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Matter-Antimatter Asymmetry of The Universe and Baryogenesis via Leptogenesis within Type I Seesaw Scenerio

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Abstract
We study matter-antimatter asymmetry of the universe in terms of Baryogenesis through leptogenesis in standard Type-I seesaw scenario where charged lepton mass matrix is assumed to take diagonal form. Considering the CP violating out of equilibrium decay of the lightest right handed neutrino, we have studied the Baryon asymmmetry of the universe by varying Majorana CP violating phase($\alpha\beta$), Dirac CP violating phase and the lightest neutrino mass. We also constrain the free parameters in the light neutrino sector ($m_{lightest}$,δ,α,β) to certain range of values which values can be tested in ongoing and future neutrino experiments.

Keywords
Neutrino Physics, Type I Seesaw Mechanism, Baryogenesis

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1. Introduction

1.1 Matter-Antimatter Asymmetry of The Universe

Observations indicate that the number of baryons (protons and neutrons) in the Universe is unequal to the number of antibaryons (antiprotons and antineutrons). To the best of our understanding, all the structures that we see in the Universe – stars, galaxies, and clusters – consist of matter (baryons and electrons) and there is no antimatter (antibaryons and positrons) in appreciable quantities. Since various considerations suggest that the Universe has started from a state with equal numbers of baryons and antibaryons, the observed baryon asymmetry must have been generated dynamically, a scenario that is known by the name of Baryogenesis [1].

One may wonder why we think that the baryon asymmetry has been dynamically generated, rather than being an initial condition. There are at least two reasons for that. First, if a baryon asymmetry had been an initial condition, it would have been a highly fine-tuned one. For every 6,000,000 antiquarks, there should have been 6,000,001 quarks. Such a fine-tuned condition seems very implausible. Second, and perhaps more important, we have excellent reasons, based on observed features of the cosmic microwave background radiation, to think that inflation took place during the history of the Universe. Any primordial baryon asymmetry would have been exponentially diluted away by the required amount of inflation.

The baryon asymmetry of the Universe poses a puzzle in particle physics. The Standard Model (SM) of particle interactions contains all the ingredients that are necessary to dynamically generate such an asymmetry in an initially baryon-symmetric Universe. Yet, it fails to explain an asymmetry as large as the one observed. New physics is called for. The new physics must first, distinguish matter from antimatter in a more pronounced way than do the weak interactions of

the SM [2]. Second, it should depart from thermal equilibrium during the history of the Universe.
The value of baryon asymmetry of the Universe is inferred from observations in two independent ways.

- The first way is via Big Bang Nucleosynthesis (BBN) [3]. One of the main successes of the standard early-universe cosmology is the prediction of the abundances of the light elements, D, He^3,He^4 andLi^7.Agreement between theory and observation is obtained for a certain range of the parameter η_B, the ratio of baryon density and photon density,

$$\eta_B^{BBN} = \frac{\eta_B}{\eta_\gamma} = (2.6 - 6.21) \times 10^{-10},$$

  Where the photon number density of photons is $\eta_\gamma \sim .400 cm^{-3}$. Since no significant amount of antimatter is observed in the universe, the baryon density yields directly the cosmological baryon asymmetry, $\eta = \frac{\eta_B - \eta_{\overline{B}}}{\eta_\gamma}$.
- The second piece of evidence is from Cosmic Microwave Background Radiation (CMBR) . On the experimental side, the precision of measurement of the baryon asymmetry has significantly improved with the observation of the acoustic peaks in the CMBR. The BOOMERanG and DASI experiments have measured the baryon asymmetry as

$$\eta_B^{CMB} = \frac{\eta_B}{\eta_\gamma} = 6 \times 10^{-10}$$

  The most recent measurement of the WMAP Collaboration[4] is consistent with this resut, with an error of only 5%.

1.2 Ingredient and Mechanism

1.2.1 Shakharav's conditions

The three ingredients required to dynamically generate a baryon asymmetry were given by Sakharov [5]:

(1) Baryon number violation: This condition is required in order to evolve from an initial state with $Y_{\Delta B} = 0$ to a state with $Y_{\Delta B} = 0$.

(2) C and CP violation: If either C or CP were conserved, then processes involving baryons would proceed at precisely the same rate as the C- or CP-conjugate processes involving antibaryons, with the overall effects that no baryon asymmetry is generated.

(3) Out of equilibrium dynamics: In chemical equilibrium, there are no asymmetries in quantum numbers that are not conserved (such as B, by the first condition.

