Published for SISSA by Springer

Received: September 22, 2019
Revised: January 17, 2020
Accepted: January 19, 2020
Published: January 30, 2020

Flavoured leptogenesis and $\mathrm{CP}^{\mu\tau}$ symmetry

Rome Samanta[a] and Manibrata Sen[b,c]

[a] *Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, U.K.*
[b] *Department of Physics, University of California Berkeley, Berkeley, CA 94720, U.S.A.*
[c] *Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, U.S.A.*

E-mail: R.Samanta@soton.ac.uk, manibrata@berkeley.edu

Abstract: We present a systematic study of leptogenesis in neutrino mass models with $\mu\tau$-flavoured CP symmetry. In addition to the strong hierarchical N_1-dominated scenario (N_1DS) in the 'two flavour regime' of leptogenesis, we show that one may choose the right-handed (RH) neutrino mass hierarchy as mild as $M_2 \simeq 4.7 M_1$ for a perfectly valid hierarchical N_1DS. This reduces the lower bound on the allowed values of M_1, compared to what is stated in the literature. The consideration of flavour effects due to the heavy neutrinos also translate into an upper bound on M_1. It is only below this bound that the observed baryon-to-photon ratio can be realized for a standard N_1 domination, else a substantial part of the parameter space is also compatible with N_2DS. We deduce conditions under which the baryon asymmetry produced by the second RH neutrino plays an important role. Finally, we discuss another scenario where lepton asymmetry generated by N_2 in the two flavour regime faces washout by N_1 in the three flavour regime. Considering a hierarchical light neutrino mass spectrum, which is now favoured by cosmological observations, we show that at the end of N_1-leptogenesis, the asymmetry generated by N_2 survives only in the electron flavour and about 33% of the parameter space is consistent with a pure N_2-leptogenesis.

Keywords: Cosmology of Theories beyond the SM, CP violation, Neutrino Physics

ArXiv ePrint: 1908.08126

https://doi.org/10.1007/JHEP01(2020)193

Contents

1 Introduction

Neutrino masses and mixings continue to intrigue. Precise measurement of the six mixing parameters — the three mixing angles: solar (θ_{12}), atmospheric (θ_{23}) and reactor (θ_{13}), the two mass-squared differences: solar (Δm^2_{12}), and atmospheric (Δm^2_{23}), and the CP phase δ — is essential for a clear understanding of neutrino physics. While we have almost zeroed in on the values of the mixing angles and mass-squared differences from solar, atmospheric and terrestrial experiments [1], we are still pretty much in the dark when it comes to the CP phase. To this end, significant improvements have been made to the experimental determination of δ in experiments such as T2K [2–4] and NOνA [5, 6]. There exists a mild preference for the normal mass ordering (NMO) of the neutrinos, while latest global fit of neutrino oscillation data [7] seem to favour the second octant of θ_{23} (the best-fit value $\sin^2\theta_{23} = 0.58$), and a maximal value of the CP phase $\delta = 3\pi/2$ (driven by T2K neutrino and anti-neutrino appearance data) for both the mass orderings. However, precise statements on the mass ordering, octant of θ_{23} and the value of δ are yet to be made with a high degree of confidence level.

This is an exciting time in low energy neutrino phenomenology. Models which have concrete predictions for the yet undetermined parameters such as θ_{23} and δ can be tested in the light of recent experimental data. From a theory standpoint, flavour symmetries [8–11] have always been invoked in neutrino mass models to estimate neutrino mixing parameters. A popular example is the $\mu\tau$ symmetry [12–19], which was ruled out by the discovery of a non-zero θ_{13}. However, after the hint of maximal CP violation by T2K [2], another variant of the $\mu\tau$ symmetry, the $\mu\tau$ flavoured CP symmetry (CP$^{\mu\tau}$) or $\mu\tau$ reflection symmetry [20–22] has been a topic of interest in the recent years [23–42].

The $\mathrm{CP}^{\mu\tau}$ symmetry, which is a CP transformation [43–45] on the left-handed (LH) neutrino fields with $\mu\tau$ interchange symmetry as the CP generator in the low energy effective neutrino Lagrangian, predicts a co-bimaximal mixing [46]: $\theta_{23} = \pi/4$ and $\delta = \pi/2,\ 3\pi/2$, along with arbitrary non-zero values of θ_{13}. To make $\mathrm{CP}^{\mu\tau}$ more predictive, a sizable body of work exists to combine flavour symmetries with CP symmetries, despite this being a non-trivial task [25, 26]. Several aspects of $\mathrm{CP}^{\mu\tau}$ and its alternative versions have also been explored [47–56].

From the point of view of cosmology, the $\mathrm{CP}^{\mu\tau}$ model has generated considerable interest in the possibility of baryogenesis via leptogenesis [58–61, 63, 64]. In an extended Standard Model (SM), augmented with right-handed (RH) neutrinos, tiny masses for the active neutrinos can be generated through the Type-I seesaw mechanism [65–67]. In such models, CP-violating and out of equilibrium decays of the heavy RH neutrinos can generate a lepton asymmetry (leptogenesis) which can be converted into a baryon asymmetry (baryogenesis) by sphalerons [57, 58, 60]. These sphaleronic transitions conserve $\mathrm{B}-\mathrm{L}$, and violate $\mathrm{B}+\mathrm{L}$, where B and L are the baryon and lepton number respectively. Given a neutrino mass model, successful baryogenesis requires [68]

$$\eta_B^{th} \equiv \eta_B^{CMB} = (6.3 \pm 0.3) \times 10^{-10}\,, \tag{1.1}$$

where η_B^{th} and η_B^{CMB} are the theoretical and observed values of baryon to photon ratio at the recombination. Assuming a N_1 dominated scenario (N_1DS), where only the decays and interactions of N_1 matter, it has been pointed out that $\mathrm{CP}^{\mu\tau}$ [22, 69, 70] as well as the CP symmetries similar to $\mathrm{CP}^{\mu\tau}$, e.g., CP-anti $\mu\tau$ ($\mathrm{CP}^{\mu\tau A}$) [35], and complex scaling [52, 55] are capable of reproducing the observed value of η_B. This, however, requires the lightest RH neutrino mass to lie within the range 10^9 GeV $< M_1 < 10^{12}$ GeV — so called the two flavour regime (2FR) [71–74] of leptogenesis. For $\mathrm{CP}^{\mu\tau}$ as well as $\mathrm{CP}^{\mu\tau A}$, it has also been argued that the regimes $M_1 > 10^{12}$ GeV — one flavour regime (1FR) and $M_1 < 10^9$ GeV — three flavour regime (3FR) — are not favoured for successful leptogenesis due to the typical structure of the symmetry (we shall discuss it in detail in section 5). In the N_1DS, leptogenesis has been studied with a strong hierarchical scenario [22, 35, 69], e.g., $M_2/M_1 = 10^3$; i.e., assuming other heavy neutrinos are not produced at all, or if produced, the lepton asymmetry due to N_2 faces a significant washout by the N_1-interactions and thus is negligible, whereas that produced by N_1 does not encounter a N_2-washout. In addition, a lower bound on M_1 has been derived [22, 35] using the neutrino oscillation data and the observed range of η_B.

In this paper we investigate viability of those results in detail. After a systematic analysis, we argue the following:

(i) In the $\mathrm{CP}^{\mu\tau}$ framework, even in the two RH neutrino seesaw model [75, 76] which is tightly constrained by the neutrino oscillation data, one can choose the heavy RH neutrino mass hierarchy as low as $M_2/M_1 \simeq 4.7$ for a perfectly valid hierarchical $\mathrm{N_1DS}$ leptogenesis scenario. This in turn leads to a decrease in the lower bound on M_1, approximately by an order of magnitude.

JHEP01(2020)193

(ii) Allowing both the RH neutrinos to contribute to the final asymmetry and taking into account the heavy neutrino flavour effects, we show that in the two flavour regime, there is a particular RH neutrino mass window $M^{\rm max} > M_1 > M^{\rm min}$ for which the hierarchical $\rm N_1DS$ is valid. Beyond $M^{\rm max}$, domination of N_2 could also become significant in addition to N_1.

(iii) Finally, we demonstrate that if the lepton asymmetry is produced by N_2 in the two flavour regime and faces washout by N_1 in the three flavour regime, then the final asymmetry mainly survives in the electron flavour. This is because the N_1-decay parameters for the other two flavours ($K_{1\mu}$ and $K_{1\tau}$) are strong enough to erase any pre-existing asymmetry in the respective flavours. We quantify the probability of N_2 leptogenesis to be around 33%. This is done by computing the probability of the electron flavour washout parameter K_{1e} to be less than unity, since typically for these values of K_{1e}, the asymmetry generated by N_2 does not get washed out by N_1 [77–80].[1]

The rest of the paper is organized as follows: in section 2 we briefly discuss the $\rm CP^{\mu\tau}$ and its other variants. For simplicity we only focus on the two RH neutrino model, commonly known as the minimal seesaw. Section 3 contains a discussion about the validity of $\rm N_1DS$ in one flavour case which can trivially be generalized into multi flavoured leptogenesis scenario. In section 4, we emphasize on the importance of heavy neutrino flavour effects which open up the possibility for N_2 leptogenesis. Section 5 contains a thorough discussion of leptogenesis in the model under consideration. We conclude our work in section 6 emphasizing the main results of this work.

2 $\rm CP^{\mu\tau}$ symmetry and its variants in seesaw model

Before we proceed, we discuss some aspects of the $\rm CP^{\mu\tau}$ symmetry in neutrino mass models. Note that we work in a basis where the charged lepton mass matrix m_ℓ and the RH neutrino mass matrix M_R are diagonal [22, 69]. Thus, the neutrino mixing matrix U can be written as

$$U = P_\phi U_{PMNS} \equiv P_\phi \begin{pmatrix} c_{12}c_{13} & e^{i\frac{\alpha}{2}} s_{12}c_{13} & s_{13}e^{-i(\delta-\frac{\beta}{2})} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & e^{i\frac{\alpha}{2}}(c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta}) & c_{13}s_{23}e^{i\frac{\beta}{2}} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & e^{i\frac{\alpha}{2}}(-c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta}) & c_{13}c_{23}e^{i\frac{\beta}{2}} \end{pmatrix}, \tag{2.1}$$

where $P_\phi = {\rm diag}\ (e^{i\phi_1},\ e^{i\phi_2}\ e^{i\phi_3})$ is an unphysical diagonal phase matrix and $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$ with the mixing angles $\theta_{ij} = [0, \pi/2]$. CP violation enters in eq. (2.1) through the Dirac phase δ and the Majorana phases α and β. For simplicity, we focus on the two RH neutrino model [75, 76], commonly known as minimal seesaw model [81–84]. Thus with m_D as the Dirac mass matrix, the neutrino part of the Lagrangian can be written as

$$-\mathcal{L}^{\nu,N}_{\rm mass} = \bar{N}_{Ri}(m_D)_{i\alpha}\nu_{L\alpha} + \frac{1}{2}\bar{N}_{Ri}(M_R)_{ij}\delta_{ij}N^C_{Rj} + {\rm h.c.}\,, \tag{2.2}$$

[1]Following [63] we address $K_{1\alpha}$ as decay parameters throughout.

with $l_{L\alpha} = \left(\nu_{L\alpha}\ e_{L\alpha}\right)^T$ as the SM lepton doublet of flavor α and $M_R = \text{diag}\,(M_1, M_2)$, $M_{1,2} > 0$. The effective light neutrino mass matrix is given by the standard seesaw relation

$$M_\nu = -m_D^T M_R^{-1} m_D\,. \tag{2.3}$$

Now a CP transformation [43, 44] on the LH neutrino field, $\nu_{Ll} \to iG_{lm}\gamma^0\nu^C_{Lm}$, leads to the following invariance of the effective light neutrino mass matrix M_ν:

$$G^T M_\nu G = M_\nu^*\,, \tag{2.4}$$

where G is the generator matrix. If G follows a $\mu\tau$-interchange symmetry [20, 21], i.e.,

$$G = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \tag{2.5}$$

then the symmetry transformation in eq. (2.4) is known as a $\mu\tau$ flavoured CP transformation or CP$^{\mu\tau}$ [22]. A simple alteration of CP$^{\mu\tau}$ has recently been studied by one of the authors, by adding a minus sign to the right hand side of eq. (2.4).[2] This symmetry, named as the CP anti-$\mu\tau$ or CP$^{\mu\tau A}$ [35], could be recast as a symmetry transformation equation similar to eq. (2.4) as

$$\mathcal{G}^T M_\nu \mathcal{G} = M_\nu^*\,, \tag{2.6}$$

with $\mathcal{G} = iG$. Intriguingly, the $\mu\tau$ symmetry (G) and the $\mu\tau$ antisymmetry ($\mathcal{G}$) have completely different predictions when they are used as an ordinary field transformation, i.e., $\nu_{Ll} \to G_{lm}\nu_{Lm}$ or $\nu_{Ll} \to \mathcal{G}_{lm}\nu_{Lm}$ [85]. However in their CP-transformed versions, along with the diagonalization condition $U^T M_\nu U = M_d$, where $M_d = \text{diag}(m_1, m_2, m_3)$, both the symmetries (eq. (2.4) and eq. (2.6)) lead to the same predictions [22, 35]

$$\cos\delta = \sin\alpha = \sin\beta = 0\,, \qquad \theta_{23} = \pi/4\,. \tag{2.7}$$

This is easy to understand. Consider a mass matrix M_ν, which follows eq. (2.6). This can be written in the form

$$M_\nu^{CP^{\mu\tau A}} = \begin{pmatrix} iA & B & -B^* \\ B & C & iD \\ -B^* & iD & -C^* \end{pmatrix}, \tag{2.8}$$

where A, D are real and B, C are complex mass dimensional quantities which are a priori unknown. Now mass matrix in eq. (2.8) also satisfies the equation

$$G^T(iM_\nu^{CP^{\mu\tau A}})G = (iM_\nu^{CP^{\mu\tau A}})^*\,, \tag{2.9}$$

which is basically a CP$^{\mu\tau}$ transformation (eq. (2.4)). Thus, if a mass matrix follows CP$^{\mu\tau A}$ invariance, 'i' times the same matrix also obeys CP$^{\mu\tau}$ symmetry, and hence both the symmetries lead to similar phenomenological consequences. Henceforth, without lack of

[2] Note that the high energy symmetry could be very different than CP$^{\mu\tau}$, as pointed out in [35].

JHEP01(2020)193

generality, we shall consider the CP-antisymmetric parametrization of m_D as well as M_ν derived in [35].

For a diagonal M_R, eq. (2.6) is satisfied through the symmetry transformation on m_D as[3]

$$m_D \mathcal{G} = -i m_D^* \,. \tag{2.10}$$

The most general form of m_D that satisfies (2.10) can be parametrized as

$$m_D = \begin{pmatrix} \sqrt{2} a_1 e^{i\pi/4} & b_1 e^{i\theta_1} & i b_1 e^{-i\theta_1} \\ \sqrt{2} a_2 e^{i\pi/4} & b_2 e^{i\theta_2} & i b_2 e^{-i\theta_2} \end{pmatrix} , \tag{2.11}$$

where the parameters $a_{1,2}$, $b_{1,2}$ and $\theta_{1,2}$ are real. Now using eq. (2.3), the effective light neutrino mass matrix M_ν can be written as

$$M_\nu^{CP^{\mu\tau A}} = \begin{pmatrix} -2i(x_1^2+x_2^2) & -\sqrt{2}e^{i\pi/4}(x_1y_1e^{i\theta_1}+x_2y_2e^{i\theta_2}) & -i\sqrt{2}e^{i\pi/4}(x_1y_1e^{-i\theta_1}+x_2y_2e^{-i\theta_2}) \\ -\sqrt{2}e^{i\pi/4}(x_1y_1e^{i\theta_1}+x_2y_2e^{i\theta_2}) & -(e^{2i\theta_1}y_1^2+e^{2i\theta_2}y_2^2) & -i(y_1^2+y_2^2) \\ -i\sqrt{2}e^{i\pi/4}(x_1y_1e^{-i\theta_1}+x_2y_2e^{-i\theta_2}) & -i(y_1^2+y_2^2) & e^{-2i\theta_1}y_1^2+e^{-2i\theta_2}y_2^2 \end{pmatrix} . \tag{2.12}$$

In (2.12), new real parameters $x_{1,2}$ and $y_{1,2}$ are defined by scaling $a_{1,2}$ and $b_{1,2}$ with the square roots of the respective RH neutrino masses $M_{1,2}$, i.e.

$$\frac{a_{1,2}}{\sqrt{M_{1,2}}} = x_{1,2} \,, \quad \frac{b_{1,2}}{\sqrt{M_{1,2}}} = y_{1,2} \,. \tag{2.13}$$

A few comments on the matrix $M_\nu^{CP^{\mu\tau A}}$ are in order. Since det $(M_\nu^{CP^{\mu\tau A}}) = 0$, the lightest neutrino mass (either m_1 for a normal mass ordering or m_3 for an inverted mass ordering) has to vanish. Furthermore, one of the phases in $M_\nu^{CP^{\mu\tau A}}$ (say θ_1) could be rotated with the phase matrix $P_\phi = \text{diag}\,(1, e^{i\phi}, e^{-i\phi})$ by the choice $\theta_1 = -\phi$. Therefore, we are left only with the phase difference $\theta_2 - \theta_1$, which can be renamed as θ. Without loss of generality, this is equivalent to the choice $\theta_1 = 0$ and $\theta_2 = \theta$ in m_D. For phenomenological analysis, we use this redefined phase θ for both $M_\nu^{CP^{\mu\tau A}}$ as well as m_D.

