Leptogenesis with four gauge singlets

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Abstract

We consider a generic type of leptogenesis model which can successfully produce the correct value of the observed baryon number to entropy ratio. The main feature of this model is that it is a simple TeV scale model, a scale accessible in near future machines, with a minimal particle content. Both supersymmetric and non-supersymmetric versions of the model are feasible. This model also gives left-handed neutrino masses compatible with all current data from direct and indirect neutrino experiments.

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1 Introduction

The determination of a mechanism which can solve the problem of the baryon asymmetry of the Universe (BAU) continues to be a great challenge for both particle physics and cosmology. Among the different mechanisms there has been renewed interest in leptogenesis [1] due to current experimental results from neutrino (astro)physics which could be a first indication of violation of lepton number if neutrinos have Majorana masses. In contrast there has been no direct experimental evidence for baryon number violation in elementary particle interactions. However, recent experimental data from WMAP [2] has determined the best fit values of the baryon density $\Omega_B h^2$ and the ratio of the baryon to photon density

$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

$$\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10}. \tag{1}$$

We now summarize the main ingredients of the leptogenesis mechanism which could generate the BAU. Without a primordial asymmetry, as usual it is necessary that Sakharov’s conditions be fulfilled [2], that is: violation of Baryon Number, violation of C and CP and a deviation from thermal equilibrium. These requirements are generic for any baryogenesis or leptogenesis mechanism. The leptogenesis scenario relies on two separate instances: first the production of a lepton asymmetry and secondly the conversion of this asymmetry into a produced baryon asymmetry. The lepton asymmetry could be produced for instance in the out-of-equilibrium decay of a particle with lepton number and CP violating interactions. It has been argued that the natural scale for this to happen is from $10^{10} - 10^{15}$ GeV. This energy scale is not directly testable making it very difficult to verify a given model. The second stage occurs via sphaleron interactions which are not suppressed for temperatures, $10^2 < T < 10^{12}$ GeV. These interactions occur in weak interaction theories in which all (left) chiral fermions participate without conserving B nor L.

Furthermore, different leptogenesis models have tried to simultaneously give an adequate explanation for non-zero values of neutrino masses, normally via the see-saw mechanism [5, 6], with a common interaction being at the origin of the asymmetry and mass generation.

Many of the models that have been considered are based on the original Fukugita and Yanagida model [1] including three right-handed neutrinos [7] in addition to the Standard Model. It is the decay of the right handed neutrinos that produces the lepton asymmetry \(^1\). An alternative model [2] originally devised in the context of the Left-Right Symmetric Model produces the lepton asymmetry via the decay of a triplet Higgs boson field. It is worth mentioning that one of the difficulties that occurs in the construction of a viable model of leptogenesis when the heavy decaying particle is not a gauge singlet arises due to the possible washout processes. To avoid any elimination of the asymmetry it is necessary that all interactions in which the decaying particle is involved should be out of equilibrium.

Recent work by Buchmuller, Di Bari and Plumacher [10,11,12] have studied in a lot of detail the case of the SM + 3 right-handed neutrinos solving the corresponding Boltzmann equations that take into account the effect of washout processes for temperatures below the mass scale of the lightest right-handed neutrino as well as the thermal production of the initial abundance of right-handed neutrinos. A lower bound on the mass on the right-handed neutrino can be placed $M \gtrsim 10^8$GeV [11,13]. One of the most interesting features of the latest leptogenesis analysis has been the determination of an upper bound on the sum of the light neutrino masses $\sim 0.2$ eV, which is stronger than the WMAP one $\sim 0.7$ eV, by requiring the appropriate amount of baryon asymmetry [11,12].

\(^1\)Several models of this type are imbedded into (SUSY) GUT models such as SO(10)[8].
The inclusion of right-handed (RH) neutrinos directly leads to the possibility of giving small masses to the light left-handed neutrinos via the see-saw mechanism [5, 6]. Since the RH neutrinos are singlets under the Standard Model gauge group, it is possible to include Majorana mass terms for these particles. These terms in conjunction with the Yukawa terms in the Lagrangian, coupling the left-handed with right-handed neutrinos via the Higgs boson interaction, produce the necessary structure to induce a see-saw mass term for the left-handed neutrinos. It is a simple way to explain the left-handed neutrinos mass scale.

