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RESONANT LEPTOGENESIS IN FROGGATT–NIELSEN MECHANISM

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ABSTRACT

We study the scenario of thermal leptogenesis in which the leptonic asymmetries are resonantly enhanced through the mixing of nearly degenerate heavy Majorana neutrinos that have mass differences comparable to their decay widths. We show that resonant leptogenesis can be realized with heavy Majorana neutrinos even as light as ~ 1 TeV, in complete accordance with the current solar and atmospheric neutrino data. In our present model, we have considered Low-Scale Heavy Majorana-Neutrino Model in which Froggatt-Nielsen (FN) mechanism is used to satisfy the condition of resonant leptogenesis and also verified that it is compatible with the observed phenomenologically favoured light neutrino mass differences.

Keywords: CP-Asymmetry, Resonant Leptogenesis, Froggatt-Nielsen Mechanism, Right-Handed Neutrinos

I INTRODUCTION

The Froggatt-Nielsen (FN) mechanism [1] is one of the attractive mechanisms to explain mass hierarchy of quarks and charged leptons. The idea is that the U (1) global symmetry is taken as a flavor symmetry and the vacuum expectation value (VEV) of a flavor field called FN field gives a proper structure of Yukawa couplings. For quarks and leptons, this mechanism seems to work well by taking an appropriate charge assignment of fields. However it is known that a mass hierarchy of neutrinos is milder than that of charged lepton. And in resonant leptogenesis [2], the two of the heavy Majorana neutrinos (N_i) have mass differences comparable to their decay widths and consequently there is a resonant enhancement of the leptonic asymmetries. In the StandardModel (SM) neutrinos are strictly massless [3]. To overcome this massless problem the SM field should contain right-handed (singlet) neutrinos. The scale of these singlet masses is rather model-dependent and may range from about 1 TeV in Left-Right Symmetric or certain E6 models up to 10^{16} GeV in typical Grand Unified Theories (GUTs) such as SO(10) models. A seesaw mechanism[4-11] which relates both large and small neutrino masses phenomenologically favoured values for neutrino masses of order 0.1 eV and smaller can be explained without unnaturally suppressing the Yukawa couplings of the theory. As is shown in Fig. 1, the interference of the tree-level decay amplitude with the absorptive parts of the one-loop self-energy and vertex graphs violates CP and hence gives rise to a non-vanishing leptonic

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asymmetry. These self-energy and vertex contributions are often termed in the literature ε and ε' -types of CP violation, respectively. Unlike ε' -type, ε -type CP violation can be considerably enhanced through the mixing of two nearly degenerate heavy Majorana neutrinos.

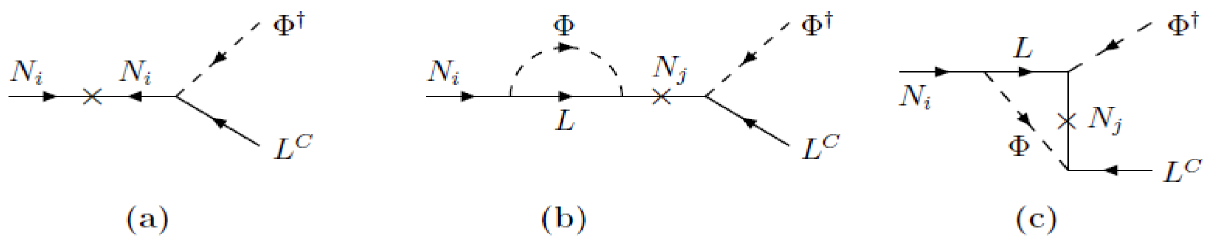

Figure1: Feynman diagrams contributing to the L-violating decays of heavy Majorana neutrinos, Ni → L^C ϕ†, where L andϕ represent lepton and Higgs-boson iso-doublets, respectively: (a) tree-level graph, and two one-loop (b) self-energy and (c) vertex graphs.

II METHODOLOGY

In deriving a lower bound of about 10^8–10^9 GeV on the leptogenesis scale, the $N_i$decay into a lepton doublet L and a Higgs doublet ϕ, $N_i \rightarrow L\phi$, and its respective charge and parity (CP) conjugate mode, $N_i \rightarrow L^c \phi^\dagger$, plays a key role. In other words, the larger the leptonic CP asymmetry, the smaller the lower bound on the leptogenesis scale becomes.
In resonant leptogenesis the heavy Majorana singlet mass scale can be drastically lowered to 1 TeV energies and analyze it in light of the current solar and atmospheric neutrino data. We then put forward a generic scenario that predicts nearly degenerate heavy Majorana neutrinos at the TeV scale and can naturally be realized by means of the FN mechanism. In this generic scenario, the light-neutrino sector admits the Large Mixing Angle (LMA) Mikheyev–Smirnov–Wolfenstein (MSW) solution and so may explain the solar neutrino data through a large $\upsilon_e - \upsilon_\mu$ mixing. The light-neutrino sector also allows for a large $\upsilon_\mu - \upsilon_\tau$ mixing to account for the atmospheric neutrino anomaly.

