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# VALIDITY OF NEUTRINO MASS MODELS THROUGH THERMAL LEPTOGENESIS

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**ABSTRACT**

*The validity of neutrino mass models through thermal leptogenesis on describing the presently available neutrino mass patterns, are studied numerically. We consider the Majorana CP violating phases coming from right-handed Majorana mass matrices, to estimate the baryon asymmetry of the universe, for different neutrino mass models, namely quasi-degenerate, inverted hierarchical and normal hierarchical models within μ-τ symmetry. Considering three possible diagonal forms of Dirac neutrino mass matrix as down-quark type, charged-lepton type or up-quark type mass matrices, the right-handed Majorana mass matrices are constructed from the light neutrino mass matrices through the inversion of seesaw formula. We also observe the enhancement in baryon asymmetry due to lepton flavour effects in thermal leptogenesis.Further enhancement from brane world cosmology may marginally modify the present finding.*

***Keywords: Leptogenesis, baryon asymmetry, neutrino masses, Majoranaright-handed neutrinos.***

## I. INTRODUCTION

The discovery of nonzero neutrino masses is one of the most important discoveries of particle physics. It shows that the standard model of particle physics in indeed incomplete. It has a great implications not only to particle physics but also to cosmology. The existence of heavy right-handed Majorana neutrinos in left-right symmetric GUT models, not only gives non-vanishing neutrino masses through the celebrated seesaw mechanism[l] but also plays an important role in explaining the baryon asymmetry of the universe (BAU) [2] $\eta_B = (6.1^{+0.3}_{-0.2})10^{-10}$. Such baryon asymmetry, $\eta = n_B/n_\gamma$ can bedynamically generated if the particle interaction rate and the expansion rate of the universe, satisfy Sakharov's three famous conditions [3]. Heavy Majorana right-handed neutrinos satisfy the second condition i.e., C and CP violation, as they can have an asymmetric decay to leptons ($l_L$) and Higgs particles ($\varphi$), and the process occurs at different rates for particles and antiparticles. The lepton asymmetry thus generated, is then partially converted to baryon asymmetry through the non-perturbative electroweak sphaleron effects [4, 5]. In case of thermal leptogenesis, the right-handed neutrinos can be generated thermally after inflation, if their masses are comparable to or below the reheating temperature $M_1 \leq T_R$. This allows high scale reheating temperature $T_R \geq 10^9$ GeV [6].

In order to calculate the baryon asymmetry from a given neutrino mass model, one usually starts with a suitable texture of light Majorana neutrino mass matrix, $m_{LL}$ and then relates it with the heavy Majorana neutrinos $M_{RR}$ and the Dirac neutrino mass matrix $m_{LR}$ by inverting the seesaw formula in an elegant way. Since the structure of Yukawa matrix for Dirac neutrino is not known, we consider the texture of Dirac neutrino mass matrix $m_{LR}$ as either the down quark mass matrix or the charged lepton mass matrix or up quark mass matrix, as allowed by SO(10) GUT models, for phenomenological analysis. The estimations of baryon asymmetry of the universe in the light of thermal leptogenesis, may thus serve as additional information to discriminate the correct pattern of neutrino mass models and also shed light on the structure of unknown Dirac neutrino mass matrix.

Section II describes briefly the formalism for estimating the lepton asymmetry in thermal leptogenesis. Important expressions related to various neutrino mass models $m_{LL}$ which obey μ-τsymmetry are given in section III. Numerical analysis and predictions are outlined in Section IV. Finally in Section V we conclude with a summary.

## II. THEORETICAL FORMALISM OF THERMAL LEPTOGENESIS

### 2.1 Thermal leptogenesis

The canonical seesaw formula (known as type I)[cf.1] relates the light left-handed Majorana neutrino mass matrix $m_{LL}$ and heavy right-handed Majorana mass matrix $M_{RR}$ in a simple way

$$m_{LL} = -m_{LR} M_{RR} m_{LR}^{T} \quad (1)$$

where $m_{LR}$ is the Dirac neutrino mass matrix. For our calculation of lepton asymmetry, we consider the model[5,7] where the asymmetric decay of the lightest of the heavy right-handed Majorana neutrinos, is assumed. The physical Majorana neutrino $N_R$ decays into two modes: $N_R \rightarrow l_L + \varphi^\dagger$, $N_R \rightarrow \bar{l}_L + \varphi$, where $l_L$ is the lepton, $\bar{l}_L$ is the antilepton, and φ is the Higgs particle. The branching ratio for these two decay modes is likely to be different. The CP-asymmetry which is caused by the interference of tree level with one-loop corrections for the decays of lightest of heavy right-handed Majorana neutrino $N_1$ is defined by[5,8]

