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Neutrino mass induced radiatively by supersymmetric leptoquarks

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Abstract

We show how nonzero Majorana neutrino masses can be radiatively generated by extending the MSSM with leptoquark chiral multiplets without violating R-parity. It is found that, with these particles, the R-parity conservation does not imply lepton number conservation. Neutrino masses generated at a one-loop level are closely related to the down quark mass matrix. The ratio of neutrino mass-squared splittings $\Delta m_{\nu_2-\nu_1}^2/\Delta m_{\nu_3-\nu_2}^2$ obtained is naturally close to $\Delta m_{s-d}^2/\Delta m_{b-s}^2 \sim 10^{-3}$ which is in the right region required to explain both the atmospheric neutrino data and the MSW solutions for the solar neutrino data. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Many recent experimental observations have hinted at non-vanishing neutrino masses [1]. The strongest hint is from the Super-Kamiokande underground experiment [2]. They observed an up-down asymmetry of atmospheric ν_μ neutrino flux, suggesting an oscillation of ν_μ into ν_τ (or ν_s). The mass squared splitting is found in the range of $1.5 \times 10^{-3} \leq \Delta m_{\nu_3-\nu_2}^2 \leq 6 \times 10^{-3} \text{eV}^2$ (with 95% C.L.), and the mixing angle is close to the maximal mixing [3].

In addition, the observed solar neutrino fluxes [4] are well below the Standard Solar Model predictions. The details may be explained by invoking neutrino mixing between ν_e and ν_μ . There are two types of solutions. One is the solution due to the MSW

mechanism [5] with either large or small mixing angles [6]. For the small mixing angle (SMA) solution, one needs $\Delta m_{\nu_2-\nu_1}^2 = (0.4-1) \times 10^{-5} \text{eV}^2$, and $\sin^2 2\theta = (0.12-1.2) \times 10^{-2}$. For the large mixing angle (LMA) solution, the mass splitting and mixing angle are $\Delta m_{\nu_2-\nu_1}^2 = (0.6-20) \times 10^{-5} \text{eV}^2$, and $\sin^2 2\theta \sim 0.76$. The other one is the so-called just-so solution, which corresponds to a neutrino oscillation in vacuum [7]. For this case, one needs the mass-squared splitting $\Delta m^2 = 8.0 \times 10^{-11} \text{eV}^2$ and the mixing angle $\sin^2 2\theta = 0.75$ for the best fit solution [6].

If neutrinos have masses, they are expected to be small from laboratory bounds and cosmological consideration [8–10]. In the Standard Model (SM) neutrinos are massless. One needs to extend the SM to accommodate massive neutrinos. A neutrino mass can be generated by a Higgs Yukawa interaction like

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any other fermions if right-handed neutrinos are introduced. However, this corresponds to an unnaturally small Higgs Yukawa coupling, $\lambda \sim m_\nu/v \leq \text{eV}/246\text{GeV} \sim 10^{-11}$, where v is the vacuum expectation value of the Higgs field. There have been extensive studies of neutrino masses in models beyond the SM [11,12]. To explain the smallness of the neutrino mass, a popular approach is to use the see-saw mechanism to trade a light neutrino with a super heavy neutrino [13] or to radiatively generate neutrino masses such that the smallness of neutrino masses are due to the loop suppression [14].

In studying neutrino masses, it is interesting to note that the ratio of the mass-squared splittings $\Delta m_{\nu_2-\nu_1}^2/\Delta m_{\nu_3-\nu_2}^2$ for the MSW solutions to the solar neutrino problem can be close to $\Delta m_{s-d}^2/\Delta m_{b-s}^2 \approx 10^{-3}$. This may be regarded as a hint that the neutrino mass matrix is proportional to the down quark mass matrix. In this case the heaviest neutrino has a mass less than ~ 0.08 eV. It is interesting to see if such a mass matrix can be obtained in a natural way. In this paper we study a model in which the Majorana neutrino mass is radiatively generated by supersymmetric leptoquarks and the mass matrix is closely related to the down quark mass matrix.

