Sparticle Spectroscopy and Phenomenology
in a New Class of Gauge Mediated
Supersymmetry Breaking Models

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Abstract

Recently, a proposal (by R.N.M. and S.N.) was made for a new class of gauge mediated supersymmetry breaking (GMSB) models where the standard model gauge group is embedded into the gauge group $SU(2)_L \times U(1)_{BR} \times U(1)_{B-L}$ (or $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$) at the supersymmetry breaking scale $\Lambda$. Supersymmetry breaking is transmitted to the visible sector via the same fields that are responsible for gauge symmetry breaking rather than by vector-like quarks and leptons as in the conventional GMSB models. These models have a number of attractive properties such as exact R-parity conservation, non-vanishing neutrino masses and a solution to the SUSYCP (and strong
CP) problem. In this paper, we present the detailed sparticle spectroscopy and phenomenological implications of the various models of this class that embody the general spirit of our previous work but use a larger variety of messenger fields. A distinct characteristic of this class of models is that unlike the conventional GMSB ones, the lightest neutralino is always the NLSP leading to photonic events in the colliders.

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I. INTRODUCTION

There are many compelling reasons to believe that nature is supersymmetric at short distances. Since the observed spectrum of fermions and gauge bosons does not exhibit any trace of supersymmetry, it must be broken at a scale around or higher than 100 GeV. The general procedure followed in building realistic models with broken supersymmetry is to assume that supersymmetry breaking takes place in a hidden sector which is completely separate from the visible sector of the standard model and have this effect transmitted to the quarks and leptons via a messenger sector. Different classes of supersymmetric models can be distinguished by the way the messengers transmit supersymmetry breaking from the hidden sector to the visible one. A scenario which has become very popular in the last two years is one where the messenger fields are replicas of the known quarks and leptons except that they are heavier and they come in vector like pairs [1] and the standard model gauge interactions of the messenger fields are the ones that transmit supersymmetry breaking to the visible sector. The advantage of these models is that they lead to degenerate squark and slepton masses at the scale $\Lambda$ which then provides a natural solution to the flavor changing neutral current (FCNC) problem of the low energy supersymmetry models. This makes the models phenomenologically very attractive. Secondly these models are extremely predictive [2] so that one can have a genuine hope that they can be experimentally tested in the not too distant future.

There are however several drawbacks of these models: (i) one needs to put in extra vectorlike quarks and leptons whose sole purpose is to transmit the supersymmetry breaking from the hidden to the visible sector; (ii) it has been argued [3] that in explicit models of supersymmetry breaking in the hidden sector, the lowest vacuum breaks color and only the false vacuum has the desirable properties; (iii) the lightest of the messenger fields is a heavy stable particle which may lead to cosmological difficulties. Moreover, in these models there is no apriori reason why the vector-like quarks cannot mix with the known quarks. If they do mix, then additional tree level FCNC effects can spoil the above naturalness property.
Finally, these models do not address some other generic problems of the MSSM such as the existence of R-parity breaking interactions that lead to arbitrary couplings for the unwanted baryon and lepton number violating couplings.

Since the general idea of the gauge mediated supersymmetry breaking is attractive, it would be useful to explore models that avoid its undesirable features while at the same time maintaining the good ones (such as the non degeneracy of squark and slepton fields). With this goal in mind, two of us (S.N. and R.N.M.) began exploring a new class of models [4] where the messenger sector consists of different fields. We also chose the electroweak gauge group to be $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ [5] so that it guarantees automatic R-parity conservation [6]. It then turns out that the messenger fields can also play the role of Higgs fields that can serve to break the above gauge group down to the standard model group. Thus the scale of supersymmetry breaking gets connected to the scale of gauge symmetry breaking and the breaking of electroweak symmetry remains radiative. This is a very minimal extension of the standard model which also leads to nonzero neutrino masses via the usual see-saw mechanism [7]. Moreover, since the messenger fields couple to the right-handed neutrinos in order to implement the see-saw mechanism, they are unstable and therefore do not cause any cosmological problem.

It is the goal of this paper to study a wider class of models which follow the spirit of this idea but use different messenger fields. We study the following different messenger sectors: (the numbers in the parenthesis denote the $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ quantum numbers) (AI) the minimal one of Ref. [4] which uses only fields $\delta(1,1,-2) + \delta(1,-1,+2)$; (AII) one pair of $\delta(1,1,-2) + \delta(1,-1,+2)$ along with two extra Higgs doublets $H_u'(2,1/2,0)$ and $H_d'(2,-1/2,0)$; (AIII) model (AII) with the addition of a pair of color octets (electroweak singlet) $Q$. We also extend the gauge group to the left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ case. We impose the requirement of electroweak symmetry breaking to be radiative and study the detailed predictions for the sparticle spectra for these models and outline the phenomenological implications. We find that the present experimental data seem to allow only the third model for both the gauge groups. Once the requirement of radiative
electroweak symmetry breaking is relaxed, all the cases become viable. We present typical particle spectra for each of these cases. They turn out to be very different from the conventional GMSB models making it possible to test the general idea of the gauge mediated supersymmetry breaking as opposed to a specific messenger version of it. A distinct and testable prediction of our models is that the lightest neutralino is always the NLSP leading to photonic events in the colliders.