$$\epsilon = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \quad (2)$$

Here $\Gamma = \Gamma(N_1 \rightarrow l_L \varphi)$ and $\overline{\Gamma} = \Gamma(N_1 \rightarrow \bar{l}_L \varphi)$ are the decay rates.A perturbative calculation from the interference between tree level and vertex plus self energy diagrams, gives [9] the lepton asymmetry $\epsilon_i$ for non-SUSY case as

$$\epsilon_i = -\frac{1}{8\pi} \frac{1}{(h^\dagger h)_{ii}} \sum_{j=2,3} \mathrm{Im}[(h^\dagger h)_{ij}]^2 [f(\frac{M_j^2}{M_i^2})\ g(\frac{M_j^2}{M_i^2})] \quad (3)$$

wheref(x)and g(x) represent the contributions from vertex and self-energy corrections respectively, f(x) = $\sqrt{x}\,[-1 + (x+1)\ln(1+\frac{1}{x})]$, g(x) = $\frac{\sqrt{x}}{x-1}$. For hierarchical right-handed neutrino masses where $x$ is large, we have the approximation [cf.2], $f(x) + g(x) \cong \frac{3}{2\sqrt{x}}$. This simplifies to

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$$\epsilon_i = -\frac{3}{16\pi}\left[\frac{\mathrm{Im}[(h^\dagger h)^2_{12}]}{(h^\dagger h)_{11}}\frac{M_1}{M_2} + \frac{\mathrm{Im}[(h^\dagger h)^2_{13}]}{(h^\dagger h)_{11}}\frac{M_1}{M_3}\right] \quad (4)$$

where $h = m_{LR}/v$ is the Yukawa coupling of the Dirac neutrino mass matrix in the diagonal basis of $M_{RR}$ and v= 174 GeV is the vev of the standard model. In term of light Majorana neutrino mass matrix $m_{LL}$ the above expression can be simplified to

$$\epsilon_1 = -\frac{3}{16\pi}\frac{M_1}{(h^\dagger h)_{11}}\mathrm{Im}((h^\dagger m_{LL} h^*)_{11}. \quad (5)$$

For quasi-degenerate spectrum of the heavy right-handed Majorana neutrino masses, i.e., for $M_1 \approx M_2 < M_3$ the asymmetry is largely enhanced by a resonance factor and in such situation, the lepton asymmetry is modified[10] to

$$\epsilon_1 = \frac{1}{8\pi}\frac{\mathrm{Im}[(h^\dagger h)^2_{12}]}{(h^\dagger h)_{11}} R \quad (6)$$

where $R = \frac{M_2^2(M_2^2 - M_1^2)}{(M_1^2 - M_2^2)^2 + \Gamma_2^2 M_1^2}$ and $\Gamma_2 = \frac{(h^\dagger h)_{22} M_2}{8\pi}$. It can be noted that in case of SUSY, the functions $f(x)$ and $g(x)$ are given by $f(x) = \sqrt{x}\ln(1+\frac{1}{x})$ and $g(x) = \frac{2\sqrt{x}}{x-1}$; for large x one can have $f(x) + g(x) \approx 3/\sqrt{x}$. Therefore the factor $3/8$ will appear in place of $3/16$ inthe expression of CP asymmetry in eq. (4).The CP asymmetry parameter $\epsilon_i$ is related to leptonic asymmetric parameter through $Y_L$ as

$$Y_L \equiv \frac{n_L - \bar{n}_L}{s} = \sum_i^3 \frac{\epsilon_i \kappa_i}{g_{*i}} \quad (7)$$

where $n_L$ is the lepton number density, $\bar{n}_L$ is the anti-lepton number density, s is the entropy density, $\kappa_i$ is the dilution factor for the CP asymmetry $\epsilon_i$, and $g_{*i}$ is the effective number of degrees of freedom at temperature $T = M_i$. The baryon asymmetry $Y_B$ produced through the sphaleron transition of $Y_L$, while the quantum number B −L remains conserved, is given by[11]

$$Y_B = \frac{n_B}{s} = CY_{B-L} = CY_L \quad (8)$$

where $C = \frac{8N_F + 4N_H}{22N_F + 13N_H}$. Here $N_F$ is the number of fermion families and $N_H$ is the number of Higgs doublets. Since $s = 7.04 n_\gamma$ the baryon number density over photon number density $n_\gamma$ corresponds to the observed baryon asymmetry of the Universe[12],

$$\eta_B^{SM} = (\frac{\eta_B}{\eta_\gamma})^{SM} \approx d\kappa_1 \epsilon_1 \quad (9)$$

where $d \approx 0.98x\,10^{-2}$ is used in the present calculation. In case of MSSM, there is no major numerical change with respect to the non-supersymmetric case in the estimation of baryon asymmetry. One expects approximate enhancement factor of about $\sqrt{2}(2\sqrt{2})$ for strong (weak) washout regime[2].

