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Neutrino Mixing and Leptogenesis in a $L_e - L_\mu - L_\tau$ model

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We present a simple extension of the Standard Model with three right-handed neutrinos in a SUSY framework, with an additional $U(1)_F$ abelian flavor symmetry with a non standard leptonic charge $L_e - L_\mu - L_\tau$ for lepton doublets and arbitrary right-handed charges. The model is able to reproduce the experimental values of the mixing angles of the PMNS matrix and of the $r = \Delta m^2_{\text{sun}}/\Delta m^2_{\text{atm}}$ ratio, with only a moderate fine tuning of the Lagrangian free parameters. The baryon asymmetry of the Universe is generated via thermal leptogenesis through CP-violating decays of the heavy right-handed neutrinos. We present a detailed numerical solution of the relevant Boltzmann Equations (BE).

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	l_e	l_μ	l_τ	l_e^c	l_μ^c	l_τ^c	F_1	F_2	$\overline{F}_1$	$\overline{F}_2$	H_u	H_d	N_1	N_2	N_3
$\mathrm{U(1)_F}$	+1	-1	-1	-13	7	3	2	1/2	-2	-1/2	0	0	-1	1	0

Table 1: *$U(1)_F$ charges for leptons, Higgses and flavon fields.*

1. Introduction

The Standard Model (SM) of particle physics has proven to be one of the most accurate theories to explain microscopic interactions at an unprecedented level. However, it fails to account for relevant low energy data, such as the structure of fermion masses and mixings (in particular, the non-vanishing neutrino masses) and the value of the baryon asymmetry of the Universe (BAU), which is commonly expressed by the parameter η_B. Latest observations [1] provide a numerical value of $\eta_B \approx 6.1 \cdot 10^{-10}$.
In recent times, an enormous experimental progress has been made in our knowledge of the neutrino properties and it has been clearly shown that the lepton mixing matrix contains two large and one small mixing angles, and that the two independent mass-squared differences are both different from zero. A very well motivated possibility to address this problem is given by the $U(1)_F$ flavor symmetry with non-standard leptonic charge $L_e - L_\mu - L_\tau$ for lepton doublets and arbitrary right-handed charges. As it is well known (see for example [2]), in the limit of exact symmetry, the neutrino mixing angles are not predicted in the right experimental spots, therefore a symmetry breaking mechanism is needed in order to provide corrections, as we will see in the following. With the present paper we aim to go beyond the existing literature, assessing whether see-saw models based on the $L_e - L_\mu - L_\tau$ quantum number can simultaneously account for neutrino masses and mixing and explain the BAU through thermal leptogenesis.

2. The Model

We summarize the relevant features of our see-saw flavor model based on a broken $U(1)_F$ symmetry. In the proposed scenario, the left handed lepton doublets have charge $L_e - L_\mu - L_\tau$ under the $U(1)_F$, while the right-handed $SU(2)$ singlets $l^c_{e,\mu,\tau}$ have the charges reported in Tab.1. Assuming a SUSY framework, two Higgs doublet fields, H_u and H_d, are considered. Also, the spectrum of the theory contains three heavy sterile neutrinos $N_{i=1,2,3}$, needed for the generation of the light neutrino masses as well as for the implementation of the leptogenesis process. The flavor symmetry is broken by vacuum expectation values (vevs) of $SU(2)$ singlet scalar fields (flavons) suitably charged under the $U(1)_F$ symmetry. Non-vanishing vevs are determined by the D-term [3] potential:

$$V_D = \frac{1}{2}(M^2_{\mathrm{FI}} - g_F|F_1|^2 - g_F|F_2|^2 - g_F|\overline{F}_1|^2 - g_F|\overline{F}_2|^2)\,, \tag{1}$$

where g_F denotes the gauge coupling constant of the $U(1)_F$ symmetry while M_{FI} is the Fayet-Iliopulos term. Non-zero vevs are obtained by imposing the SUSY minimum $V_D = 0$. Without loss of generality, we can assume equal vevs for the flavons and define $\lambda = \langle F_1\rangle/M_F = \langle F_2\rangle/M_F = \langle \overline{F}_1\rangle/M_F = \langle \overline{F}_2\rangle/M_F$ the common ratio between the vevs of the flavons and the scale M_F at which the flavour symmetry is broken.

