]^2$. These constraints for the nonsupersymmetric type III model has already been studied in \cite{3, 7} and further analyzed in \cite{8} where it has been shown that only for three triplets, there is a solution to the anomaly equations. The resulting charges for the various SM fields are shown in the first six rows of table I. They are expressed in terms of two arbitrary numbers $n_q$ and $n_l$, which denote the quark and lepton doublet charges under $U(1)_X$. We assume throughout this paper that $U(1)_X$ is generation blind.

In order to construct a realistic supersymmetric extension of this model, we need two Higgs doublet superfields, $H_{u,d}$ and add two singlet superfields $S, \bar{S}$. Since their contributions to the anomaly equations cancel, the anomaly constraints are satisfied for the MSSM$_{III}$ case.
also for the same charges of matter fields as in [4, 7]. The $U(1)_X$ charges of all the fields are given in Table I.

| Fields | $U(1)_X$ quantum number |
|--------|-------------------------|
| $Q$    | $n_q$                   |
| $u^c$  | $-\frac{1}{4}(7n_q - 3n_t)$ |
| $d^c$  | $-\frac{1}{4}(n_q + 3n_t)$ |
| $L$    | $n_t$                   |
| $e^c$  | $-\frac{1}{4}(-9n_q + 5n_t)$ |
| $\Sigma$ | $-\frac{1}{4}(3n_q + n_t)$ |
| $H_u$  | $\frac{3}{4}(n_q - n_t)$ |
| $H_d$  | $-\frac{3}{4}(n_q - n_t)$ |
| $S$    | $+\frac{1}{2}(3n_q + n_t)$ |
| $\overline{S}$ | $-\frac{1}{2}(3n_q + n_t)$ |

Table Caption: Anomaly free quantum numbers for various fields in MSSM$_{III}$.

Note that this symmetry allows the Yukawa coupling part of the superpotential of the form:

$$W_{III} = h_u Q H_u u^c + h_d Q H_d d^c + h_l L H_d e^c \frac{\overline{S}}{M_{Pl}} h_u L H_u \Sigma + f \Sigma \overline{\Sigma} S$$

For the Higgs part of the superpotential, we have

$$W_H = \mu H_u H_d + Y(S\overline{S} - M^2)$$

where $Y$ is a SM singlet and $U(1)_X$ neutral fields. A curious feature of this superpotential is that the charged lepton masses which arise from the $h_l$ term in the superpotential are suppressed by the factor $\frac{\overline{S}}{M_{Pl}}$. Note however that $<S>$ and $<\overline{S}>$ also give mass to the $\Sigma$ field and implement the type III seesaw mechanism. These considerations restrict the value of $<S>$.

To reproduce the charged lepton masses (mainly the tau lepton), it seems that we must choose, $<S> = <\overline{S}> = M_U \sim 3 \times 10^{15} - 10^{16}$ GeV (using $M_{Pl} \sim 1.22 \times 10^{18}$ GeV) for a
tau Yukawa coupling from 3-1. This says that the charged lepton masses are automatically suppressed compared to quark masses as well as the Dirac mass of the neutrinos. Also the observed neutrino masses of order 0.05 eV or less imply that the triplet fermion masses doing seesaw should of order $10^{14} - 10^{15}$ GeV or so for $h_\nu \sim 1 - 3$. This will mean that $f \sim 0.1 - 0.01$. The model can reproduce all observed fermion masses. As we show below, the above $<S>$ limits the degree of suppression of the $p$-decay operators in MSSM$_{III}$. It could of course be that the lepton Yukawa coupling term is scaled by some new physics scale below the Planck scale. In that case the vev$<S>$ could be lot lower, again with implications for the degree of suppression of the proton decay operators.

Note incidentally that if indeed the lepton Yukawa term is scaled by $M_{Pl}$, the subsequent large value of the triplet mass will only slightly disturb the coupling unification of MSSM somewhat. On the other hand, if the scale is set by lower mass scale, the effect on gauge coupling running will affect unification. However as we remark below, these models do not grand unify in the usual manner to $SU(5)$ or $SO(10)$ groups and still keep the extra $U(1)_X$ gauge symmetry.