It is interesting to consider an alternative energy scale, ∼ TeV, at which the lepton asymmetry could be produced and which additionally could be testable at future experiments. Several of the difficulties that arise in this scenario have been discussed in reference [14]. These include: a) obtaining adequate values of the lepton asymmetry given the constraint from the out-of-equilibrium decay, b) damping effects if the decaying particle has gauge interactions, c) a much too small value of the neutrino masses, or d) it is difficult to have a model in which the same interactions produce the asymmetry and non-zero neutrino masses. The author of Ref. [14] also discusses possible enhancement mechanisms which could overcome the above mentioned difficulties. Other possible TeV scale models have been recently discussed in Refs. [15, 16, 17].

In this paper we present a (generic type of) TeV scale model which can be an interesting candidate for a viable leptogenesis model. In section 2 we present the model and its main features. In section 2.1 we present a non supersymmetric toy model with only two generations to point out the main characteristics of the model. In section 2.2 we illustrate possible textures which can be used successfully in the case with four gauge singlets. In section 2.3 we comment on additional features of the supersymmetric version of the model. We finally conclude in section 3.

2 The Model

Let us first explore a simple (non-supersymmetric) version of the model to distinguish certain features. The Lagrangian is given by

\[ L = L_{SM} + \bar{\psi}_{R_I} i \theta \psi_{R_I} - \frac{M_{N_I}}{2} (\bar{\psi}^c_{R_I} \psi_{R_I} + h.c.) - (Y^c_{\nu IJ} \bar{L}_J \psi_{R_I} \phi + h.c.) , \]

where \( \psi_{R_I} \) are two-component spinors describing the right-handed neutrinos and we define a Majorana 4-component spinor, \( N_I = \psi_{R_I} + \psi^c_{R_I} \). Our index I runs from 0 to 3. The zeroth component of \( L_I \) corresponds to a left-handed lepton doublet which must satisfy the LEP constraints from the Z- width on a fourth left-handed neutrino [18]. The \( Y_{IJ} \) are Yukawa couplings and the field \( \phi \) is the SM Higgs boson doublet whose vacuum expectation value is denoted by \( v_u \).

We work in the basis in which the mass matrix for the right-handed neutrinos \( M \) is diagonal,

\[ M = \text{diag}(M_0, M_1, M_2, M_3) \]

and define \( m_D = Y_\nu v_u \). The neutrino mass matrix for the left-handed neutrinos is given by,

\[ m_\nu = m^T_D M^{-1} m_D = Y^c_\nu M^{-1} Y_\nu v^2_u . \]

which is diagonalized by the matrix \( U \). We will consider the out-of-equilibrium decay of the lightest of the gauge singlets \( N_I \), which we take to be \( N_1 \). The decay rate at tree-level is given by

\[ \Gamma_{N_I} = \Gamma(N_I \rightarrow L_J + \phi^*) + \Gamma(N_I \rightarrow L^*_J + \phi) = \frac{1}{(8\pi)} [Y_\nu Y^c_\nu]_{II} M_{N_I} . \]

\(^2\)We do not write out explicitly the terms involving quark fields.
To ensure an out-of equilibrium decay of $N_1$ it is necessary that $\frac{\Gamma_{N_1}}{H(T= M_1)} \ll 1$, where $H$ is the Hubble expansion rate at $T = M_1$. This condition can also be expressed in terms of the quantity $\tilde{m}_1$, an effective mass parameter [19] defined as

$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \lesssim 5 \times 10^{-3} \text{ eV}. \quad (6)$$

This effective mass $\tilde{m}_1$ depends on $g_*$, which is the effective number of relativistic degrees of freedom at $T = M_1$, for four generations the upper bound will slightly increase.