The supersymmetry (SUSY) is one of the leading candidates for physics beyond the SM [15]. In order to generate neutrino masses one needs to violate R-parity and/or introduce new physics [16,17]. We will show that it is possible to generate Majorana neutrino masses without the violation of R-parity if leptoquarks are introduced in the model. In the presence of these leptoquarks, the lepton number (L) can be broken explicitly even if the R-parity is conserved. The lepton number violating interaction can generate Majorana neutrino masses at a one-loop level and naturally lead to a mass matrix proportional to the down quark mass matrix. This is due to a special feature of the scalar leptoquark interaction. It can be shown that a lepton number violating vector leptoquark model will relate a neutrino mass matrix to the up quark mass matrix, which would not naturally give neutrino mass hierarchies mentioned above. In the SUSY extension with the SM gauge group, vector leptoquarks are not allowed. This provides additional motivation to study SUSY models with leptoquark multiplets.

2. The model

The matter and Higgs superfields in the MSSM are $\hat{L}$, $\hat{E}$, $\hat{Q}$, $\hat{U}$, $\hat{D}$, $\hat{H}_1$ and $\hat{H}_2$. Their quantum numbers under $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ are $(1, 2, -1/2)$, $(1, 1, +1)$, $(3, 2, +1/6)$, $(3^*, 1, -2/3)$, $(3^*, 1, +1/3)$, $(1, 2, -1/2)$ and $(1, 2, +1/2)$, respectively. To avoid lepton number and baryon number violations, R-parity is introduced. The ordinary fields, the quarks, leptons and Higgses, are assigned with positive R-parity and their superpartners are assigned with negative R-parity. There are in general seven types of leptoquarks which can couple directly to the quark and lepton field products, $\hat{U} \times \hat{E}$, $\hat{Q} \times \hat{L}$, $\hat{D} \times \hat{E}$, $\hat{U} \times \hat{L}$, $\hat{Q} \times \hat{E}$, and $\hat{D} \times \hat{L}$, at the tree level with their gauge quantum numbers given, respectively, by [18]

$$\begin{aligned}\hat{S}: (3, 1, -1/3), \quad \hat{S}': (3^*, 1, +1/3), \\ \hat{T}: (3^*, 3, +1/3), \quad \hat{S}'': (3, 1, -4/3), \\ \hat{R}: (3, 2, +7/6), \quad \hat{R}': (3^*, 2, -7/6), \\ \hat{I}: (3, 2, +1/6).\end{aligned}\tag{1}$$

The R-parity assignments of these leptoquark supermultiplets are determined by their interaction with lepton and quark multiplets to be the same as that of Higgs multiplets.

For the purpose of generating Majorana neutrino masses only two types of leptoquarks are needed which are $\hat{S}'$ and $\hat{I}$. These leptoquarks provide two units of the lepton number violation needed for Majorana neutrino masses through the R-parity conserving interaction in the superpotential by a term, $\epsilon_{ij} \hat{H}_1^i \hat{I}^j \hat{S}'$. In order to cancel the gauge anomalies due to the fermion partners of leptoquarks for consistency more leptoquark multiplets are required. We note that the quantum number of $\hat{S}$ is conjugate to that of $\hat{S}'$ and accordingly it can be used to cancel the anomalies due to $\hat{S}'$. We need to introduce a new leptoquark multiplet $\hat{I}'$ with quantum number conjugates to $\hat{I}$ to cancel the anomalies. We also note that the R-parity does not forbid a baryon number violating term $\hat{U} \hat{D} \hat{S}'$. To avoid rapid proton decay, we must either assume the coupling is very small, or introduce further symmetry. To make use of the

Table 1

The particle content of leptoquark chiral supermultiplets related to the neutrino mass generation. The L denotes the lepton number.