2.1 Condition for Resonant Leptogenesis using heavy majorana neutrino model and neutrino data

Our generic scenario leads to a mass spectrum for the light neutrinos, can accommodate the phenomenologically favoured neutrino-mass differences [12]:

$$1.4\times10^{-3} < \Delta m^2_{atm}\,(\mathrm{eV}^2) < 3.7\times10^{-3},\ 5.4\times10^{-5} < \Delta m^2_{sol}\,(\mathrm{eV}^2) < 9.5\times10^{-5}, \qquad (1)$$

at the 3σ confidence level, where $\Delta m^2_{atm} = m_3^2 - m_2^2$, $\Delta m^2_{sol} = m_2^2 - m_1^2$.

In the physical basis, the lagrangian for Yukawa leptonic sector reads

$$\mathcal{L}_{\rm Y} \;=\; -\sum_{i,j=1}^{3} \Big(h^{\nu}_{ij}\, \bar{L}_i\, \tilde{\Phi}\, P_R\, N_j \;+\; \hat{h}^{l}_{ii}\, \bar{L}_i\, \Phi\, P_R\, l_i \quad + \quad {\rm H.c.} \Big)\,, \tag{2}$$

where a four-component chiral representation for all fermionic fields should be understood. In (2), $\hat{h}^{l}_{ii}$ is a diagonal positive matrix and h^{υ}_{ij} is related to $h^{\upsilon_R}_{ij}$ through a bi-unitary transformation:$h^{\upsilon} = V_L^{+} h^{\upsilon} U$, where V_L is a 3-by-3 unitary matrix that transforms the left-handed charged leptons to their corresponding mass eigenstates. Our computations of the leptonic asymmetries and collision terms relevant to leptogenesis will be based on the Lagrangian (2).Having set the stage, it is now instructive to discuss the possible flavour structure of low singlet-scale models with nearly degenerate heavy Majorana neutrinos. Such a class of models may be constructed by assuming that lepton-number violation (and possibly baryon-number violation) occurs at very high energies at the GUT scale $M_{GUT} \approx 10^{15} - 10^{17}$ GeV, or even higher close to the Planck scale $M_{Planck} \approx 10^{19}$ GeV through gravitational interactions. On the other hand, operators that conserve lepton number are allowed to be at the TeV scale.Since our interest is to discuss resonant leptogenesis, the following sufficient and necessary conditions under which leptonic asymmetries of order unity can take place have to be satisfied by the model under discussion:

$$m_{N_i} \;-\; m_{N_j} \;\sim\; \frac{\Gamma_{N_{i,j}}}{2}\;, \qquad \frac{|{\rm Im}\,(h^{\nu\dagger}h^{\nu})^2_{ij}\,|}{(h^{\nu\dagger}h^{\nu})_{ii}\,(h^{\nu\dagger}h^{\nu})_{jj}} \;\sim\; 1\,, \tag{3}$$

for a pair of heavy Majorana neutrinos $N_{i,j}$. In (3), Γ_{N_i} are the $N_i$decay widths, which at the tree level are given by:

$$\Gamma^{(0)}_{N_i} \;=\; \frac{(h^{\nu\dagger}h^{\nu})_{ii}}{8\pi}\; m_{N_i}\ .$$

In the following, we present a rather generic scenario that minimally realizes the above requirements and still has sufficient freedom to describe the neutrino data. Our genericscenario is based on the FN mechanism. Specifically, we introduce two FN fields, Σ and $\overline{\Sigma}$, with opposite $U(1)_{FN}$charges, i.e. $Q_{FN}(\Sigma) = -Q_{FN}(\overline{\Sigma}) = +1$. Under $U(1)_{FN}$, thefollowing charges for the right-handed neutrinos are assigned:

$$Q_{\rm FN}\,(\nu_{1R}) \;=\; -1\,, \qquad Q_{\rm FN}\,(\nu_{2R}) \;=\; +1\,, \qquad Q_{\rm FN}\,(\nu_{3R}) \;=\; 0\,.$$