The CP asymmetry calculated from the interference of the tree diagrams of figure 1 with the one-loop diagrams (self-energy and vertex corrections) given in figure 2 is [20]

$$\epsilon_I = \frac{1}{(8\pi)} \frac{1}{|Y_\nu Y_\nu^\dagger|_{11}} \sum_J \text{Im}[Y_\nu Y_\nu^\dagger]_{IJ} \left[ f \left( \frac{M_J^2}{M_I^2} \right) + g \left( \frac{M_J^2}{M_I^2} \right) \right], \quad (7)$$

where

$$f(x) = \sqrt{x} [1 - (1 + x) \ln \frac{1 + x}{x} ],$$

$$g(x) = \frac{\sqrt{x}}{1 - x}. \quad (8)$$

![Figure 1: Decay Diagrams at Tree-level.](image1)

![Figure 2: One-loop diagrams contributing to the decay $\Gamma(N_I \to \bar{L}_J \phi$). There are similar diagrams that contribute to $\Gamma(N_I \to L_J \phi$).](image2)

The full lepton asymmetry $\eta_L$ will be given by,

$$\eta_L = \frac{1}{f} \frac{n_{\nu_R}}{n_{\gamma}} d, \quad (9)$$
where $\epsilon$ is the CP asymmetry, $f$ is the dilution factor from photon production from the time of leptogenesis to recombination, $d$ is the washout factor which takes into account dilution effects of inverse decays, scatterings, annihilations, etc., which affect the final result of the lepton number density and $\frac{n_{eL}}{n_{\gamma}}$ determines the initial abundance of the right-handed neutrinos and depends on the production mechanism. In order to obtain the exact value of the latter two quantities, one must solve the corresponding Boltzmann equations. In this paper we will not solve the Boltzmann equations but will work under the assumption of having an initial thermal abundance for the right-handed neutrinos, unless explicitly stated, and we will check that the values of our Yukawa couplings are such that the washout effects will be small and not affect the overall features of the model. In an upcoming paper we will solve in detail the Boltzmann equations for this model [21].

The ratio $\eta$ of the baryon to photon density is related to $\eta_L$ by

$$\eta = \frac{n_B}{n_{\gamma}} = -\left(\frac{8N_F + 4N_H}{22N_F + 13N_H}\right)\eta_L,$$

where $N_H$ is the number of Higgs doublets and $N_F$ is the number of fermionic families.

Using the fact that the matrix $\Omega = \left(\frac{m_\nu}{m_\nu M_\nu}\right)^{1/2} U^\dagger Y_\nu$ is orthogonal [22] and following the procedure of Ref. [13] it is easy to show that the upper bound of the CP-asymmetry produced in the decay of the lightest right-handed neutrino $N_1$ is now

$$|\epsilon_1| \lesssim \frac{3}{8\pi} \frac{M_1 m_4}{v^2_u},$$

where $m_4$ denotes the largest eigenvalue of the left-handed neutrino mass matrix $m_\nu$. Due to experimental constraints we require that $m_4 > 45$ GeV, which implies that the bound on $\epsilon_1$ is irrelevant. We will have regions of parameter space in which the produced CP asymmetry can be very large, thus the final allowed region of parameter space will include areas in which the washout processes can be very large as well.

### 2.1 Toy Model

As a simple toy model consider the Lagrangian of eq. (2) for the case with only two generations; that is index $I$ runs from 0, 1. The decay rate and CP asymmetry are given by,

$$\Gamma_1 = \frac{1}{8\pi} (y_{11} y_{11}^* + y_{10} y_{10}^*) M_1,$$

$$\epsilon_1 = \frac{1}{8\pi} \left( f(M_0^2/M_1^2) + g(M_0^2/M_1^2) \right) \frac{\text{Im} [y_{10}^* y_{10} y_{00} y_{00} + 2 y_{10}^* y_{11} y_{00} y_{01} + y_{11}^* y_{11} y_{01} y_{00}]}{y_{11} y_{11}^* + y_{10} y_{10}^*}.$$

We will analyze two possible textures for the Yukawa coupling matrix. We first will consider a texture which has a straightforward implementation when we consider the 4 generations case, see below. The second texture allows us to illustrate the interplay of the different terms which contribute to the CP asymmetry in eq. (3). Both textures will be useful when the supersymmetric version of the model is considered. The first texture $T_1$ is of the form

$$Y_\nu = \begin{pmatrix} \epsilon & \epsilon \\ \alpha & 1 \end{pmatrix}.$$
This just means that \( y_{11} \sim y_{10} \sim \epsilon \) and \( y_{01} \sim \alpha \) while \( y_{00} \sim 1 \). We choose to insert the CP phase of the Yukawa couplings in \( \alpha \) \(^4\). Thus, the first term in the numerator of the expression for \( \epsilon_1 \) in eq. (13) does not contribute to the asymmetry.