We arrange this paper as follows: in section II, we outline the model and present the mass formulae for the various sparticles at the scale \( \Lambda \) of supersymmetry breaking; in section III, we present the particle spectra for these models and we discuss the phenomenological implications and tests of the models. Section IV contains the minimization of the Higgs potential for one typical version of these models and in section V, we present some concluding remarks.

II. THE MODELS

A: Models with \( SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L} \)

We begin our discussion with a brief recap of the model of Ref. [4] which we call model AI. The electroweak gauge group is \( SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L} \) with quarks and leptons (including the right-handed neutrinos, \( \nu^c \)) transforming as follows:

- \( Q \) (2, 0, \( 1/3 \)) ; \( L \) (2, 0, \( -1 \)) ; \( u^c \) (1, \(-1/2, -1/3\)) ; \( d^c \) (1, \( +1/2, -1/3 \)) ; \( e^c \) (1, \( +1/2, +1 \)) ; \( \nu^c \) (1, \(-1/2, +1 \)).

The two MSSM Higgs doublet superfields transform as \( H_u(2, +1/2, 0) \) and \( H_d(2, -1/2, 0) \). In addition to these, we add the fields \( \delta \) and \( \bar{\delta} \) (three such pairs) that break the \( U(1)_{I_{3R}} \times U(1)_{B-L} \) symmetry down to the \( U(1)_Y \) of the standard model. They have the quantum numbers \( \delta(1, +1, -2) \) and \( \bar{\delta}(1, -1, +2) \). The superpotential for the matter sector of the theory (denoted \( W_{\text{vis}} \)) is given by:

\[
W_{\text{vis}} = h_u Q H_u u^c + h_d Q H_d d^c + h_u L H_u e^c + h_d L H_d \nu^c + \mu H_u H_d + f \delta \nu^c \nu^c. \tag{1}
\]

This is common to all versions of the type A models. The different cases arise from the
different choices of the messenger sector.

*Model AI*

The messenger sector in this case consists of three pairs of fields $\delta$ and $\bar{\delta}$ mentioned above. The messenger sector superpotential $W_m$ (representing only a part of the complete superpotential) is given by

$$W_m = \lambda S \delta \bar{\delta} + M_\delta \delta \bar{\delta}. \quad (2)$$

We will show in section V that the $F_S$, $\delta$ and $\bar{\delta}$ acquire nonzero vacuum expectation values (VEV) so that supersymmetry as well as $U(1)_B \times U(1)_I$ are broken at the same scale. As a result, the supersymmetry breaking scale and the $B - L$ breaking scale get linked to each other and cannot be arbitrarily adjusted in the physics discussion.

Next, we note that the supersymmetry breaking is transmitted from the hidden sector to the visible sector via the $B - L$ and $I_{3R}$ gauge interactions. As a result, it is the exchange of $B - L$ and $I_{3R}$ gauge particles that replaces the standard model (and MSSM) particles in the GMSB model graphs that give a Majorana mass to the gauginos at the one loop and sfermions at the two loop level. The resulting Majorana mass of the $B - L$ and $I_{3R}$ gauginos ($\lambda_{B-L,I_{3R}}$) is such that the Bino $\lambda_Y \equiv (g_{B-L}^{-1}\lambda_{B-L} + g_{R}^{-1}\lambda_{I_{3R}})$ remains massless. In other words, in the language of the MSSM, $M_1 = 0$. Furthermore, the $SU(2)_L$ gauginos also do not have any Majorana mass (i.e. $M_2 = 0$). The gluino is also massless in this model as was already noted in [4]. It is worth pointing out that there are tiny contributions to all gaugino masses in this model at the electroweak scale. For instance, gluino masses arise from the diagram in Fig. 1 and can be estimated to be

$$M_\tilde{G} \simeq \frac{\alpha_s m_t^2 \mu cot \beta}{4\pi M_t^2} \quad (3)$$

leading to a mass of the order of a GeV or less. The same holds for all the models discussed here. This loop induced mass becomes important if there are no other larger contribution in the model and leads to the light gluino scenario advocated in recent literature [10]. These, as we will see, have profound implications for phenomenology.
Turning now to the remaining sfermions, we find that:

\[ M_F^2 \simeq 2\left[x_F^2 \left(\frac{\alpha_{B-L}}{4\pi}\right)^2 \Lambda_S^2 + y_F^2 \left(\frac{\alpha_R}{4\pi}\right)^2 \Lambda_S^2\right] \]  

(4)

where \( x_F \) and \( y_F \) denote the \( \sqrt{\frac{3}{2}} \frac{B-L}{4} \) and \( I_{3R} \) values for the different superfields \( F \) (both matter as well as Higgs) and \( \Lambda_S \) denotes ratio \( <F_S> / <S> \) where \( <S> \) denotes the VEV of S field. It is therefore clear that the good FCNC properties of the usual GMSB are maintained in this class of models. Furthermore the spectrum of squarks and sleptons here is very different from that of the usual GMSB models, where messenger fields carry color. For example, the sleptons are heavier than the squarks. In section III, we present the predictions for the various sfermion masses in this model.