In the expression for baryon-to-photon ratio in eq. (9), $\kappa_1$describes the washout of the lepton asymmetry due to various lepton number violating processes. This efficiency factor (also known as dilution factor) mainly depends on the effective neutrino mass

$$\tilde{m}_1 = \frac{(h^+h)_{11}v^2}{M_1} \qquad (10)$$

where $v$ is the electroweak vev, $v = 174$ GeV. For $10^{-2}eV < \tilde{m}_1 < 10^3 eV$, the washout factor $\kappa_1$can be well approximated by[8, 13]

$$\kappa_1(\tilde{m}_1) = 0.3[\frac{10^{-3}}{\tilde{m}_1}]\,[log\,\frac{\tilde{m}_1}{10^{-3}}]^{-0.6} \qquad (11)$$

We adopt a single expression for $\kappa_1$valid only for the given range of $\tilde{m}_1$[13, 14].

### 2.2 Flavoured thermal leptogenesis

Many authors[15] have included the flavour effects in thermal leptogenesis, and such effects lead to enhancement in baryon asymmetry over the single flavour approximation. In the flavour basis the equation for lepton asymmetry in $N_1 \rightarrow l_\alpha \varphi$decay where $\alpha = (e, \mu, \tau)$, becomes

$$\varepsilon_{\alpha\alpha} = \frac{1}{8\pi}\frac{1}{(h^+h)_{11}}[\sum_{j=2,3} \mathrm{Im}[h^*_{\alpha 1}(h^+h)_{1j}h_{\alpha j}]g(x_j) + \sum_j \mathrm{Im}[h^*_{\alpha 1}(h^+h)_{j1}h_{\alpha j}]\frac{1}{(1-x_j)}]. \qquad (12)$$

Here we have $x_j = \frac{M_j^2}{M_i^2}$ and $g(x_j) \sim \frac{3}{2}\frac{1}{\sqrt{x_j}}$. The efficiency factor for the out-of-equilibruim situation is given by

$\kappa_\alpha = \frac{m_*}{\tilde{m}_{\alpha\alpha}}$. Here $m_* = 8\pi H v^2/M_1^2 \sim 1.1x10^{-3}$ eV, and $\tilde{m}_{\alpha\alpha} = \frac{h^\dagger_{\alpha 1}h_{\alpha 1}}{M_1}v^2$. This leads to BAU

$$\eta_{3B} = \frac{n_B}{n_\gamma} \sim 10^{-2}\sum_\alpha \epsilon_{\alpha\alpha}\kappa_\alpha \sim 10^{-2} m_* \sum_\alpha \frac{\epsilon_{\alpha\alpha}}{\tilde{m}_{\alpha\alpha}}. \qquad (13)$$

For single flavor case, the second term in $\epsilon_{\alpha\alpha}$vanishes when summed over all flavours. Thus

$$\epsilon_1 \equiv \sum_\alpha \epsilon_{\alpha\alpha} = \frac{1}{8\pi}\frac{1}{(h^\dagger h)_{11}}\sum_j Im[(h^\dagger h)^2_{1j}]g(x_j) \quad (14)$$

This leads to baryon asymmetry,

$$\eta_{1B} \approx 10^{-2} m_* \frac{\epsilon_1}{\tilde{m}} = 10^{-2}\kappa_1\epsilon_1 \quad (15)$$

Where $\epsilon_1 = \sum_\alpha \epsilon_{\alpha\alpha}$ $and$ $\tilde{m} = \sum_\alpha \tilde{m}_{\alpha\alpha}$

## III. CLASSIFICATION OF NEUTRINO MASS MODELS

After parameterizations of the general $\mu - \tau$ matrix, the required specific neutrino mass matrices are listed below.