A. Suppression of baryon violating operators

Using the $U(1)_X$ charge assignments for fields in the Table I, we compute the $U(1)_X$ charges of the baryon and lepton number violating operators and list them in Table 2 below.

| Operator | $U(1)_X$ Charge |
|----------|-----------------|
| QQQL $u^c u^c d^c e^c$ | $3n_q + n_l$ |
| $QLd^c$ | $-\frac{1}{2}(3n_q + n_l)$ |
| $LLe^c$ | $\frac{1}{3}(3n_q + n_l)$ |
| $u^c d^c d^c$ | $-\frac{3}{4}(3n_q + n_l)$ |
| $LH_u LH_u$ | $\frac{2}{3}(3n_q + n_l)$ |
| $LH_u$ | $\frac{1}{4}(3n_q + n_l)$ |

Table Caption: $U(1)_X$ charges of the various baryon and lepton number violating operators.
Note that all the R-parity breaking and higher dimensional proton decay operators have $U(1)_X$ charges which are multiples of the $U(1)_X$ charge of the triplet field $n_\Sigma = -\frac{1}{4}(3n_q + n_l)$.

We require the latter to be nonzero so that the smallness of the triplet mass compared to the Planck mass can be understood. As a result, we find that all R-parity breaking as well as $QQQL$ operators are forbidden to all orders. As far as the $u^c u^c d^c e^c$ operator goes, while it is forbidden in the symmetry limit, it is induced when $U(1)_X$ symmetry is broken by the operator $u^c u^c d^c e^c S/M_{Pl}$; if we choose $< S > = 3 \times 10^{15}$, the suppression is about $3 \times 10^{-3}$ and one still needs to dial the coupling of this operator down by a factor of $3 \times 10^{-5}$ or so to keep it compatible with current proton lifetime limits. The $QQQL$ operator is induced at the next higher order i.e. $QQQLS^2/M_{Pl}^2$ so that after symmetry breaking, its strength is $\sim 10^{-5}$ and one needs a coupling for this operator of about $10^{-2}$. Thus there is suppression for these operators but not enough due to lepton mass constraint. It does however ameliorate the fine tuning problem somewhat. As far as the R-parity violating operators are concerned though, they are forbidden to all orders.

Note that if the lepton Yukawa is scaled by a lower mass scale, the $< S >$ induced proton decay operators are more easily suppressed.

III. “TYPE III SEESAW” WITH LEFT-RIGHT SYMMETRY

In this section, we extend our analysis to the case where the electroweak gauge group is the left-right symmetric group $G_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Left right models with “type III seesaw” have been considered in the literature. We will study the susy version of this model and discuss the p-decay operators. The full gauge group will be $G_{LR} \times U(1)_X$, where $U(1)_X$ is the new anomaly free gauge group arising from type III seesaw as we show below. In this section, we choose the quark and lepton assignment to the LR group as follows:

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} (2, 1, 1/3); \quad Q^c = \begin{pmatrix} d^c \\ u^c \end{pmatrix} (1, 2, -1/3);$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} (2, 1, -1); \quad L^c = \begin{pmatrix} e^c \\ \nu^c \end{pmatrix} (1, 2, +1).$$

The $U(1)_X$ charges are given by the numbers in the parenthesis next to the field in what follows: $Q(n_q); \quad Q^c(-n_q); \quad L(n_l); \quad L^c(-n_e)$. The left-right symmetric assignment of the
triplets required for the type III seesaw are given by:

\[
\Sigma^c = \begin{pmatrix} T^+ \\ T^0 \\ T^- \end{pmatrix} (1, 3, 0, -n_{\Sigma^c});
\]

\[
\Sigma = \begin{pmatrix} t^+ \\ t^0 \\ t^- \end{pmatrix} (3, 1, 0, n_{\Sigma})
\]

where the $U(1)_X$ charges are included above. There are six anomaly conditions in this case
and a solution to the vanishing of all the anomaly constraints is:

\[
n_q = n_{q^c} \equiv n_q; \quad n_l = n_{l^c} \equiv n_l; \quad n_{\Sigma} = n_{\Sigma^c} = -\frac{1}{4}(3n_q + n_l)
\]

In order to implement symmetry breaking, this model will have left and right Higgs doublets
which will come in pairs so that their anomalies will cancel among themselves: we denote
them by $\chi(2, 1, +1), \bar{\chi}(2, 1, -1); \chi^c(1, 2, -1), \bar{\chi}^c(1, 2, +1)$. The $U(1)_X$ quantum numbers for
$\chi$ and $\bar{\chi}$ are $\pm \frac{3}{4}(n_q - n_l)$ respectively and opposite for the $\chi^c$ and $\bar{\chi}^c$ fields. We also have
a bi-doublet $\phi(2, 2, 0)$ with zero $U(1)_X$ quantum number in the model. As in the MSSM$_{III}$
case, here have two singlet fields $S$ ans $\bar{S}$ that have $U(1)_X$ quantum number of $\pm \frac{1}{2}(3n_q + n_l)$
The Yukawa coupling superpotential for this model is given by:

\[
W_{Y}^{LR} = h_q Q \phi Q^c + h_l L \phi L^c + f(L \chi \Sigma + L^c \chi^c \Sigma^c) + \lambda(\Sigma^2 S + \Sigma^c S)
\]

