Neutrino mass and low-scale leptogenesis in a testable SUSY SO(10) model

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Abstract

It is shown that a supersymmetric $\mathbf{SO(10)}$ model extended with fermion singlets can accommodate the observed neutrino masses and mixings as well as generate the desired lepton asymmetry in concordance with the gravitino constraint. A necessary prediction of the model is near-TeV scale doubly-charged Higgs scalars which should be detectable at the LHC.

The observed neutrino masses constitute a compelling evidence of interactions beyond the Standard Model of particle physics and leave an impact in areas as diverse as astrophysics, cosmology, nuclear physics, and geophysics. The smallness of these masses finds a natural explanation in the see-saw mechanism [1], which requires a heavy Majorana (self-conjugate) neutrino. Such heavy neutrinos appear in grand unified theories (GUTs) based on $\mathbf{SO(10)}$, which incorporate quark-lepton unification and left-right symmetry [2, 3]. The wide disparity between the weak and unification scales in these models calls for a protection mechanism and supersymmetry (SUSY) is widely considered to be an attractive candidate. Further, such a model with a low SUSY scale leads to a unification of gauge couplings at high energies. These positive features have encouraged many explorations of the SUSY $\mathbf{SO(10)}$ model.

Another open problem, also of much interest, is the origin of the observed baryon asymmetry of the universe. Originally it was expected that baryon number violation inherent in GUTs will lead to this small asymmetry when heavy gauge (and/or Higgs) bosons decay while they are out of equilibrium. This hope was belied however since any primordial GUT-origin asymmetry will be totally diluted in the inflationary epoch. This has provided impetus to look for lower energy avenues for generating this asymmetry. An oft-chosen route is to generate a lepton asymmetry through the C and CP-violating out-of-equilibrium decay of heavy Majorana neutrinos. This is later converted to a baryon asymmetry through anomalous $(B + L)$ violation, which is implicit in the Standard Model [4, 5].

It is but natural to ask whether the heavy Majorana neutrino which drives the neutrino mass see-saw can also generate the lepton asymmetry through its decay. This would have been truly economical.

Hindrances to this programme arise from several directions. (a) The observed light neutrino masses require the heavy neutrino, which is right-handed (RH), to have a mass $\sim 10^{13}$ GeV. This sets the scale, M_R, for the $\mathbf{SU(2)_R} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_{(B-L)}} \to \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$ gauge symmetry breaking. (b)

Within the **SO(10)** GUT framework, the intermediate symmetry breaking scales are fixed through the Renormalization Group (RG) equations which reflect the gauge couplings' evolution with energy. In the simplest **SO(10)** GUT it is well-known that M_R turns out to be $\sim 10^{16}$ GeV. (c) In a SUSY context there is an additional constraint, namely, to ensure that there is no overabundance of gravitinos in the universe. To maintain consistency with this, it has been demonstrated [6, 7, 8] that the lepton asymmetry must be generated through the decay of a heavy neutrino whose mass does not exceed $\sim 10^{7-9}$ GeV in order to prevent a washout, whereas leptogenesis through the canonical Type-I see-saw mechanism sets the lower bound 4.5×10^9 GeV. These conflicting requirements have acted as obstacles to a successful implementation of this attractive possibility.

In this letter we propose a remedy for these maladies confining ourselves to the SUSY **SO(10)** GUT. If sterile – i.e., **SO(10)** singlet – leptons are introduced, one for each generation [9, 10, 11, 12], then a novel way can be found to meet the demands outlined in the previous paragraph.

The uncharged fermions in this model, per generation, are the following: a left-handed neutrino ν, a right-handed neutrino, N, and a sterile neutrino, S. For the three generation neutral fermion system, the mass matrix on which we focus is:

$$
M_\nu = \begin{pmatrix} \nu & N^c & S \end{pmatrix}_L \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_N & M_X \\ 0 & M_X^T & \mu \end{pmatrix} \begin{pmatrix} \nu^c \\ N \\ S \end{pmatrix}_R \tag{1}
$$

where m_D, M_N, M_X, and μ are all 3×3 matrix blocks.