**Model AII**

The second class of models with the same gauge group, we consider, is characterized by the following Higgs content that changes the character of the messenger sector. In addition to one pair of \( \delta \) fields as in model AII, we include two pairs of \( SU(2)_L \times U(1)_Y \) Higgs doublets \( H^a_u \) and \( H^a_d \) (with \( a=1,2 \)). The standard model Higgs doublets will arise out of these Higgs fields and below the SUSY breaking scale there are only light doublets. We will assume that the second pair (\( a=2 \)) does not couple to the quarks and leptons. We will show in section V that the minimization of the Higgs potential will lead to VEV’s for the \( \delta \) fields which will induce supersymmetry breaking \( F_S \neq 0 \). The relevant part of the hidden sector superpotential \( W_m \) has the form

\[ W_H = \lambda S H^1_u H^1_d + M_H H^1_u H^1_d \]  

(5)

The \( H^1_u \) and \( H^1_d \) will play the role of messenger fields. It is then clear that now \( M_{1,2} \) are nonzero removing a major constraint in the phenomenological analysis. The gluino is however still massless. The masses \( M_k \) with \( k = 1,2 \) denoting the \( SU(2) \) and \( U(1) \) gauge groups are given by:

\[ M_1 = \frac{3 \alpha_1}{5 \pi} \Lambda_S \]  

(6)

\[ M_2 = \frac{\alpha_{2L}}{4 \pi} \Lambda_S \]
As far as the other sfermion masses go, we give the relevant formulae below:

\[
M_\tilde{Q}^2 = m_{2L}^2 + \frac{1}{24}m_{BL}^2 \\
M_\tilde{u}^2 = m_R^2 + \frac{1}{24}m_{BL}^2 \\
M_\tilde{L}^2 = m_{2L}^2 + \frac{3}{8}m_{BL}^2 \\
M_\tilde{e}^2 = m_R^2 + \frac{3}{8}m_{BL}^2 \\
M_{H_u}^2 = m_{2L}^2 + m_R^2 = M_{H_d}^2
\]

where

\[
m_{2L}^2 = 2\Lambda_S^3 \left( \frac{\alpha_2}{4\pi} \right)^2 \\
m_{BL}^2 = 2\Lambda_S^3 \left( \frac{\alpha_{B-L}}{4\pi} \right)^2 \\
m_R^2 = 2\Lambda_S^3 \frac{1}{4} \left( \frac{\alpha_R}{4\pi} \right)^2.
\]

Model AIII

The last class of models we will consider will have some messengers with color so that the gluinos can pick up mass. We do not consider colored fields with quantum numbers identical with the quarks as in the usual GMSB models since they could mix with the known quarks and generate new undesirable FCNC effects. As an example we will consider a pair of color octet fields along with two pairs of Higgs doublets as in AII. We will show in sec. IV that our superpotential is such that these color fields do not acquire VEV’s and therefore there is no danger of color breaking. We will now have all gauginos picking up Majorana masses. The \( U(1) \) and \( SU(2)_L \) gaugino masses are same as in the model AII. The gluino mass is given by:

\[
M_\tilde{g} = 3\frac{\alpha_s}{4\pi}\Lambda_S
\]

As far as the other sfermion masses are concerned, the slepton and the Higgs masses are same as in the model AII; the squark masses are given as follows:
\[ M_Q^2 = m_{2L}^2 + \frac{1}{24} m_{B_L}^2 + m_{3c}^2 \]
\[ M_{\tilde{q}}^2 = m_{R}^2 + \frac{1}{24} m_{B_L}^2 + m_{3c}^2 \]

where \( m_{3c} = 8 \Lambda_S^2 \left( \frac{\alpha}{4\pi} \right)^2 \).

**B: Models with \( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \) gauge group**

Let us now turn to the models with the left-right symmetric gauge group. The quarks and leptons transform under the gauge group as: \( Q(2, 1, 1/3); Q^c(1, 2, -1/3); L(2, 1, -1) \) and \( L^c(1, 2, +1) \). We implement the breaking of \( SU(2)_R \times U(1)_{B-L} \) symmetry by means of the triplet Higgs pair as in the usual left-right models [8]. The messenger sectors will essentially be the same as in case (A) except that the doublet pairs everywhere will now be replaced by bi-doublets \( \phi_a(2, 2, 0) \). We will assume that the spectrum below the scale \( \Lambda_S \) is same as in MSSM; this will require that we enforce a doublet-doublet splitting at that scale. One way to do this is to follow a recent suggestion [9] where the parameters of the superpotential involving the bidoublets are finetuned. This fine tuning is essentially the same as the unresolved \( \mu \) problem of the MSSM and we do not have anything more to say on this question. In any case, as far as the contribution to the gaugino masses go, the \( M_{\tilde{g}} \) will remain the same as before for the various cases, and the \( M_1 \) and \( M_2 \) are as follows:

Model BI : \( M_1 = M_2 = 0 \); \hspace{1cm} (11)

Model BII and BIII : \( M_1 = \frac{3}{5} \frac{\alpha_1}{4\pi} \Lambda_S; M_2 = \frac{\alpha_2 L}{4\pi} \Lambda_S \).