3 Validity of N$_1$DS in one flavour thermal leptogenesis

In this section, we start by discussing the standard N_1 dominated leptogenesis (N$_1$DS) scenario in the presence of another heavy neutrino N_2, assuming both of them are thermally produced [86–89] so that the reheating temperature $T_{\text{RH}} > M_{1,2}$. To begin with, we focus on the one-flavour scenario (i.e., no charged lepton flavour effects). The overall conclusions drawn from one flavour approximation can easily be generalized in the presence

[3] We shall refer the reader refs. [22, 55, 69] to have a look to realize how in the diagonal basis of m_ℓ and M_R, CP symmetry could be applied in the neutrino mass terms.

of flavour effects, as we discuss later. The set of classical kinetic equations [63] relevant for leptogenesis could be written as

$$\frac{dN_{N_i}}{dz} = -D_i(N_{N_i} - N_{N_i}^{\rm eq}), \quad \text{with } i = 1, 2\,, \tag{3.1}$$

$$\frac{dN_{B-L}}{dz} = -\sum_{i=1}^{2} \varepsilon_i D_i(N_{N_i} - N_{N_i}^{\rm eq}) - \sum_{i=1}^{2} W_i N_{B-L}\,, \tag{3.2}$$

with $z = M_1/T$. The N_i's and N_{B-L} are the abundances per N_1's in ultra relativistic thermal equilibrium. The equilibrium abundances of N_i's are given by $N_i^{\rm eq} = \frac{1}{2} z_i^2 \mathcal{K}_2(z_i)$, where $\mathcal{K}_2(z_i)$ are the modified Bessel functions. The total CP asymmetry is quantified by $\varepsilon_i = \sum_\alpha \varepsilon_{i\alpha}$ where

$$\varepsilon_{i\alpha} = \frac{\Gamma_{i\alpha} - \bar{\Gamma}_{i\alpha}}{\Gamma_i + \bar{\Gamma}_i}. \tag{3.3}$$

The flavoured CP asymmetry parameter $\varepsilon_{i\alpha}$ can be estimated as

$$\begin{aligned}\varepsilon_{i\alpha} = {}& \frac{1}{4\pi v^2 h_{ii}} \sum_{j\neq i} \mathrm{Im}\{h_{ij}(m_D)_{i\alpha}(m_D^*)_{j\alpha}\}\left[f(x_{ij}) + \frac{\sqrt{x_{ij}}(1-x_{ij})}{(1-x_{ij})^2 + h_{jj}^2(16\pi^2 v^4)^{-1}}\right] \\ & + \frac{1}{4\pi v^2 h_{ii}} \sum_{j\neq i} \frac{(1-x_{ij})\mathrm{Im}\{h_{ji}(m_D)_{i\alpha}(m_D^*)_{j\alpha}\}}{(1-x_{ij})^2 + h_{jj}^2(16\pi^2 v^4)^{-1}},\end{aligned} \tag{3.4}$$

where $h_{ij} \equiv (m_D m_D^\dagger)_{ij}$, $\langle\phi^0\rangle = v/\sqrt{2}$, $x_{ij} = M_j^2/M_i^2$ and $f(x_{ij})$ has the standard expression [35]. The decay parameter is given by

$$K_i \equiv \frac{\Gamma_{D,i}(T=0)}{H(T=M_i)}\,, \tag{3.5}$$

where $H(T = M_i)$ is the Hubble paramter defined at the temperature $T = M_i$). Using $z_i = z\sqrt{x_{1i}}\,$, the decay terms can be written as

$$D_i = \frac{\Gamma_{D,i}}{Hz} = K_i x_{1i} z \langle 1/\gamma_i\rangle\,, \tag{3.6}$$

where the total decay rates $\Gamma_{D,i} = \bar{\Gamma}_i + \Gamma_i = \Gamma_{D,i}(T = 0)\langle 1/\gamma_i\rangle$ with $\langle 1/\gamma_i\rangle$'s as the thermally averaged dilution factors given by the ratios of two modified Bessel functions

$$\langle 1/\gamma_i\rangle = \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)}\,. \tag{3.7}$$

The washout factor W_i typically contains three terms: the inverse decay term $W_i^{\rm ID}$, the $\Delta L = 1$ scattering term $W_i^{\Delta L=1}$, and the nonresonant part of the $\Delta L = 2$ term $W_i^{\Delta L=2}$. For a strong washout scenario[4] and hierarchical light neutrino masses, the scattering terms and the $\Delta L = 2$ terms can be safely neglected [64, 90, 91]. Thus, the relevant washout term $W_i \simeq W_i^{\rm ID}$ can be written as (after properly subtracting the real intermediate state contribution of $\Delta L = 2$ process [61])

$$W_i^{\rm ID} = \frac{1}{4} K_i \sqrt{x_{1i}} \mathcal{K}_1(z_i) z_i^3\,. \tag{3.8}$$

[4]We show later that a strong wash-out scenario is preferred in the model under consideration.

The final $B-L$ asymmetry could be written as

$$N^f_{B-L} = N^{\rm in}_{B-L} e^{-\sum_i \int dz' W_i(z')} + N^{\rm lepto}_{B-L}\,, \tag{3.9}$$

where $N^{\rm in}_{B-L}$ could be a possible pre-existing asymmetry [92, 93] at an initial temperature $T_{\rm in}$. However in this work, we do not consider any possible pre-existing asymmetry which would impose additional constraints[5] on the model parameter space [86, 94]. In fact, as we shall discuss, given the RH neutrino masses in our model, $10^9{\rm GeV} < M_1, M_2 < 10^{12}{\rm GeV}{-}2{\rm FR}$, it is not possible to washout a pre-existing asymmetry which is orthogonal to the direction of N_1-washout [83, 95]. Thus, the scenario of a pure leptogenesis from RH neutrino decay breaks down. Assuming standard thermal history of the universe, the final baryon-to-photon ratio can be written as

$$\eta_B = a_{\rm sph}\frac{N^{\rm lepto}_{B-L}}{N^{\rm rec}_\gamma} \simeq 0.96\times 10^{-2} N^{\rm lepto}_{B-L}\,, \tag{3.10}$$

where $N^{\rm rec}_\gamma$ is the normalised photon density at the recombination and the sphaleron conversion coefficient $a_{\rm sph}\sim 1/3$. This theoretically calculated value of η_B has to be compared with measured value given in eq. (1.1).

Before discussing validity of the N_1DS in presence of $N_{i(i\neq 1)}$, let us introduce another important parameter $\delta_{1i} = (M_i - M_1)/M_1$ which accounts for the mass difference between M_i and M_1. This is related to x_{1i} as

$$\sqrt{x_{1i}} = 1 + \delta_{1i} \Rightarrow z_i = z(1+\delta_{1i})\,. \tag{3.11}$$

Armed with all the necessary prerequisites, we solve eqs. (3.1), and (3.2) for N_1 in the presence of washouts due to both N_1 and N_2. Note that for the fixed values of z and K_2, the strength of the N_2-washout ($W_2^{\rm ID}$) depends on δ_{21} (cf. eq. (3.8)). As a result, solutions of eq. (3.2) for different values of δ_{12} indicates a minimum, below which the effect of $W_2^{\rm ID}$ starts to become prominent. This helps to reproduce the standard hierarchical N_1 dominated scenario.

In figure 1, we show the variation of the produced asymmetry, $|N_{B-L}|$, with z. In each figure, N_{B-L} lines in red and blue correspond to the asymmetry produced by N_1 subjected to N_1, and N_1+N_2 washout respectively. The asymmetry showed in black is that produced by N_2 subjected to N_1+N_2 washout. Figures in the top and bottom panel are for $K_1 = K_2 = 25$ and $K_1 = K_2 = 5$ respectively.

It is clear from the top-left panel that for $\delta_{12} = 1$, even if one takes into account the N_2 washout alongwith the N_1 washout, the final asymmetry perfectly coincide with standard N_1DS. This is simply because the N_2 washout goes out of equilibrium before the asymmetry production due to N_1 stops. Thus, the final dynamics is governed by the inverse decays of N_1 (i.e., N_1 washout). On the other hand, the asymmetry produced

[5] By "pre-existing asymmetry" we mean asymmetries that may originate not only from heavier RH neutrinos but also from other external sources. These asymmetries may be large in magnitude. Therefore one needs several conditions on the flavoured decay parameters to washout the pre-existing asymmetry. In literature, somtimes these conditions are referred to as "strong thermal conditions". See e.g., refs. [96, 97].

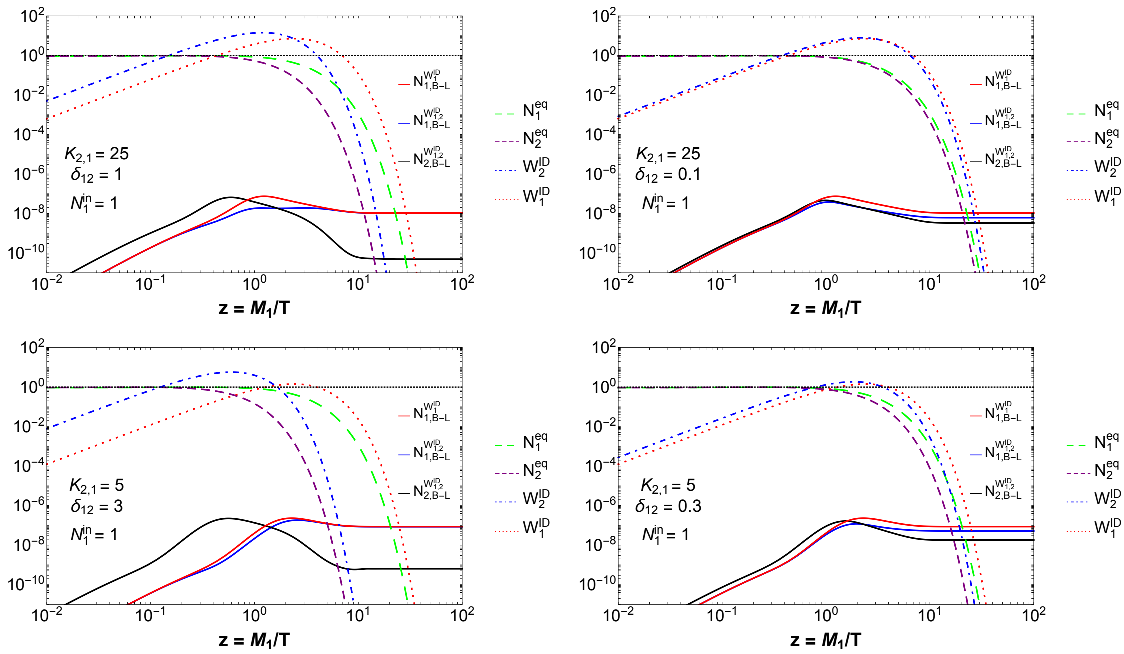


Figure 1. Top left: $|N_{B-L}|$ as a function of $z = M_1/T$ for the decay parameters $K_1 = K_2 = 25$ (the other relevant quantities, e.g., $N_1^{\rm eq}$, $W_1^{\rm ID}$ etc., are mentioned on the right side of each figure). Solid red line shows $|N_{B-L}|$ for a pure N_1 dominated scenario. The solid blue line shows the asymmetry generated by N_1, for $\delta_{12} = 1$, subjected to both N_1 and N_2 washout, given by $W_{1,2}^{\rm ID}$ respectively. The solid black line shows N_{B-L}, generated by N_2 subjected to $W_{1,2}^{\rm ID}$ washout. Top right: for the same value of the decay parameters we generate similar plots for $\delta_{12} = 0.1$. Bottom panel shows similar plots as those in the top panel for $\delta_{12} = 3$ (left) and $\delta_{12} = 0.3$ (right), for $K_1 = K_2 = 5$.

by N_2 is significantly washed out by N_1 (showed in black). This is due to the fact that when the strength of the N_1 inverse decay reaches its maximum value, the asymmetry production due to N_2 is practically switched off. On the top-right panel, we show the same quantities, but for $\delta_{12} = 0.1$. Note that in this case, there is a clear distinction between a pure N_1 dominated scenario, and that where N_2 washout is also taken into account. Here, the N_2 washout of the asymmetry production due to N_1 cannot be ignored, and hence, the magnitude of N_{B-L} reduces. Furthermore, the N_1 inverse decay cannot fully washout the asymmetry produced by N_2, since even when the N_1 washout is significant, asymmetry production due to N_2 does not cease. This causes a significant increase in the magnitude of the asymmetry produced by N_2. The bottom panel shows the same plots for $K_1 = K_2 = 5$. In this case, however, pure N_1DS is realised with slightly increased value of $\delta_{12} = 3$, as opposed to $\delta_{12} = 1$. For completeness, we also show the plots with $\delta_{12} = 0.3$ for which one cannot assume a pure N_1DS due to the crucial role played by N_2.

This begs the following question: what is the minimum hierarchy in the RH neutrino masses so that a pure hierarchical N_1DS is realized? For example, as discussed, if some model predicts a simple correlation between the decay parameters, say, $K_1 = K_2 \in (5-25)$, one can safely assume $\sqrt{x_{12}} = M_2/M_1 = (1 + \delta_{12}) = 4$, so that the effect of N_2 washout at N_1-leptogenesis phase, as well as the asymmetry produced by N_2, can be neglected.

However, for a realistic scenario, the correlation of the decay parameters may not be this simple; also, a realistic model might contain lots of data points constrained by neutrino oscillation data. Thus in terms of computation, it would be tedious to solve Boltzmann equations for each and every pair of decay parameters. It is useful then to consider explicit and accurate analytic formalism for the computation of these parameters [63, 64, 71]. To this end, we use the analytic formulae outlined in [63]. We first do a consistency check of the results that we discussed after solving the Boltzmann equations with those obtained by the analytic formulae. Then we briefly discuss the overall implementation procedure of the analytic solutions that will be followed in the context of the concerned model.

Solutions to eq. (3.1) and (3.2) can be written as [60]

$$N_{B-L}^{\text{lepto}} = -\sum_{i}^{2} \varepsilon_i \kappa_i \,, \tag{3.12}$$

where κ_i is the efficiency of the asymmetry production due to the i^{th} RH neutrino and is given by

$$\kappa_i(z) = -\int_{z_{\text{in}}\to 0}^{z_{\text{fin}}\to\infty} \frac{dN_{N_i}}{dz'} e^{-\sum_i \int_{z'}^{z} W_i^{\text{ID}}(z'')dz''} dz' \,. \tag{3.13}$$

For a strong washout regime, $\frac{dN_{N_i}}{dz'} \simeq \frac{dN_{N_i}^{\text{eq}}}{dz'}$, since the Yukawa couplings are strong enough to let any species of N_i reach the equilibrium density, even if one starts from vanishing thermal abundance. One has to compare the $\kappa_i(z\to\infty)$, obtained by solving eq. (3.13) numerically, with the efficiency factor κ_i^{∞}, obtained for a pure N_1 or N_2 dominated scenario, calculated at $z\to\infty$ and for thermal initial abundances of the RH neutrinos [63],[6]

$$\kappa_1^{\infty} = \frac{2}{K_1 z_B(K_1)}\left(1 - e^{-\frac{K_1 z_B(K_1)}{2}}\right), \tag{3.14}$$

$$\begin{aligned} \kappa_2^{\infty} &= \frac{2}{K_2 z_B(K_2)}\left(1 - e^{-\frac{K_2 z_B(K_2)}{2}}\right) e^{-\int_0^{\infty} W_1^{\text{ID}}(z)dz}\,, \\ &= \frac{2}{K_2 z_B(K_2)}\left(1 - e^{-\frac{K_2 z_B(K_2)}{2}}\right) e^{-3\pi K_1/8}\,, \end{aligned} \tag{3.15}$$

where

$$z_B(K_i) = 2 + 4K_i^{0.13} e^{-\frac{2.5}{K_i}} \,. \tag{3.16}$$

To arrive at the exponential washout of κ_2^{∞} by N_1, we use

$$\int_0^{\infty} z^{\alpha-1}\mathcal{K}_n(z)dz = 2^{\alpha-2}\Gamma\left(\frac{\alpha-n}{2}\right)\Gamma\left(\frac{\alpha+n}{2}\right) \,. \tag{3.17}$$

In figure 2, we show the comparison between κ_1 and κ_1^{∞} for two different values of $K_{1,2} \in (15, 25)$. We find that for $K_{1,2} = 25$, there is an excellent match between κ_1 and κ_1^{∞} for $\delta_{12} \geq 1$, which is consistent with the conclusions drawn in figure 1 (top-left). However, as expected, when one considers a lower value for K_1, say $K_1 = 15$, it is no longer safe to use $\delta_{12} = 1$ for a hierarchical N_1DS.