In figures 3 and 4 we plot the value of \( \epsilon_1 \) and \( \tilde{m}_1 \) as a function of the coupling \( y_{11} \) for \( M_1 = 400 \text{GeV} \), \( M_0 = 650 \text{ GeV} \), \( y_{00} = 1 \), \( y_{10} = 10^{-8} \) and for two values of \( y_{01} = i10^{-4}, i10^{-7} \). We are taking these values for the sake of illustration, as they allow us to satisfy all constraints from low energy data and cosmology. For the same values of the parameters we obtain a heavy left-handed neutrino with a mass above 45 GeV, and a light neutrino with a mass on the order of \( 10^{-4} \) eV.

![Figure 3: \( \epsilon_1 \) as a function of \( y_{11} \) for the first texture \( T_1 \) considered in the text. The solid line corresponds to \( y_{01} = i10^{-4} \), the dashed line is for \( y_{01} = i10^{-7} \). The rest of the parameters are defined in the text.](image)

We can then see quite easily that for these values of the Yukawa couplings \( \Gamma_{N_1}/H \ll 1 \), (or equivalently \( \tilde{m}_1 < 10^{-3} \) eV) which allows for an out-of-equilibrium decay of \( N_1 \) and suppresses the washout from inverse decays, \( \Delta L = 2 \) and \( \Delta L = 1 \) scatterings. The decay rate and the decay temperature increase as \( y_{11}, y_{10} \) increase making it harder to have an out-of-equilibrium decay and increasing the suppression of the final lepton asymmetry.

In figure 5 we plot the baryon asymmetry \( \eta \) as a function of \( \tilde{m}_1 \) for two values of \( y_{01} = i10^{-4}, i10^{-7} \) and for three different values of the product of \( \frac{n_{\nu R}}{y_t d} = 1, 0.1, 0.001 \).

The second texture \( T_2 \) we would like to analyze has a Yukawa coupling matrix of the form

\[
Y_\nu = \begin{pmatrix}
\epsilon & \alpha \\
1 & 1
\end{pmatrix}.
\]

(15)

Once again we choose to include the CP phase in the Yukawa couplings only in \( \alpha \) which allows us to see the interplay of different terms contributing to the CP asymmetry in eq. (13). In this case

\(^4\) It is possible to parametrize the CP violation of the neutrino sector à la Jarlskog. However, we will leave this issue for future work.
Figure 4: The effective mass $\tilde{m}_1$ as a function of $y_{11}$ for the first texture $T_1$. The rest of the parameters are defined in the text.

Figure 5: The baryon asymmetry $\eta$ as a function of $\tilde{m}_1$ in the case of the first texture $T_1$ for different values of the coupling $y_{01}$ and the product $w = \frac{n_e n_d}{n_p}$. The rest of the parameters are defined in the text.
we can have larger values of the right-handed neutrino masses $M_1$ and $M_0$, and we can still obtain appropriate values for neutrinos masses. We plot in figure 6 the values of $\epsilon_1$ as a function of $y_{11}$ for $y_{00} = 1, y_{01} = 1, M_1 = 600$ GeV, $M_0 = 1$ TeV for $y_{10} = (1 + i)10^{-8}, (1 + i)10^{-10}, (1 + i)10^{-12}$. The value of the CP asymmetry can be quite large and in order to obtain an adequate value of $\epsilon_1$ we must impose a hierarchy between the couplings which enter the decay rate, $y_{11}$ and $y_{10}^5$. In figure 7 we plot the value of $\bar{m}_1$ as a function of the coupling $y_{11}$ for two values of $y_{10} = (1 + i)10^{-8}, (1 + i)10^{-12}$, the other parameters are taken to be the same as the ones chosen to plot $\epsilon_1$ ($y_{00} = 1, y_{01} = 1, M_1 = 600$ GeV, $M_0 = 1$ TeV). Figure 8 shows the value of the baryon asymmetry $\eta$ as a function of $\bar{m}_1$ for $\frac{n_{\nu R}}{n_{\gamma}}d = 0.001$.