**Quasi-degenerate model [IA]** with $Diag\,(m_{1,} -m_2, m_3)$:

$$m_{LL} = \begin{pmatrix} \epsilon - 2\eta & -a\epsilon & -a\epsilon \\ -a\epsilon & \frac{1}{2} - b\eta & -\frac{1}{2} - \eta \\ -a\epsilon & -\frac{1}{2} - \eta & \frac{1}{2} - b\eta \end{pmatrix} m_0$$

The input values of the parameters are fixed at $\epsilon$ = 0.66115, $\eta = 0.16535, m_0 = 0.4eV$(for $\tan^2\theta_{12}$ =0.45 we take $a$ = 0.868 and $b$ = 1.025).

**Quasi-degenerate model [IB]** with$Diag\,(m_1, m_2, m_3)$:

$$m_{LL} = \begin{pmatrix} 1 - \epsilon - 2\eta & a\epsilon & a\epsilon \\ a\epsilon & 1 - b\eta & -\eta \\ a\epsilon & -\eta & 1 - b\eta \end{pmatrix} m_0$$

with input values: $\epsilon$ =8.314x10$^{-5}$, $\eta$=0.00395,$m_0$=0.4eV (for $\tan^2\theta_{12}$ = 0.45 we take $a$ = 0.945 and $b$ = 0.998)

**Inverted Hierarchical model [II]**with $Diag\,(m_1, m_2, -m_3)$:

$$m_{LL}(IH) = \begin{pmatrix} 1 - 2\epsilon & -\epsilon & -\epsilon \\ -\epsilon & \frac{1}{2} & \frac{1}{2} - \eta \\ -\epsilon & \frac{1}{2} - \eta & \frac{1}{2} \end{pmatrix} m_0$$

(a) Inverted Hierarchy with even CP parity in the first two mass eigenvalues [IIA], $(m_i = m_1, m_2, m_3)$: $\eta/\epsilon = 1.0, \eta = 0.0048, m_0 = 0.05eV$.

(b) Inverted Hierarchy with odd CP parity in the first two mass eigenvalues [IIB], $(m_i = m_1, -m_2, m_3)$: $\eta/\epsilon = 1.0, \eta = 0.6607, m_0 = 0.05eV$.

**Normal Hierarchy model [III]**

$$m_{LL}(IH) = \begin{pmatrix} 0 & -\epsilon & -\epsilon \\ -\epsilon & 1 - \epsilon & 1 + \eta \\ -\epsilon & 1 + \eta & 1 - \epsilon \end{pmatrix} m_0$$

with input values:$\eta/\epsilon = 0.0, \epsilon = 0.146, m_0 = 0.028\ eV$.The above mass matrices have the potential to decrease the solar mixing angle from the tri-bimaximal value, without sacrificing μ-τ symmetry, through the identification of a flavour twister term $\eta/\epsilon$.

| Type | $\Delta m^2_{21}$ $[10^{-5} eV^2]$ | $\Delta m^2_{23}$ $[10^{-3} eV^2]$ | $tan^2\theta_{12}$ | $tan^2\theta_{23}$ | $sin\theta_{13}$ |
|---|---|---|---|---|---|
| (IA) | 7.82 | 2.20 | 0.45 | 1.0 | 0.0 |
| (IB) | 7.62 | 2.49 | 0.45 | 1.0 | 0.0 |
| (IC) | 7.62 | 2.49 | 0.45 | 1.0 | 0.0 |
| (IIA) | 7.91 | 2.35 | 0.45 | 1.0 | 0.0 |
| (IIB) | 8.40 | 2.03 | 0.45 | 1.0 | 0.0 |
| (III) | 7.53 | 2.45 | 0.45 | 1.0 | 0.0 |

**Table 1:**Predicted values of the solar and atmospheric neutrino mass-squared

differences for $tan^2\theta_{12} = 0.45$, using $m_{LL}$in section III.