[6] In any case, for strong washout regime, final asymmetry does not depend upon initial conditions, e.g., see [63, 64].

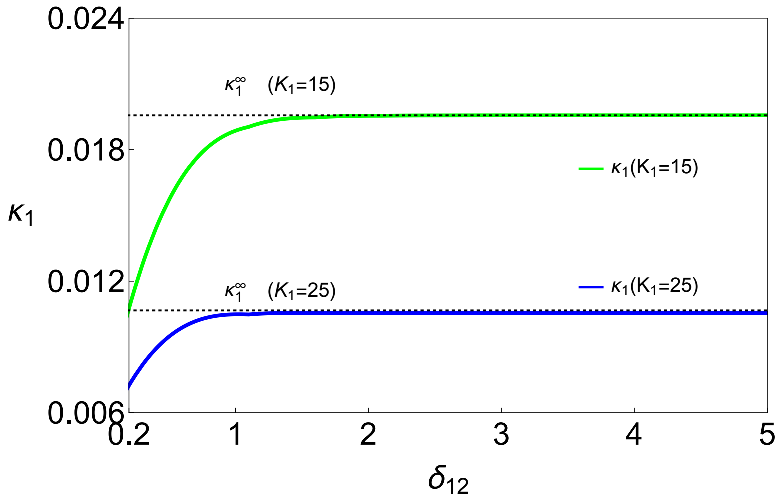


Figure 2. Efficiency factor with δ_{12} for two different values of K_1 with a fixed value of $K_2 = 25$.

It is also useful to have an expression for the efficiency factor for a strong washout scenario and any value of δ_{12}. In this context, one can use [98]

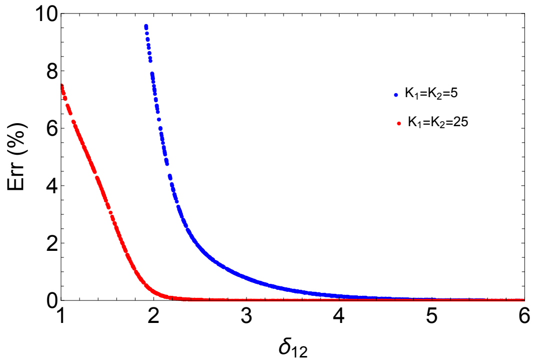
$$\kappa_1^{\rm fit} = \frac{2K_1}{z_B \left(K_1 + K_2^{(1-\delta_{12})^3}\right)\left(K_1 + K_2^{1-\delta_{12}}\right)}\,, \tag{3.18}$$

to scan the model, and estimate the minimum hierarchy of the RH neutrino masses for which $\kappa_1^{\rm fit} \to \kappa_1^\infty$. To quantify the goodness of this estimate, one can define an error function given by

$$\text{Err} = \left|\frac{\kappa_1^{\rm fit} - \kappa_1^\infty}{\kappa_1^\infty}\right| \times 100\%\,. \tag{3.19}$$

In figure 3 (left panel), we show the error function for the two discussed cases, $\delta_{12} = 1$ and $\delta_{12} = 3$. It is obvious from this figure, that for the values of $\delta_{12} = 1$ and $\delta_{12} = 3$ chosen in figure 1, the scope of error is always less that $\mathcal{O}(10\%)$. In right panel of figure 3, we show the comparison between $\kappa_1^{\rm fit}$ and κ_1^∞ for the given values of δ_{12} in the strong washout regime. Clearly, if $\delta_{12} = 0.3$ (blue dashed line), one needs larger values for the decay parameter K_1 to circumvent the washout effect by N_2. Therefore, eq. (3.18) is also a reasonably good analytic approximation that can be used in the computation.

Thus, given the ranges of K_1 and K_2, one can do a random scanning over δ_{12} for each pair of $K_{1,2}$ to compare $\kappa_1(z)$ of eq. (3.13) or $\kappa_1^{\rm fit}$ of eq. (3.18) to κ_1^∞ upto desired accuracy, and extract the minimum values of δ_{12} needed to probe a perfectly valid hierarchical N_1DS. We shall show in the next section that lowering the value of δ_{12} has two major consequences. Firstly, for low values of δ_{12}, one enhances the CP asymmetry parameter, which in turn increases the magnitude of the asymmetry due to an enhancement in the loop functions (particularly in the self energy contribution [61]). Secondly, when flavour effects are accounted for, the contribution from N_2 [78, 95] to the final asymmetry plays an important role in a successful leptogenesis. Thus, given a particular flavour regime,



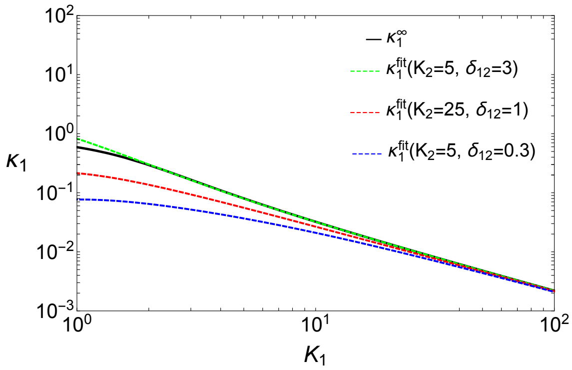


Figure 3. Left: possible error due to $\kappa_1^{\rm fit}$ as the efficiency factor in a hierarchical scenario, as a function of δ_{12}. Right: comparision of $\kappa_1^{\rm fit}$ to κ_1^∞ for different values of δ_{12} and K_2.

lowering the value of δ_{12} enables us to extract information regarding N_2-leptogenesis over a wide range of RH neutrino mass scale.

4 Flavour effects and importance of N_2-leptogenesis

The one flavour regime (1FR) is typically characterised by $M_i > 10^{12}\,\text{GeV}$ where all the charged lepton flavours are out of equilibrium, and thus the lepton doublet $|\ell_i\rangle$ produced by the decay of the RH neutrinos can be written as a coherent superposition of the corresponding flavour states $|\ell_\alpha\rangle$ as,

$$|\ell_i\rangle = \mathcal{A}_{i\alpha}\,|\ell_\alpha\rangle \qquad (i=1,2,3;\alpha=e,\mu,\tau) \tag{4.1}$$

$$|\bar\ell_i\rangle = \bar{\mathcal{A}}_{i\alpha}\,|\bar\ell_\alpha\rangle \qquad (i=1,2,3;\alpha=e,\mu,\tau)\,, \tag{4.2}$$

where the amplitudes are given by

$$\mathcal{A}^0_{i\alpha} = \frac{m_{D_{i\alpha}}}{\sqrt{(m_D m_D^\dagger)_{ii}}} \qquad \text{and} \qquad \bar{\mathcal{A}}^0_{i\alpha} = \frac{m^*_{D_{i\alpha}}}{\sqrt{(m_D m_D^\dagger)_{ii}}}. \tag{4.3}$$

Since there is hardly any interaction to break the coherence of the quantum states before it inversely decays to N_1, the asymmetry will be produced along the direction of $|\ell_i\rangle$(or $|\bar\ell_i\rangle$) in the flavour space. However, this is not the case if $M_i < 10^{12}\,\text{GeV}$, since below this scale, flavour effects become important. We give a brief overview of the flavour effects at play during leptogenesis in this section.

The flavour effects are taken into account by defining the branching ratios into individual flavours as $P_{i\alpha} = |\mathcal{A}_{i\alpha}|^2$ and $\bar P_{i\alpha} = |\bar{\mathcal{A}}_{i\alpha}|^2$. As a result, the decays into individual flavours could be written as $\Gamma_{i\alpha} \equiv P_{i\alpha}\,\Gamma_i$ and $\bar\Gamma_{i\alpha} \equiv \bar P_{i\alpha}\bar\Gamma_i$ with $\sum_\alpha (P_{i\alpha}, \bar P_{i\alpha}) = 1$. It is also convenient to introduce the flavoured decay parameter $K_{i\alpha}$ given by

$$K_{i\alpha} = \frac{\Gamma_{i\alpha}+\bar\Gamma_{i\alpha}}{H(T=M_i)} \simeq \frac{P^0_{i\alpha}(\Gamma_i+\bar\Gamma_i)}{H(T=M_i)} \equiv P^0_{i\alpha} K_i \equiv \frac{|m_{D_{i\alpha}}|^2}{M_i m^*}, \tag{4.4}$$

where $m^* \simeq 10^{-3}\,\text{eV}$ is the equilibrium neutrino mass. These flavoured probabilities can be re-written as

$$P_{i\alpha} = P^0_{i\alpha} + \frac{\Delta P_{i\alpha}}{2}\,, \tag{4.5}$$

$$\bar{P}_{i\alpha} = P^0_{i\alpha} - \frac{\Delta P_{i\alpha}}{2}\,, \tag{4.6}$$

where

$$P^0_{i\alpha} = \frac{1}{2}\left(P_{i\alpha} + \bar{P}_{i\alpha}\right)\,, \tag{4.7}$$

$$\Delta P_{i\alpha} = P_{i\alpha} - \bar{P}_{i\alpha} \tag{4.8}$$

are the tree level projectors. Here $\Delta P_{i\alpha}$, the difference between the tree level and the loop level projectors, arises from the fact that $\mathcal{A}_{i\alpha} \neq \bar{\mathcal{A}}_{i\alpha}$ [64], except at tree level. This allows us to define the flavoured CP asymmetry parameter $\varepsilon_{i\alpha}$ (see eq. (3.3)) as

$$\varepsilon_{i\alpha} = P^0_{i\alpha}\varepsilon_i + \Delta P_{i\alpha}/2\,. \tag{4.9}$$

Thus, due to the incorporation of flavour effects, an extra amount of CP violation, characterised by $\Delta P_{i\alpha}$, is generated. Note that in eq. (4.9) one can have CP violation in each flavour even if the total CP asymmetry is vanishing [99]. Typically, the effect of $\Delta P_{i\alpha}$ can be neglected in the washout terms, however, this is not the case for $\varepsilon_{i\alpha}$.

In the regime $10^9\,\text{GeV} < M_i < 10^{12}\,\text{GeV}$, the τ flavored lepton comes into equilibrium, thereby breaking the coherent evolution of $|\ell_i\rangle$ before it inverse decays to N_i. As a result, $|\ell_i\rangle$ is projected onto a two flavour basis, characterised by the eigenstates along the directions of τ, and perpendicular to it ($\tau_i^\perp$), which is essentially a coherent superposition of the μ and the e flavour. In the three flavour regime, i.e. all $M_i < 10^9\,\text{GeV}$, the μ lepton also comes into equilibrium, thus breaking the coherent evolution of the states along $\tau_i^\perp$. This allows for the individual resolution of all the flavours. Thus, calculating the asymmetry produced requires tracking the lepton asymmetry in the relevant flavours.

For example, in the 2FR, the lepton asymmetry has to be tracked in τ and $\tau_i^\perp$. The Boltzmann equations can be written as

$$\frac{dN_{N_i}}{dz} = -D_i(N_{N_i} - N^{\text{eq}}_{N_i}),\ \text{with } i = 1,2. \tag{4.10}$$

$$\frac{dN_{\Delta_\alpha}}{dz} = -\sum_{i=1}^{2}\varepsilon_{i\alpha}D_i(N_{N_i} - N^{\text{eq}}_{N_i}) - \sum_{i=1}^{2}P^0_{i\alpha}W^{\text{ID}}_i N_{\Delta_\alpha}\,. \tag{4.11}$$

The asymmetry in the flavour α is given by

$$N_{\Delta_\alpha} = -\sum_{i}^{2}\varepsilon_{i\alpha}\kappa_{i\alpha}\,, \tag{4.12}$$

with the efficiency factor

$$\kappa_{i\alpha}(z) = -\int_{z_{\text{in}}}^{\infty}\frac{dN_{N_i}}{dz'}e^{-\sum_j\int_{z'}^{z}P^0_{j\alpha}W^{\text{ID}}_j(z'')dz''}dz'\,. \tag{4.13}$$

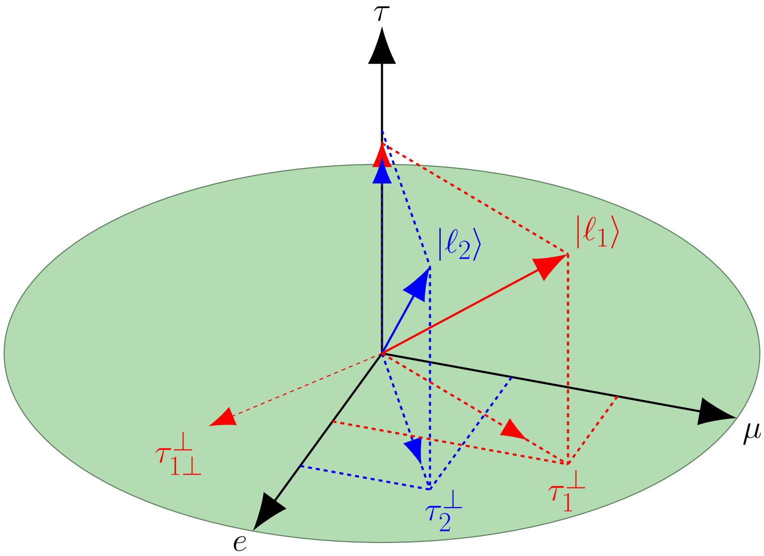


Figure 4. Ilustration of the two flavour regime for two RH neutrino model.

With this definition, the final baryon to photon ratio is

$$\eta_B = 0.96 \times 10^{-2} \sum_{\alpha} N_{\Delta_\alpha} \,. \tag{4.14}$$

In the hierarchical limit of the RH neutrino masses, eq. (4.12) can be simplified as

$$N_{\Delta_\alpha} = -\varepsilon_{1\alpha}\kappa_{1\alpha}^{\infty} - \varepsilon_{2\alpha}\kappa_{2\alpha}^{\infty} e^{-3\pi K_{1\alpha}/8} \,, \tag{4.15}$$

where the first term is the asymmetry generated by N_1, and the second term is the asymmetry generated by N_2, subjected to N_1-washout. However, there are two important issues, which are usually overlooked in the leptogenesis studies of models with flavour symmetries.

(i) A pure N_1-leptogenesis scenario which is studied in most of the neutrino mass models, requires large values of the N_1 decay parameter $K_{1\alpha}$ to washout the contribution from N_2. Thus given a neutrino mass model constrained by 3σ oscillation data, one has to check the strength of $K_{1\alpha}$ so that the second term of eq. (4.15) can be neglected.

(ii) Most importantly, if the masses of both the RH neutrinos are in the 2FR, i.e., 10^9 GeV $< M_i < 10^{12}$ GeV, after the τ-interactions of both the states $|\ell_1\rangle$ and $|\ell_2\rangle$, the resultant states orthogonal to the τ flavour will not be in the same direction on the $e-\mu$ plane. This is demonstrated in figure 4, where the new directions are denoted by $\tau_1^{\perp}$ and $\tau_2^{\perp}$ respectively. This is simply due the fact that, in general $\mathcal{A}_{1\alpha} \neq \mathcal{A}_{2\alpha}$, and hence, there is no reason for the states to maintain a common direction.