The different symmetry breaking stages are as follows: We have $< S > \sim < \chi^c > \gg < \phi >$. The first breaks the $U(1)_X$ symmetry and give large masses to the triplet fields. $< \chi^c >$ breaks the left right group down to the standard model symmetry and gives mass term of the form $\nu^c T^0$ and $e^c T^-$ field. The bi-doublet vev which breaks the standard
model group and gives mass to the charged fermions as well as the quarks. The vev of the
$\chi$ field is assumed to be zero.

The neutrino mass in this model arises from a double seesaw mechanism involving the
fields ($\nu, \nu^c, T^0$) as discussed in [9]. Strictly speaking, since in this model, the left triplet
fermion does not participate in the seesaw mechanism, it is not a canonical type III seesaw
model; it is more appropriate to call it the triplet version of double seesaw mechanism [10].

A fundamental difference between this model and the MSSM$_{III}$ discussed in section 2 is
that the $< S >$ vev in this model need not be at the GUT scale and in fact, since neutrino
mass involves the double seesaw, this vev can be anywhere between tens of TeV range to $10^{14}$ GeV. This has implications for the suppression of R-parity and baryon violating operators.

A. R-parity and higher dimensional proton decay operators

Let us now discuss the R-parity and baryon number violating operators in this model. In the usual susy left-right case with doublets breaking B-L symmetry, there are tree level R-P violating operators of the form $L^c \chi^c$ and nonrenormalizable ones of the form $LLL^c \bar{\chi}^c$ and $Q^c Q^c Q^c \bar{\chi}^c$. However in this model, these operators are forbidden by $U(1)_X$ gauge symmetry since their $U(1)_X$ charges respectively are: $-\frac{1}{4}(3n_q + n_l)$, $+\frac{1}{4}(3n_q + n_l)$, $-\frac{3}{4}(3n_q + n_l)$. Again as in the MSSM case, these charges are all proportional to the triplet charges and therefore as long as the triplet charges are nonvanishing, which we require to understand their masses being smaller than the Planck mass, the R-parity breaking operators are forbidden.

Turning to higher dimensional proton decay operator, we note that the $QQQL$ and $Q^c Q^c Q^c L^c$ operators are forbidden by $U(1)_X$ symmetry. The leading order $U(1)_X$ invariant operator that contributes to $QQQL$ and $Q^c Q^c Q^c L^c$ after symmetry breaking are $QQQL \bar{S}^2 / M_{Pl}^2$ giving strength of these operators to be $(< \bar{S} > / M_{Pl})^2$. For $< \bar{S} >$ vev below $10^{12}$ GeV, this is fully consistent with current limits discussed in the introduction. Thus the model is safe with respect to rapid proton decay due to the presence of $U(1)_X$ symmetry.

IV. COMMENTS AND CONCLUSION

In summary, in this brief note, we have analysed and pointed out a novel feature of the extra gauged $U(1)_X$ symmetry which is present in type III seesaw extensions of standard model for explaining small neutrino masses. First we show that this symmetry remains in the supersymmetric extensions of the simple type III model, MSSM$_{III}$ as well as its left-right symmetric extension. These models provide realistic descriptions of nature and more importantly, they not only forbid the R-parity breaking interactions of MSSM but they also suppress the undesirable and dangerous Planck scale induced proton decay interactions. The suppression of the latter operators to the desired level is more easily achieved in the supersymmetric left-right versions of the model than in the MSSM$_{III}$. These results eliminate a
conceptual problem of MSSM and its generalizations to include neutrino masses and puts type III seesaw models at an advantage over the type I seesaw models. However we also find that these models fail to grand unify to conventional SU(5) or SO(10) groups while keeping the extra $U(1)_X$, unlike the type I seesaw models which naturally grand unify to SO(10) (although an extension to the case of $SU(2)_L \times SU(2)_R \times SU(4)_c \times U(1)_X$ seems straightforward).

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