Superfield	SU(3)×SU(2) ×U(1)× L	Boson fields	Fermionic partners
$\hat{S}$	(3, 1, -1/3; -1)	S_L	$\tilde{S}_L$
$\hat{S}^*$	(3*, 1, +1/3; +1)	S_R^*	$\tilde{S}_L^c$
$\hat{I}$	(3, 2, +1/6; +1)	(O_L, P_L)	($\tilde{O}_L, \tilde{P}_L$)
$\hat{I}^*$	(3*, 2, -1/6; -1)	($P_R^*, -O_R^*$)	($\tilde{P}_L^c, -\tilde{O}_L^c$)

symmetry, we may assign a negative Z_2 parity to $\hat{U}$, $\hat{D}$ and $\hat{Q}$, while all other matter fields in the MSSM have a positive Z_2 parity. The Z_2 parity of leptoquarks is negative as determined from leptoquark interactions. Thus, the Z_2 symmetry will forbid the baryon number violating terms. In short, we are considering the leptoquark interaction instead of the diquark interaction.

The model we now have is an extended MSSM with the standard particle content plus leptoquarks and leptoquarkinos in Table 1. With these multiplets we can construct the leptoquark R-parity conserving superpotential W_{LQ} with

$$\begin{aligned}
 W_{LQ} = & -(h^*)_{ab} \hat{U}_a \hat{E}_b \hat{S} - (h')_{ab} \epsilon_{ij} \hat{Q}_a^i \hat{L}_b^j \hat{S} \\
 & - (h'')_{ab} \epsilon_{ij} \hat{D}_a^i \hat{L}_b^j \hat{I} + g \epsilon_{ij} \hat{H}_1^i \hat{I}^j \hat{S} \\
 & + M_S \hat{S}_d \hat{S}_d + M_I \epsilon_{ij} \hat{I}^i \hat{I}^j, \quad (2)
 \end{aligned}$$

where a and b are generation indices of quarks and leptons in the weak basis. Note that $\tilde{S}_R$ and $\tilde{P}_L$ can be mixed by the g term when the H_1 takes its vacuum expectation value (VEV) v_1 ; otherwise, the masses are M_S and M_I respectively.

With this superpotential and the Higgs VEVs, we get leptoquark mixings of S_L with P_L , S_R with P_R , and S_R with P_L . The F-term causes mixings, and the D-term contributes to diagonal parts of the mass matrix only. The mixing terms are

$$V = gv_1 (M_S S_L^\dagger P_L + M_I S_R^\dagger P_R - \mu \tan \beta S_R^\dagger P_L) + \text{h.c.} \quad (3)$$

There are more terms due to the SUSY soft breaking,

$$\begin{aligned}
 V_{\text{soft}} = & \frac{1}{2} M_{S_R}^2 S_R^\dagger S_R + \frac{1}{2} M_{S_L}^2 S_L^\dagger S_L + \frac{1}{2} M_{I_L}^2 I^\dagger I \\
 & + \frac{1}{2} M_{I_R}^2 I'^\dagger I' + M_{S_R-S_L}^2 S_R^\dagger S_L + M_{I-I'}^2 \epsilon_{ij} I^i I'^j \\
 & + M_{HIS} \epsilon_{ij} H_1^i I^j S_R^\dagger + \text{h.c.} \quad (4)
 \end{aligned}$$

Note that the (standard) SUSY soft breaking terms do not include $H_1 I S_L^\dagger$ or $H_2^\dagger I S_R^\dagger$ and so on [19]. The mass parameters M_i in the Eq. (4) are naturally in the SUSY breaking scale. The $M_{HIS} \epsilon_{ij} H_1^i I^j S_R^\dagger$ term violates lepton number by two units. After spontaneous symmetry breaking this term produces the mixing of S_R and P_L which plays a crucial role in generating Majorana masses at a one-loop level. This is the dominant source for the lepton number violation related to the Majorana neutrino masses although other leptoquarks contribute through mixings among S_L , S_R , P_L and P_R . We note that the mass parameters, M_S and M_I , from the superpotential are free parameters which may in general be smaller or larger than the SUSY breaking scale M_{SUSY} , while those mass parameters contained in soft breaking terms are naturally in the scale of M_{SUSY} .