The left-chiral squark and slepton mass contributions remain the same as in the case A. As far as the masses of \( q^c, L^c \) are concerned, in formula Eq. (7), we now have \( m^2_{R} = 2 \Lambda_S^2 \left( \frac{\alpha_R}{4\pi} \right)^2 \)

**III. SPARTICLE SPECTROSCOPY**

In this section, we discuss the sparticle spectroscopy of the type A models. The predictions for the type B models are same for the left-chiral sparticles but only slightly different for the right chiral ones. We therefore do not discuss the type B models in this section.
In giving the numerical predictions for the sfermion masses in this model, we start by first requiring that the electroweak symmetry be radiatively broken. As is well-known this requires that:

\[
\frac{M_Z^2}{2} = \frac{M_{H_u}^2 - M_{H_d}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2
\]  

(12)

where all radiative corrections are absorbed into the parameters. The reasons why it is nontrivial to satisfy this equation in predictive models such as the GMSB models are the following: the Higgs masses are predicted to be positive at the scale \( \Lambda_S \) and to be proportional to various gauge couplings \( \alpha_i \) and \( \Lambda_S \) and the renormalization group evolution of the Higgs masses depends on the value of the stop masses at \( \Lambda_S \). So for instance, if in a model, the \( M_{H_u}^2(\Lambda_S) \) is too large and the stop masses are not large enough at that scale, \( M_{H_u}^2 \) will remain positive at \( M_Z \) and will not lead to electroweak symmetry breaking. In one of the models to be discussed later this is what happens. To see this in a qualitative manner, let us write down the extrapolated value of the \( M_{H_u}^2(m_{\tilde{t}}) \) in the lowest order approximation (neglecting running of squark masses and the effect of the gaugino masses).

\[
m_{H_u}^2(m_{\tilde{t}}) \approx m_{H_u}^2(\Lambda_S) - \frac{3\lambda_{\tilde{t}}^2}{8\pi^2} \ln(\Lambda_S/m_{\tilde{t}}) \left( m_{H_u}^2(\Lambda_S) + m_{\tilde{Q}}^2(\Lambda_S) + m_{\tilde{u}}^2(\Lambda_S) \right)
\]  

(13)

In the minimal model (AI), it is clear from Eq. (13) that electroweak symmetry breaking depends on the relative values of \( \alpha_{B-L} \) and \( \alpha_R \). The masses in the above Eqn. are given by:

\[
m_{H_u}^2(\Lambda_S) \simeq \frac{1}{12} \left( \frac{\alpha_R}{4\pi} \right)^2 \Lambda_S^2
\]

(14)

\[
m_{t}^2(\Lambda_S) \simeq \frac{1}{12} \left( \frac{\alpha_{B-L}}{4\pi} \right)^2 \Lambda_S^2
\]

It is clear from Eq.(13) and Eq.(14) that \( m_{H_u}^2 \leq 0 \) for \( r^2 \geq \left( (1 - \frac{6\lambda_{\tilde{t}}^2(\Lambda_S/m_{\tilde{t}})}{8\pi^2})/(\ln(\Lambda_S/m_{\tilde{t}})) \right) \), where \( r = \alpha_{B-L}/\alpha_R \). We find that for \( r \geq 3 \), the radiative symmetry breaking becomes possible and that we can satisfy the above EWSB equation for \( \Lambda_S \simeq 50 - 100 \) TeV for reasonable values of the \( \mu \) parameter. We should mention that this way of determining the allowed values of \( r \) is very rough and we have determined \( r \) numerically. In table 1, we
list the predictions for the various sparticle masses (where we have numerically solved the renormalization group equations exactly in the one loop approximation) for two different choices of the scale $\Lambda_S$, $\tan\beta$, $r \equiv \frac{\alpha_{B-L}}{\alpha_{\mu}}$ and sign($\mu$). We emphasize that these are the only four inputs into the model and all other masses are predictions (including the $\mu^2$ parameter, which is chosen to satisfy the EWSB constraint).

A detailed study shows that this model predicts the light Higgs mass to be in the range of 30 to 50 GeV. The Higgs production cross-section in $e^+e^-$ collision is of course slightly lowered by the factor $\sin(\alpha - \beta)$ [11]. There are two important decay modes of the lightest Higgs boson: $h \rightarrow b\bar{b}$ and $\chi_1\chi_1$; however, detailed study of the neutralino mass matrix in the allowed parameter space seems to give $h \rightarrow b\bar{b}$ mode to be the dominant one. It is therefore hard to reconcile with the present LEP II data. Increasing the value of $\mu$ does not seem to be of any help, since it would decrease the chargino mass. The lightest neutralino in this model is primarily a combination of the gauginos and next to lightest neutralino is a combination of the Higgsinos. The next to lightest neutralino is also very light (less than 20 GeV in the two illustrative scenarios given in the Table 1). Since these next to lightest neutralinos decay hadronically (each neutralino would decay into a anti-quark, a quark and a gluino), they would contribute to the hadronic decay width of Z. However the contribution to the Z decay width is 7-15 MeV for the scenarios in the Table 1 and is allowed by the present data. The lighter chargino pair production cross-section in this model (for the scenarios given in the Table 1) is little higher $\sim 4$ pb for $\sqrt{s}=172$ GeV.