Henceforth, we denote the $\tau_i^{\perp}$ states as $|\ell_1^{\tau^\perp}\rangle$ and $|\ell_2^{\tau^\perp}\rangle$, which are given by

$$|\ell_1^{\tau^\perp}\rangle = \frac{\mathcal{A}_{1e}}{\sqrt{|\mathcal{A}_{1e}|^2 + |\mathcal{A}_{1\mu}|^2}}\,|\ell_e\rangle + \frac{\mathcal{A}_{1\mu}}{\sqrt{|\mathcal{A}_{1e}|^2 + |\mathcal{A}_{1\mu}|^2}}\,|\ell_\mu\rangle \,, \tag{4.16}$$

$$|\ell_2^{\tau^\perp}\rangle = \frac{\mathcal{A}_{2e}}{\sqrt{|\mathcal{A}_{2e}|^2 + |\mathcal{A}_{2\mu}|^2}}\,|\ell_e\rangle + \frac{\mathcal{A}_{2\mu}}{\sqrt{|\mathcal{A}_{2e}|^2 + |\mathcal{A}_{2\mu}|^2}}\,|\ell_\mu\rangle \,. \tag{4.17}$$

In order to guess how much asymmetry generated by N_2 along $\tau_2^\perp$ can be washed out by the interactions between the Higgs and the component of $|\ell_2^{\tau^\perp}\rangle$ along $|\ell_1^{\tau^\perp}\rangle$ (N_1 inverse decay), one has to calculate the probability of $|\ell_2^{\tau^\perp}\rangle$ being in the $|\ell_1^{\tau^\perp}\rangle$ state. Note that for the N_1 inverse decay, only $\left(\langle\ell_1^{\tau^\perp}|\ell_2^{\tau^\perp}\rangle\right)|\ell_1^{\tau^\perp}\rangle$ will interact with the Higgs, whereas $\left(\langle\ell_{1\perp}^{\tau^\perp}|\ell_2^{\tau^\perp}\rangle\right)|\ell_{1\perp}^{\tau^\perp}\rangle$, which is perpendicular to $|\ell_1^{\tau^\perp}\rangle$, will be blind to it. Thus, the asymmetry in the direction of $|\ell_{1\perp}^{\tau^\perp}\rangle$ will escape the N_1 washout and survive as a pure contribution from N_2.

The overlap probability p_{12} can be calculated as

$$p_{12} \equiv |\langle\ell_1^{\tau^\perp}|\ell_2^{\tau^\perp}\rangle|^2 = \frac{K_1 K_2}{K_{1\tau^\perp}K_{2\tau^\perp}}\frac{|(m_D^*)_{1e}(m_D)_{2e} + (m_D^*)_{1\mu}(m_D)_{2\mu}|^2}{h_{11}h_{22}}\,, \tag{4.18}$$

where $h_{ii} = (m_D m_D^\dagger)_{ii}$.

With this understanding, the r.h.s. of eq. (4.15) can be split into three parts

$$N_{\Delta_\tau} = -\varepsilon_{1\tau}\kappa_{1\tau}^\infty - \varepsilon_{2\tau}\kappa_{2\tau}^\infty e^{-3\pi K_{1\tau}/8}, \tag{4.19}$$

$$N_{\Delta_{\tau_1^\perp}} = -\varepsilon_{1\tau^\perp}\kappa_{1\tau^\perp}^\infty - p_{12}\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^\infty e^{-3\pi K_{1\tau^\perp}/8}, \tag{4.20}$$

$$N_{\Delta_{\tau_{1\perp}^\perp}} = -(1-p_{12})\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^\infty\,, \tag{4.21}$$

where the final $B-L$ asymmetry is given by

$$N_{B-L}^f = N_{\Delta_\tau} + N_{\Delta_{\tau_1^\perp}} + N_{\Delta_{\tau_{1\perp}^\perp}}\,. \tag{4.22}$$

Note that in a situation where a strong washout by the N_1 inverse decay prevails, the second term in eq. (4.19) and (4.20) can be dropped. Hence, the $p_{12} \to 1$ would imply a pure N_1-leptogenesis. In the literature, along with a strong N_1-washout, it is usually assumed that $p_{12} = 1$, which is not true in general.

Another interesting situation arises when M_2 is in the two flavour regime and M_1 is in the three flavour regime. In this case, the produced asymmetry by N_2 in two flavour regime will be washed out by N_1 in the three flavour regime. Therefore, at the end of N_1-washout, we need to track the final asymmetry in individual flavours (e,μ,τ). Thus, the asymmetry in each flavour can be written as

$$N_{\Delta_\tau} = -\varepsilon_{1\tau}\kappa_{1\tau}^\infty - \varepsilon_{2\tau}\kappa_{2\tau}^\infty e^{-3\pi K_{1\tau}/8}, \tag{4.23}$$

$$N_{\Delta_\mu} = -\varepsilon_{1\mu}\kappa_{1\mu}^\infty - \frac{K_{2\mu}}{K_{2\tau^\perp}}\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^\infty e^{-3\pi K_{1\mu}/8}, \tag{4.24}$$

$$N_{\Delta_e} = -\varepsilon_{1e}\kappa_{1e}^\infty - \frac{K_{2e}}{K_{2\tau^\perp}}\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^\infty e^{-3\pi K_{1e}/8}, \tag{4.25}$$

where the final $B-L$ asymmetry now is given by

$$N_{B-L} = \sum_\alpha N_{\Delta_\alpha} \qquad (\alpha = e,\mu,\tau)\,. \tag{4.26}$$

Note that in eq. (4.23)–(4.25), the first term is the contribution to the final asymmetry from N_1 which produces the lepton asymmetry in 3FR, where one can distinguish each of

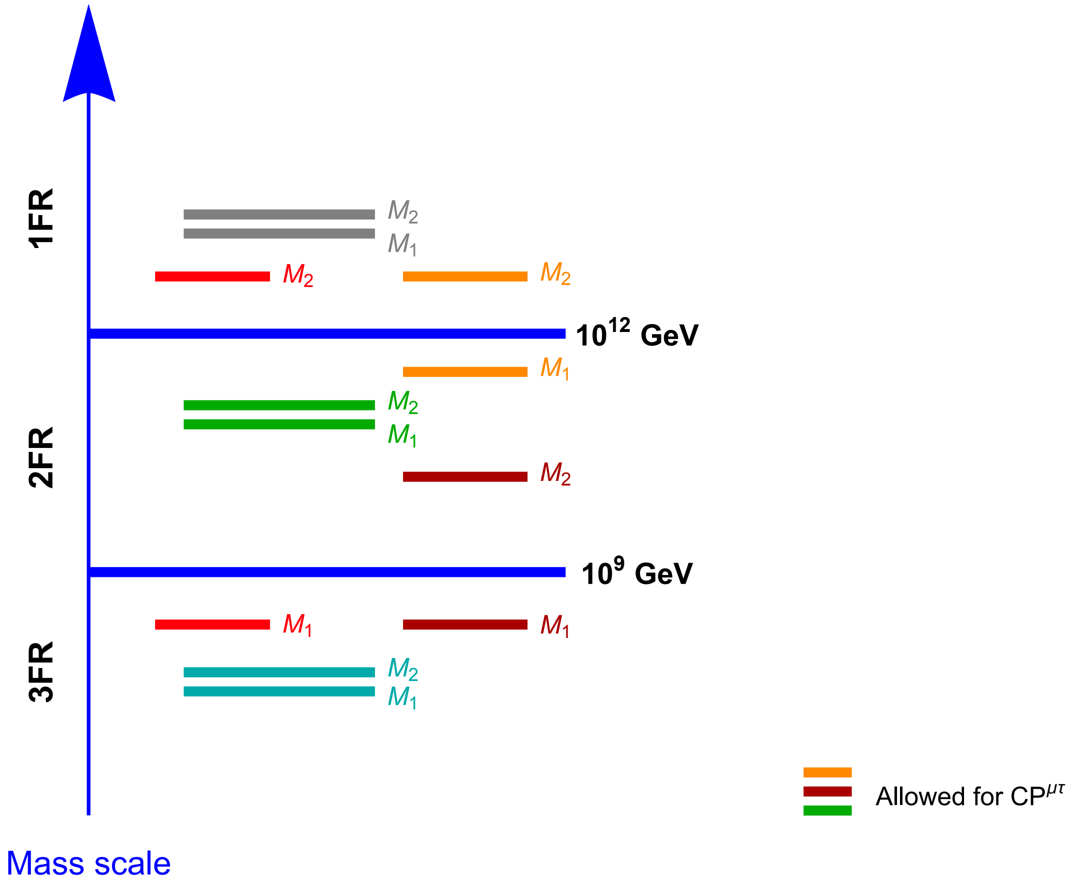


Figure 5. Various mass pattern in a leptogenesis scenario dominated by two right handed neutrinos. A particular RH neutrino mass which is either above 10^{12} GeV or below 10^9 GeV, can not generate baryon asymmetry in the $\mathrm{CP}^{\mu\tau}$ framework.

the three flavours. There could be other possibilities such as $M_i < 10^9$ GeV, $M_i > 10^{12}$, and $M_2 > 10^{12}$ GeV but $M_1 < 10^9$ GeV as shown in figure 5. Among these three possibilities, whilst the first one is not compatible to the standard thermal hierarchical leptogenesis scenario due to Davidson-Ibarra bound on M_i [100], for the rest of the cases, successful leptogenesis cannot be realized unless we invoke some special conditions.

5 Leptogenesis in the $\mathrm{CP}^{\mu\tau}$ symmetric model

To carry out a numerical computation pertaining to a successful leptogenesis, we need to constrain the model parameters of eq. (2.12) with the present neutrino oscillation data [7]. For a normal neutrino mass ordering with solar and atmospheric mass squared differences, $\Delta m^2_{12} = 7.39^{+0.21}_{-0.20} \times 10^{-5}\mathrm{eV}^2$ and $\Delta m^2_{31} = 2.52^{+0.033}_{-0.032} \times 10^{-3}\mathrm{eV}^2$, the current global-fit values of the three mixing angle and the Dirac CP phases are tabulated in table 1. To this end, we follow the exact diagonalization procedure of a 3×3 light neutrino mass matrix, first demonstrated in [101]. This gives $-150^\circ < \theta < 150^\circ$, while the ranges of the other parameters are shown in the figure 6.

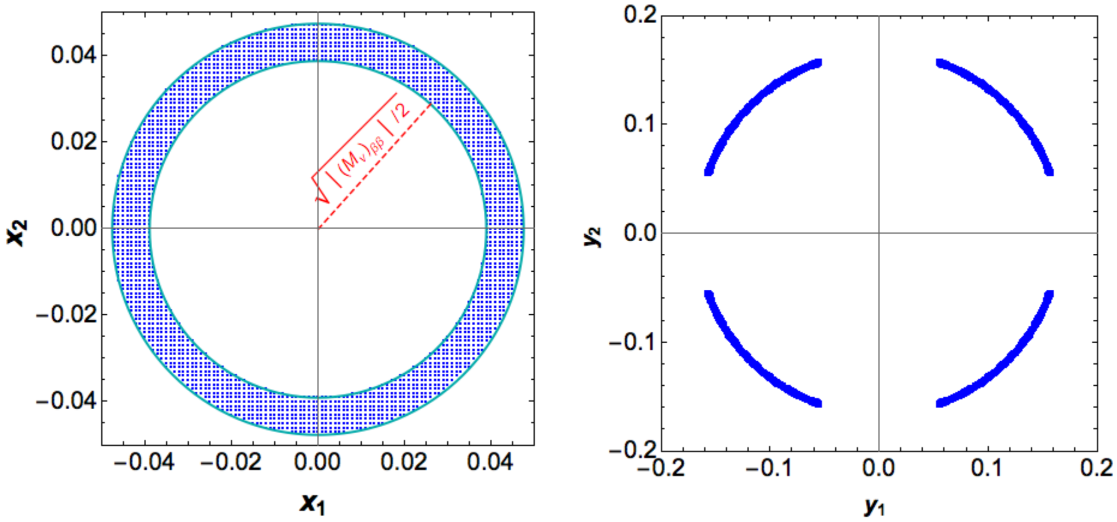


Figure 6. Parameter space of $\mathrm{CP}^{\mu\tau}$ symmetric mass matrix within a two RH neutrino scenario: x_1 vs x_2 (left) and y_1 vs y_2 (right), where these dimensional parameters (in $\sqrt{\mathrm{eV}}$) are defined in eq. (2.13).

	$\theta_{12}/°$	$\theta_{23}/°$	$\theta_{13}/°$	$\delta/°$
bf $\pm 1\sigma$	$33.82^{+0.78}_{-0.76}$	$49.6^{+1.0}_{-1.2}$	$8.61^{+0.13}_{-0.13}$	215^{+40}_{-29}
3σ	$31.61 \to 36.27$	$40.3 \to 52.4$	$8.22 \to 8.99$	$125 \to 392$

Table 1. Best-fit, 1σ and 3σ ranges of three mixing angles and the Dirac CP phase δ for NMO (NuFIT [7]).

The shape of the allowed parameter space in figure 6 could intuitively be inferred as follows. For a fixed value of $|(M_\nu)_{ee}|$ or $|(M_\nu)_{\mu\tau}|$ (say c), the solution is that of a circle,[7] given by $x_1^2 + x_2^2 = c$ or $y_1^2 + y_2^2 = c$. Considering the left panel of figure 6, since the radii of each of these circles are related to the neutrinoless double-beta decay parameter $\sqrt{|(M_\nu)_{\beta\beta}|/2}$ (cf. eq. (2.12)), there exists an upper limit ~ 5 meV and a lower limit ~ 3 meV (represented by the cyan circles) on $|(M_\nu)_{\beta\beta}|$. However both the limits on $|(M_\nu)_{\beta\beta}|$ are beyond the sensitivity reach of the present experiments such as GERDA [102], KamLAND-Zen [103], EXO [104] etc., as well as the next generation experiments [105] like KamLAND2-Zen [106], nEXO [107], CUPID [108], CUORE [109], LEGEND-1k [110]. Thus, this model lacks testability from these experiments.

From eq. (2.12) and eq. (4.4), it is trivial to derive analytic correlations between the flavoured decay parameters as

$$K_{2e} = \frac{|(M_\nu)_{\beta\beta}|}{m^*} - K_{1e}\,, \tag{5.1}$$

$$K_{2\mu} = \frac{|(M_\nu)_{\mu\tau}|}{m^*} - K_{1\mu} \tag{5.2}$$

[7] Though it has been noticed that vanishing or close to vanishing values of $y_{1,2}$ are not compatible with present neutrino oscillation data. Discussion regarding the parameter sapce can be found in ref. [35].

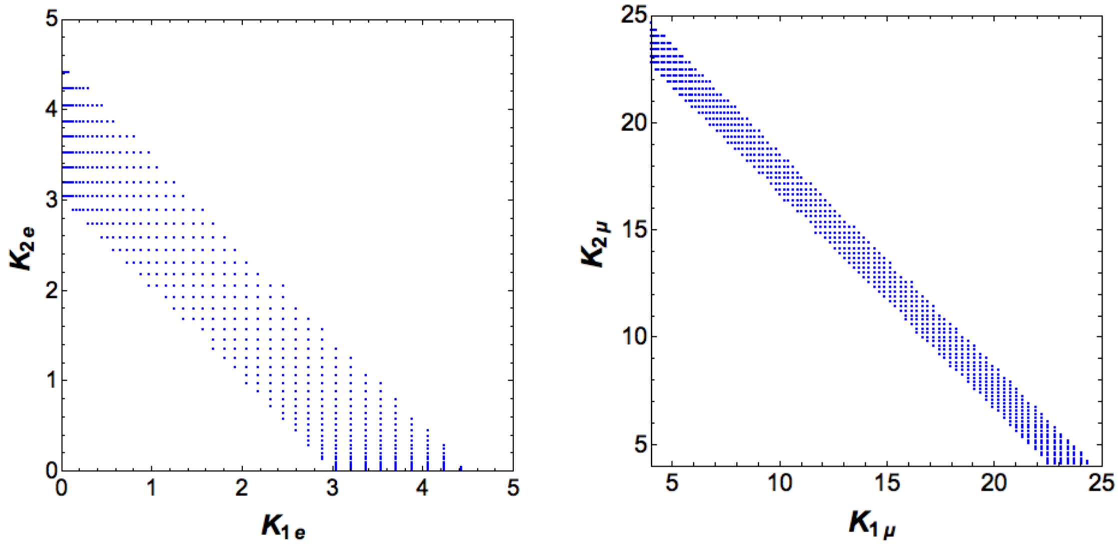


Figure 7. Flavoured decay parameters for both the RH neutrinos.

which are shown in figure 7. There are two interesting observations to be made from these plots. Firstly, note that the decay parameters in the electron flavour can have approximately vanishing values, as is clear from the left panel. Secondly, the decay parameters in the muon flavour or tau flavour (in this case $K_{i\mu} = K_{i\tau}$) have a lower bound (~ 5) due to the discontinuity in parameter space of y_1 and y_2 (see right panel of figure 6). We see later that these ranges of the decay parameters have very interesting consequences on the process of leptogenesis in this model.