In addition, all other fields, including charged leptons, are singlets under $U(1)_{FN}$. Then, the singlet mass matrix M_S assumes the generic form:

$$M_S \;\sim\; M \begin{pmatrix} \varepsilon^2 & 1 & \varepsilon \\ 1 & \bar{\varepsilon}^2 & \bar{\varepsilon} \\ \varepsilon & \bar{\varepsilon} & M_X/M \end{pmatrix}\,, \tag{4}$$

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where $\varepsilon = \langle\Sigma\rangle/M_{GUT}$ and $\bar{\varepsilon} = \langle\bar{\Sigma}\rangle/M_{GUT}$. In (4), M sets up the scale of the leptonic symmetry $L_e - L_\mu$ while M_X represents the scale of L_τ violation. It is conceivable thatthese two scales may be different from one another. For the case of our interest, it isM ~ 1 TeV, while M_X is considered to be many orders of magnitude larger close to M_{GUT}. The FN mechanism also determines the strength of the Yukawa couplings. After spontaneous symmetry breaking (SSB), the resulting Dirac-neutrino mass matrix m_D has the generic form:

$$m_D \equiv \frac{v}{\sqrt{2}} h \sim \frac{v}{\sqrt{2}} \begin{pmatrix} \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \end{pmatrix}, \qquad (5)$$

where h is a 3 × 3 matrix containing the neutrino Yukawa couplings expressed in the positive and diagonal basis of the respective charged-lepton Yukawa couplings.If one assumes that $\langle\Sigma\rangle \sim \langle\bar{\Sigma}\rangle \sim \sqrt{MM_{GUT}}$ and $M_X \sim M_{GUT}$, a rather simple pattern for the mass matrices m_D and M_S emerges. In this case, the mass spectrum of the generic scenario under investigation contains one super-heavy Majorana neutrino, with a mass $m_{N3} \sim M_X \sim M_{GUT}$, and two nearly degenerate heavy Majorana neutrinos $N_{1,2}$with $m_{N1,2} \sim$ M and a mass difference $m_{N1} \sim m_{N2} \approx \varepsilon^2 M \approx M^2/M_{GUT}$. Since it is $\Gamma^{(0)}_{N_{1,2}} \sim \varepsilon^2 M \sim M^2/M_{GUT}$, it can be readily seen that one of the crucial conditions forresonant leptogenesis in (3), i.e. $m_{N1} \sim m_{N2} \approx \frac{1}{2}\Gamma_{N_{1,2}}$ can naturally be satisfied withinour generic framework.In the above exercise, one should bear in mind that the FN mechanism can only give rise to an order-of-magnitude estimate of the different entries in the mass matrices m_D and M_S. Moreover, since our focus will be on the neutrino sector of this minimal model of resonant leptogenesis, we will not attempt to explain the complete quark- and charged-lepton-mass spectrum of the SM by analyzing all possible solutions through the FN mechanism. Such an extensive study is beyond the scope of the present article and may be given elsewhere.We will now explicitly demonstrate that the mass textures stated in (4) and (5) can lead to viable light-neutrino scenarios, when the latter are confronted with the present solar and atmospheric neutrino data. To further simplify our discussion, we assume that the super-heavy neutrino decouples completely from the light-neutrino spectrum. As a result, to leading order in the FN parameters ε and $\bar{\varepsilon}$, the 3-by-3 light-neutrino mass-matrix m^υ may be cast into the form:

$$\mathbf{m}^\nu \approx -\frac{v^2}{2M} \begin{pmatrix} 2h_{11}h_{12} & h_{11}h_{22} + h_{12}h_{21} & h_{11}h_{32} + h_{31}h_{12} \\ h_{11}h_{22} + h_{12}h_{21} & 2h_{21}h_{22} & h_{21}h_{32} + h_{31}h_{22} \\ h_{11}h_{32} + h_{31}h_{12} & h_{21}h_{32} + h_{31}h_{22} & 2h_{31}h_{32} \end{pmatrix}. \qquad (6)$$

Here,h_{ij} are the neutrino Yukawa couplings in the weak basis described after (5). Notethat effects due to the mass degeneracy of the heavy Majorana neutrinos contribute termsO($\varepsilon^3\bar{\varepsilon}, \varepsilon\bar{\varepsilon}^3$) to m^υ. As long as $\varepsilon, \bar{\varepsilon} \sim 10^{-7}$, these sub-leading terms do not affect the light neutrino mass spectrum and hence they can be safely neglected.Let us now present a concrete example by considering the following set of Yukawacouplings with normal mass hierarchy in units of $\varepsilon = \bar{\varepsilon}$:

$$h_{11} = -\frac{1}{3};\ h_{12} = \frac{2}{3};\ h_{21} = 2;\ h_{22} = 1;\ h_{31} = 1;\ h_{32} = 2. \qquad (7)$$