These ingredients are all present in the Standard Model. However, no SM mechanism generating a large enough baryon asymmetry has been found [6]. Therefore baryogenesis requires new physics that extends the SM in at least two ways: It must introduce new sources of CP violation and it must either provide a departure from thermal equilibrium in addition to the electroweak phase transition (EWPT)[7, 8] or modify the EWPT itself. Some possible new physics mechanisms for baryogenesis are the following:

- **GUT baryogenesis**[9, 10, 11] which generates the baryon asymmetry in the out-of-equilibrium decays of heavy bosons in Grand Unified Theories (GUTs).
- **Leptogenesis** [1] from decay heavy right handed neutrinos by producing B–L asymmetry above T_{EW}.
- **Electroweak baryogenesis**[12, 13] by producing B=L at T_{EW}, where the departure from thermal equilibrium is provided by the electroweak phase transition

1.3 A new input for Baryogenesis- 'Right-handed Neutrino'

The recent huge progress in the Neutrino Physics basically in experimental sectors have able to convince us that neutrinos do have masses though Standard Model can't predict, because right handed neutrino doesn't exists in SM. But Experimentally established Neutrino Oscillation reveals the tiny neutrino masses [14, 15].

1.3.1 Neutrinos Within Standard Model

In standard model, neutrinos are known to be massless. Rather going to the quantitative treatment we can explain why neutrinos are massless in standard model qualitatively as follows. No matter how empty the vacuum looks, it is packed with particles called Higgs bosons that have zero spin (and are therefore neither left or right handed). According to Higgs mechanism[16, 17] in standard model, particles in the vacuum acquire their masses as they collide with the Higgs boson. Quantum field theory and Lorentz invariance show that when a particle is injected into the "vacuum", its handedness changes when it interacts with a Higgs boson (figure-1).

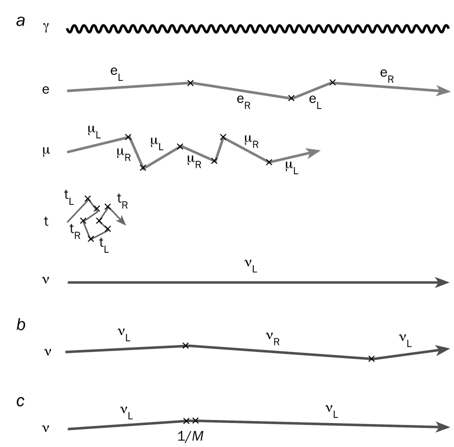

Figure 1. According to the Higgs mechanism in the Standard Model, particles in the vacuum acquire mass as they collide with the Higgs boson.[18]

For, example photons (γ) are massless because they do not interact with the Higgs boson. But left-handed electron will become right-handed after the first collision,then again left-handed following a second collision, and so on. Simply since the electron cannot travel through the vacuum at the speed of light; it has to become massive. Similarly muons collide with Higgs bosons more frequently than electrons, making them 200 times heavier than the electron, while the top quark interacts with the Higgs boson almost all the time.Thats why mass of top quark is found to be very high as compared to other fermions.

This picture also explains why neutrinos are massless. If a left-handed neutrino tried to collide with the Higgs boson, it would have to become right-handed. But experiments show that neutrinos are always left handed. Since right handed neutrinos do not exist in Standard Model, the theory predicts that neutrinos can never acquire mass. In this way right-handed neutrino go hand in hand with the absence of right-handed neutrinos in Standard Model.

To explain the masses of neutrinos we have to go beyond the Standard Model. One such beyond standard model, theoretical framework is See-saw mechanism.

1.3.2 Neutrinos Beyond Standard Model: "See-saw Mechanism"

Basically there are two ways to extend the Standard Model in order to make neutrinos massive.One approach involves new particles called Dirac neutrinos, while the other approach involves a completely different type of particle called the Majorana neutrino. The Dirac neutrino is a simple idea with a serious flaw. According to this approach, the reason that right-handed neutrinos have escaped detection so far is that their interactions are at least 26 orders of magnitude weaker than ordinary neutrinos.The idea of the Dirac neutrino works in the sense that we can generate neutrino masses via the Higgs mechanism (figure 1(b)). However, it also suggests that neutrinos should have similar masses to the other particles in the Standard Model.To avoid this problem,we have to make the strength of neutrino interactions with the Higgs boson at least 10^{12} times weaker than that of the top quark.

The second way to extend the Standard Model involves particles that are called Majorana neutrinos. Massive neutrinos sit naturally within this framework. Earlier we argued that the absence of right-handed neutrinos means that neutrinos are massless. But if neutrinos and antineutrinos are the same particle, then we do not neeed such kind of urgument anymore.

So how is neutrino mass generated? In this scheme, it is possible for right-handed neutrinos to have a mass of their own without relying on the Higgs boson. Unlike other quarks and leptons, the mass of the right-handed neutrino,M, is not tied to the mass scale of the Higgs boson. Rather, it can be much heavier than other particles.