Let us first discuss two interesting mass patterns of the RH neutrinos: $M_i > 10^{12}$ GeV and $M_i < 10^9$ GeV.[8] First of all, for the one flavour regime ($M_i > 10^{12}$ GeV), the second term in eq. (3.4) vanishes when summed over 'α', i.e, $\text{Im}\{h_{ji}(m_D)_{i\alpha}(m_D^*)_{j\alpha}\} = \text{Im}[|h_{ji}|^2] = 0$. The first term, however, is proportional to $\text{Im}\{h_{ij}^2\}$. Using eq. (2.11), one can show that $h = m_D m_D^\dagger$ is a real matrix [35]. Thus, the flavour-summed CP asymmetry $\varepsilon_i = \sum_\alpha \varepsilon_{i\alpha}$ vanishes for any i. Therefore, successful leptogenesis is not possible in the unflavoured regime. Interestingly, ε_{ie} is also vanishing, since the phases associated with the relevant parameters of m_D will cancel when one uses eq. (3.4) to calculate the CP asymmetry in the electron flavour. Thus in this model, $\varepsilon_{i\mu} \equiv \Delta P_{i\mu}/2 = -\varepsilon_{i\tau}$. On the other hand, if all the RH neutrino masses are in the three flavour regime $M_i < 10^9$ GeV, one might wonder whether there would be possibilities for a resonant leptogenesis [61, 62]. However, in [111], it has been analytically argued that due to the typical structure of the symmetry (the efficiency factors in μ and τ flavour are same), such a possibility still leads to a vanishing asymmetry even after taking into account the flavour coupling effects [72, 112, 113].

Another interesting possibility is to consider $M_2 > 10^{12}$ GeV, and $M_1 < 10^{12}$ GeV. In that case, since the asymmetry is produced by N_2 in the unflavoured regime and

[8]Both these mass patterns have been discussed in literature, e.g., for the first one see [22, 69] and for the seconed one, see [111]. We recall the discussion here for comprehensiveness.

$\varepsilon_i = \sum_\alpha \varepsilon_{i\alpha} = 0$, the final baryon asymmetry only has contributions from N_1.[9] As a result, all the results derived in refs. [22, 35] will be valid upto minor changes due to the newly released global-fit data [7].

In this paper, we shall focus on the following mass patterns: (i) $10^9\,\text{GeV} < M_{1,2} < 10^{12}\,\text{GeV}$, and (ii) $10^9\,\text{GeV} < M_2 < 10^{12}$ and $M_1 < 10^9\,\text{GeV}$. Before discussing these cases explicitly, we list the flavoured CP asymmetry parameters in this model. Using eq. (2.11) and eq. (3.4) the $\varepsilon_{i\alpha}$ can be obtained as

$$\varepsilon_{ie} = 0,\ \varepsilon_{i\mu} = -\xi_i \frac{g'(x_{ij})}{4\pi v^2}\left[\frac{(a_i a_j + b_i b_j \cos\theta) b_i b_j \sin\theta}{a_i^2 + b_i^2}\right] = -\varepsilon_{i\tau}\,, \quad i \neq j (= 1, 2), \tag{5.3}$$

where $g'(x_{ij})$ is given by

$$g'(x_{ij}) \simeq [f(x_{ij}) + \sqrt{x_{ij}}/(1 - x_{ij})] + (1 - x_{ij})^{-1} \equiv g_1(x_{ij}) + g_2(x_{ij})\,, \tag{5.4}$$

and $\xi_i = \pm 1$ for $i = 1$ and 2 respectively. Using eq. (2.13) we can now simplify eq. (5.3) for $i = 1$ as

$$\varepsilon_1^\mu = -\frac{g'(x_{12}) M_2}{4\pi v^2}\left[\frac{(x_1 x_2 + y_1 y_2 \cos\theta) y_1 y_2 \sin\theta}{x_1^2 + y_1^2}\right] = -\varepsilon_1^\tau\,, \tag{5.5}$$

which in the strong hierarchical limit can further be simplified as

$$\varepsilon_1^\mu \simeq \frac{3M_1}{8\pi v^2}\left[\frac{(x_1 x_2 + y_1 y_2 \cos\theta) y_1 y_2 \sin\theta}{x_1^2 + y_1^2}\right] = -\varepsilon_1^\tau\,. \tag{5.6}$$

Similarly for $i = 2$ the CP asymmetry parameter can be calculated as

$$\varepsilon_2^\mu = \frac{g'(x_{21}) M_1}{4\pi v^2}\left[\frac{(x_1 x_2 + y_1 y_2 \cos\theta) y_1 y_2 \sin\theta}{x_2^2 + y_2^2}\right] = -\varepsilon_2^\tau\,. \tag{5.7}$$

Armed with these equations, we can proceed toward a systematic discussion of leptogenesis for the relevant cases.

5.1 Two flavour regime: 10^9 GeV $< M_{1,2} < 10^{12}$ GeV

The N_1-decay parameters in the muon and tau flavour are strong enough [63, 64] to washout any pre-existing asymmetry (see right panel of figure 7). Thus, all the terms which contain the exponential washout factors in eq. (4.19) and eq. (4.20) can be neglected. Therefore the total N_{B-L} asymmetry can be written as

$$\begin{aligned} N_{B-L} &= -(\varepsilon_{1\tau}\kappa_{1\tau}^\infty + \varepsilon_{1\tau^\perp}\kappa_{1\tau^\perp}^\infty) - (1 - p_{12}^\perp)\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^\infty \\ &= -\varepsilon_{1\tau}(\kappa_{1\tau}^\infty - \kappa_{1\tau^\perp}^\infty) - (1 - p_{12}^\perp)\varepsilon_{2\mu}\kappa_{2\mu}^\infty\,, \end{aligned} \tag{5.8}$$

where we use the fact, that $\varepsilon_{ie} = 0$, $\varepsilon_{i\mu} = -\varepsilon_{i\tau}$, and the electron decay parameters are much weaker than the muon decay parameters. Clearly, the first term in eq. (5.8), which is a contribution from N_1, is non-vanishing when $\kappa_{1\tau}^\infty \neq \kappa_{1\tau^\perp}^\infty$, i.e, when there is an asymmetric washout in the τ and $\tau^\perp$ flavour. The second term, driven by the muon flavour, is a pure

[9] N_2 might contribute to the final asymmetry via phantom terms [78]. However, phantom leptogenesis in this context is beyond the scope of this study.

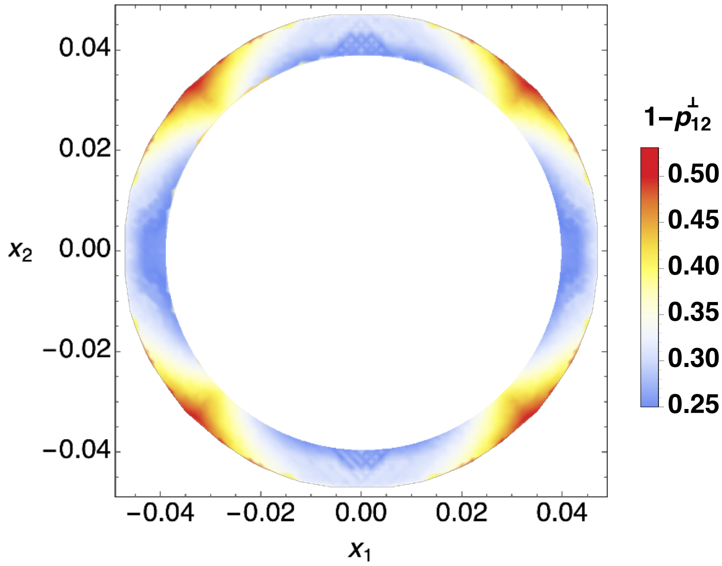


Figure 8. Plot showing the quantity $(1 - p^{\perp}_{12})$ with the model parameter x_1 and x_2. Since lepton asymmetry generated by N_2 is proportional to $(1 - p^{\perp}_{12})$, and clearly this never vanishes in this model, a pure N_1 dominated scenario is not possible. Note that $x_{1,2}$ are dimensional quantities, and are plotted in units of $\sqrt{\text{eV}}$.

contribution from N_2, and is non-zero when $p^{\perp}_{12} \neq 1$. Using eq. (4.18), one can arrive at an expression for the probability $p^{\perp}_{12}$ as,

$$p^{\perp}_{12} = \frac{4x_1^2x_2^2 + y_1^2y_2^2 + 4x_1x_2y_1y_2\cos\theta}{(2x_1^2 + y_1^2)(2x_2^2 + y_2^2)}\,. \tag{5.9}$$

In figure 8 we show the variation of $(1 - p^{\perp}_{12})$ with the model parameter x_1 and x_2. An interesting fact is that $(1 - p^{\perp}_{12})$ never vanishes in this model. This means N_2 always contributes to the final asymmetry. In addition, one has a strong concentration of points towards the higher values (~ 0.5) of $(1-p^{\perp}_{12})$ which indicates there could be sizeable number of data points for which N_2 domination could be realized. In fact we show as we proceed, N_2 domination in this model is possible for a significant amount of parameter space ($\sim 26\%$).

We first concentrate on the choice of RH neutrino mass hierarchy in this model. To find the minimum value of M_2/M_1, we generalise the procedure described in section 3 and find that one may choose the RH neutrino mass hierarchy as mild as $M_2/M_1 \sim 4.7$ for a perfectly valid N_1DS.[10] In the upper panel of figure 9, we show the evolution of the $B - L$ asymmetry produced by both the RH neutrinos, in the two extreme cases of $K_{1\tau}$ and $K_{2\tau}$ (see right panel of figure 7). Note that, though for the first set of the decay parameters ($K_{2\tau} = 5$ and $K_{1\tau} = 25$), hierarchical N_1DS can be reproduced with $\delta_{12} \sim 1$, the second set ($K_{2\tau} = 25$ and $K_{1\tau} = 5$) requires a larger value of $\delta_{12} \sim 3.7$. For the first case, the N_2-washout is not strong enough to affect the asymmetry production by N_1 up to very low values of $\delta_{12}(\sim 1)$. Thus for $\delta_{12} \geq 1$, the final dynamics is governed only by the

[10]We have checked this using eq. (3.13) as well as eq. (3.18).

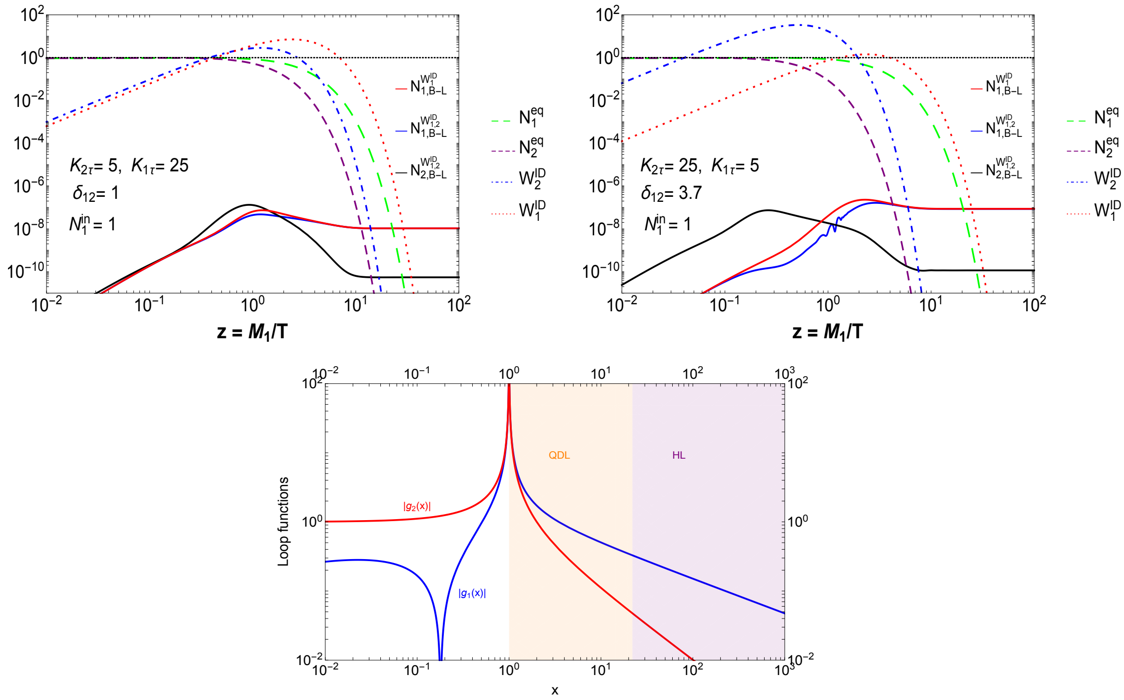


Figure 9. Upper panel: (Colour codes for the N_{B-L} asymmetries are same as figure 1): representative plots showing the validity of N_1 dominated scenario when the decay parameter of N_2 is weaker than the decay parameters of N_1 (left), and vice-versa (right). Bottom panel: variation of the involved loop functions in the CP asymmetry parameters. The light violet region is the region where hierarchical scenario is valid in the model under consideration.

N_1-interactions. On the other hand, for the second case, the N_2-washout is much stronger and it starts to reduce the magnitude of the asymmetry produced by N_1, unless one goes beyond $\delta_{12} \geq 3.7$. Henceforth, we designate $\delta_{12} = 3.7$ as the critical point which separates the hierarchical (HL) and quasi-degenerate limit (QDL) of leptogenesis in CP$^{\mu\tau}$ model. We use this mild hierarchy criteria, i.e., $M_2/M_1 = 4.7$ in the computation of leptogenesis for rest of the paper.

Once we go from strong to a mild hierarchy, we immediately see an enhancement in the loop functions (cf. the bottom panel of figure 9). In hierarchical limit, it is sufficient to consider the enhancement in the function $g_1(x_{12} = M_2^2/M_1^2)$ which dominates in $\varepsilon_{1\alpha}$. Due to this enhancement, the previously quoted lower bound on M_1 ($\sim 6 \times 10^{10}$ GeV) [22, 35] gets lowered to $M_1^{\rm min} \sim 7.5 \times 10^9$ GeV. Note that this can be further relaxed with the inclusion of flavour couplings, which tend to increase the efficiency of the asymmetry production. In addition, due to this choice of mild hierarchy M_2 would likely to be in the 2FR (the green rectangles in figure 5). However we stress that if one chooses a strong hierarchy, say $M_2/M_1 = 10^3$ ([22, 35, 69]), M_2 is necessarily in the 1FR, if we take M_1 to be in the 2FR. Thus contribution from M_2 can be neglected since the total CP asymmetry vanishes in the unflavoured (1FR) regime. Therefore, the results obtained in the above references (for a pure N_1 domination) hold true.

JHEP01(2020)193

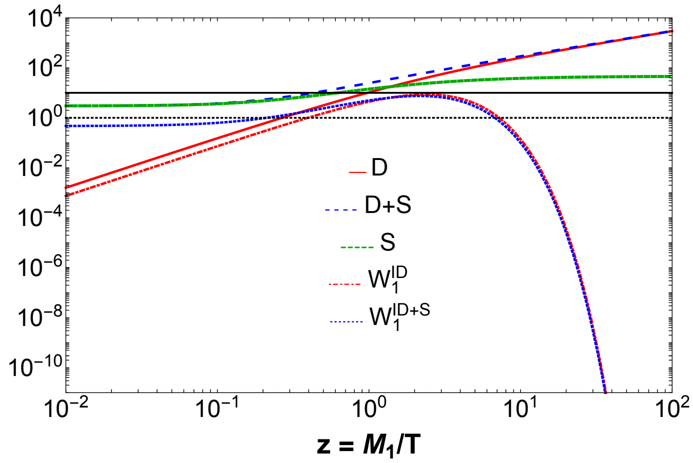


Figure 10. Comparison among rates of various processes involved in the leptogenesis. The horizontal black line is the rate of the τ charged lepton flavour interaction Γ_τ/Hz at the N_1 leptogenesis temperature $T \sim M_1 \sim 10^{11}$ GeV. Domination of Γ_τ/Hz (over all the rates) has been considered to ensure a strongly decoherent picture for simplicity.

