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Connecting Neutrino Parameters in the Light of Laptogenesis Considering Seesaw Models

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Abstract—*We present an analysis of all the experimentally undetermined neutrino parameters namely lightest neutrino mass, neutrino CP phases and baryon asymmetry of the Universe within the framework of a model where both type I and type II seesaw mechanisms can contribute to tiny neutrino masses. Considering both normal and inverted hierarchical neutrino mass models, we study the effects of Dirac and Majorana neutrino phases in the origin of baryogenesis through the mechanism of leptogenesis. Here we consider Type I seesaw mass matrix as tri-bimaximal (TBM) type neutrino mixing which always gives non zero reactor mixing angle. The type II seesaw mass matrix is then considered as a correction term to generate the best fit values of neutrino parameters. We consider different contribution from type I and type II seesaw mechanism to study the effects of neutrino Dirac and Majorona CP phases in the baryon asymmetry of the universe. We further study to connect all these experimentally undetermined neutrino parameters by considering various contribution of type I and type II seesaw*

1. INTRODUCTION

After the discovery of the Higgs Boson we have found that Standard Model of particle physics is one of the most famous and precise model that can explain the fundamental interactions of elementary particles . Apart from its various successful predictions in particle physics, origin of tiny neutrino masses and their large mixing **[1-5]** is one of the major observed phenomena which the Standard model (SM) of particle physics fails to account for. Several Neutrino oscillation experiments namely T2K **[6]** ,Double ChooZ **[7]** , Daya-Bay **[8]** and RENO **[9]** have made the earlier predictions for neutrino parameters more precisely and also predicted non-zero value of the reactor mixing angle θ_{13}. From the latest global fit value for 3σ range of neutrino oscillation parameters **[10]** and **[11]** it is clear that the neutrino oscillation experiments measure only two mass squared difference and therefore the lightest neutrino mass which are remains a free parameter can be constrained from the upper bound on the sum of absolute neutrino masses from cosmology $\sum m_i \leq$ 0.23 eV **[12].** With addition to the neutrino mass hierarchy problem recent neutrino experiments also have not found anything about the nature of the neutrino mass. In recent years several new experiments have been proposed to solve neutrino mass hierarchy and CP violation problems and also India based neutrino observatory (INO) has proposed some idea to solve some of these issues.

In several literature reviews we have found that smallness of neutrino mass can be explained by seesaw mechanism and it can be of three types: type I **[13],** type II **[14]** and type III. All these mechanisms include extra heavy fermionic or scalar fields into the SM. Although seesaw mechanism can explain small neutrino mass but still SM is far away from understanding the neutrino mass hierarchy and observed matter-antimatter asymmetry of universe. The baryon to photon ratio from the Planck experiment **[12**] is found to be $Y_B \cong (6.065 \pm 0.090) \times 10^{-10}$.

In this present work we consider leptogenesis as the only mechanism of producing baryon asymmetry of the Universe, recent work has been studied **[15-19]** the possibility of generating non-zero θ_{13} and also the Dirac CP phase δ in some cases by considering a BSM framework where both type I and type II seesaw mechanisms contribute to neutrino masses. In this work the type I seesaw is considered to be the origin of TBM (Tri-bi maximal) whereas type II seesaw gives rise to the necessary corrections to generate nonzero reactor mixing angle. Here only source of CP violation is coming from type II seesaw term as TBM is a real mass matrix which is considered as a type I seesaw. Hence the lightest right handed neutrino decaying into SM particles through a virtual Higgs triplet (responsible for type II seesaw) is the only source of creating the required lepton asymmetry. However, if neutrinos are Majorana fermions, then two additional Majorana phases come to the picture in neutrino mixing which remain unconstrained from neutrino oscillation experiments. In this work, along with Dirac CP phase we include these two Majorana phases into account and study the effects of these phases in the baryon asymmetry of the Universe and try to study all these experimentally undetermined neutrino parameters with the help of baryon asymmetry of the Universe.

This paper is organized as follows. In section 2 we discuss the TBM mixing matrix and type II seesaw. In section 3 we describe the numerical analysis adopted here and finally conclude in section 4.