It is not unreasonable to expect that the mass matrix in eq. (1) will alleviate the tension, summarised earlier, between light neutrino masses and adequate low-scale thermal leptogenesis. As discussed below, the double see-saw structure for the light neutrino masses, arising from eq. (1), also decouples it to some extent from low-scale leptogenesis; M_N, M_X, and μ appear in different fashions in the expressions. Utilizing an extension of the Minimal Supersymmetric Standard Model (MSSM) by the addition of RH neutrinos and extra fermion singlets, which results in a neutrino mass matrix of the structure of eq. (1), Kang and Kim [12] have found solutions to both the above issues. There, m_D has been identified, as is done in the MSSM, with the charged lepton mass matrix. On the other hand, in the **SO(10)** model which is espoused here, quark-lepton symmetry [2] identifies the neutrino Dirac mass matrix m_D with the up-quark mass matrix whose 33 element is nearly 100 times heavier. This, along with other GUT constraints, pose additional hurdles in addressing the problems in SUSY **SO(10)**.

We work in a basis in which the down-quark and charged lepton mass matrices are diagonal. This ensures that the entire mixings in the quark and lepton sectors can be ascribed to the mass matrices of the up-type quarks and the neutrinos, respectively. Using quark-lepton unification, the quark masses, and the Cabibbo-Kobayashi-Maskawa mixing angles, one therefore obtains m_D, upto $\mathcal{O}(1)$ effects due to RG evolution.

We utilize spontaneous symmetry breaking of SUSY **SO(10)** with the Higgs representations $\mathbf{210}, \mathbf{54}$, $\mathbf{126} \oplus \overline{\mathbf{126}}, \mathbf{16} \oplus \overline{\mathbf{16}}$, and $\mathbf{10}$. By using the mechanism of D-Parity breaking near the GUT scale [13], the RH-triplet pair $\Delta_R(1,3,1,-2) \oplus \overline{\Delta}_R(1,3,1,2)$, and the RH-doublet pair $\chi_R(1,2,1,-1) \oplus \overline{\chi}_R(1,2,1,1)$ are treated to have masses at much lower scales compared to their left-handed counterparts. $M_X = Fx_R$, in eq. (1), is generated *via* the vacuum expectation value (vev) $< \chi_R(1,2,1,-1) >= < \overline{\chi}_R(1,2,1,1) >= x_R$, where we take F to be a matrix with entries $\mathcal{O}(0.1)$.

Although we do not assign any direct vev to the RH-triplets, through a Δ_R exchange involving a

trilinear coupling in the superpotential, $\lambda \Delta_R \bar{\chi}_R \bar{\chi}_R$, an effective vev $< \Delta_R(1,3,1,-2) > \equiv v_R = \lambda \frac{x_R^2}{m_{\Delta_R}}$ is generated, resulting in the mass term $M_N \sim f < \Delta_R(1,3,1,-2) >$, where f is a typical Yukawa coupling of Majorana type. If m_{Δ_R} is around 1 TeV, which can be arranged by a tuning of the D-parity breaking term in the Lagrangian, the entries of M_N are $\mathcal{O}(10^{11})$ GeV. Without any loss of generality, M_N can be chosen to be diagonal.

Notice that the $SU(2)_R \times U(1)_{B-L}$ symmetry breaks at the scale $< \Delta_R(1,3,1,-2) > \simeq 10^{11}$ GeV while $x_R \sim 10^7$ GeV. The states Δ_R^+ and $Re(\Delta_R^0)$ are eaten up as Goldstone bosons by the $W_R^{\pm}$ and W_R^0 fields and Δ_R^{++} and $Im(\Delta_R^0)$ survive as physical states with mass ~ 1 TeV. The Type-II seesaw contribution to the light neutrino mass matrix is damped out in this case because of the large masses of the left-handed Higgs triplet leading to $m_{II} \simeq 10^{-5}$ eV – 10^{-6} eV [14, 15]. Further, the vev of χ_L is zero or negligible.

