A New Messenger Sector for Gauge Mediated Supersymmetry Breaking

R. N. Mohapatra\textsuperscript{a)} and S. Nandi\textsuperscript{b)}

\textit{a)} Department of Physics, University of Maryland, College Park, Md-20742
\textit{b)} Department of Physics, Oklahoma State University, Stillwater, OK-74078

Abstract

We propose a new class of gauge mediated supersymmetry breaking (GMSB) models where the standard model gauge group is embedded into the gauge group $SU(2)_L \times U(1)_{I_3R} \times U(1)_{B-L}$ (or $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$) at the supersymmetry breaking scale $\Lambda_S$. The messenger sector in these models can consist of color singlet but $U(1)_{I_3R}$ and $U(1)_{B-L}$ non-singlet fields. The distinguishing features of such models are: (i) exact R-parity conservation, (ii) non-vanishing neutrino masses and (iii) a solution to the SUYCP problem. We present a complete hidden plus messenger sector potential that leads to the desired supersymmetry breaking pattern. The simplest version of these models predicts the existence of very light gluinos which can be made heavier by a simple modification of the supersymmetry breaking sector.

Understanding the origin and nature of supersymmetry breaking is one of the major research areas in particle physics right now. The general strategy is to postulate the existence of a hidden sector where supersymmetry is assumed to be broken and then have it transmitted to the visible sector. A currently popular way of transmitting the supersymmetry breaking is to use the standard model gauge interactions in which case one can choose the SUSY breaking scale to be $\simeq 10 - 100$ TeV or so. These models are known as gauge mediated supersymmetry breaking (GMSB) models\cite{1}. They are attractive for two primary reasons: one is that they lead to degenerate squark and slepton masses at the SUSY breaking scale $\Lambda_S$ which then provides a natural solution to the flavor changing neutral current problem of the low energy supersymmetry models. Secondly, these models are extremely predictive
so that one can have a genuine hope that they can be experimentally tested\[2\] in the not too distant future.

There are however several drawbacks in the usual construction of these models: first, one uses extra vectorlike quarks and leptons whose sole purpose is to transmit the supersymmetry breaking from the hidden to the visible sector; secondly, it has been argued\[3\] that in explicit models of supersymmetry breaking in the hidden sector, the lowest vacuum breaks color and finally the lightest of the messenger fields is a heavy stable particle which may lead to cosmological difficulties. Finally, these class of 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 violation. Our goal in this paper is to propose an alternative messenger sector which eliminates some of these problems of the GMSB models.

Our model is based on the electroweak gauge group $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ and uses the color singlet but $B-L$ and $I_{3R}$ non-singlet vectorlike fields as the messenger fields in the simplest version. These fields not only play the role of messenger fields but also serve to break the above gauge group down to that of the standard model group. Secondly, the above group automatically guarantees the conservation of R-parity\[4\] so that the model conserves baryon and lepton number automatically, a property that made the standard model so attractive and is sadly missing in MSSM. It also leads to nonzero neutrino masses via the usual see-saw mechanism. Moreover, since the messenger fields couple to the right-handed neutrinos they are unstable and therefore do not cause any cosmological problems. Finally, since in this model, the Majorana masses for the gauginos vanish upto one loop level as does the A-parameter, one has a solution to the SUSYCP problem. Key predictions of this model are: (i) the existence of very light gluinos, which, as far as we know,
are not conclusively ruled out \cite{5}; (ii) the existence of a chargino lighter than the W-boson and (iii) photino as the lightest neutralino with mass in the 1/2 to 1 GeV range. When photinos are the lighter than gluinos, big bang nucleosynthesis puts an upper bound on the gravitino mass of 40 eV. We also give an explicit model for supersymmetry breakdown in the hidden sector and its transmission to the visible sector.

The Model

Under the gauge group $SU(2)_L \times U(1)_{I_3R} \times U(1)_{B-L}$, the quarks and leptons (including the right-handed neutrinos, $\nu^c$) transform as $Q(2, 0, 1/3) ; L(2, 0, -1) ; u^c(1, -1/2, -1/3) ; d^c(1, +1/2, -1/3) ; e^c(1, +1/2, +1) ; \nu^c(1, -1/2, +1)$ and the two MSSM Higgs doublets as $H_u(2, +1/2, 0)$ and $H_d(2, -1/2, 0)$. In addition to these, we add the fields $\delta$ and $\bar{\delta}$ with quantum numbers $\delta(1, +1, -2)$ and $\bar{\delta}(1, -1, +2)$ that will break the $U(1)_{I_3R} \times U(1)_{B-L}$ symmetry down to the $U(1)_Y$ of the standard model. The interesting point illustrated in this simplest version of our model is that the same $\delta$ and $\bar{\delta}$ fields which play a role in supersymmetry breaking also play the role of messenger fields.