Figure 6: $\epsilon_1$ as a function of $y_{11}$ for the second texture $T_2$ considered in the text. The solid line corresponds to $y_{10} = (1 + i)10^{-8}$, the dashed line is for $y_{10} = (1 + i)10^{-10}$ and the long-dashed line to $y_{10} = (1 + i)10^{-12}$. The rest of the parameters are defined in the text. The left part is a zoom to separate the $y_{10} = (1 + i)10^{-10}$ and $y_{10} = (1 + i)10^{-12}$ lines.

In this toy model an additional aspect that must be taken into account is the decay temperature for the RH neutrinos, as it can be just above the electroweak phase transition temperature. The reason for this is that in order to obtain adequate values for the LH neutrino masses, $M_1$ and $M_0$ cannot be of the order of (1-10) TeV. This will not be an important issue in the supersymmetric version of this toy model. In figure 9 we plot the decay temperature $T_d$ as a function of $y_{11}$ for the set of parameters described in the caption.

There are a few important issues that must be discussed. At first sight it would seem that we are creating an asymmetry on both light ($L_1$) and heavy left-handed leptons ($L_0$). However, as has been shown in refs. $[8, 10, 19]$ there are an important class of washout processes which are proportional to $m_i^2$, where $m_i$ denotes the eigenmasses of the LH neutrino mass matrix. For the $L_0$ fermion, this mass is large ($> 45$ GeV). Thus this type of processes will washout any asymmetry in $L_0$ and we remain only with the asymmetry in $L_1$.

An important point in the analysis of Ref. $[12]$ is that for values of $\bar{m}_1 < 10^{-3}$ eV, washout processes will not affect significantly the value of the baryon asymmetry. For our model this will continue to be true as well, however, as mentioned above, in our case we will have regions where the initial asymmetry can be very large as well as regions where the dilution effects are large or the

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5We can also choose values of the couplings that enter the decay rate such that $\bar{m}_1 > 10^{-3}$eV which implies that washout processes can be large and it is necessary to solve the Boltzmann equations to obtain a precise value for the final baryon asymmetry.
Figure 7: The effective mass $\tilde{m}_1$ as a function of $y_{11}$ for the second texture $T_2$. The solid line corresponds to $y_{10} = (1 + i)10^{-8}$ and the dashed line is for $y_{10} = (1 + i)10^{-12}$. The rest of the parameters are defined in the text.

Figure 8: The baryon asymmetry $\eta$ as a function of $\tilde{m}_1$ in the case of the second texture $T_2$ for three different values of the coupling $y_{10}$ and for $w=\frac{n_\nu}{n_d}d = 0.001$. The coupling $y_{11}$ varies from $10^{-9}$ to $10^{-7}$ and the rest of the parameters are defined in the text. The left part is a zoom to separate the $y_{10} = (1 + i)10^{-10}$ and $y_{10} = (1 + i)10^{-12}$ lines.
Figure 9: The decay temperature $T_d$ as a function of $y_{11}$ for the first texture $T_1$, for $M_1 = 400\text{GeV}$, $M_0 = 650 \text{GeV}$, $y_{00} = 1$ and $y_{10} = 10^{-8}$.

initial abundance of the RH neutrinos is small which will still remain viable. We also note that as in the usual model of the SM + 3 right-handed neutrinos $\tilde{m}_1 > m_1$, where $m_1$ denotes the smallest eigenvalues of $m_\nu$.

The main conclusion for our model is that there clearly is enough room to produce the BAU at the TeV scale even if there is a strong suppression of $\eta$ from processes which occur at $T < M_1$.