2. TBM MIXING + TYPE II SEESAW

In this work, we consider type I seesaw mass matrix as a TBM type mixing which gives an approximation to observe neutrino mixing as $\theta_{12} \cong 35.3°, \theta_{23} = 45°$ and $\theta_{13} = 0$. This Tri-bimaximal mixing matrix can be written as

$$U_{TBM} = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

The necessary correction to TBM type neutrino mass matrix in order to generate non-zero but small θ_{13} can be given by the type II seesaw term. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) leptonic mixing matrix is related to the diagonalizing matrices of neutrino and charged lepton mass matrices U_ν, U_l respectively, as

$$U_{PMNS} = {U_l}^{+} U_\nu$$

The PMNS mixing matrix can be parametrized as

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{13} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{13}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} U_{Maj}$$

Where $c_{ij} = cos\theta_{ij}, s_{ij} = sin\theta_{ij}$ and δ is the Dirac CP phase. The diagonal matrix $U_{Maj} = diag(1, e^{i\alpha}, e^{i(\beta+\delta)})$ contains the Majorana CP phases α, β which do not play any role in neutrino oscillations and hence are not constrained by neutrino data. In the diagonal charged lepton basis $U_{PMNS} = U_\nu$. If $U_{TBM} = U_\nu$ then for diagonal charged lepton mass matrix both the reactor mixing angle θ_{13} and the leptonic Dirac CP phase δ vanish in the neutrino sector. Thus, the type I seesaw mass matrix gives rise to vanishing θ_{13} as well as δ whereas type II seesaw mass matrix gives the necessary correction in order to generate non-zero θ_{13} and non-trivial values of Dirac CP phase. Considering the type II seesaw term as the necessary correction to TBM mixing, we write the neutrino mass matrix as

$$M_\nu = M_I + M_{II} = m_D {M_{RR}}^{-1} {m_D}^T + M_{II}$$

Where $m_{D,}$ M_{RR} Dirac and the right are handed neutrino mass matrices respectively. Since the diagonalizing matrix of M_ν is U_{PMNS} and that of type I mass matrix M_I is U_{TBM} the above equation can be written as

$$U_{PMNS} {m_\nu}^{diag} {U_{PMNS}}^T = U_{TBM} {M_I}^{diag} {U_{TBM}}^T + M_{II}$$

To vary the relative strength of type I and type II seesaw terms, we parametrize the diagonal type I mass matrix as ${M_I}^{diag} = Z {m_\nu}^{diag}$,. Where Z is a parameter which determine the contribution of type I seesaw. . Now the symmetric type II seesaw mass matrix can be represented by

$$M_{II} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix}$$

For normal mass hierarchy (NH), the diagonal mass matrix of the light neutrinos can be written as

$${m_\nu}^{diag} = diag(m_1, \sqrt{{m_1}^2 + {\Delta m_{21}}^2}, \sqrt{{m_1}^2 + {\Delta m_{31}}^2})$$

Whereas for inverted mass hierarchy (IH) it can be written as

$${m_\nu}^{diag} = diag(\sqrt{{m_3}^2 + {\Delta m_{23}}^2 - {\Delta m_{21}}^2}, \sqrt{{m_3}^2 + {\Delta m_{23}}^2}, m_3)$$

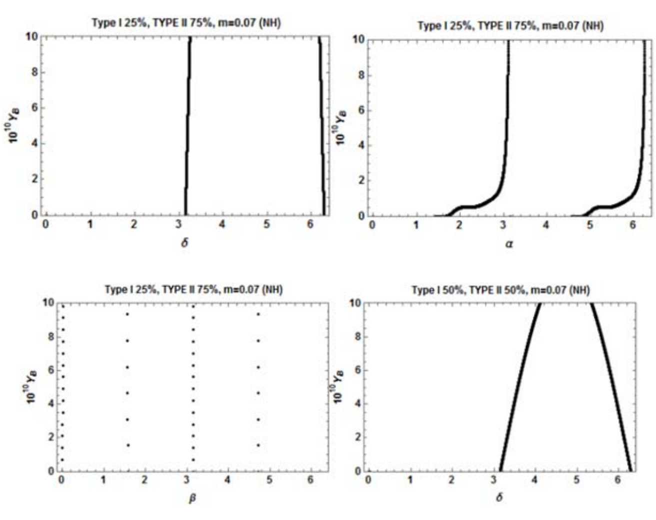
Thus, five free parameters available in our model and they are one Dirac Phase δ and two Majorana phases α, β , the lightest neutrino mass and the numerical factor Z which decides the relative strength of type I and type II seesaw terms. We consider $m = m_1$ and $m = m_3$ are the lightest neutrino masses for Normal and Inverted hierarchy cases respectively. The Dirac CP phase δ is also not tightly constrained from neutrino experiments and hence any value of it is possible at the3σ level. Therefor we consider three different cases to connect all these experimentally undetermined neutrino parameters. In our first case we consider Both Majorana phases to be zero and study the effects of Dirac CP phase in the formation of baryon asymmetry of the Universe. Similarly we consider Dirac CP phase and one Majorana phase are to be zero and study the effects of non-zero Majarona phase in our last two cases.