3. Radiative Majorana neutrino masses

The Majorana neutrino mass term $1/2(\bar{\nu}_{Ra}^c \times m_{ab} \nu_{Lb} + \text{h.c.})$ can be obtained from one-loop diagrams with all possible leptoquark mass insertions in the internal leptoquark line and the internal quark line. The leading contribution comes from a mass insertion each in the quark line and the other insertion in the leptoquark line as shown in Fig. 1. The mass matrix m_{ab} is symmetric and the leading term is given by,

$$m_{ab} = \frac{N_c}{8\pi^2} \frac{\Delta \mathcal{M}^2}{(\bar{M}_{LQ}^2)^{1/2}} (h^T M_D h'' + h'^T M_D^T h')_{ab}, \quad (5)$$

where $N_c = 3$ is the number of color, M_D is the down type quark mass matrix, $\bar{M}_{LQ}$ is the average leptoquark mass and $\Delta \mathcal{M}^2 = \mathcal{M}_{P_L-S_R}^2 = -gv_1 \mu \tan \beta + M_{HIS} v_1 \sim M_{\text{SUSY}} v$ denotes the $P_L - S_R$ mixing element as shown in Eq. (3) and Eq. (4).

Fig. 1. The leading one-loop diagram which gives rise to nonzero neutrino masses, the X represent a mass insertion.

The quark mass matrix can be diagonalized in the usual way, $V_{dL} M_D V_{dR}^\dagger = M_D^{\text{diag}}$, where the diagonal mass matrix is given by [20],

$$\begin{aligned} M_D^{\text{diag}}(\mu) &= \text{diag}(m_d, m_s, m_b) \\ &= m_b(\mu) \text{diag}((1.36 \pm 0.42) \times 10^{-3}, \\ &\quad (2.66 \pm 0.87) \times 10^{-2}, 1 \pm 0.05). \end{aligned} \quad (6)$$

From Eq. (5), it is clear that the neutrino mass matrix obtained is closely related to the down quark mass matrix. We will work in a quark field basis where the down quark mass matrix is hermitian, which can always be done [21]. If small CP violation entries are neglected the down quark mass matrix is symmetric, V_{dL} becomes orthogonal and equals to V_{dR} . This choice of basis is convenient for our purpose since the Majorana neutrino mass matrix is symmetric.

To finally obtain numerical numbers for neutrino masses, we need to know parameters related to leptoquarks. The couplings h' , h'' and the leptoquark mass M_{LQ} relevant to neutrino masses in our model are unknown which must be subjected to experimental constraints. The typical experimental lower bound on the leptoquark mass is about 200 GeV [22]. There are many studies on leptoquark couplings and masses from indirect searches [8,23–25]. We now consider the constraints on h'_{ab} , h''_{ab} and M_{LQ} . We follow Ref. ([23]) to evaluate the constraints. We note that h', h'' are denoted as λ_{LS_o} , $\lambda_{L\bar{S}_{1/2}}$ in Ref. [23].

For h'_{ab} the strongest constraint comes from the lepton flavor-changing rate for a muon to turn into an electron when scattered off a nucleus, such as $\mu\text{Ti} \rightarrow e\text{Ti}$. This gives the constraint on the coupling of S_R as [23]

$$\sqrt{h'_{11} h'_{12}} / M_{LQ} \leq 0.01 \text{ TeV}^{-1}. \quad (7)$$

Similar consideration gives a constraint on the coupling of I^i with $\sqrt{h''_{11} h''_{12}} / M_{LQ} \leq 0.01 \text{ TeV}^{-1}$. The

leptoquark exchanges also contributes to the kaon semileptonic decay, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. By requiring that the prediction is smaller than the observed bound of $Br(K^+ \rightarrow \pi^+ \nu_l \bar{\nu}_{l'}) = 0.42^{+0.97}_{-0.35} \times 10^{-9}$ gives constraints [23,26],

$$\sqrt{h'_{1l} h'_{2l'}} / M_{LQ}, \sqrt{h''_{1l} h''_{2l'}} / M_{LQ} \leq 0.03 \text{ TeV}^{-1}. \quad (8)$$