2.2 4 Generations

One of the possible textures for $Y_\nu$ in the case of four generations of leptons which can generate the appropriate amount of CP-asymmetry and fit neutrino data is of the form

$$Y_\nu = C \begin{pmatrix} \epsilon & \epsilon & \epsilon & \epsilon \\ \epsilon & 1 & 1 & 0 \\ \epsilon & 1 & 1 & 0 \\ \alpha & 0 & 0 & 1/C \end{pmatrix}.$$  

(16)

This will induce to first order a mass matrix for the light left-handed neutrinos of

$$m_\nu = C^2 \frac{v_a^2}{M} \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix},$$

(17)

which is a simple form of the light neutrino mass matrix which can account for all data \cite{23,24}. $C$ is a small number that makes $C^2 v_a^2 / M$ to be of the correct order of magnitude.
2.3 Supersymmetric Version of the Model

The supersymmetrized version of our toy model is very straightforward. The additional contributions to the usual MSSM superpotential are

\[ W = \frac{1}{2} Y^k_{eIJ} L^I L^J E^c_k + Y^\nu_{IJ} L^J H_u N^{cI} + M^I N^I N^I. \] (18)

The zeroth component of \( L_I \) is now the down-type Higgsino and there is no full fourth generation of fermions. The decay rate of \( N_I \) is given by,

\[ \Gamma_{N_I} = \Gamma(N_I \to L_J H_u) + \Gamma(N_I \to \bar{L}_J \bar{H}_u) = \frac{1}{(8\pi)} |Y^\nu Y^\nu_\dagger|_{II} M_{N_I}. \] (19)

There is an analogous expression for the CP asymmetry produced in the decay of \( N_1 \) to that of equation (7). There are however, a few crucial points:

- In this case there are new Yukawa couplings for Higgsino-gauge singlet fields which enter into the expression for \( \epsilon_1 \) which are not constrained to be tiny by left-handed neutrino mass bounds. The upper bound on the value of the asymmetry, analogous to eq. (11), is now proportional to the neutral down-type Higgsino mass.

- Due to the existence of the \( \mu \)-term which couples the \( H_u \) and \( H_d \) fields, the asymmetry in the \( H_d \) will be washed out leaving only the asymmetry in the \( L_i \) fields when the lightest gauge singlet decays, \( i = 1, 2, 3 \).

- A clear distinction with the non-supersymmetric case is that here we are not required to have such a low value for \( M_1 \), as the Higgsino has other contributions to its mass arising from the \( \mu \)-term. So now we can easily have values for \( M_1 \sim (1 - 10) \text{ TeV} \) and still obtain an adequate value of the asymmetry and neutrino masses and mixings.

- The right-handed neutrino mass spectrum can be much more hierarchical.

- For a Yukawa matrix \( Y^\nu \) with a texture of the second type presented in section 2.1 we can then deviate from having both \( y_{00} \sim y_{01} \sim 1 \) and the hierarchy between \( y_{11} \) and \( y_{10} \) and still obtain an adequate value of the baryon asymmetry as we are less constrained by neutrino data.

- The gravitino problem which appears in supersymmetric leptogenesis models with 3 RH neutrinos is avoided in our model.

3 Conclusions and Outlook

We have presented a new and simple model that can provide an adequate scenario for leptogenesis at the TeV scale. The inclusion of an additional gauge singlet allows new contributions to the CP asymmetry which are not constrained to be small. Thus it is relatively simple to obtain the correct amount of baryon asymmetry. The detailed discussion of the toy model has allowed us to illustrate essential features of the model. Neutrino masses and mixings that satisfy low energy experimental constraints can also be obtained. Our preliminary numerical analysis has been very simple, we will address the important issues involved in solving the Boltzmann equations in an upcoming paper [21].

\[^6\text{Terms of the form } S^{ijk}_{N_J N_K} \text{ are neglected we will consider the possible implications of the inclusion of this term in particular regarding the possibility of generating a spontaneous vacuum expectation value for the scalar component of the singlet superfields in an upcoming paper [25].}\]
The supersymmetric version of our model is also quite interesting as it could generate dynamically the $\mu$ terms of the superpotential as well as the masses for the right-handed neutrinos. We will explore these aspects in more detail in a further analysis [25].

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