It is worth emphasizing that a crucial assumption that leads to the above conclusions is that the electroweak symmetry breaking be radiative. If however, we give up that assumption and only assume that the supersymmetry breaking be transmitted via $B - L$ gauge interactions, then Higgs and the chargino masses can become much higher and no such conflict with present data occurs. In such a model, electroweak symmetry breaking may, for example, arise from terms like $S(H_uH_d - v^2)$ in the superpotential.

Turning to the model $AII$, we find that the model fails to give rise to electroweak symmetry breaking. Fig. 2 shows the extrapolation of the Higgs masses from the scale...
Λ_S down to the weak scale and the main feature to notice is that \( M_{H_u}^2 \) (and of course \( M_{H_d}^2 \)) remains positive. The main reason for this is the small value for the stop masses at the \( \Lambda_S \) scale, since it is the stop mass that drives the up-type Higgs mass negative in the renormalization group evolution. One can see this in a qualitative manner as follows. Note that we have

\[
m_{H_u}^2 (m_t) \approx m_{2L}^2 + m_R^2 \frac{3 \lambda_t^2}{8 \pi^2} (2 m_{2L}^2 + 2 m_R^2 + \frac{1}{12} m_{RL}^2) \ln \frac{\Lambda_S}{m_t}
\]

Defining \( y \equiv \frac{\alpha_2}{\alpha_R} \), we get

\[
m_{H_u}^2 \left( \frac{4 \pi}{\alpha_R} \right)^2 = \left( \frac{1}{2} + \frac{3}{2} y^2 \right) (1 - 2 x) - \frac{x r^2}{6}
\]

where \( x \equiv \frac{3 \lambda_t^2 \ln(\Lambda_S/m_t)}{8 \pi^2} \) is roughly 0.25. The condition for the \( m_{H_u}^2 \) to turn negative at the weak scale is \( r^2 \geq 6 + 18 y^2 \) under the constraint \( 1.9 r = 0.6 y + 0.4 y \). Only for a very narrow range of values of \( y \approx 2.9 - 3.4 \), these two constraints are satisfied. We consider this to be extreme fine tuning. \( r \) is also large in that range which implies very large value of \( \alpha_{B-L} \).

Outside this very narrow range, the typical value of \( m_{H_u}^2 \) is shown in Fig.2.

Let us now turn to the model AIII which includes the color octet messengers. In this model the stop masses at the scale \( \Lambda_S \) are enhanced due to the octet contribution. As a result, the electro-weak symmetry breaking condition is satisfied more easily. In Table 2, we give the prediction for the sparticle masses as well as the Higgs masses for this model.

The squark masses in this model are close to one TeV and are higher than the prediction of the usual GMSB models. The chargino masses in this model are well allowed by the experimental data and due to the color octet contribution the gluino masses are \( \sim 1 \) TeV.

An important feature of this model is the prediction of a relatively light neutralino, \( \chi_0 \) in the mass range of 54 GeV or less. \( \chi_0 \) decays to a photon and a gravitino. Thus a production of this neutralino pair in electron positron collider will give rise to two photons plus missing energy in the final state. Both the OPAL and the ALEPH collaboration at LEPII have looked for this signal. From the non observation of this signal at \( \sqrt{s} = 172 \) GeV, they have established the following bounds:
OPAL Collaboration: $\sigma < 0.41$ pb (95% C.L.) [12].

ALEPH Collaboration: $\sigma < 0.18$ pb [13].

In Fig (3a), we plot the cross-sections for $e^+e^- \to \chi_0\chi_0$ as functions of the neutralino mass for the three LEPII energies, $\sqrt{s}=172$, 182, 194 GeV. The cross-sections in our model is much lower than those in the usual GMSB model [14] because of the larger mass of the lighter scalar electron. These curves are for $\tan\beta=9$ and $r=4$. With the increase of the value of $r$, the cross-sections gets smaller, whereas the dependence on $\tan\beta$ is very small.

As $r$ increases, $\alpha_{B-L}$ increases. We restrict to $r \leq 6$ to keep $\alpha_{B-L}$ in the perturbative region (for $r=6$, $\alpha_{B-L}(\Lambda_s)=0.075$). In Fig (3b), we show that the values of the cross-sections for $\tan\beta=9$ and $r=6$. In both Fig (3a) and (3b), $\Lambda_s$ has been varied from 40 to 60 GeV (the corresponding values for the squark masses lie between 0.9 to 1.5 TeV). We do not increase $\Lambda_s$ any further in order to keep SUSY a viable explanation for the hierarchy problem. From Figs (3a) and (3b), we see that the current LEP II bounds on the neutralino pair productions are satisfied. The important point is to note that the smallest allowed values of the cross-sections are not too much below the current experimental bounds. Thus, the photon signals in our model could be within reach in the LEPII experiments in very near future.

Now we discuss the consequences of this model at the Tevatron collider ($\sqrt{s}=1.8$ TeV).