To study the general profile of the model, we start with the following superpotential $W = W_m + W_g$ where $W_m = \lambda S \delta \bar{\delta}$ corresponds to the messenger sector and is part of the complete unified hidden and messenger sector superpotential (described in the subsequent section). $W_g$ describes the visible sector of our model.

$$W_g = h_u Q H_u u^c + h_d Q H_d d^c + h_e L H_d e^c + h_u L H_u \nu^c + \mu H_u H_d + f \delta \nu^c \nu^c \quad (1)$$

We will show that $F_S, S, \delta$ and $\bar{\delta}$ acquire nonzero vacuum expectation values (vev) so that supersymmetry as well as $U(1)_{B-L} \times U(1)_{I_3R}$ 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. It is also worth pointing out that the fields ($\delta$ and $\bar{\delta}$) are essential for the supersymmetry
breaking. Next, we note that the same mechanisms that give mass to the gauginos at the one loop and sfermions at the two loop level in the usual GMSB models help to give mass to the $B - L$ and $I_{3R}$ gauginos ($\lambda_{B-L,I_{3R}}$) at the one loop and all sfermions at the two loop level; The mass matrix for the $I_{3R}$ and $B - L$ gaugino- $\tilde{\delta}$, $\tilde{\bar{\delta}}$ is given in the basis ($\lambda_{B-L}, \lambda_{R}, \tilde{\delta}, \tilde{\bar{\delta}}$) by:

$$M = \frac{1}{4\pi} \begin{pmatrix}
-\alpha_{B-L} & \sqrt{\alpha_{B-L}\alpha_{R}} & -\sqrt{24\pi g_{B-L}}v_\delta & \sqrt{24\pi g_{B-L}}v_\bar{\delta} \\
\sqrt{\alpha_{B-L}\alpha_{R}} & -\alpha_{R} & \sqrt{24\pi g_{R}}v_\delta & -\sqrt{24\pi g_{R}}v_\bar{\delta} \\
-\sqrt{24\pi g_{B-L}}v_\delta & \sqrt{24\pi g_{R}}v_\delta & 0 & <S> \\
\sqrt{24\pi g_{B-L}}v_\bar{\delta} & -\sqrt{24\pi g_{R}}v_\bar{\delta} & <S> & 0 
\end{pmatrix}$$

(2)

where $\Lambda_S = \langle F_S \rangle / \langle S \rangle$. It is clear from this mass matrix that it has a zero eigenstate corresponding to the $\lambda_Y \equiv (g_{B-L}^{-1}\lambda_{B-L} + g_{R}^{-1}\lambda_{I_{3R}})$. In other words, in the language of the MSSM, $M_1 = 0$. The masses of the $\tilde{\nu}$ arise at the tree level and are therefore of order $\Lambda_S$ as are the masses of the right-handed neutrinos. Turning now to the remaining sfermions, we find that:

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

(3)

where $x_F$ and $y_F$ denote the $\frac{B-L}{2}$ and $I_{3R}$ values for the different superfields $F$ (both matter as well as Higgs). 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.

There are already several differences from the usual GMSB models apparent at this stage: first is that Majorana masses for the usual Winos and the Binos are vanishing to this order as are the masses of the gluinos. We will address the question of their masses later. The next point to note is that unlike in the usual GMSB models, the squark and slepton masses are of same order (upto their $B-L$ and $I_{3R}$ values). The renormalization group extrapolation of $M_{R_u}^2$ from the scale $\Lambda_S$ to the
weak scale makes it negative i.e. $M_{H_u}^2 - M_{H_d}^2 \simeq -\frac{3}{8\pi^2} M_t^2 \ln \frac{\Lambda}{M_t}$. An important new point is that since $M_t^2$ to start with is down compared to the prediction of the usual GMSB models, by a factor roughly $(\alpha_B - /\alpha_c)^2 \sim 1/36$ or so, for $\Lambda_s \sim 100$ TeV, the value of $M_{H_u}^2$ at the weak scale is of the order of $-(100 \text{ GeV})^2$. This makes further fine tuning unnecessary to achieve electroweak symmetry breaking unlike in the usual GMSB models where the $\mu^2$ must be fine tuned to get the weak scale right. Furthermore, our model predicts that the MSSM A-parameter is also zero up to one-loop level.