2.1 Charged lepton sector

After flavor and electroweak symmetry breakings, including higher dimensional operators proportional to power of λ, the charged lepton mass matrix, factoring out the τ mass, assumes the following form:

$$m_l \sim m_\tau \begin{pmatrix} a_{11}\lambda^5 & a_{12}\lambda^3 & a_{13}\lambda \\ a_{21}\lambda^6 & a_{22}\lambda^2 \mathrm{e}^{i\phi_{22}} & a_{23}\mathrm{e}^{i\phi_{23}} \\ a_{31}\lambda^6 & a_{32}\lambda^2\mathrm{e}^{i\phi_{32}} & 1 \end{pmatrix}. \tag{2}$$

For $\lambda < 1$, the following mass ratios $m_e : m_\mu : m_\tau = \lambda^5 : \lambda^2 : 1$ is found, which naturally reproduces the observed pattern if $\lambda \sim 0.22$.

2.2 Neutrino sector

In the neutrino sector, masses are generated through the standard type-I see-saw mechanism: $m_\nu \simeq -v_u^2 Y^\mathrm{T} M_R^{-1} Y$, where Y and M_R are respectively the Yukawa matrix and the Majorana mass matrix. After the symmetry breaking and at the price of some fine tuning, they can be written as:

$$Y = \frac{m_D}{v_u} \sim \begin{pmatrix} \lambda^2 d_{11} & a e^{i\Sigma} & b e^{i\Omega} \\ c e^{i\Phi} & \lambda^2 d_{22} & \lambda^2 d_{23} e^{i\Theta} \\ \lambda^2 d_{31} & \lambda^2 d_{32} & \lambda^2 d_{33} \end{pmatrix}, \quad M_R \sim \mathcal{M} \begin{pmatrix} \lambda^2 m_{11} & W & \lambda^2 m_{13} \\ W & \lambda^2 m_{22} & \lambda^2 m_{23} \\ \lambda^2 m_{13} & \lambda^2 m_{23} & Z \end{pmatrix}, \tag{3}$$

where $\mathcal{M}$ is the sterile neutrinos overall mass scale and $(W, Z, m_{ij}.dij)$ can be regarder as free parameters. Notice that the Dirac mass matrix contains un-suppressed entries because of the choice $Q_{N_1} = -Q_{N_2}$ for two of the right-handed neutrinos. The four physical phases $\Sigma, \Omega, \Phi, \Theta$ in Y, obtained after a suitable redefinition of the fermion fields, are the only source of CP violation of our model and are not fixed by the symmetries of the Lagrangians. For the sake of simplicity and without any loss of generality, we can assume the parameters $m_{ij} \sim m$ and consider m as a real quantity. In general, from the type-I seesaw master formula follows that the mass scale of the sterile neutrinos must be set around 10^{15} GeV, so that the light neutrino masses are below the experimental upper bounds. In our case, this means that there are three very massive sterile neutrinos with masses close to 10^{15} GeV. We dub this scenario the *resonant scenario*. On the other hand, one could lower the overall mass scale to 10^{13} GeV. In such a case, in order to maintain a good agreement with the low energy phenomenology[1] we must assume a hierarchy among the parameters in the Majorana mass matrix: $W/Z \sim 10^2$. This leads to a splitting of the sterile neutrino masses, in other words we end up with one lighter state at $M_3 \sim 10^{13}$ GeV and two heavier states with $M_{1,2} \sim 10^{15}$ GeV. From now on we refer to this scenario as the *hierarchical scenario*.
Also, it can be proved that, in both cases, it is possible to recast the m_ν obtained from the type-I seesaw master formula in this simple form:

$$m_\nu = m_0 \begin{pmatrix} \lambda^2 x_1 & 1 & x \\ 1 & x_2\lambda^2 & x_3\lambda^2 \\ x & x_3\lambda^2 & x_4\lambda^2 \end{pmatrix}, \tag{4}$$

where m_0 is the overall mass scale and (x, x_i) are suitable combinations of the coefficients present in Dirac and Majorana matrices in Eq. 3. Computing U_ν and U_l, which are the neutrino mixing