It is also worth mentioning that in this work, we consider a fully flavoured scenario where the charged lepton flavour interaction rate is dominant throughout the thermal history of the asymmetry production. Mathematically, this implies that the washout term $W(z^{\max}, K_1) < \Gamma_\tau/2Hz$, where Γ_τ is the τ interaction rate. This condition translates into

$$F_\tau \equiv \Gamma_\tau/2Hz_i = \frac{5\times\ 10^{11}\mathrm{GeV}}{M_i} > W(z_i^{\max})\,, \tag{5.10}$$

where the washout term $W(z)$ contains inverse decays as well as dominant scattering rates (cf. figure 10). Notice that for a weak washout scenario, eq. (5.10) is trivially satisfied. In that case, the washout terms never reach equilibrium and thus, for any value of $M_i < 5\times 10^{11}$ GeV, the interaction rate Γ_τ is fast enough to break the coherence of the states produced by N_i. But for a strong washout, this is not the case since the washout term $W(z) \gg 1$. Thus, the masses for the RH neutrinos should be chosen carefully so that throughout the thermal history, Γ_τ dominates over the relevant washout rates. Otherwise, one needs to take into account the off-diagonal terms of the density matrix[11] that account for the coherence among the basis states [78, 114, 115]. In this context, it is also worthwhile to recall refs. [116–119] that discuss leptogenesis using full quantum kinetic equations.

In the washout term, in addition to the inverse decay we include dominant $\Delta L = 1$ scattering processes involving top quark. These processes include a combined contribution of the Higgs mediated s-channel ($N_i\ell \leftrightarrow qt$) and t-channel processes ($N_i q \leftrightarrow \ell t$). The relevant scattering rates for both the channels can be written as

$$S^a_{\phi i} = \frac{\Gamma^a_{\phi i}}{Hz}\,, \qquad\qquad a = s, t\,. \tag{5.11}$$

[11]Note that thus the CP asymmetry parameter defined in eq. (4.9) appears in the '$\alpha\alpha$' (diagonal) term of the density matrix evolution equation [78, 115].

The quantity $\Gamma^a_{\phi i}$ is related to the reaction density $\gamma^a_{\phi i}$ as $\Gamma^a_{\phi i} = \frac{\gamma^a_{\phi i}}{n^{\rm eq}_{N_i}}$, where for the reaction density of a generic $2 \leftrightarrow 2$ process, one has the expression [64]

$$\gamma(2 \leftrightarrow 2) = \frac{g_x g_y T}{32\pi^4} \int ds s^{3/2} K_1(\sqrt{s}/T) \lambda \left(1, \frac{m_x^2}{s}, \frac{m_y^2}{s}\right) \sigma(s)^a \,, \tag{5.12}$$

where g_x and g_y are initial state degrees of freedom, s is the center of mass energy and the quantity λ is given by

$$\lambda \left(1, \frac{m_x^2}{s}, \frac{m_y^2}{s}\right) = \left(1 - \frac{m_x^2}{s} - \frac{m_y^2}{s}\right)^2 - 4\frac{m_x^2 m_y^2}{s^2} \,. \tag{5.13}$$

The washout for the $\Delta L = 1$ term could be written as

$$W_i^{\Delta L=1} = W_i^s + 2W_i^t \,, \tag{5.14}$$

which are related to the scattering rate as

$$W_i^s = \frac{N_{N_i}}{N_\ell^{\rm eq}} S^s_{\phi i}, W_i^t = \frac{N^{\rm eq}_{N_i}}{N_\ell^{\rm eq}} S^t_{\phi i} \,. \tag{5.15}$$

We compare the total washout term $W = W_i^{\rm ID} + W_i^{\Delta L=1}$ with the charged lepton interaction rate F_τ. Given the ranges of the decay parameters, we find that $M_1 \sim 4\times 10^{10}$ GeV could be a safe value to circumvent the dominance of the washout processes over the charged lepton interaction.[12] Notice that, for the mass window $M^{\rm max} \sim 4 \times 10^{10}$ GeV $\gtrsim M_1 \gtrsim M_1^{\rm min} \sim 7.5 \times 10^9$, the formulae we use in this paper are technically valid. While the inclusion of flavour couplings could lower the value of $M_1^{\rm min}$ (as already pointed out before), one may still go beyond $M^{\rm max}$ and opt for a diagonal density-matrix formalism. However, in that case one has to neglect the higher values of the decay parameters (i.e., there would be upper bound on the decay parameters) which are responsible for the dominance of washout terms over the charged lepton interactions. In order to understand the contribution from N_1 and N_2 to N_{B-L}, we can write eq. (5.8) as

$$N_{B-L} = -\varepsilon_{1\tau}(\kappa^\infty_{1\tau} - \kappa^\infty_{1\tau^\perp}) - (1 - p^\perp_{12})\varepsilon_{2\mu}\kappa^\infty_{2\mu} = N^{N_1}_{B-L} + N^{N_2}_{B-L} \tag{5.16}$$

where $N^{N_1}_{B-L}$ is the contribution from N_1 and $N^{N_2}_{B-L}$ is the contribution from N_2. The ratios

$$R_{N_1} = \left|\frac{N^{N_1}_{B-L}}{N^{N_2}_{B-L}}\right|, \qquad R_{N_2} = \left|\frac{N^{N_2}_{B-L}}{N^{N_1}_{B-L}}\right| \tag{5.17}$$

can be used to realize a particular N_i domination quantitatively. We use the criteria $R_{N_i} > 10$ to signify a particular N_i domination. Notice from figure 11 that indeed both the R parameters can have values $\gg 10$; also, in general, $R_{N_1} > R_{N_2}$. Thus lepton asymmetry produced by both the neutrinos can dominate for certain region of the parameter space.

[12] In the numerical computaion we use $M_\phi/M_1 = 10^{-5}$ [120, 121], where M_ϕ is the Higgs thermal mass needed to cut off the infrared divergences of t channel process. For the scattering cross sections please see ref. [122].

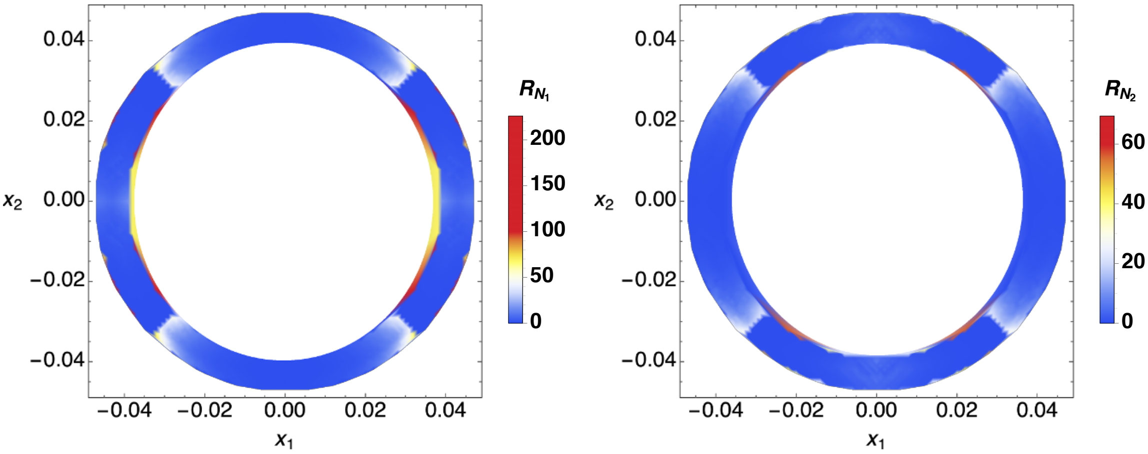


Figure 11. Top panel: $R_{N_1} \equiv \eta_B^{N_1}/\eta_B^{N_2}$ with the model parameters x_1 and x_2. Bottom panel: $R_{N_2} \equiv \eta_B^{N_2}/\eta_B^{N_1}$ with the model parameters x_1 and x_2. All the plots are generated for $M_1 = 4 \times 10^{10}$ GeV. Note that $x_{1,2}$ are dimensional quantities, and are plotted in units of $\sqrt{\text{eV}}$.

Quantitatively, 37% of the parameter space favours a N_1 dominated scenario ($R_{N_1} > 10$) and 26% of the parameter space favours a N_2 dominated scenario ($R_{N_2} > 10$). These percentages have been calculated by taking the ratios of the number of data points corresponding to $R_{N_i} > 10$ and the total number of data points compatible with 3σ neutrino oscillation data. We stress that the above quantification is valid for any arbitrary values of M_1 in the mass window 4×10^{10} GeV $\gtrsim M_1 \gtrsim M_1^{\text{min}}$.

However, the real challenge is now to check whether the parameters corresponding to $R_{N_1} > 10$ or $R_{N_2} > 10$ are able to reproduce the *observed range* of the baryon to photon ratio. We checked that though the N_1 domination can be realized within the allowed mass window, N_2 domination can be realized marginally even if we take the maximal allowed value of $M_1^{\text{max}} \sim 4 \times 10^{10}$ GeV. In figure 12, we plot the baryon to photon ratio normalised to 6.3×10^{-10} with the R parameters for $M_1 = 7 \times 10^{10}$ GeV. Note that, though this value of M_1 is beyond M_1^{max}, we do not lose any information on the RH neutrino masses by discarding the higher values of the decay parameters. Since higher values of η_B correspond to lower values of the decay parameter, exclusion of higher values of the decay parameter implies truncating the lower portion of the parameter space (right hand side of figure 12) in the $R_{N_2} - \overline{|\eta_B|}$ plane which is anyway much below $\overline{|\eta_B|} = 1$.

5.2 10^9 GeV $< M_2 < 10^{12}$ GeV and $M_1 < 10^9$ GeV

In this section we give a qualitative picture of what happens in the case 10^9 GeV $< M_2 < 10^{12}$ GeV and $M_1 < 10^9$ GeV. Two important points should be stressed a priori. Firstly, since the mass of N_1 is much less than 10^9 GeV, the CP asymmetry parameter $\varepsilon_{1\alpha}$ is highly suppressed and does not suffice to reproduce the correct baryon asymmetry [100]. One might wonder whether N_2 could produce a viable CP asymmetry or not. However, if we are in a two RH neutrino scenario (i.e., the third heavy neutrino does not couple to Higgs and leptons), the CP asymmetry parameter $\varepsilon_{2\alpha}$ (cf eq. (5.7)) is also proportional to

JHEP01(2020)193

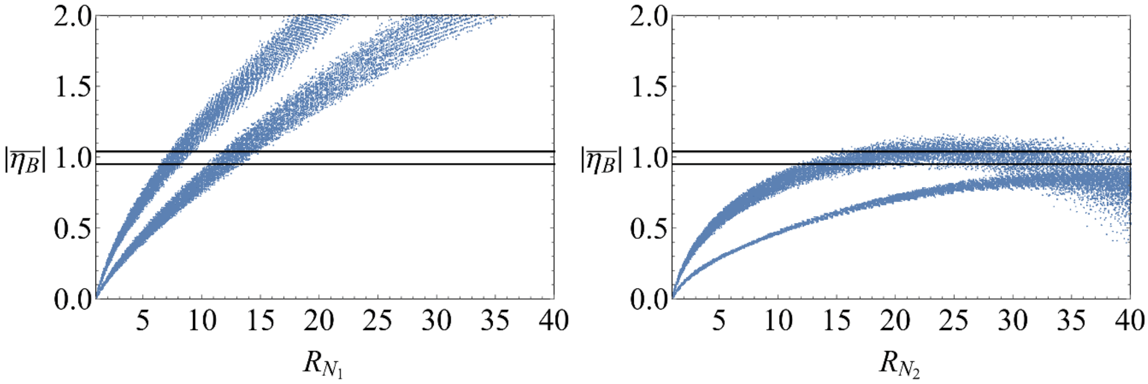


Figure 12. Normalised baryon to photon ratio with the R parameters which quantify a particular N_i dominance.

M_1 and hence, suppressed by the small values of M_1. Therefore, in order to produce the correct amount of CP violation, one must need the N_3 to couple with N_2.

Once N_3 is included in the discussion, we have more combinations of the RH mass spectrum on top of what has been shown in figure 5. However in this paper, we only consider the case $M_3 > 10^{12}$ GeV so that the asymmetry generated by M_3 vanishes (due to $\text{CP}^{\mu\tau}$) and we have contributions from N_2 with $10^9\,\text{GeV} < M_2 < 10^{12}\,\text{GeV}$. Note that this mass spectrum[13] ($M_3 \gg M_2 \gg M_1$), implies a strong hierarchical scenario. Thus, unlike the case discussed in the earlier section, any of the components of the asymmetry generated by N_2 does not escape N_1-washout since, for this mass spectrum of the RH neutrinos, M_1 is in the 3FR and the directions of N_1-washout coincide with that of the charged leptons.

Following the above discussion, neglecting the contribution from N_1 and using eq. (4.23)–eq. (4.25), $B-L$ asymmetry parameter can now be written as

$$N_{B-L} = -\varepsilon_{2\tau}\kappa_{2\tau}^{\infty} e^{-3\pi K_{1\tau}/8} - \frac{K_{2\mu}}{K_{2\tau^\perp}}\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^{\infty} e^{-3\pi K_{1\mu}/8} - \frac{K_{2e}}{K_{2\tau^\perp}}\varepsilon_{2\tau^\perp}\kappa_{2\tau^\perp}^{\infty} e^{-3\pi K_{1e}/8}. \tag{5.18}$$

Note that each term in the r.h.s. of eq. (5.18) contains the exponential washout factor involving the flavoured decay parameters. Thus strength of the N_1-decay parameters would finally decide whether the asymmetry generated by N_2 would survive against N_1-washout. Typically, $K_{1\alpha} < 1$ is the condition for the washout processes to be considered ineffective (see [79, 80]), and thus $P(K_{1\alpha} < 1)$ is the probability for the asymmetry generated by N_2 to survive in the direction of 'α'. Given a general seesaw formula (constituent mass matrices are not subjected to any symmetry), it has been shown for hierarchical light neutrinos that $P(K_{1e} < 1) : P(K_{1\mu} < 1) : P(K_{1\tau} < 1) \simeq 0.36 : 0.058 : 0.067 \simeq 6.2 : 1 : 1.15$ [80]. For the $\text{CP}^{\mu\tau}$ symmetric case, it is natural to infer that these probabilities would decrease, since in this case due to the imposed symmetry, there are now lesser number of parameters in the light neutrino mass matrix. For example., we compute these probabilities assuming

[13]This is a very interesting mass spectrum for which a particular RH neutrino lies in a particular flavour regime, i.e., M_3 is in 1FR, M_2 is in 2FR and M_1 is in 3FR. This mass spectrum is often realized in SO(10) models [77, 123, 124].

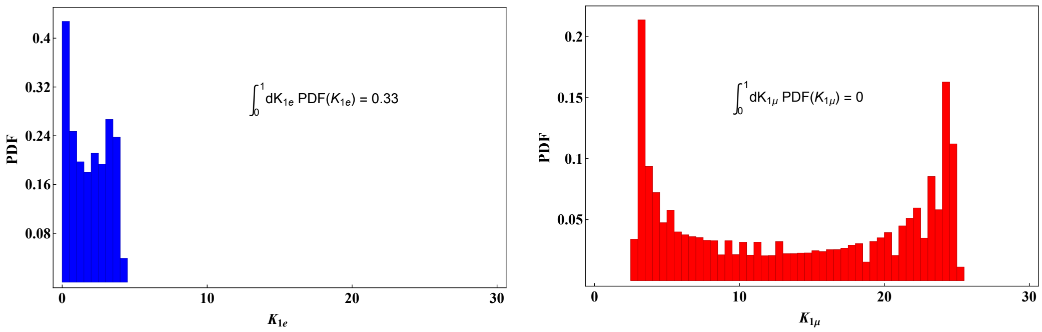


Figure 13. Distributions of the flavoured decay parameters. The probability for the electron decay parameter K_{1e} being less than 1 is almost 33% which corresponds to the fact that asymmetry generated by N_2 is most likely to survive against N_1 washout in the electron flavour.