In table 2, our lightest neutralino mass varies from 29 to 40 GeV, while the lighter chargino mass varies from 94 to 126 GeV. At Tevatron these could be produced in the following processes:

$$p\bar{p} \to \chi_i^+\chi_j^-, \chi^\pm\chi_a, \chi_a\chi_b$$ (17)

where $i,j$ run over 1,2 while $a,b$ run from 0 to 3. For the mass range given in table 2, $\chi_i^+\chi_i^-$, $\chi^\pm\chi_0$, $\chi^\pm\chi_1$ can be produced at Tevatron with significant cross-section. The subsequent decays of the neutralino to a photon and a gravitino and the decay of a chargino to a $\ell\nu\gamma\tilde{G}$ or $q\bar{q}\gamma\tilde{G}$ will give rise to inclusive $\gamma\gamma\gamma$ plus missing $E_T$ final states. Recently, the authors of Ref. [15] have studied these signals in great detail, including detector simulation. They conclude that with the assumption of gaugino unification, $m_{\chi^+} \leq 125$ GeV and $m_{\tilde{N}_1} \leq 70$
GeV can be excluded with 100 $pb^{-1}$ of Tevatron data (such masses give rise to about 10 two photon events plus missing energy inclusive events). Without the assumption of gaugino unification (which is the case in our model), they exclude $m_{\chi^+} \leq 100$ GeV for $m_{\chi^0} \geq 50$ GeV. (In this analysis, $m_{\chi^0} \geq 50$ GeV is needed for the photons and missing energy to satisfy the detector cut, $p_T^\gamma \geq 12$ GeV, missing $E_T \geq 30$ GeV). Thus the mass range presented in Table 2 are not excluded by the current Tevatron data, but in the interesting boundary of being tested with the complete analysis of the Tevatron data and could be easily tested in the upgraded Tevatron.

Another interesting feature of this model is that the lightest $\chi_0$ is always the NLSP. This is to be contrasted with the usual GMSB models, where the NLSP can be either the lightest neutralino or the lighter stau depending on the parameter space. In addition, in the usual GMSB models, $\chi_0$ need not be as light, whereas in our model as argued before, $\chi_0$ is in the 50 GeV range or lighter because its mass is tied to the squark masses. The lighter chargino in our model can be around 130GeV. Each chargino decays into a W and a neutralino, where the neutralino decays 100% into $\gamma$ and gravitino and the W decays partly into an electron and an anti-neutrino. The final state has $e^+e^-\gamma\gamma$ plus missing energy. For other decays of the W boson, we would in general have $l_i^+l_j^-\gamma\gamma$ plus missing energy or $l_i^\pm+jets+\gamma\gamma$ plus missing energy or multijet $+\gamma\gamma$ plus missing energy. Such a signal with two hard photons will be easily detected and will have negligible SM background. The detailed predictions for this phenomenon at collider energies is presently under investigation and will be the subject of a forthcoming publication [16].

If two pairs of Higgs doublets, instead of one, contribute to the squark and gaugino masses, then the lightest neutralino mass and the chargino mass become larger due to the larger values of $M_1$ and $M_2$ at the Gauge mediated scale. The values of $M_1$ and $M_2$ are larger by a factor of 4 than the previous case. The squark masses do not get affected much due to this new contribution, since the color octet has a bigger contribution. The slepton masses also become larger. We show some scenarios for this model in Table 3. It is interesting to note that in this case the squark masses can be lower than the previous model. This
is because the lightest neutralino mass is heavier in this model which reduces the Λ and subsequently reduces the squark masses. The pseudo scalar mass and the charged Higgs mass can also be lower in this case due to the same reason. The superpartner masses in this case can be safely beyond the present lower limits.

The mass spectrum for the models BI-BIII are almost comparable to the model AI-AIII.

IV. AN EXPLICIT MODEL FOR THE HIDDEN SECTOR

In this section we address the question of the explicit model that leads to a VEV for $F_S$ used in the previous section while at the same time allowing the appropriate messengers to transmit the supersymmetry breaking. This discussion is nontrivial for the following reasons. While it is easy to construct a superpotential that leads to a singlet having a non-zero VEV and a non-zero $<F_S>$, it is not simple to communicate the supersymmetry breaking to the visible sector. For some of the problems see the paper by Dasgupta et al [3]. Below we provide an explicit superpotential which enables us to attain all our goals simultaneously [17]. Furthermore, we will not need Fayet-Iliopoulos terms to break supersymmetry.