3. NUMERICAL ANALYSIS

We first write down the type I seesaw mass matrix in terms of $\boldsymbol{U_{TBM}}, \boldsymbol{U_{Maj}}, \boldsymbol{Z}$ using the expressions shown in the section 2. Now we can write normal and inverted neutrino masses in terms of the lightest one and the mass squared differences, the free parameters available in the type I mass matrix are the lightest neutrino mass, the numerical factor $\boldsymbol{Z}$and the CP phases contained in $\mathbf{U_{Maj}}$. Similarly, the total neutrino mass matrix is also evaluated as $\boldsymbol{U_{PMNS} {m_\nu}^{diag} {U_{PMNS}}^T}$ containing lightest neutrino mass and CP phases as the free parameters. Using the best fit values of three mixing angles, two mass squared differences, we then evaluate the elements of type II seesaw mass matrix in terms of lightest neutrino mass, Dirac and Majorana CP phases and the numerical factor Z. We then calculate the baryon asymmetry following the procedure adopted in some earlier works [16-19].

Therefore we have not repeated the leptogenesis formula here. Here we consider type I seesaw as a TBM type matrix so we can write $m_D {M_{RR}}^{-1} {m_D}^T = U_{TBM} {M_I}^{diag} {U_{TBM}}^T$. Using this equation we can evaluate the right hand neutrino mass matrix by considering a diagonal form of Dirac neutrino mass matrix. Although leptogenesis can be studied in all three regions namely one flavor, two flavor and three flavor. But in this work we study only two flavor regime and leave the other regimes for future studies.

We choose a diagonal form of Dirac neutrino mass matrix m_D similar to up type quarks such that the lightest right handed neutrino mass falls in the appropriate flavor regime. The expressions for baryon asymmetry for all flavor regimes are given in **[15-17]** as well as our earlier work **[18]** and hence not repeated here. We choose the numerical factor Z to be $0.25, 0.50, 0.75$ which includes the scenarios where type II dominating, type I - type II seesaw contribute equally as well as type I seesaw dominating respectively. We choose two different values of lightest neutrino mass one corresponding to purely hierarchical type light neutrino spectrum and the other giving rise to a quasi-degenerate type spectrum. The largest possible value of the lightest neutrino is chosen in such a way that the Planck bound on the sum of absolute neutrino masses is satisfied. This value turns out to be around 0.07 eV for normal hierarchy and 0.065 eV for inverted hierarchy. The smallest value we choose to be 10^{-6} eV for both the hierarchies. We choose three different scenarios to study the baryon asymmetry of the Universe as discussed earlier. In our first case we choose Dirac CP phase as a free parameter and varying with Y_B keeping two Majorana phases to be zero. Similarly in other cases we vary Majorana phases individually keeping Dirac CP phase and one Majorana phase to be zero.



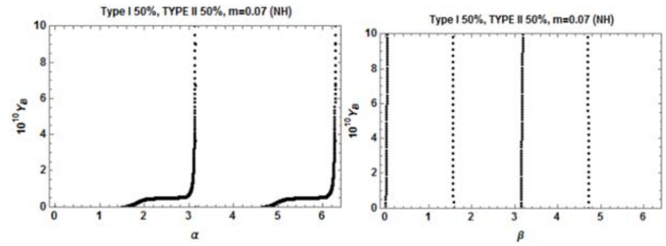


Fig. 1: Correct baryon asymmetry results for NH

4. RESULTS AND CONCLUSION

In this work without considering pure type I or pure type II seesaw, we consider numerical factor Z to be 0.25, 0.50 and 0.75 corresponding to 25% type I contribution, 50% type I – and 50% type II contribution and 75% type I contribution respectively. We derive the type II seesaw mass matrix by using the best fit neutrino parameters in the total neutrino mass matrix and TBM form of the type I seesaw mass matrix. We then compute the baryon asymmetry through leptogenesis due to the lightest right handed neutrino decay by taking both type I and type II seesaw contributions into account. Using some specific values of leptonic CP phases, we constrain the Dirac and two Majorana phases by demanding correct baryon asymmetry. The allowed regions of parameter space in terms of the three leptonic phases are shown in the Fig. 1 and Fig. 2 for two flavor regime of leptogenesis. We have shown only few plots and summarize all the results of leptogenesis in Table 1 and Table 2 for NH and IH. In this table tick and cross mark refers to the correct and incorrect baryon asymmetry respectively that we have observed in our study. From the above table we observe that for Dirac CP phase we do