More stringent constraints on the I^i couplings come from lepton family number violating leptonic kaon decay, $K_L^0 \rightarrow \mu^\pm e^\mp$. Using the constraint in Ref. [23] and the new experimental result [8], $Br(K_L^0 \rightarrow \mu^\pm e^\mp) \leq 3.3 \times 10^{-11}$, we have

$$\sqrt{h'_{11} h'_{22}} / M_{LQ}, \sqrt{h''_{12} h''_{21}} / M_{LQ} \leq 6 \times 10^{-3} \text{ TeV}^{-1}. \quad (9)$$

One can find constraints on other elements of h'_{ab} , h''_{ab} in Ref. [23], they are in general weaker than the ones discussed here.

As we turn on the mixing of S_R with P_L , these chiral leptoquarks become non-chiral leptoquarks, there are further constraints for them. The constraints from the chirally suppressed pion decay, $\pi^+ \rightarrow e^+ \nu_l$ give [8,25],

$$\begin{aligned} &\sqrt{h'_{1l} h'_{1l'}} \frac{\sqrt{M_{\text{SUSY}} v}}{M_{LQ}^2}, \\ &\sqrt{h'_{1l} h'_{11}} \frac{\sqrt{M_{\text{SUSY}} v}}{M_{LQ}^2} \leq 4 \times 10^{-3} \text{ TeV}^{-1}. \end{aligned} \quad (10)$$

The similar kaon leptonic decay gives a weaker constraint due to $m_s > m_u, m_d$. The mixing of S_R with P_L contributes to the lepton number violating ($\Delta L = 2$) $K^+ \rightarrow \pi^+ \nu_l \nu_{l'}$ decay. This gives

$$\begin{aligned} &\sqrt{h'_{1l} h'_{2l'}} \frac{\sqrt{M_{\text{SUSY}} v}}{M_{LQ}^2}, \\ &\sqrt{h'_{2l} h'_{1l'}} \frac{\sqrt{M_{\text{SUSY}} v}}{M_{LQ}^2} \leq 2 \times 10^{-3} \text{ TeV}^{-1}. \end{aligned} \quad (11)$$

The factor $\sqrt{M_{\text{SUSY}} v} / M_{LQ}$ in Eqs. (10) and (11) reminds us that these non-chiral leptoquark behavior is due to the mixing and the constraints are weaker

than the constraints obtained in Eq. (9) if $\sqrt{M_{\text{SUSY}} v} / M_{\text{LQ}} \ll 1$. Without any mixing, there is no non-chiral leptoquark in the SUSY model.

To estimate what value of m_{ab} may be, we may work with a simplified situation for illustration, with $h'_{ij} \sim h''_{ij} \sim h \delta_{ij}$. We obtain a very simple and very interesting mass matrix with the mass eigenvalues of the neutrinos given by

$$(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) = \frac{N_c}{8\pi^2} \frac{\Delta \mathcal{M}^2}{\bar{M}_{\text{LQ}}^2} h^2 (m_d, m_s, m_b), \quad (12)$$

and the mixing matrix is given by V_{dL} . We note that the small mixing behavior of Cabbibo-Kobayashi-Maskawa matrix ($V_{CKM} = V_{uL} V_{dL}^\dagger$) does not necessarily imply any small mixing pattern in the down quark mass matrix or up quark mass matrix separately. There are parameter spaces in which the required mixing angles for the atmospherical and the solar neutrino data can be produced.