For our illustrations, we also neglect the existence of possible CP-odd phases in the Yukawa couplings. Then, the light-neutrino mass matrix exhibits the structure:

$$\mathbf{m}^{\nu} \approx -\frac{v^2 \varepsilon \bar{\varepsilon}}{2M} \begin{pmatrix} -4/9 & 1 & 0 \\ 1 & 4 & 5 \\ 0 & 5 & 4 \end{pmatrix}. \qquad (8)$$

It is not difficult to see that the above light-neutrino mass matrix m can be diagonalizedby large $\upsilon_\mu - \upsilon_\tau$ and $\upsilon_e - \upsilon_\mu$ mixing angles, i.e. $|\theta_{\upsilon_\mu \upsilon_\tau}| \approx \frac{\Pi}{4}$ and $|\theta_{\upsilon_e \upsilon_\mu}| \approx \frac{\Pi}{6}$. Instead, the $\upsilon_e - \upsilon_\tau$ mixing angle is estimated to be small, i.e. $\theta_{\upsilon_e \upsilon_\tau} \leq 0.1$. Furthermore, the physical light-neutrino masses derived from m^{υ} are approximately given by:

$$(m_1, m_2, m_3) \approx \frac{v^2 \varepsilon \bar{\varepsilon}}{2M}(0.04, 1.5, 9) = \frac{m_t^2}{M_{GUT}}(0.04, 1.5, 9) \qquad (9)$$

In deriving the last step of (9), we have used the fact that $|\varepsilon\bar{\varepsilon}| \approx \frac{M}{M_{GUT}}$, $m_t \approx \frac{v}{\sqrt{2}}$ .Now, the vacuum expectation value of the standard model Higgs doublet, v ~ 100 GeV and M_{GUT} ~ 10^{15}-10^{17} GeV.

So, $$\frac{v^2 \varepsilon \bar{\varepsilon}}{2M} \approx \frac{m_t^2}{M_{GUT}} = \frac{v^2}{2M_{GUT}} \sim \frac{1}{2} \times \frac{100^2 GeV^2}{10^{15} GeV} = \frac{1}{2} \times 10^{-11} GeV = 0.005 eV$$

So, we get, $\Delta m_{atm}^2 = m_3^2 - m_2^2 = (0.005)^2 \times [9^2 - (1.5)^2] eV^2 = 1.97 \times 10^{-3} eV^2$, (10)

Similarly, $\Delta m_{sol}^2 = m_2^2 - m_1^2 = (0.005)^2 \times [(1.5)^2 - (0.04)^2] eV^2 = 5.621 \times 10^{-5} eV^2$. (11)

Thus, both equations (10) and (11) match with the limits of Δm_{atm}^2 and Δm_{sol}^2 as stated in (1), i.e. it is compatible with the observed light-neutrino mass difference stated in equation (1). Even though the present example realizes a light-neutrino mass spectrum with normal hierarchy, an inverted hierarchy can easily be obtained by appropriately rearranging the Yukawa couplings in (7).From (9), we also get the idea of the order of the neutrino masses m_1, m_2 and m_3.Here, $\frac{v^2 \varepsilon \bar{\varepsilon}}{2M}$ ~ 0.005 eV

So, we get, m_1 ~ 0.05 × 0.04 eV = 0.02 eV,

$m_2 \sim 0.05 \times 1.5$ eV = 0.075 eV,

$m_3 \sim 0.05 \times 9$ eV = 0.45 eV.

$$\therefore\ m_2 - m_1 = (0.02 - 0.075)eV = 7.279 \times 10^{-3} eV$$

Now, Froggatt-Nielson parameters, $\varepsilon, \bar{\varepsilon}$ ~ 10^{-7}. Also, $|\varepsilon\bar{\varepsilon}| \approx \dfrac{M}{M_{GUT}}$

$$M \approx |\varepsilon\bar{\varepsilon}| M_{GUT} \approx 10^{-14} \times 10^{17} GeV = 10^{3} GeV = 10^{12} eV$$

$$\therefore \Gamma^{(0)}_{N_{1,2}} \approx \varepsilon^2 M = 10^{-14} \times 10^{12} eV = 10^{-2} eV, \Rightarrow \frac{1}{2}\Gamma^{(0)}_{N_{1,2}} = 5 \times 10^{-3} eV.$$

$$\therefore m_2 - m_1 \approx \frac{1}{2}\Gamma^{(0)}_{N_{1,2}}$$

And this is the condition of Resonance Leptogenesis.