## IV. NUMERICAL CALCULATIONS AND RESULTS

To compute the numerical analysis, we first choose the light left-handed Majorana neutrino mass matrix $m_{LL}$ presented in section 3. These mass matrices obey the μ-τ symmetry [16] which guarantees the deviation of solar angle from tri-bimaximalmixing[17]. The three input parameters are fixed at the stage of predictions of neutrino mass parameters and mixing given in Table 1.These results are consistent with the recent data on neutrino oscillation parameters. For the calculation of baryon asymmetry, we then translate these mass matrices to $M_{RR}$via the inversion of the seesaw formula,$M_{RR}$= $-m_{LR}^T m_{LL}^{-1} m_{LR}$. We choose a basis $U_R$where $M_{RR}^{diag} = U_R^T M_{RR} U_R = diag\,(M_1, M_2, M_3)$with real and positive eigenvalues. We then transform diagonal form of Dirac mass matrix, $m_{LR} = diag\,(\lambda^m, \lambda^n, 1)v$to the $U_R$basis: $m_{LR} \rightarrow m'_{LR}$= $m_{LR} U_R Q$where $Q = diag\,(1, e^{i\alpha}, e^{i\beta})$is the complex matrix containing CP-violating Majorana phases derived from $M_{RR}$. Here λ is the Wolfeinstein parameter and the choice *(m, n)* in $m_{LR}$gives the type of Dirac neutrino mass matrix. At the moment we consider phenomenologically three possible forms of Dirac neutrino mass matrix such as (i) *(m,n)* = (4,2) for the down-quark mass matrix, (ii) (6,2) for the charged-lepton type mass matrix, and (iii) (8,4) for up-quark type mass matrix. In this prime basis the Dirac neutrino Yukawa coupling becomes $h = \frac{m'_{LR}}{v}$which enters in the expression of CP- asymmetry $\epsilon_i$in (3) and (12). The new Yukawa coupling matrix *h* also becomes complex, and hence the term $Im(h^\dagger h)_{1j}$appearing in lepton asymmetry $\epsilon_1$gives a non-zero contribution. A straightforward simplification shows that$(h^\dagger h)_{1j}^2$= $(Q_{11}^*)^2 Q_{22}^2 R_2$ + $(Q_{11}^*)^2 Q_{33}^2 R_2$where $R_{2,3}$are real parameters. After inserting thevalues of phases the above expression leads to $Im(h^\dagger h)_{1j}^2 = -[R_2 sin2\,(\alpha - \beta) + R_3 sin2\alpha]$imparts non-zero CP asymmetry for particular choice of $(\alpha, \beta)$.

In our numerical estimation of lepton asymmetry, we choose some arbitrary values of $\alpha$ and $\beta$other than $\pi/2$ and 0.For example, light neutrino masses $(m_1, -m_2, m_3)$leads to $M_{RR}^{diag} = diag(M_1, -M_2, M_3)$, and we thus fix the Majorana phase $Q = diag\,(1, e^{i\alpha}, e^{i\beta})$ =$diag\,(1, e^{i(\pi/2+\pi/4)}, e^{i\pi/4})$ for $\alpha = (\pi/2 + \pi/4)$ and $\beta = \pi/4$. The extra phase $\pi/2$ in $\alpha$absorbs the negative sign before heavy Majorana mass.Our search programme such choice of the phase leads to highest numerical estimations oflepton CP asymmetry. In Table 1 we give numerical predictions on $\Delta m_{21}^2$and $\Delta m_{23}^2$of these neutrino mass models under consideration for the case of $\tan^2\theta_{12}$= 0.45. The three heavy right-handed Majorana neutrino masses are extracted from the right-handed Majorana mass matrices which are constructed through the inversion of seesaw formula, for three choices of diagonal Dirac-neutrino mass matrices discussed before.We get degenerate spectrum of right-handed heavy Majorana masses for normal hierarchical model and this allows us to use resonant leptogenesis formula in (4). The corresponding baryon asymmetries $\eta_B$are estimated for both non-flavour $\eta_{1B}$and flavour $\eta_{3B}$leptogenesis respectively in Table 2. As expected there is enhancement in baryon asymmetry in case of flavour leptogenesis. We also observe the sensitivity of baryon asymmetry predictions on the choice of Dirac neutrino mass matrix (m, n). For single flavour approximation neutrino mass models which can accommodate relatively good predictions are 111-(6, 2), IIB-(4,2) and IA-(4,2) respectively. In case of flavour leptogenesis there is enhancement on the scope of predictability on $\eta_B$ as shown in Table 2.