To obtain $\Delta m_{\nu_3-\nu_2}^2$ to be below $6 \times 10^{-3} \text{ eV}^2$ as required by the atmospheric neutrino data, h/M_{LQ} is restricted to be less than $0.55 \times 10^{-4} \text{ TeV}^{-1}$ which is safely below the above constraints for $M_{\text{LQ}} \geq M_{\text{SUSY}}$. We note that for the particular case where h' and h'' are universal and flavor blind, constraints in Eqs. (8)–(11) all apply. Using $h/M_{\text{LQ}} = 0.53 \times 10^{-4} \text{ TeV}^{-1}$ with m_b at the top quark mass scale and Eq. (5), we obtain Majorana neutrino masses,

$$\begin{aligned} m_{\nu_1} &= (9.92 \pm 3.08) \times 10^{-5} \text{ eV}, \\ m_{\nu_2} &= (1.94 \pm 0.64) \times 10^{-3} \text{ eV}, \\ m_{\nu_3} &= (7.30 \pm 0.36) \times 10^{-2} \text{ eV}. \end{aligned} \quad (13)$$

These values correspond to mass-squared splittings of

$$\begin{aligned} \Delta m_{\nu_3-\nu_2}^2 &= (5.32 \pm 0.53) \times 10^{-3} \text{ eV}^2, \\ \Delta m_{\nu_2-\nu_1}^2 &= (3.75 \pm 2.48) \times 10^{-6} \text{ eV}^2, \end{aligned} \quad (14)$$

which are in the right regions with the atmospheric neutrino solution and the MSW solar neutrino small mixing angle and large mixing angle solutions. These Majorana neutrino masses are well below the bound

on the effective Majorana mass ($m_{\nu_e \nu_e} \leq 0.2 \text{ eV}$) from the negative result of the neutrinoless double beta decay [9].

If we use vector leptoquarks instead of scalar leptoquarks, we would have obtained neutrino masses proportional to up type quark masses. There is an important difference when compared with the scalar leptoquark case discussed above. One would naturally obtain $(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ to be proportional to (m_u, m_c, m_t) . The ratio $\Delta m_{\nu_2-\nu_1}^2 / \Delta m_{\nu_3-\nu_2}^2$ is then given by $\Delta m_{u-c}^2 / \Delta m_{c-t}^2 \sim 2 \times 10^{-5}$ which disagrees with the data.

4. Conclusion

In this paper, we have shown that a simple extension of the MSSM with leptoquark multiplets contains a lepton number violating interaction which can generate Majorana neutrino masses at a one-loop level without the breaking of R-parity. One may contrast this scenario to the R-parity violating extension of MSSM. In both cases, in order to obtain a light neutrino mass, one needs the ratio h/M (or $\lambda_R/M_{\text{MSSM}}$ in the extended MSSM) to be of the order of 10^{-4} TeV^{-1} . In the particle content of the MSSM all particle masses (M_{MSSM}) should be below M_{SUSY} , and this would correspond to suppressed R-parity violating Yukawa couplings (λ_R). In our case, in the presence of the leptoquark multiplets, the Yukawa couplings can in general be not artificially suppressed. The $\Delta L = 2$ interaction in this model is favored than the $\Delta L = 1$ interaction in the extended MSSM in light of leptogenesis [17]. Furthermore, the radiatively generated neutrino mass matrix in this model is closely related to the down quark mass matrix as leptoquarks couple to leptons and down quarks. In the simplest scenario with the coupling matrices for leptoquarks, quarks and leptons being proportional to unit matrix, that is, $h'_{ij} \sim h''_{ij} \sim h \delta_{ij}$, it predicts a hierarchy structure in neutrino masses $\Delta m_{\nu_2-\nu_1}^2 / \Delta m_{\nu_3-\nu_2}^2 \sim \Delta m_{d-s}^2 / \Delta m_{s-b}^2$ which provides mass-squared splittings required to explain both the atmospheric neutrino and the MSW solar neutrino data.

More complicated structures for h' and h'' can lead to different mass hierarchy patterns. The simple

neutrino mass matrix that is proportional to the down quark mass matrix, depends on that the matrices $h'(h'')$ being proportional to the unit matrix. It remains to be seen that if this can be obtained from some symmetry principle.

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