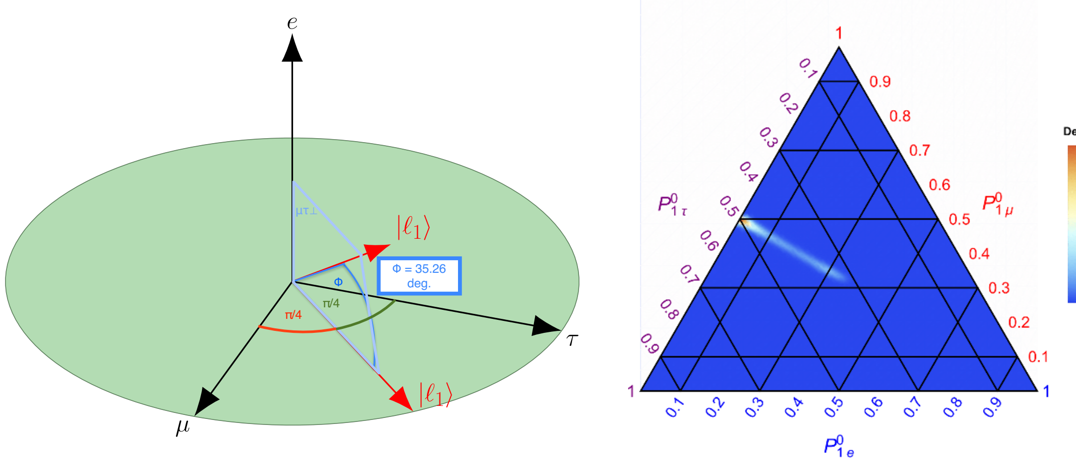


Figure 14. Left: possible range of the orientation of the state $|\ell\rangle_1$ in the CP symmetric model with hierarchical light neutrinos. Right: in the same model, ternary plot for the probabilities $P_{1\alpha} = K_{1\alpha}/\sum_\alpha K_{1\alpha}$ with corresponding densities.

hierarchical light neutrinos[14] and in figure 13, we show the corresponding distributions. It is evident that, though for the electron flavour we have $P(K_{1e} < 1) \sim 0.33$, for the other two flavours (having same distribution due the $\mu\tau$ symmetry), the parameter space for $P(K_{1\mu,\tau} < 1)$ closes. This implies that the asymmetry generated by N_2 would survive in the electron flavour only. Note that since smaller values of K_{1e} are most probable, there are more number of points for the smaller values of $P_{1e} = K_{1e}/K_1$. This implies the states $|\ell\rangle_1$ tend to lie on the $\mu - \tau$ plane. The feature of getting mostly smaller values of P_{1e} is quite generic [80], but there is a clear difference between the general case and CP$^{\mu\tau}$. For the latter, the entire $\mu - \tau$ plane is not accessible to $|\ell\rangle_1$, since in this case $P_{1\mu} = P_{1\tau}$, and therefore the state $|\ell\rangle_1$ will have a definite direction (45^0 w.r.t. μ or τ axis) on the $\mu - \tau$ plane. In addition, all possible orientations of the $|\ell\rangle_1$ will lie on the plane $\mu\tau\perp$ as shown in the left panel of figure 14. In the right panel, we show the triangle plot for the $P_{1\alpha}$

[14] In our case assuming N_3 has Yukawa couplings $(m_D)_{3\alpha}$ which are similar order of magnitude as that of N_1 or N_2 so that in the seesaw light neutrino mass matrix $(m_D)_{3\alpha}$ is suppressed by the mass of M_3.

JHEP01(2020)193

with corresponding densities. It is evident that the maximum dense region corresponds to $P_{1\mu} = P_{1\tau} = 0.5$ and the probability densities can have values upto the center of mass of the probability triangle, i.e., $P_{1e} : P_{1\mu} : P_{1\tau} \simeq 1 : 1 : 1$. This suggests that there would be an upper limit (in this model $\sim 35.26^0$) on the angle Φ which measures the angular deviation of the state $|\ell\rangle_1$ from the $\mu\tau$ plane as shown in figure 14.

6 Summary

In this work, we have performed a detailed study of the flavoured leptogenesis scenario in $\mathrm{CP}^{\mu\tau}$ symmetric neutrino mass models. We have shown how a mildly hierarchical leptogenesis ($M_2 \simeq 4.7 M_1$) can be realized within the two flavour regime. Within this class of models, even within the N_1-dominated scenario, the previously existing lower bound on M_1 can further be lowered approximately by an order of magnitude. Contrary to the previous works we have shown how in the two flavour regime, one can have a comparable parameter space for N_2- leptogenesis in addition to the standard N_1- leptogenesis. We have quantified the relevant mass scales of the RH neutrinos for a N_i-leptogenesis to dominate.

Taking the appropriate flavour effects into account, we have argued that the standard hierarchical N_1-dominated scenario is valid only for the mass window $(M_1^{\max}) \sim 4 \times 10^{10}$ GeV $> M_1 > (M_1^{\min}) \sim 7.5 \times 10^9$ GeV. Else, if the mass of N_1 goes beyond $M_1^{\max}$, there is a substantial amount of parameter space for which a N_2-dominated scenario could also be realized. We have considered other mass spectra of the heavy neutrinos for which the lepton asymmetry generated by N_2 in two flavour regime faces washout by N_1 in the three flavour regime. For a hierarchical light neutrino mass spectrum, we have demonstrated that approximately one third of the parameter space allows an *electron-flavoured* N_2-leptogenesis to be realized.

The possibility of having a mildly hierarchical leptogenesis opens up several interesting avenues. With this detailed work, we hope to elucidate some aspects of this involved problem. Certainly, inclusion of several other effects, e.g., consideration of flavour couplings, quantum corrections to the neutrino parameters would improve the results presented in this paper. We plan to include these effects in a future work.

Acknowledgments

We would like to thank Pasquale Di Bari for many useful discussions regarding leptogenesis. RS is supported by a Newton International Fellowship (NF 171202) from Royal Society (UK) and SERB (India). MS acknowledges support from the National Science Foundation, Grant PHY-1630782, and to the Heising-Simons Foundation, Grant 2017-228.

References

[1] Particle Data Group collaboration, *Review of Particle Physics*, Phys. Rev. **D 98** (2018) 030001 [INSPIRE].

[2] T2K collaboration, *Combined Analysis of Neutrino and Antineutrino Oscillations at T2K*, Phys. Rev. Lett. **118** (2017) 151801 [arXiv:1701.00432] [INSPIRE].

[3] T2K collaboration, *Measurement of neutrino and antineutrino oscillations by the T2K experiment including a new additional sample of ν_e interactions at the far detector*, Phys. Rev. **D 96** (2017) 092006 [*Erratum ibid.* **D 98** (2018) 019902] [arXiv:1707.01048] [INSPIRE].

[4] T2K collaboration, *Search for CP-violation in Neutrino and Antineutrino Oscillations by the T2K Experiment with 2.2×10^{21} Protons on Target*, Phys. Rev. Lett. **121** (2018) 171802 [arXiv:1807.07891] [INSPIRE].

[5] NOvA collaboration, *Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA*, Phys. Rev. Lett. **118** (2017) 231801 [arXiv:1703.03328] [INSPIRE].

[6] NOvA collaboration, *New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment*, Phys. Rev. **D 98** (2018) 032012 [arXiv:1806.00096] [INSPIRE].

[7] I. Esteban, M.C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni and T. Schwetz, *Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of θ_{23}, δ_{CP} and the mass ordering*, JHEP **01** (2019) 106 [arXiv:1811.05487] [INSPIRE].

[8] G. Altarelli and F. Feruglio, *Discrete Flavor Symmetries and Models of Neutrino Mixing*, Rev. Mod. Phys. **82** (2010) 2701 [arXiv:1002.0211] [INSPIRE].

[9] H. Ishimori, T. Kobayashi, H. Ohki, Y. Shimizu, H. Okada and M. Tanimoto, *Non-Abelian Discrete Symmetries in Particle Physics*, Prog. Theor. Phys. Suppl. **183** (2010) 1 [arXiv:1003.3552] [INSPIRE].

[10] S.F. King, *Unified Models of Neutrinos, Flavour and CP-violation*, Prog. Part. Nucl. Phys. **94** (2017) 217 [arXiv:1701.04413] [INSPIRE].

[11] S.T. Petcov, *Discrete Flavour Symmetries, Neutrino Mixing and Leptonic CP-violation*, Eur. Phys. J. **C 78** (2018) 709 [arXiv:1711.10806] [INSPIRE].

[12] R.N. Mohapatra and S. Nussinov, *Bimaximal neutrino mixing and neutrino mass matrix*, Phys. Rev. **D 60** (1999) 013002 [hep-ph/9809415] [INSPIRE].

[13] C.S. Lam, *A 2-3 symmetry in neutrino oscillations*, Phys. Lett. **B 507** (2001) 214 [hep-ph/0104116] [INSPIRE].

[14] E. Ma and M. Raidal, *Neutrino mass, muon anomalous magnetic moment and lepton flavor nonconservation*, Phys. Rev. Lett. **87** (2001) 011802 [*Erratum ibid.* **87** (2001) 159901] [hep-ph/0102255] [INSPIRE].

[15] K.R.S. Balaji, W. Grimus and T. Schwetz, *The Solar LMA neutrino oscillation solution in the Zee model*, Phys. Lett. **B 508** (2001) 301 [hep-ph/0104035] [INSPIRE].

[16] T. Fukuyama and H. Nishiura, *Mass matrix of Majorana neutrinos*, hep-ph/9702253 [INSPIRE].

JHEP01(2020)193

[17] T. Fukuyama, *Twenty years after the discovery of μ-τ symmetry*, *PTEP* **2017** (2017) 033B11 [arXiv:1701.04985] [INSPIRE].

[18] R.N. Mohapatra and W. Rodejohann, *Broken mu-tau symmetry and leptonic CP-violation*, *Phys. Rev.* **D 72** (2005) 053001 [hep-ph/0507312] [INSPIRE].

[19] Z.-z. Xing, H. Zhang and S. Zhou, *Nearly Tri-bimaximal Neutrino Mixing and CP-violation from mu-tau Symmetry Breaking*, *Phys. Lett.* **B 641** (2006) 189 [hep-ph/0607091] [INSPIRE].

[20] P.F. Harrison and W.G. Scott, *μ-τ reflection symmetry in lepton mixing and neutrino oscillations*, *Phys. Lett.* **B 547** (2002) 219 [hep-ph/0210197] [INSPIRE].

[21] W. Grimus and L. Lavoura, *A Nonstandard CP transformation leading to maximal atmospheric neutrino mixing*, *Phys. Lett.* **B 579** (2004) 113 [hep-ph/0305309] [INSPIRE].

[22] R.N. Mohapatra and C.C. Nishi, *Implications of μ-τ flavored CP symmetry of leptons*, *JHEP* **08** (2015) 092 [arXiv:1506.06788] [INSPIRE].

[23] R.N. Mohapatra and C.C. Nishi, *S_4 Flavored CP Symmetry for Neutrinos*, *Phys. Rev.* **D 86** (2012) 073007 [arXiv:1208.2875] [INSPIRE].

[24] S. Gupta, A.S. Joshipura and K.M. Patel, *Minimal extension of tri-bimaximal mixing and generalized $Z_2 \times Z_2$ symmetries*, *Phys. Rev.* **D 85** (2012) 031903 [arXiv:1112.6113] [INSPIRE].

[25] F. Feruglio, C. Hagedorn and R. Ziegler, *Lepton Mixing Parameters from Discrete and CP Symmetries*, *JHEP* **07** (2013) 027 [arXiv:1211.5560] [INSPIRE].

[26] M. Holthausen, M. Lindner and M.A. Schmidt, *CP and Discrete Flavour Symmetries*, *JHEP* **04** (2013) 122 [arXiv:1211.6953] [INSPIRE].

[27] M.-C. Chen, M. Fallbacher, K.T. Mahanthappa, M. Ratz and A. Trautner, *CP Violation from Finite Groups*, *Nucl. Phys.* **B 883** (2014) 267 [arXiv:1402.0507] [INSPIRE].

[28] G.-J. Ding, S.F. King, C. Luhn and A.J. Stuart, *Spontaneous CP-violation from vacuum alignment in S_4 models of leptons*, *JHEP* **05** (2013) 084 [arXiv:1303.6180] [INSPIRE].

[29] F. Feruglio, C. Hagedorn and R. Ziegler, *A realistic pattern of lepton mixing and masses from S_4 and CP*, *Eur. Phys. J.* **C 74** (2014) 2753 [arXiv:1303.7178] [INSPIRE].

[30] C.C. Nishi and B.L. Sánchez-Vega, *Mu-tau reflection symmetry with a texture-zero*, *JHEP* **01** (2017) 068 [arXiv:1611.08282] [INSPIRE].

[31] W. Rodejohann and X.-J. Xu, *Trimaximal μ-τ reflection symmetry*, *Phys. Rev.* **D 96** (2017) 055039 [arXiv:1705.02027] [INSPIRE].

[32] J.T. Penedo, S.T. Petcov and A.V. Titov, *Neutrino mixing and leptonic CP-violation from S_4 flavour and generalised CP symmetries*, *JHEP* **12** (2017) 022 [arXiv:1705.00309] [INSPIRE].

[33] R. Samanta and A. Ghosal, *Probing maximal zero textures with broken cyclic symmetry in inverse seesaw*, *Nucl. Phys.* **B 911** (2016) 846 [arXiv:1507.02582] [INSPIRE].

[34] Z.-h. Zhao, *Modifications to the neutrino mixing from the μ-τ reflection symmetry*, *Nucl. Phys.* **B 935** (2018) 129 [arXiv:1803.04603] [INSPIRE].

[35] R. Samanta, P. Roy and A. Ghosal, *Consequences of minimal seesaw with complex $\mu\tau$ antisymmetry of neutrinos*, *JHEP* **06** (2018) 085 [arXiv:1712.06555] [INSPIRE].

[36] S.F. King and C.C. Nishi, *Mu-tau symmetry and the Littlest Seesaw*, Phys. Lett. **B 785** (2018) 391 [arXiv:1807.00023] [INSPIRE].

[37] Z.-C. Liu, C.-X. Yue and Z.-H. Zhao, *On the textures of neutrino mass matrix for maximal atmospheric mixing angle and Dirac CP phase*, JHEP **10** (2018) 106 [arXiv:1807.10031] [INSPIRE].

[38] M.H. Rahat, P. Ramond and B. Xu, *Asymmetric tribimaximal texture*, Phys. Rev. **D 98** (2018) 055030 [arXiv:1805.10684] [INSPIRE].

[39] C.C. Nishi, B.L. Sánchez-Vega and G. Souza Silva, *$\mu\tau$ reflection symmetry with a high scale texture-zero*, JHEP **09** (2018) 042 [arXiv:1806.07412] [INSPIRE].

[40] D.M. Barreiros, R.G. Felipe and F.R. Joaquim, *Combining texture zeros with a remnant CP symmetry in the minimal type-I seesaw*, JHEP **01** (2019) 223 [arXiv:1810.05454] [INSPIRE].

[41] F.J. de Anda, S.F. King and E. Perdomo, SU(5) *Grand Unified Theory with A_4 Modular Symmetry*, arXiv:1812.05620 [INSPIRE].

[42] S.F. King and Y.-L. Zhou, *Littlest mu-tau seesaw*, JHEP **05** (2019) 217 [arXiv:1901.06877] [INSPIRE].

[43] G. Ecker, W. Grimus and H. Neufeld, *A Standard Form for Generalized CP Transformations*, J. Phys. **A 20** (1987) L807 [INSPIRE].

[44] W. Grimus and M.N. Rebelo, *Automorphisms in gauge theories and the definition of CP and P*, Phys. Rept. **281** (1997) 239 [hep-ph/9506272] [INSPIRE].

[45] P. Chen, C.-Y. Yao and G.-J. Ding, *Neutrino Mixing from CP Symmetry*, Phys. Rev. **D 92** (2015) 073002 [arXiv:1507.03419] [INSPIRE].

[46] E. Ma, *Neutrino mixing: A_4 variations*, Phys. Lett. **B 752** (2016) 198 [arXiv:1510.02501] [INSPIRE].

[47] P. Chen, G.-J. Ding, F. Gonzalez-Canales and J.W.F. Valle, *Generalized μ-τ reflection symmetry and leptonic CP-violation*, Phys. Lett. **B 753** (2016) 644 [arXiv:1512.01551] [INSPIRE].

[48] P. Chen, G.-J. Ding, F. Gonzalez-Canales and J.W.F. Valle, *Classifying CP transformations according to their texture zeros: theory and implications*, Phys. Rev. **D 94** (2016) 033002 [arXiv:1604.03510] [INSPIRE].