Let us illustrate our method using an example from the class A models with $\delta$ and $\bar{\delta}$ and two pairs of Higgs doublets: $H_{u,d}$ and $H'_{u,d}$. The generalization to the other cases is straightforward. We choose the superpotential of the form:

$$\begin{align*}
W_H &= \lambda S (\delta \bar{\delta} - M^2 + H_u H_d) + \lambda' S' \delta \bar{\delta} + M_1 (H_u H'_d + H_d H'_u) + M_2 H_u H_d.
\end{align*}$$

The potential can be written down from this as follows:

$$\begin{align*}
V &= V_F + V_D \\
V_F &= \lambda^2 |\delta \bar{\delta} - M^2 + H_u H_d|^2 + \lambda' |\delta \bar{\delta}|^2 + |\lambda S + \lambda' S'|^2 (|\delta|^2 + |\bar{\delta}|^2) \\
&\quad + M_1^2 (|H_u|^2 + |H_d|^2) + |\lambda S H_d + M_2 H_d + M_1 H'_d|^2 + |\lambda S H_u + M_1 H'_u + M_2 H_u|^2.
\end{align*}$$

The D-terms are not shown but they are given by standard expressions. We choose $M_1 \gg M, M_2$. It is then easy to see that global minimum of the theory corresponds to $\langle H_{u,d} \rangle = 0$;
<δ>² = <δ̄>² = \frac{\lambda^2 M_2^2}{\lambda^2 + \lambda'M_2^2} and \(F_S = \frac{\lambda' M_2^2}{\lambda + \lambda'M_2^2}\). To get the gaugino masses, we do not need the S VEV since the mass term \(M_2\) plays that role in this theory. An important point to emphasize is that in the tree level \(\lambda S + \lambda' S'\) vanishes giving rise to a flat direction. This is however stabilized giving small S VEV once loop effects are taken into account.

The important point to note is that the fields \(H_u,d\) which play the role of messenger fields do not have VEV. This was guaranteed by the fact that there is a second pair of similar fields and that the mass parameter \(M_1\) is larger than other mass parameters in the theory. One can therefore include any pair of fields (including colored fields) as messenger fields and keep them from acquiring VEV provided we add a second identical pair and add a mass term analogous to \(M_1\) which is large. Note that, below the SUSY breaking scale we have only a pair of light Higgs doublets.

Let us now apply the above discussion to the model AI. We start with three pairs of \(\delta, \bar{\delta}\) which have the same quantum numbers under the gauge group \(SU(2)_L \times U(1)_{B-L}\) as before and distinguished from each other by a prime. We then write the following superpotential:

\[
W = \lambda S (\delta \bar{\delta} - M^2 + \delta'' \bar{\delta}'') + \lambda' S' \delta \bar{\delta} + M_1 (\delta'' \bar{\delta}' + \delta' \bar{\delta}'') + M_2 \delta'' \bar{\delta}''
\]  

(20)

It is easy to see that for \(M_1 \gg M, M_2\), the ground state corresponds to \(F_S, F_S'\) and \(<\delta> = <\bar{\delta}>\) having nonvanishing VEV’s exactly as in the case above and \(<\delta''> = <\bar{\delta}''> = 0\). The supersymmetry breaking is then transmitted via the \(\delta\) fields to the visible sector.

An exactly analogous construction applies to the case AIII with two pairs of color octets [18] replacing the doublets in the case above. As far as the left-right symmetric group is concerned, we replace the the \(\delta\)’s above by the \(SU(2)_R\) triplets and the doublets by the appropriate bidoublets. Again the above discussion carries through in a straight forward manner.

Finally, we wish to note that, it is possible to give a superpotential for the case AI, for which both the electroweak as well as the \(U(1)_{B-L}\) symmetry breaking arises from radiative corrections. We discuss this in Appendix A. The phenomenological profile of this model is
similar to the case AI with the difference that there is an extra light gaugino (with mass in the 100 GeV range). This model will also predict a light Higgs in the range of 30 to 40 GeV and hence is not consistent with present observations. We present it in the appendix in any case since it has the amusing feature that all gauge symmetries in this model are broken radiatively and $B - L$ is the sole mediator of supersymmetry breaking.

V. DISCUSSIONS AND CONCLUSION

In this paper we have investigated the sparticle spectroscopy and tests of a new class of gauge mediated supersymmetry breaking models with the gauge group $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ and its left-right symmetric version. The main reason for choosing the alternative messenger sectors is that we want to maintain R-parity conservation and the good FCNC properties while keeping the model phenomenologically viable. In one of the models, model AI, the supersymmetry breaking is transmitted via the $B - L$ gauge interactions. In this case however, we find that the light Higgs mass is too low for most of the parameter range that we investigated. We then investigate alternative messenger sectors involving color octets and $SU(2)_L$ doublets. We find that when we have a pair of color octets and a pair of $SU(2)_L$ doublets, the model $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ has the interesting prediction that the lightest neutralino is always the NLSP and is very light (in the 50 GeV range or less). This would therefore be testable at LEP II through the direct production of the neutralinos or at Tevatron through the decays of the charginos that would eventually lead to photonic events accompanied by lepton pairs, leptons and jets or pairs of jets. The lightest neutralino mass is however larger in another version of the model where we have two pairs of doublets contributing to the SUSY breaking soft masses. In this case the masses of the SUSY particles can be safely beyond the present experimental bound. The left-right version of the model also has similar results.

Acknowledgement
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Appendix A

In this appendix we discuss a superpotential where the scales of supersymmetry breaking and the $B-L$ symmetry breaking are decoupled from each other and all gauge symmetry breakings arise from the radiative renormalization group evolution of the soft breakings. Furthermore the supersymmetry breaking is transmitted to the visible sector only via the $B-L$ gauge interactions. The phenomenological profile of this model is similar in all respects to the model AI except that the $B-L$ gaugino in this model is also light. It therefore leads to a light Higgs mass which is too low in the absence of any new contributions. Nevertheless we present the model since it is particularly simple and could be of interest as a realistic model if any new contribution to the Higgs mass could be found.