Table 1: Summary of Baryon to photon ratio results for NH

MODEL		$m_{1=0.07\ eV}$ (NH)	$m_{1=}\ 10^{-6}$ eV (NH)
Dirac CP phase δ	Type I 25%, Type II 75%	✓	×
	Type I 50%, Type II 50%	✓	×
	Type I 75%, Type II 25%	×	×
Majorana CP phase α	Type I 25%, Type II 75%	✓	×
	Type I 50%, Type II 50%	✓	×
	Type I 75%, Type II 25%	×	×
Majorana CP phase β	Type I 25%, Type II 75%	✓	✓
	Type I 50%, Type II 50%	✓	✓
	Type I 75%, Type II 25%	✓	×

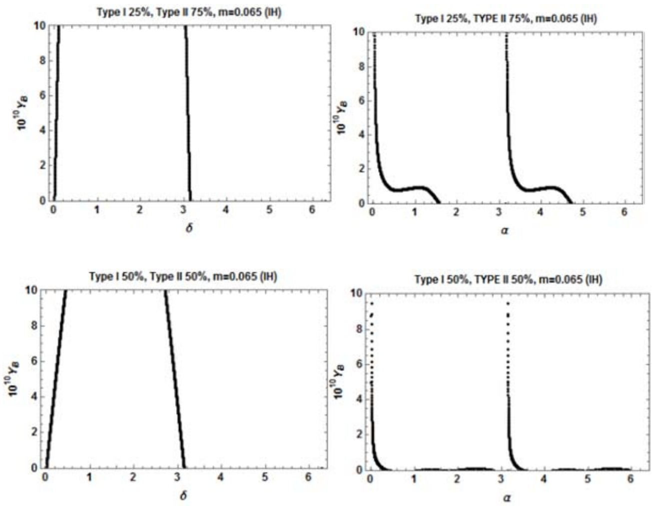


Fig. 2: Correct baryon asymmetry results for IH

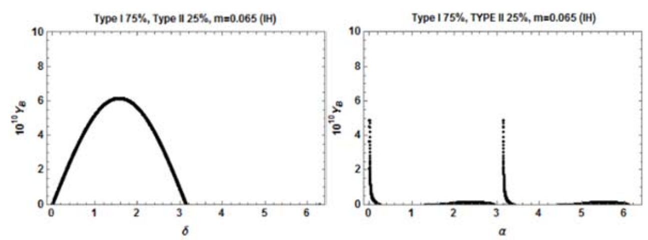


Fig. 2: Correct baryon asymmetry results for IH

Table 2: Summary of Baryon to photon ratio results for IH

MODEL		$m_{3=0.065}$ eV (IH)	$m_{3=}10^{-6}$ eV (IH)
Dirac CP phase δ	Type I 25%, Type II 75%	✓	×
	Type I 50%, Type II 50%	✓	✓
	Type I 75%, Type II 25%	✓	✓
Majorana CP phase α	Type I 25%, Type II 75%	✓	✓
	Type I 50%, Type II 50%	✓	✓
	Type I 75%, Type II 25%	✓	×
Majorana CP phase β	Type I 25%, Type II 75%	×	×
	Type I 50%, Type II 50%	×	×
	Type I 75%, Type II 25%	×	×

not get correct baryon asymmetry for 75% contribution of Type I seesaw for NH with $m = 0.07$ eV and NH with $m = 10^{-6}$ eV for all the cases. Similarly in case of Majorana phase α we observe the same results as Dirac CP phase. However, in case of Majorana phase β, we have not found the correct baryon asymmetry for all the IH cases and NH with $m = 10^{-6}$ eV for 75% contribution of Type I seesaw. Thus, assuming thermal leptogenesis as the only source of baryon asymmetry, we can discriminate between different possible values of leptonic CP phases within the framework of these models.

Currently ongoing neutrinoless double beta decay experiments might be able to expose the nature of neutrino masses. In future work it will be very interesting to constrain the Majorana CP phases further by computing other observables like neutrinoless double beta decay lifetime by taking contributions from multiple seesaw mechanisms operating at TeV scale or above and then taking the experimental bounds.

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