[49] R. Sinha, P. Roy and A. Ghosal, *CP transformed mixed $\mu\tau$ antisymmetry for neutrinos and its consequences*, Phys. Rev. **D 99** (2019) 033009 [arXiv:1809.06615] [INSPIRE].

[50] R. Samanta, P. Roy and A. Ghosal, *Extended scaling and residual flavor symmetry in the neutrino Majorana mass matrix*, Eur. Phys. J. **C 76** (2016) 662 [arXiv:1604.06731] [INSPIRE].

[51] R. Samanta, P. Roy and A. Ghosal, *Complex Scaling in Neutrino Mass Matrix*, Acta Phys. Polon. Supp. **9** (2016) 807 [arXiv:1604.01206] [INSPIRE].

[52] R. Samanta, M. Chakraborty, P. Roy and A. Ghosal, *Baryon asymmetry via leptogenesis in a neutrino mass model with complex scaling*, JCAP **03** (2017) 025 [arXiv:1610.10081] [INSPIRE].

[53] A. Ghosal and R. Samanta, *Probing texture zeros with scaling ansatz in inverse seesaw*, JHEP **05** (2015) 077 [arXiv:1501.00916] [INSPIRE].

JHEP01(2020)193

[54] R. Samanta and M. Chakraborty, *A study on a minimally broken residual TBM-Klein symmetry with its implications on flavoured leptogenesis and ultra high energy neutrino flux ratios*, *JCAP* **02** (2019) 003 [arXiv:1802.04751] [INSPIRE].

[55] R. Sinha, R. Samanta and A. Ghosal, *Generalized $\mathbb{Z}_2 \times \mathbb{Z}_2$ in scaling neutrino Majorana mass matrix and baryogenesis via flavored leptogenesis*, *JHEP* **12** (2017) 030 [arXiv:1706.00946] [INSPIRE].

[56] R. Sinha, S. Bhattacharya and R. Samanta, *Phenomenological implications of the Friedberg-Lee transformation in a neutrino mass model with $\mu\tau$-flavored CP symmetry*, *JHEP* **03** (2019) 081 [arXiv:1810.05391] [INSPIRE].

[57] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, *On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe*, *Phys. Lett.* **155B** (1985) 36 [INSPIRE].

[58] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, *Phys. Lett.* **B 174** (1986) 45 [INSPIRE].

[59] A. Riotto and M. Trodden, *Recent progress in baryogenesis*, *Ann. Rev. Nucl. Part. Sci.* **49** (1999) 35 [hep-ph/9901362] [INSPIRE].

[60] E.W. Kolb and M.S. Turner, *The Early Universe*, *Front. Phys.* **69** (1990) 1 [INSPIRE].

[61] A. Pilaftsis and T.E.J. Underwood, *Resonant leptogenesis*, *Nucl. Phys.* **B 692** (2004) 303 [hep-ph/0309342] [INSPIRE].

[62] F.F. Deppisch and A. Pilaftsis, *Lepton Flavour Violation and θ_{13} in Minimal Resonant Leptogenesis*, *Phys. Rev.* **D 83** (2011) 076007 [arXiv:1012.1834] [INSPIRE].

[63] W. Buchmüller, P. Di Bari and M. Plümacher, *Leptogenesis for pedestrians*, *Annals Phys.* **315** (2005) 305 [hep-ph/0401240] [INSPIRE].

[64] S. Davidson, E. Nardi and Y. Nir, *Leptogenesis*, *Phys. Rept.* **466** (2008) 105 [arXiv:0802.2962] [INSPIRE].

[65] P. Minkowski, *$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?*, *Phys. Lett.* **67B** (1977) 421 [INSPIRE].

[66] M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, *Conf. Proc.* **C 790927** (1979) 315 [arXiv:1306.4669] [INSPIRE].

[67] R.N. Mohapatra and G. Senjanović, *Neutrino Mass and Spontaneous Parity Nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912 [INSPIRE].

[68] Planck collaboration, *Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth*, *Astron. Astrophys.* **596** (2016) A107 [arXiv:1605.02985] [INSPIRE].

[69] P. Chen, G.-J. Ding and S.F. King, *Leptogenesis and residual CP symmetry*, *JHEP* **03** (2016) 206 [arXiv:1602.03873] [INSPIRE].

[70] C. Hagedorn and E. Molinaro, *Flavor and CP symmetries for leptogenesis and $0\nu\beta\beta$ decay*, *Nucl. Phys.* **B 919** (2017) 404 [arXiv:1602.04206] [INSPIRE].

[71] A. Abada, S. Davidson, A. Ibarra, F.X. Josse-Michaux, M. Losada and A. Riotto, *Flavour Matters in Leptogenesis*, *JHEP* **09** (2006) 010 [hep-ph/0605281] [INSPIRE].

[72] E. Nardi, Y. Nir, E. Roulet and J. Racker, *The Importance of flavor in leptogenesis*, *JHEP* **01** (2006) 164 [hep-ph/0601084] [INSPIRE].

[73] S. Blanchet and P. Di Bari, *Flavor effects on leptogenesis predictions*, *JCAP* **03** (2007) 018 [hep-ph/0607330] [INSPIRE].

[74] P.S.B. Dev, P. Di Bari, B. Garbrecht, S. Lavignac, P. Millington and D. Teresi, *Flavor effects in leptogenesis*, *Int. J. Mod. Phys.* **A 33** (2018) 1842001 [arXiv:1711.02861] [INSPIRE].

[75] S.F. King, *Large mixing angle MSW and atmospheric neutrinos from single right-handed neutrino dominance and* U(1) *family symmetry*, *Nucl. Phys.* **B 576** (2000) 85 [hep-ph/9912492] [INSPIRE].

[76] S.F. King, *Constructing the large mixing angle MNS matrix in seesaw models with right-handed neutrino dominance*, *JHEP* **09** (2002) 011 [hep-ph/0204360] [INSPIRE].

[77] P. Di Bari and A. Riotto, *Successful type-I Leptogenesis with* SO(10)*-inspired mass relations*, *Phys. Lett.* **B 671** (2009) 462 [arXiv:0809.2285] [INSPIRE].

[78] S. Blanchet, P. Di Bari, D.A. Jones and L. Marzola, *Leptogenesis with heavy neutrino flavours: from density matrix to Boltzmann equations*, *JCAP* **01** (2013) 041 [arXiv:1112.4528] [INSPIRE].

[79] P. Di Bari, *Seesaw geometry and leptogenesis*, *Nucl. Phys.* **B 727** (2005) 318 [hep-ph/0502082] [INSPIRE].

[80] P. Di Bari, M. Re Fiorentin and R. Samanta, *Representing seesaw neutrino models and their motion in lepton flavour space*, *JHEP* **05** (2019) 011 [arXiv:1812.07720] [INSPIRE].

[81] P.H. Frampton, S.L. Glashow and T. Yanagida, *Cosmological sign of neutrino CP-violation*, *Phys. Lett.* **B 548** (2002) 119 [hep-ph/0208157] [INSPIRE].

[82] M. Raidal and A. Strumia, *Predictions of the most minimal seesaw model*, *Phys. Lett.* **B 553** (2003) 72 [hep-ph/0210021] [INSPIRE].

[83] S. Antusch, P. Di Bari, D.A. Jones and S.F. King, *Leptogenesis in the Two Right-Handed Neutrino Model Revisited*, *Phys. Rev.* **D 86** (2012) 023516 [arXiv:1107.6002] [INSPIRE].

[84] G. Bambhaniya, P.S. Bhupal Dev, S. Goswami, S. Khan and W. Rodejohann, *Naturalness, Vacuum Stability and Leptogenesis in the Minimal Seesaw Model*, *Phys. Rev.* **D 95** (2017) 095016 [arXiv:1611.03827] [INSPIRE].

[85] W. Grimus, S. Kaneko, L. Lavoura, H. Sawanaka and M. Tanimoto, *mu-tau antisymmetry and neutrino mass matrices*, *JHEP* **01** (2006) 110 [hep-ph/0510326] [INSPIRE].

[86] G.F. Giudice, M. Peloso, A. Riotto and I. Tkachev, *Production of massive fermions at preheating and leptogenesis*, *JHEP* **08** (1999) 014 [hep-ph/9905242] [INSPIRE].

[87] M.Yu. Khlopov and A.D. Linde, *Is It Easy to Save the Gravitino?*, *Phys. Lett.* **138B** (1984) 265 [INSPIRE].

[88] G.F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, *Towards a complete theory of thermal leptogenesis in the SM and MSSM*, *Nucl. Phys.* **B 685** (2004) 89 [hep-ph/0310123] [INSPIRE].

[89] D. Croon, N. Fernandez, D. McKeen and G. White, *Stability, reheating and leptogenesis*, *JHEP* **06** (2019) 098 [arXiv:1903.08658] [INSPIRE].

[90] W. Buchmüller, P. Di Bari and M. Plümacher, *The Neutrino mass window for baryogenesis*, *Nucl. Phys.* **B 665** (2003) 445 [hep-ph/0302092] [INSPIRE].

[91] W. Buchmüller, P. Di Bari and M. Plümacher, *Cosmic microwave background, matter-antimatter asymmetry and neutrino masses*, *Nucl. Phys.* **B 643** (2002) 367 [*Erratum ibid.* **B 793** (2008) 362] [hep-ph/0205349] [INSPIRE].

[92] S. H.-S. Alexander, M.E. Peskin and M.M. Sheikh-Jabbari, *Leptogenesis from gravity waves in models of inflation*, *Phys. Rev. Lett.* **96** (2006) 081301 [hep-th/0403069] [INSPIRE].

[93] P. Adshead, A.J. Long and E.I. Sfakianakis, *Gravitational Leptogenesis, Reheating and Models of Neutrino Mass*, *Phys. Rev.* **D 97** (2018) 043511 [arXiv:1711.04800] [INSPIRE].

[94] E. Bertuzzo, P. Di Bari and L. Marzola, *The problem of the initial conditions in flavoured leptogenesis and the tauon N_2-dominated scenario*, *Nucl. Phys.* **B 849** (2011) 521 [arXiv:1007.1641] [INSPIRE].

[95] G. Engelhard, Y. Grossman, E. Nardi and Y. Nir, *The Importance of N2 leptogenesis*, *Phys. Rev. Lett.* **99** (2007) 081802 [hep-ph/0612187] [INSPIRE].

[96] P. Di Bari and L. Marzola, SO(10)*-inspired solution to the problem of the initial conditions in leptogenesis*, *Nucl. Phys.* **B 877** (2013) 719 [arXiv:1308.1107] [INSPIRE].

[97] M. Chianese and P. Di Bari, *Strong thermal* SO(10)*-inspired leptogenesis in the light of recent results from long-baseline neutrino experiments*, *JHEP* **05** (2018) 073 [arXiv:1802.07690] [INSPIRE].

[98] S. Blanchet and P. Di Bari, *Leptogenesis beyond the limit of hierarchical heavy neutrino masses*, *JCAP* **06** (2006) 023 [hep-ph/0603107] [INSPIRE].

[99] D. Aristizabal Sierra, L.A. Muñoz and E. Nardi, *Purely Flavored Leptogenesis*, *Phys. Rev.* **D 80** (2009) 016007 [arXiv:0904.3043] [INSPIRE].

[100] S. Davidson and A. Ibarra, *A Lower bound on the right-handed neutrino mass from leptogenesis*, *Phys. Lett.* **B 535** (2002) 25 [hep-ph/0202239] [INSPIRE].

[101] B. Adhikary, M. Chakraborty and A. Ghosal, *Masses, mixing angles and phases of general Majorana neutrino mass matrix*, *JHEP* **10** (2013) 043 [*Erratum ibid.* **09** (2014) 180] [arXiv:1307.0988] [INSPIRE].

[102] M. Agostini et al., *Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA*, arXiv:1703.00570 [INSPIRE].

[103] KamLAND-Zen collaboration, *Limit on Neutrinoless $\beta\beta$ Decay of ^{136}Xe from the First Phase of KamLAND-Zen and Comparison with the Positive Claim in ^{76}Ge*, *Phys. Rev. Lett.* **110** (2013) 062502 [arXiv:1211.3863] [INSPIRE].

[104] EXO-200 collaboration, *Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200*, *Phys. Rev. Lett.* **109** (2012) 032505 [arXiv:1205.5608] [INSPIRE].

[105] M. Agostini, G. Benato and J. Detwiler, *Discovery probability of next-generation neutrinoless double-β decay experiments*, *Phys. Rev.* **D 96** (2017) 053001 [arXiv:1705.02996] [INSPIRE].

[106] J. Shirai, *Results and future plans for the KamLAND-Zen experiment*, *J. Phys. Conf. Ser.* **888** (2017) 012031 [INSPIRE].

[107] B. Mong, *nEXO Double Beta Decay*, in *HQL2016*, Blacksburg, VA, U.S.A. (2016) [http://indico.phys.vt.edu/event/31/session/29/contribution/103/material/slides/0.pdf].

[108] CUPID collaboration, *CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle IDentification*, arXiv:1504.03599 [INSPIRE].

[109] CUORE collaboration, *CUORE: A Cryogenic underground observatory for rare events*, *Nucl. Instrum. Meth.* **A 518** (2004) 775 [hep-ex/0212053] [INSPIRE].

[110] B. Schwingenheuer, *Neutrinoless double beta decay with 76Ge*, in *CERN EP Seminar*, Geneva, Switzerland (2017) [https://indico.cern.ch/event/581028/attachments/1395349/2129744/ge76_cern.pdf].

[111] R. Samanta, R. Sinha and A. Ghosal, *Importance of generalized $\mu\tau$ symmetry and its CP extension on neutrino mixing and leptogenesis*, *JHEP* **10** (2019) 057 [arXiv:1805.10031] [INSPIRE].

[112] R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, *Baryogenesis through leptogenesis*, *Nucl. Phys.* **B 575** (2000) 61 [hep-ph/9911315] [INSPIRE].

[113] S. Antusch, P. Di Bari, D.A. Jones and S.F. King, *A fuller flavour treatment of N_2-dominated leptogenesis*, *Nucl. Phys.* **B 856** (2012) 180 [arXiv:1003.5132] [INSPIRE].

[114] K. Moffat, S. Pascoli, S.T. Petcov, H. Schulz and J. Turner, *Three-flavored nonresonant leptogenesis at intermediate scales*, *Phys. Rev.* **D 98** (2018) 015036 [arXiv:1804.05066] [INSPIRE].

[115] P.S. Bhupal Dev, P. Millington, A. Pilaftsis and D. Teresi, *Flavour Covariant Transport Equations: an Application to Resonant Leptogenesis*, *Nucl. Phys.* **B 886** (2014) 569 [arXiv:1404.1003] [INSPIRE].

[116] A. De Simone and A. Riotto, *Quantum Boltzmann Equations and Leptogenesis*, *JCAP* **08** (2007) 002 [hep-ph/0703175] [INSPIRE].

[117] M. Garny, A. Kartavtsev and A. Hohenegger, *Leptogenesis from first principles in the resonant regime*, *Annals Phys.* **328** (2013) 26 [arXiv:1112.6428] [INSPIRE].

[118] P.S. Bhupal Dev, P. Millington, A. Pilaftsis and D. Teresi, *Kadanoff-Baym approach to flavour mixing and oscillations in resonant leptogenesis*, *Nucl. Phys.* **B 891** (2015) 128 [arXiv:1410.6434] [INSPIRE].

[119] A. Kartavtsev, P. Millington and H. Vogel, *Lepton asymmetry from mixing and oscillations*, *JHEP* **06** (2016) 066 [arXiv:1601.03086] [INSPIRE].

[120] M.A. Luty, *Baryogenesis via leptogenesis*, *Phys. Rev.* **D 45** (1992) 455 [INSPIRE].

[121] F. Hahn-Woernle, M. Plümacher and Y.Y.Y. Wong, *Full Boltzmann equations for leptogenesis including scattering*, *JCAP* **08** (2009) 028 [arXiv:0907.0205] [INSPIRE].

[122] M. Plümacher, *Baryon asymmetry, neutrino mixing and supersymmetric* SO(10) *unification*, *Nucl. Phys.* **B 530** (1998) 207 [hep-ph/9704231] [INSPIRE].

[123] E.K. Akhmedov, M. Frigerio and A.Yu. Smirnov, *Probing the seesaw mechanism with neutrino data and leptogenesis*, *JHEP* **09** (2003) 021 [hep-ph/0305322] [INSPIRE].

[124] C.S. Fong, D. Meloni, A. Meroni and E. Nardi, *Leptogenesis in* SO(10), *JHEP* **01** (2015) 111 [arXiv:1412.4776] [INSPIRE].