Now, we use the inverted hierarchy mechanism. We consider the realization of the inverted hierarchy in this mass formula. For this purpose, we may start the study from the neutrino mass matrix which brings the tri-bimaximal mixing. Since the recent experiments suggest nonzero mixing angle θ13, it can be just an approximation for the realistic mixing. Taking this strategy, we assume that the neutrino Yukawa couplings have the following flavor structure:

$$h_{e1} = -2h_{\mu 1} = 2h_{\tau 1} = 2h_1; h_{e2} = h_{\mu 2} = -h_{\tau 2} = h_2; h_{e3} = 0; h_{\mu 3} = h_{\tau 3} = h_3$$

This flavor structure for the neutrino Yukawa couplings induce a following simple form for the neutrino mass matrix:

$$\mathcal{M}^{\nu} = \begin{pmatrix} 4 & -2 & 2 \\ -2 & 1 & -1 \\ 2 & -1 & 1 \end{pmatrix} h_1^2 \Lambda_1 + \begin{pmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix} h_2^2 \Lambda_2 + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} h_3^2 \Lambda_3.$$

A easily found, this matrix can be diagonalized as:

$U^T_{PMNS} M^{\nu} U_{PMNS} = diag(m_1, m_2, m_3)$

We used the tri-bimaximal PMNS matrix:

$$U_{PMNS} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From here, we get the mass eigenvalues which are expressed as:

$$m_1 = 6\left|h_1^2 \Lambda_1\right|; \quad m_2 = 3\left|h_2^2 \Lambda_2\right|; \quad m_3 = 2\left|h_3^2 \Lambda_3\right|. \qquad (12)$$

Here, neutrino masses are considered to be fixed by Λ's which have the dimension of mass and h's are the Yukawa couplings.In the inverted hierarchy, the squared mass differences for atmospheric and solar neutrinos are defined as:

$$\Delta m_{atm}^2 = m_1^2 - m_3^2, \Delta m_{sol}^2 = m_1^2 - m_2^2. \qquad (13)$$

Now, experimental results suggest that, $\Lambda_1 = 15702.7$ eV, $\Lambda_2 = 21687.75$ eV, $\Lambda_3 = 21687.75$ eV,
$h_1 = 6.7 \times 10^{-4}$, $h_2 = 7.5 \times 10^{-4}$, $h_3 = 3 \times 10^{-8}$.
Putting these values in equation (12), we get,
$m_1 = 0.04229$ eV; $m_2 = 0.036598$ eV; $m_3 = 3.90 \times 10^{-11}$ eV
So, from equation (13), we get that,

$$\Delta m_{atm}^2 = m_1^2 - m_3^2 = 1.788 \times 10^{-3} \text{ eV}^2, (14)$$

$$\Delta m_{sol}^2 = m_1^2 - m_2^2 = 8.98 \times 10^{-5} \text{ eV}^2. \qquad (15)$$

Thus, here also both equations (14) and (15) match with the limits of Δm_{atm}^2 and Δm_{sol}^2 as stated in (1), i.e. it is compatible with the observed light-neutrino mass difference stated in equation (1).Now,
$m_1 - m_2 = 5.692 \times 10^{-3}$ eV.

Again, $\frac{1}{2}\Gamma_{N_{1,2}}^{(0)} = 5 \times 10^{-3}$ eV as calculated before.

Thus, in this case also $m_1 \sim m_2 \approx \frac{1}{2}\Gamma_{N_{1,2}}^{(0)}$, which is the condition of Resonance Leptogenesis. The recent results of the Planck and other cosmological measurements for the sum of the neutrino masses too is fulfilled [14]$\sum_i m_i < 0.23$ eV.

III CONCLUSIONS

We have studied the scenario of thermal leptogenesis in which the leptonic asymmetries are resonantly amplified through the mixing of nearly degenerate heavy Majorana neutrinos that have mass differences comparable to their decay widths. We have shown that resonant leptogenesis, can be realized with heavy Majorana neutrinos even as light as 0.5-1 TeV, in complete accordance with the current solar and atmospheric neutrino data. Models that might predict nearly degenerate heavy Majorana neutrinos at the TeV and sub-TeV scales and lead to light-neutrino mass matrices compatible with neutrino oscillation data can be constructed by means of the Froggatt–Nielsen mechanism. The analysis also satisfied the recent results of the Planck and other cosmological measurements for the sum of the neutrino masses too is fulfilled is less than 0.23 eV.It would be very interesting to study in detail the phenomenological implications of this exciting scenario of resonant leptogenesis for low-energy and collider experiments.

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