The messenger sector of the model consists only of two pairs $\delta, \bar{\delta}$ fields and a singlet field $S$. The superpotential of the model is given by:

$$ W = \lambda S(\delta \bar{\delta} - M^2) + M_1(\delta \bar{\delta}' + \delta' \bar{\delta}) + M_2 \delta \bar{\delta} $$ (21)

For $M_1 \gg M, M_2$, the ground state of this theory has all $\delta$'s having zero vevs and $F_S = -\lambda M^2$. Thus supersymmetry is broken at the scale and can be transmitted to the visible sector via the $\delta$ fields. A combination of the $B-L$ and $I_{3R}$ gaugino acquires mass at the one loop level via the usual GMSB diagrams and the squarks and the sleptons acquire masses at the two loop level. Once we include the $f \nu^c \nu^c \delta$ term in the superpotential to implement the see-saw mechanism, there appears another minimum of the potential with $< \bar{\nu}^c >, < \bar{\delta'} > \neq 0$ but other fields with zero VEV which is degenerate with the other minimum. This leads to the breakdown of $U(1)_{I_{3R}} \times U(1)_{B-L}$ down to $U(1)_Y$. This model then leads to dynamical breaking of R-parity symmetry which however conserves baryon number.
REFERENCES


[5] It has been brought to our attention by Ann Nelson that the idea of gauged $B-L$ as a mediator of supersymmetry breaking was first noted by I. Affleck, M. Dine and N. Seiberg, Nucl. Phys. B256, 557 (1997).


[18] One motivation for the inclusion of a color octet Q8 as messenger field is that in the
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ version of the model it can lead to gauge coupling constant unification with a low $W_R$ scale if in addition to the color octet field the model contains two bidoublets $\phi(2, 2, 0)$, a pair of $\Delta^c$ and $\bar{\Delta}^c$ with quantum numbers $(1, 3, \pm 2)$ and a $B-L$ neutral $SU(2)_L$ triplet field $\Sigma(3, 1, 0)$. The particle spectrum of the model is not left right symmetric (although the gauge symmetry consists of both $SU(2)_{L,R}$ groups) due to broken D-parity at the GUT scale (see for instance D. Chang, R. N. Mohapatra and M. K. Parida, Phys. Rev. Lett. 52, 1072 (1984) for D-parity broken models).
Table Caption:

**Table 1:** Mass spectrum for the superpartners in the scenarios 1 to 5 in Model A1 (1 pair of Higgs doublet contribute to the soft supersymmetry breaking masses); 1st and 2nd generation superpartner masses are almost same.

**Table 2:** Mass spectrum for the superpartners in the scenarios 1 to 5 in Model AIII (1 pair of Higgs doublet along with color octet contribute to the soft supersymmetry breaking masses); 1st and 2nd generation superpartner masses are almost same.

**Table 3:** Mass spectrum for the superpartners in the scenarios 1 to 5 in Model AIII (2 pairs of Higgs doublets along with color octet contribute to the soft supersymmetry breaking masses); 1st and 2nd generation superpartner masses are almost same.

Figure Caption:

**Fig. 1:** One loop graph contributing to the gluino mass.

**Fig. 2:** Running of the $m_{H_u}^2$ and $m_{H_d}^2$ in model AII. The solid line corresponds to $m_{H_u}^2$ and the dashed line corresponds to $m_{H_d}^2$. The pair of lines in the bottom of the figure corresponds to $\Lambda_s = 50$ TeV, $r(\equiv \alpha_{B-L}/\alpha_R) = 3.33$ and $\tan \beta = 3$ and the pair of lines in the top corresponds to $\Lambda_s = 30$ TeV, $r(\equiv \alpha_{B-L}/\alpha_R) = 3.33$ and $\tan \beta = 3$.

**Fig. 3:** a) The value of the cross-section for $\sigma(e^+e^- \rightarrow \chi^0\chi^0)$ as a function of the $\chi^0$ mass at various LEP energies for $r(\equiv \alpha_{B-L}/\alpha_R) = 4$ and $\tan \beta = 9$. The dot-dashed line corresponds to $\sqrt{s} = 194$ GeV, the solid line corresponds to $\sqrt{s} = 182$ GeV and the dashed line corresponds to $\sqrt{s} = 172$ GeV.

b) The value of the cross-section for $\sigma(e^+e^- \rightarrow \chi^0\chi^0)$ as a function of the $\chi^0$ mass at various LEP energies for $r = 6$ and $\tan \beta = 9$. 

23
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<td>277,376</td>
<td>354,485</td>
<td>231,324</td>
<td>332,486</td>
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<td>278,376</td>
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<td>655,713</td>
<td>1009,1100</td>
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<td>1068,1102</td>
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<td>857</td>
<td>1101</td>
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<tr>
<td>$\mu$</td>
<td>-250</td>
<td>-268</td>
<td>-360</td>
<td>-216</td>
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FIG. 1.
Fig. 2
Fig. 3a

Fig. 3b