The $B\mu$ term which leads to nonzero Majorana masses for the Wino and Bino arises at the two loop level from the Feynman diagram that involves the Majorana mass for the $\lambda_{I_{3R}}$ and the $\mu$ term and leads at three loop level to Majorana masses for the Wino and the Bino. Note that electroweak symmetry breaking also leads to Dirac type masses for the Wino. Coming to the gluino masses, they arise at the one loop level via the top and stop intermediate states and can be estimated to be

$$M_{\tilde{G}} \simeq \frac{\alpha_s m_t^2 \mu \cot \beta}{4\pi} \frac{M^2}{M^2}$$

where $M$ is the larger of $(m_t, m_{\tilde{t}})$. Thus the gluino mass in this model is of the order of a GeV. Perhaps such low values of the gluino mass are not ruled out at present\[5\]. It is however worth pointing out that the light gluinos are only a prediction of the simplest version of our model and we show below how the superpotential for the hidden sector can be trivially modified to make the gluinos heavy.

The fact that this model leads to see-saw model for neutrino masses and exact R-parity conservation have already been discussed in the literature and will not be repeated here. The values of left-handed neutrino masses can be adjusted by “dialing” the values of the Yukawa coupling constants $h_\nu$ in Eq. 1.

An explicit model for the Hidden sector

Let us now present an explicit model that leads to a vev for $F_S$ and $S$ used in
the previous section. This discussion is nontrivial for the following reasons. While it is easy to construct a superpotential that leads to a singlet having nonzero vevs as above, it is not simple to communicate the supersymmetry breaking to the visible sector. Furthermore, our goal is somewhat different from the usual GMSB scenario in that we want the messenger fields to develop a vev at the supersymmetry breaking scale. It turns out that one can construct a rather simple superpotential that unifies the hidden sector and the messenger sector while simultaneously breaking the gauge symmetry down to the standard model.

We use three pairs of $\delta$, $\hat{\delta}$ fields denoted by $\delta$, $\delta'$ and $\delta''$ and the corresponding fields with bar's (i.e. $\bar{\delta}$ etc) and two singlets $S, S'$ and construct the following superpotential:

$$W_{m+h} = \lambda S(\delta \bar{\delta} - M_0^2 + \delta'' \bar{\delta''}) + \lambda' S'\delta \bar{\delta} + M_1(\delta'' \bar{\delta'} + \delta' \bar{\delta''}) + M_2 \delta'' \bar{\delta''}$$

It is easy to see that for $M_1 \gg M_0, M_2$, the ground state corresponds to $F_S, F_{S'}$, $<\delta>=<\hat{\delta}>$ having nonzero vevs which therefore break not only supersymmetry but also the $B-L$ gauge symmetry. We also have $<\delta''>=<\bar{\delta''}>0$ and these fields play the role of the messengers. Furthermore, the role $<S>\neq 0$ is played by the mass term $M_2$. It is also important to note that the D-terms all vanish in the lowest ground state. As a result, fields such as $\nu$, which couple to the $\delta$ fields for implementing the see-saw mechanism will not acquire vevs in the lowest ground state and thus do not effect the minimum found above. Similarly, we have checked that the inclusion of the squark and slepton fields into the potential also does not effect this minimum.

**Phenomenological Implications**

The fact that the Majorana masses for the gauginos vanish up to the one loop level has important implications. The first point is that the model has light gluinos as well as a light neutralino with masses in the range of 1/2 to 1 GeV. It has been
argued\cite{5} that all known data do allow a light gluino window in this range. As far as the light neutralino is concerned, it is given by $\tilde{\gamma} \equiv (\cos \theta_W \tilde{B} + \sin \theta_W \tilde{W}_3)$. As a result, it does not couple to the Z-boson and is allowed by the LEP Z-pole observations. Of course, which of the two (photino ($\tilde{\gamma}$) or the gluino, $\tilde{G}$) is lighter depends on the parameters of the model. We will therefore comment on both cases.