| Type | (m, n) | $M_1$ | $\epsilon_1$ | $\eta_{1B}$ | $\eta_{3B}$ |
|---|---|---|---|---|---|
| IA | (4,2) | 5.43xl0$^{10}$ | 1.49x10$^{-5}$ | 7.03x10$^{-}$ | 2.16x10$^{-}$ |
| IA | (6,2) | 4.51x10$^{8}$ | 1.31x10$^{-7}$ | $^{9}$5.76x10$^{-11}$ | $^{8}$1.34x10$^{-10}$ |
| IA | (8,4) | 3.65x10$^{6}$ | 1.16x10$^{-9}$ | 5.12x10$^{-13}$ | 1.19x10$^{-12}$ |
| IB | (4,2) | 5.01x10$^{9}$4.0 | 2.56x10$^{-14}$ | 7.15x10$^{-}$ | 1.09x10$^{-}$ |
| IB | (6,2) | 5x10$^{7}$ | 2.06x10$^{-16}$ | $^{1S}$5.76xl0$^{-20}$ | $^{9}$8.84x10$^{-12}$ |
| IB | (8,4 | 3.28x10$^{5}$ | 1.68x10$^{-18}$ | 4.67xl0$^{-22}$ | 7.16x10$^{-14}$ |
| IC | (4,2) | 5.01x10$^{9}$4.0 | 1.85x10$^{-13}$ | 5.12x10$^{-}$ | 7.16x10$^{-}$ |
| IC | (6,2) | 5x10$^{7}$ | 1.47x10$^{-15}$ | $^{17}$3.77x10$^{-19}$ | $^{9}$5.80x10$^{-11}$ |
| IC | (8,4 | 3.28x10$^{5}$ | 1.02x10$^{-16}$ | 2.82x10$^{-20}$ | 4.34x10$^{-12}$ |
| IIA | (4,2) | 4.02x10$^{10}$ | 1.12x10$^{-12}$ | 2.49x10$^{-15}$ | 7.90x10$^{-11}$ |
| IIA | (6,2) | 3.25x10$^{8}$ | 9.00x10$^{-15}$ | 2.00x10$^{-17}$ | 6.34x10$^{-13}$ |
| IIA | (8,4 | 2.63x10$^{6}$ | 7.53x10$^{-17}$ | 1.67x10$^{-19}$ | 5.35x10$^{-15}$ |
| IIB | (4,2) | 9.76x10$^{10}$ | 4.02x10$^{-6}$ | 3.25xl0$^{-}$ | 7.53x10$^{-}$ |
| IIB | (6,2) | 8.10x10$^{8}$ | 3.33x10$^{-8}$ | $^{9}$2.57xl0$^{-11}$ | $^{9}$5.96x10$^{-11}$ |
| IIB | (8,4 | 6.56x10$^{6}$ | 2.71x10$^{-10}$ | 2.09x10$^{-13}$ | 4.86x10$^{-13}$ |
| III | (4,2) | 3.73x10$^{12}$ | 3.09x10$^{-5}$ | 8.13x10$^{-}$ | 1.85x10$^{-}$ |
| III | (6,2) | 4.08x10$^{11}$ | 3.74x10$^{-5}$ | $^{8}$7.37xl0$^{-9}$ | $^{6}$1.62x10$^{-8}$ |
| III | (8,4 | 3.31x10$^{9}$ | 3.09x10$^{-7}$ | 6.06x10$^{-11}$ | 1.13x10$^{-10}$ |

**Table 2:**Lightest right-handed Majorana neutrino mass $M_1$ and values of CP asymmetry and baryon asymmetry for quasi-degenerate models (IA, IB, IC), inverted models (IIA, IIB) and normal hierarchical models (III), with $\tan^2\theta_{12}$=0.45, using neutrino mass matrices given in the text. The entry *(m, n)* in $m_{LR}$indicates the type of Dirac neutrino mass matrix taken as charged lepton mass matrix (6, 2) or up quark mass matrix (8,4), or down quark mass matrix(4,2) as explained in the text.

## V. SUMMARY AND DISCUSSIONS

To conclude, we first parameterize the light left-handed Majorana neutrino mass matrices describing the possible patterns of neutrino masses viz, quasi-degenerate, inverted hierarchical and normal hierarchical, which obey the μ↔τ symmetry. As a first test, these mass matrices predict the neutrino mass parameters and mixings consistent with neutrino oscillation data (Table 1), and all the three input parameters are fixed at this stage. In the next stage, these mass matrices are employed to estimate the baryon asymmetry of the universe, in thermal leptogenesis scenario (Tables 2). We use the CP violating Majorana phases derived from right-handed Majorana mass matrix, and also three possible forms of

Dirac neutrino mass matrices in the calculation. The overall analysis shows that normal hierarchical model appears to be the most favourable choice in nature. The present analysis though phenomeno-logical, may serve as additional criteria to discard some of the presently available neutrino mass models. The conclusion also agrees with other criteria such as stability under quantum radiative corrections. We also observe some enhancement effects in flavour leptogenesis compared to non-flavour leptogenesis. Further enhancement from brane world cosmology [18] may marginally modify the present finding.

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