[1]The complete discussion can be found in [4].

matrix and the charged lepton mixing matrix respectively, we can obtain the final expression of the neutrino mixing angles, using $U_{PMNS} = U_l^\dagger U_\nu$. These, as well as the mass ratio $r = \Delta m^2_{sol}/\Delta m^2_{atm}$, are in good agreement with the results given in [5]. This conclusion has been further strengthened by a succesful numerical scan [6] over the model free parameters, with moduli extracted flat in the intervals $[0.2, 5]$ and all the phases in $[-\pi, \pi]$.

3. Leptogenesis

As stated above, our study of leptogenesis will be performed within two reference scenarios, identified by different mass patterns for the heavy right-handed neutrinos: the *resonant* and *hierarchical* scenarios. The three Majorana neutrinos decay in the early Universe creating a lepton asymmetry, which is consequently conversed in a baryon asymmetry through non perturbative processes, known as *sphaleron processes*. As we will clarify in the following, a different Majorana neutrino mass spectrum can lead to different CP-violating parameters, affecting the final amount of baryon asymmetry in the Universe.

3.1 Resonant Scenario

The first scenario we consider is the *resonant scenario*, with three degenerate sterile neutrinos with mass $M \sim 10^{15}$ GeV. Being mass degenerate, we expect that all three right-handed neutrinos contribute to the leptogenesis process. The resonant regime is characterised by the presence of an enhancement of the CP-violation; this is a very powerful tool because it allows producing the right amount of BAU even if the sterile neutrinos are much lighter than 10^{10} GeV. However, in our case this is a problem since the masses of the Majorana neutrinos are very high, close to the GUT scale; this would lead to an excess of the BAU. In other words, in order to obtain a value of the baryon-asymmetry comparable to the one observed so far, we need to impose a fine tuning on the CP-violating phases in the Majorana mass matrix.
The full BE[2] in this scenario are:

$$\begin{aligned} \frac{dN_i}{dz} &= -\left(D_i + S_i\right)\left(N_i - N_i^{\rm eq}\right) \qquad i = 1, 2, 3 \\ \frac{dN_{B-L}}{dz} &= \sum_i^3 \varepsilon_i D_i \left(N_i - N_i^{\rm eq}\right) - W_i N_{B-L}\,, \end{aligned} \tag{5}$$

where N_i stands for the number density of the RH sterile neutrinos, while N_{B-L} is the amount of $B - L$ asymmetry, both normalized by comoving volume. D_i and S_i indicate, respectively, inverse decay and scattering contributions to the production of the right-handed neutrinos while the W_i represent the total rate of Wash-out processes including both inverse decay and $\Delta L \neq 0$ scattering contributions. Also, $\varepsilon_i = \varepsilon_i(z)$ are the full time dependent asymmetry parameters as discussed in [4] and in references therein. As shown in Fig. 1, the time dependence of the CP-asymmetry parameters does not affect the final amount of baryon-asymmetry. This is because this scenario is characterised by the *strong wash-out regime*, *i.e.* the lepton asymmetry generated during the N_i creation phase is efficiently washed out. After the fine tuning on the CP-violating phases, as

[2]All the details regarding the Boltzmann Equations can be found in [4] and in references therein.