Since in all GMSB models the lightest supersymmetric particle is the gravitino, the lighter of the two particles $\tilde{\gamma}$ and $\tilde{G}$ will be the NLSP and will decay to the gravitino and the photon or gluon. Let us discuss the case of the photino being the NLSP below: $\Gamma(\tilde{\gamma} \to \gamma + \tilde{g}) \simeq \frac{\kappa^2 M_\gamma^2}{48\pi m_{\tilde{g}}^2}$ where $\kappa^{-1} = M_{Pl}/\sqrt{8\pi}$. In the early universe, there will be an abundance of photinos at some point. In order that they do not effect the predictions of the big bang nucleosynthesis and the subsequent evolution of the universe, its life time must be less than one second. Using the above formula for the decay width of the photino, we conclude that, we must have $m_{\tilde{g}} M_P \leq 5 \times 10^{11}(M_\gamma/GeV)^{5/2} \text{GeV}^2$. So for a one GeV NLSP, we get $m_{\tilde{g}} \leq 40 \text{ eV}$.

This implies that the gravitino in this model cannot constitute the warm dark matter of the universe. This also leads to the conclusion that if the photino is produced in an accelerator experiment, it will not decay in the detector and for all practical purposes will behave like a stable invisible particle. We can further conclude that NNLSP (i.e. the next to the next to the lightest superparticle, denoted here by $N_2$) whether it be the gluino or the photino, will decay as $N_2 \to q\bar{q} + \text{missing energy due to undetected longlived NLSP}$.

The next particle in the mass hierarchy will be either a neutralino or a chargino. In either case we expect the masses to be in the 60 to 100 GeV range and the particle will decay rapidly. In the neutralino case, for arbitrary $\tan \beta$, the masses are determined by the solutions of the following cubic equation:

$$y^3 + y(M_Z^2 - \mu^2) - \mu M_Z^2 \sin2\beta = 0$$ (6)
It is clear that for $\tan \beta = 1$, one of the eigenvalues of this equation is less than $M_Z$ for all values of $\mu$. However, as $\tan \beta$ gets larger, this property does not necessarily hold and depends on the value of $\mu$. One can also show that if $\mu^2 \geq 2M_Z^2$, all neutralinos (except the photino) are heavier than the Z for arbitrary $\tan \beta$.

Turning to the chargino mass matrix, it is well-known that one of the charginos in this case will be lighter than the W-boson. The phenomenology of this case has been discussed recently and we simply reemphasize the fact that the ongoing LEP run can test this prediction and at the moment, such a scenario with light gluinos and charginos is phenomenologically viable.

Finally, we point out that it is simple to extend the above superpotential to make the gluinos massive by including a pair of color octet (denoted by $\theta_{1,2}$) but weak gauge singlet fields in the theory. The superpotential in this case will be given by:

$$W_{m+h}' = \lambda S (\delta \bar{\delta} - M_0^2 + \delta'' \bar{\delta}' + \theta_1^2) + \lambda' S' \delta \bar{\delta} + M_1 (\delta'' \bar{\delta}' + \bar{\delta}'' \delta') + M_2 \delta'' \bar{\delta}' + M_3 \theta_1 \theta_2 + M_4 \theta_1^2$$

There will now exist one loop graphs that will make the gluino massive. Moreover, similar method can be used to make the weak gauginos also acquire Majorana masses by adding pairs of weak doublets.

**Simultaneous Breaking of Parity and Supersymmetry**

This model can be embedded into the left-right symmetric gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ by assigning the quarks and leptons as in the usual left-right models i.e. $Q(2,1,1/3); Q^c(1,2,-1/3)$; $L(2,1,-1)$ and $L^c(1,2,+1)$. The Higgs fields $H_{u,d}$ are embedded into two bidoublet fields $\phi_a(2,2,0)$ ($a = 1, 2$). The fields that are chosen to break the $SU(2)_R \times U(1)_{B-L}$ symmetry carry two units of lepton number and therefore lead to the see-saw mechanism. They are same as in the usual supersymmetric left-right model i.e. $\Delta(3,1,+2); \Delta(3,1,-2)$ and $\Delta^c(1,3,-2)$;
\( \Delta^c(1,3,+2) \). Note that the \( \delta \) and \( \bar{\delta} \) fields used earlier are part of the \( \Delta^c \) and \( \bar{\Delta}^c \) fields.

We will assume that both parity and supersymmetry will break at the same scale by a mechanism similar to the one already discussed here. In order to implement supersymmetry breaking and convey it to the visible sector, we replace the \( \delta \) fields in the Eq. 5 by the \( \Delta \) and \( \Delta^c \) fields in a straightforward manner and obtain \( \langle \Delta^c \rangle = \langle \bar{\Delta}^c \rangle \neq 0 \). The rest of the discussion is similar to what is already given for the simple model.