Block diagonalization of the mass matrix in eq. (1) in the limit in which we are working (*i.e.,* $M_N \gg M_X \gg \mu \gg m_D$) leads to:

$$m_\nu \sim -m_D \left[M_X^{-1} \mu (M_X^T)^{-1} \right] m_D{}^T, \quad M_S \sim \mu - \frac{M_X^2}{M_N}, \quad M \sim M_N + \frac{M_X^2}{M_N}, \tag{2}$$

where m_ν, M_S, and M are 3×3 matrices. The light neutrino masses are in a double see-saw pattern and μ is determined once M_X is fixed. It may be noted that the mass matrix structure in eq. (1) ensures that the type I see-saw contribution is absent and M_N remains unconstrained by the light neutrino masses. This freedom in M_N – a hallmark of the model – is vital to ensure adequate leptogenesis.
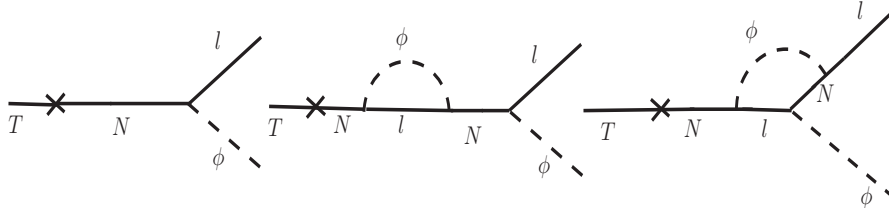

Figure 1: The tree and one-loop contributions to the decay of T_1 that generate the lepton asymmetry.

The eigenstates of M_S, which we denote by $T_i, (i = 1, 2, 3)$, are superpositions of the sterile neutrinos S (predominant) and the right-handed ones N. These states are found to lie well-below 10^9 GeV, consistent with the gravitino constraint. In fact we show that this model allows successful leptogenesis at a temperature $T \simeq M_T \simeq 5 \times 10^5$ GeV, which is nearly 4 orders below the maximum allowed value. Further, the singlet fermions decay through their mixing with the N_i which is controlled by the ratio M_X/M_N. The latter, which have masses $\mathcal{O}(10^{11})$ GeV and are off-shell, decay to a final $l\phi$ state, where l is a lepton doublet and ϕ the up-type MSSM Higgs doublet. This two-step process – for which tree and loop diagrams are depicted in Fig. 1 (SUSY contributions are small) – results in a lepton asymmetry of the correct order. Because of the large value of $M_N \gg M_X$, a small $S - N$ mixing results naturally in the T_i which in turn guarantees the out-of-equilibrium condition to be realized near temperatures $T \simeq M_T$.

A quantitative analysis of this programme has been carried out using the Boltzmann equations determining the number densities in a co-moving volume $Y_T = n_T/n_S$ and $Y_L = n_L/n_S$, where n_T, n_L and

n_S are respectively the number densities of the decaying neutrinos, leptons and the entropy:

$$\frac{dY_T}{dz} = -\left(Y_T - Y_T^{eq}\right)\left[\frac{\Gamma_D^T}{zH(z)} + \frac{\Gamma_s^T}{zH(z)}\right], \quad \frac{dY_L}{dz} = \epsilon_T \frac{\Gamma_D^T}{zH(z)}\left(Y_T - Y_T^{eq}\right) - \frac{\Gamma_W^\ell}{zH(z)}Y_L. \qquad (3)$$

where Γ_D^T, Γ_s^T and Γ_W^ℓ represent the decay, scattering, and wash-out rates, respectively, that take part in establishing a net lepton asymmetry. We refrain from presenting their detailed expressions here [16]. The Hubble expansion rate $H(z)$, where $z = M_T/T$, and the CP-violation parameter are given by

$$H(z) = \frac{H(M_T)}{z^2}, \quad H(M_T) = 1.67g_*^{1/2}\frac{M_T^2}{M_{pl}}, \quad \epsilon_T = \frac{\Gamma(T \to l\phi) - \Gamma(T \to \bar{l}\phi^*)}{\Gamma(T \to l\phi) + \Gamma(T \to \bar{l}\phi^*)}. \qquad (4)$$