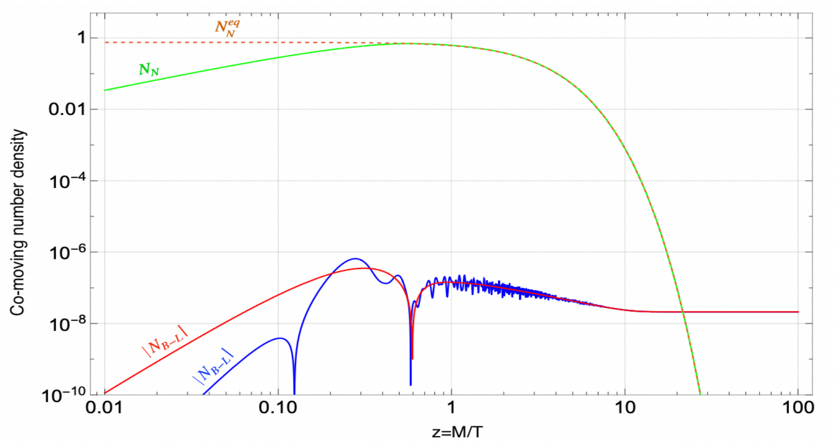

Figure 1: $B - L$ asymmetry and neutrino abundance evolution during the expansion of the Universe. The blue line refers to the full solution of the Boltzmann's equations, obtained retaining the time dependence of the CP-violation parameter. The red line refers to the solution of the analogous system but adopting a time-constant value of the asymmetry parameters. Finally, the green line represents the abundance of the right-handed neutrinos, as given by the solution of the system. For reference, the latter is compared with the function $N_N^{\rm eq}$ (dashed line) which represents a thermal equilibrium abundance for right-handed neutrinos.

discussed above, and keeping all the other parameters to order one, we evaluated the final BAU solving the set of differential equation in Eq. 5 obtaining $\eta_B \simeq 3.01 \cdot 10^{-10}$. Notice that the relatively good value for η_B has been obtained for a particular representative choice of the model parameters (also adopted in Fig. 1); we are confident that regions of the parameter space consistent with the correct baryon asymmetry exist in our model.

3.2 Hierarchical scenario

This alternative scenario is obtained by lowering the mass scale $\mathcal{M}$ down to a value of the order of 10^{13} GeV, which brings to a hierarchical mass spectrum for the sterile neutrinos, with two heavy, almost degenerate, states with $M_1 \simeq M_2 \sim 10^{15}$ GeV, and a lighter one with $M_3 \simeq 10^{13}$ GeV. In this set-up, the relevant BE presents the same structure as in the previous case with the substantial difference that now only the out-of-equilibrium decay of the lightest heavy neutrino generates the BAU via thermal leptogenesis, and the CP-asymmetry parameter ε is no longer time dependent, but it is constant and essentially it depends on the mass splitting M_3/M_i, with $i = 1, 2$. The numerical solution of the BE is shown in Fig. 2. The result is $\eta_B = 3.96 \cdot 10^{-10}$. It is interesting to notice that, contrary to the resonant regime, in the hierarchical scenario it is possible to find a parameter assignation leading to viable leptogenesis without imposing a fine tuning on the CP violating phases.

4. Conclusions

In this paper, we have provided a proof of existence about the possibility of contemporary achieving viable masses and mixing patterns for the SM neutrinos and a value of the BAU, via

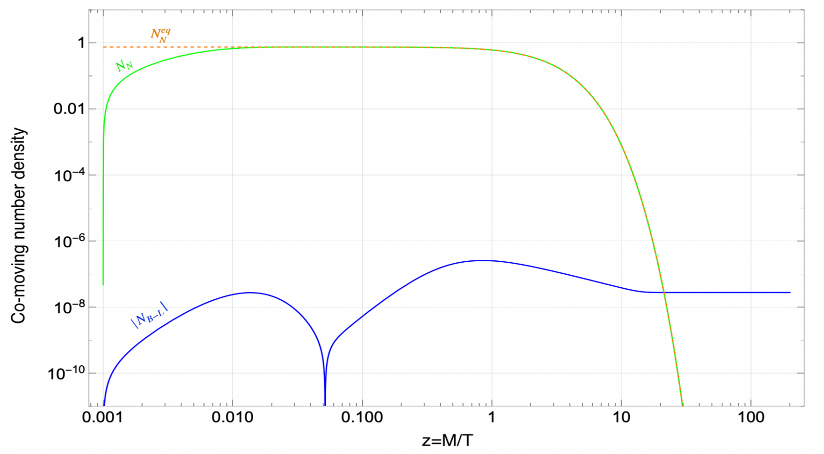

Figure 2: Evolution of the $B - L$ asymmetry in the *hierarchical scenario*. The color code is the same as in fig.1.

leptogenesis, compatible with the experimental determination, in models based on the abelian flavor symmetry $L_e - L_\mu - L_\tau$. We have identified two reference scenarios and we have shown how it is possible to obtain the right amount of BAU in both of them.

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