An advantage of this left-right embedding of our model is that it provides a solution to the strong CP problem in addition to solving the SUSYCP as well as the R-parity problems[7].

There are now extra singly and doubly charged Higgs and Higgsino fields arising from the \( \Delta \) fields. The rest of the low energy spectrum of particles is same except that the Winos now pick up a one loop Majorana mass from the \( \Delta \) intermediate states. As a result, the chargino need not be lighter than the W-boson.

We wish to point out that since the simplest \( SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L} \) model leads to \( M_1 = M_2 = M_3 = A = 0 \) in the model, one has a solution to the SUSYCP problem i.e. the electric dipole moment of the neutron is naturally below the present experimental upper limit. Secondly, our model does not lead to coupling constant unification at higher scales for supersymmetry breaking scale in the 100 TeV range unless there are additional new physics above the \( \Lambda_{SUSY} \).

In conclusion, we have presented a new messenger sector unified with the hidden sector for gauge mediated supersymmetry breaking and explicitly constructed a superpotential that leads to both supersymmetry breaking as well as the breaking of extra gauge symmetries. The model connects the supersymmetry breaking scale to the scale of new electroweak physics such as \( B - L \) or parity invariance. The
simplest version of the model predicts the existence of light gluinos which could be used to test this version of the model[5]. It is however possible to extend the model that is free of the light gluinos. It also has the attractive features of automatic R-parity conservation, nonzero neutrino masses and no SUSYCP problem.

We thank Z. Chacko and B. Dutta for discussions. The work of R. N. M. is supported by the National Science Foundation grant no. PHY-9421386 and the work of S. N. is supported by the DOE under grant no. DE-FG02-94-ER40852.

References

[1] M. Dine, A.E. Nelson, Y. Nir, and Y. Shirman, hep-ph/9507378; Phys. Rev. D53 (1996) 2658; A.E. Nelson, hep-ph/9511218; M. Dine and A.E. Nelson, Phys. Rev. D48 (1993) 1277. M. Dine, A.E. Nelson, and Y. Shirman, Phys. Rev. D51 (1995) 1362.

[2] S. Ambrosanio, G. Kane, G. Kribs, S. Martin and S. Mrenna, Phys. Rev. Lett. 76 (1996) 3498; S. Dimopoulos, M. Dine, S. Raby and S. Thomas, ibid 76 (1996) 3494; K. S. Babu, C. Kolda and F. Wilczek, hep-ph/9605408; S. P. Martin, hep-ph/9608224; G. Dvali, G. F. Giudice and A. Pomarol, hep-ph/9603238; A. Riotto, N. Tornquist and R. N. Mohapatra, Phys. Lett. B 388, 599 (1996); S. Dimopoulos, S. Thomas and J. Wells, hep-ph/9609434; D. A. Dicus, B. Dutta and S. Nandi, hep-ph/9701341; A. de Gouvea, T. Moroi and H. Murayama, hep-ph/9701244; N. Arkani-Hamed, J. March-Russel and H. Murayama, hep-ph/9701286.

[3] N. Arkani-Hamed, C. Carone, L. Hall and H. Murayama, hep-ph/9612468; I. Dasgupta, B. Dobrescu and L. Randall, hep-ph/9607487; L. Randall, hep-ph/9612426; N. Haba, N. Maru and T. Matsuoka, hep-ph/9612468.
[4] R. N. Mohapatra, Phys. Rev. D 34, 3457 (1986); A. Font, L. Ibanez and F. Quevedo, Phys. Lett. B 228, 79 (1989); S. Martin, Phys. Rev. D 46, 2769 (1992).

[5] G. Farrar, hep-ph/9608387; Phys. Rev. Lett. 76, 4111, 4115 (1996). L. Clavelli and Z. Surguladge, Phys. Rev. Lett. 78, 1632 (1997); F. Csikor and Z. Fodor, hep-ph/9611320 and A. de Gouvea and H. Murayama, hep-ph/9606449.

[6] Z. Chacko, B. Dutta, R. N. Mohapatra and S. Nandi, hep-ph/9704307.

[7] R. N. Mohapatra and A. Rasin, Phys. Rev. D 54, 5835 (1996); R. Kuchimanchi, Phys. Rev. Lett. 76, 3486 (1996).