Our target is to use eqs. (2) and (3) to obtain an acceptable solution within the framework of SUSY **SO(10)**. Through an exhaustive analysis we find an appropriate choice of the block matrices appearing in eq. (1) which guarantees adequate leptogenesis while maintaining full consistency with the observed neutrino masses and mixing as well as the gravitino constraint. The mass scales are fixed as dictated by the RG evolution of gauge couplings in SUSY **SO(10)** when effects of two dim.5 operators scaled by the Planck mass are included [16, 17, 18]. The strategy we follow is to choose the matrix M_X first. To minimize the number of independent parameters, we take the matrix F to be real and diagonal, which is reflected in M_X. Then using m_D, as fixed by quark-lepton unification, μ is determined from the double see-saw formula given in eq. (2). Using these inputs, one has to examine, by trial and error, different choices of M_N for adequate lepton asymmetry generation.
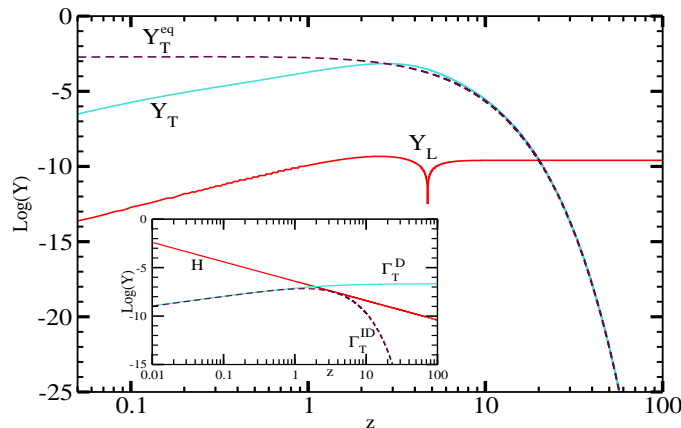

Figure 2: The comoving density of T_1 – Y_T – and the leptonic asymmetry – Y_L – as a function of z. Also shown is Y_T^{eq}. The inset displays the decay (Γ_T^D) and inverse-decay (Γ_T^{ID}) rates of T_1 compared with the Hubble expansion rate, H, as a function of z.

The results for the development of the leptonic asymmetry as the universe evolves are shown in Fig. 2. They are obtained with the choice $M_X = \text{diag}(0.2, 0.3, 0.4)x_R$ with $x_R = 6 \times 10^6$ GeV. The neutrino Dirac mass matrix, m_D, is constructed utilizing quark-lepton symmetry; the up-type quark mass eigenvalues and the CKM mixings are taken at the PDG [19] values with the CKM-phase as 1 radian. The neutrino masses are fixed so as to satisfy $\Delta m_{21}^2 = 8.0 \times 10^{-5}$ eV^2 and $\Delta m_{32}^2 = 2.5 \times 10^{-3}$ eV^2 with the lightest neutrino taken massless. The neutrino mixing angles used are $\theta_{23} = 45°$, $\theta_{12} = 32°$,

4

and $\theta_{13} = 7°$. No other CP-phases are introduced in the lepton sector except the one through the CKM matrix for quarks. With these inputs the matrix μ is calculated following eq. (2). For the RH-neutrino we use the mass matrix $M_N = \text{diag}(0.1, 0.5, 0.9) \times 10^{11}$ GeV. This is consistent with $m_{\Delta_R} \sim 1$ TeV. We assume that in the very initial stages the number densities, Y_{T_i}, $i = 1, 2, 3$, and the leptonic asymmetry, Y_L, are zero. The chosen input values of the mass parameters result in a T_i mass spectrum such that only one state – T_1 – is above the kinematic threshold for $l\phi$ production ($m_{T_1} = 3.9 \times 10^5$ GeV) and the lepton asymmetry results through its decay. This ensures that the leptogenesis is consistent with the gravitino bound. It is seen from Fig. 2 that T_1 decays fall out of equilibrium as the universe expands (inset) and Y_L achieves the right order ($\sim 10^{-10}$) starting off from a vanishing initial value while Y_T steadily tends towards Y_T^{eq}.

We stress again that an important outcome of the symmetry breaking is that out of the triplet Δ_R the components $\Delta_R^{\pm}$ and $Re\Delta_R^{\circ}$ are absorbed as longitudinal modes of the broken generators of $SU(2)_R \times U(1)_{B-L}$. The physical states are Δ_R^{++} and $Im\Delta_R^{\circ}$ and their superpartners. They will be within striking range of the LHC and the ILC with $m_\Delta \simeq 300$ GeV – 1 TeV.

Finally, we briefly discuss the mechanism of SUSY **SO(10)** breaking [16, 17, 18]:

$$SO(10) \xrightarrow{\mathbf{M_U}} SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \quad [\mathcal{G}_{3221}]$$
$$\xrightarrow{\mathbf{M_R}} SU(3)_C \times SU(2)_L \times U(1)_Y \quad [\mathcal{G}_{std}] \xrightarrow{\mathbf{M_Z}} SU(3)_C \times U(1)_Q \qquad (5)$$

The **SO(10)** Higgs multiplets **210** and **54** are utilized to break the symmetry at M_U. Within the **210** there are two components which develop vevs; one breaks **SO(10)** to $\mathcal{G}_{3221}$ while the other is responsible for D-parity breaking. The vev of the singlet under the Pati-Salam group contained in **54** ensures that there are no light pseudo-goldstone bosons arising from the **210** to upset perturbative gauge coupling evolution. As already discussed, $\mathbf{SU(2)_R \times U(1)_{B-L}}$ is broken by the vevs of RH-triplets in $\mathbf{126 \oplus \overline{126}}$. This induced vev, $v_R \sim 10^{11}$ GeV, is also responsible for the masses of the N_i. The last step of breaking in eq. (5) relies on the electroweak vev of the weak bi-doublet in **10**. We have carried out an analysis of the RG evolution of the gauge couplings to determine the intermediate mass scales. We find that $M_R \sim 10^{9-11}$ GeV can be obtained through the introduction of effective dim.5 operators scaled by the Planck mass, M_{Pl} [18]. It is noteworthy that both **210** and **54** are necessary for a viable SUSY **SO(10)** breaking pattern and that the resulting two dim.5 operators are instrumental in alleviating the problem of leptogenesis under the gravitino constraint:

$$\mathcal{L}_{NRO} = -\frac{\eta_1}{2M_{Pl}}Tr\left(F_{\mu\nu}\Phi_{210}F^{\mu\nu}\right) - \frac{\eta_2}{2M_{Pl}}Tr\left(F_{\mu\nu}\Phi_{54}F^{\mu\nu}\right). \qquad (6)$$

The details of this analysis will be presented elsewhere [16]. Suffice it to state that $|\eta_{1,2}| \sim \mathcal{O}(1)$ and the interactions in eq. (6) lead to finite corrections to the gauge couplings at the GUT-scale. The couplings of the left-right gauge group thus emerge from one effective GUT-gauge coupling. The upshot of this is that with these additional contributions it is possible to lower M_R to as low as $10^9 - 10^{11}$ GeV as required in this model. The grand unification scale is high: $M_U \sim 10^{17-18}$ GeV and the model predicts a stable proton for all practical purposes.

We expect that this model will have a natural extension to an **E(6)**-GUT wherein the matter multiplets and the singlet fields will constitute the fundamental **27** representation of the gauge group.

In conclusion, we have presented a SUSY **SO(10)**-based model relying on a double see-saw mechanism which is (a) consistent with the known neutrino masses and mixing, and (b) can lead to a correct lepton asymmetry via the decays of sterile, i.e., **SO(10)** singlet, neutrinos while remaining in concordance

with the gravitino constraint. The intermediate scales are obtained through an RG analysis of the gauge coupling running and are consistent with a long-lived proton. The model is falsifiable through its prediction of doubly-charged Higgs bosons within the reach of the LHC.

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