When a left-handed neutrino collides with the Higgs boson, it acquires a mass, m, which is comparable to the mass of other quarks and leptons. At the same time it transforms into a right-handed neutrino, which is much heavier than energy conservation would normally allow. However, the Heisenberg uncertainty principle allows this state to exist for a short time interval Δt, given by $\Delta t = \hbar/Mc^2$, after which the particle transforms back into a left-handed neutrino with mass m by colliding with the Higgs boson again. Put simply, we can think of the neutrino as having an average mass of m^2/M over time.

This so-called seesaw mechanism can naturally give rise to light neutrinos with normal-strength interactions. Normally we would worry that neutrinos with a mass, m, that is similar to the masses of quarks and leptons would be too heavy.However, we can still obtain light neutrinos if M is much larger than the typical masses of quarks and leptons. Right-handed neutrinos must therefore be very heavy, as predicted by Grandunified theories that aim to combine electromagnetism with the strong and weak interactions.

1.4 Theory of Type I See-saw Mechanism

The relative smallness of three Standard Model neutrino masses can be explained via seesaw mechanism which can be of three types: Type I[19, 20] , Type II[21] and Type III[22] . In this literature we will concentrate only in the Type I seesaw.

The minute we talk about masses of spin 1/2 particles, we need both spin up and down states because we can stop any massive particle. When the particle is at a relativistic speed, a more useful label is left or right-handed states.For massless particles, left- and right-handed states are completely independent from each other and we do not need both of them; this is how neutrinos are described in the Standard Model. Once they are massive, though, we need both, so that we can write a mass term called Dirac mass term using both of them:

$$L^D_{mass} = m_D \bar{\nu}_R \nu_L + h.c = \frac{1}{2}(m_D \bar{\nu}_R \nu_L + m_D \nu^C_R \bar{\nu}^C_L) + h.c \quad (1)$$

But then the mass term is exactly the same as the other quarks and leptons, and then why are the neutrinos so much lighter? The first step is to rewrite the mass term Eq. (5) in a matrix form

$$\mathrm{L_{mass}} = \frac{1}{2} \begin{pmatrix} \nu_L & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \overline{\nu_R} \end{pmatrix} + \mathrm{h.c.} \quad (2)$$

Here, we have to put ν_L and $\overline{\nu_R}$ (CP conjugate of ν_R) together so that both of them are left-handed and are allowed to be in the same multiplet. The problem is that we expect the "Dirac mass" m_D be of the same order of magnitudes as other quarks and lepton masses in the same generations which would be way too large. The point is that the right-handed neutrino is completely neutral under the standard-model gauge groups and is not tied to the electroweak symmetry breaking (v = 246 GeV) to acquire a mass. Therefore, it can have a mass much larger than the electroweak scale without violating gauge invariance, and the mass term is

$$\mathrm{L_{mass}} = \frac{1}{2} \begin{pmatrix} \nu_L & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \overline{\nu_R} \end{pmatrix} + \mathrm{H.c} \quad (3)$$

Because one of the mass eigenvalues is clearly dominated by $M \gg m_D$, while the determinant is $-m_D^2$, the other eigenvalue mustbe suppressed, $\frac{-m_D^2}{M} \ll m_D$ This way, physics at high-energy scale M suppresses the neutrino mass in a natural way. In order to obtain the mass scale for the atmospheric neutrino oscillation$(m_{atm}^2)^2 \sim 0.05$ eVand taking the third generation mass $m_D \sim m_t \sim 170$ GeV we find $M = \frac{m_D^2}{m_\nu} \sim 0.6 \times 10^{15}$GeV

It is almost the grand-unification scale 2×10^{16} where all gauge coupling constants appear to unify in the minimal supersymmetric standard model.

1.5 Baryogenesis via Leptogenesis

Leptogenesis is one of the most well motivated framework of producing baryon asymmetry of the universe which creates an asymmetry in leptonic sector first and then con erts it into baryon asymmetry through $B+L$ violating electroweak transitions.As pointed out first by Fukugita and Yanagida , the out of equilibrium CP violating decay of heavy Majorana neutrinos provides a natural way to create the required lepton asymmetry.This decay of right handed neutrinos obeys the theee Sakharav's conditions because

- Violation of $B+L$ Guaranteed if neutrinos are Majorana particles. i.e. Lepton number is violated(M)
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases. i.e. New sources of CP violation(λ)
- Departure from thermal equilibrium. Guaranteed, due to the expansion of the Universe.

Although the standard model satisfies the first two requirements and out of equilibrium conditions in principle, can be achieved in an expanding Universe like ours, it turns out that the amount of CP violation measured in the SM quark sector is too small to account for the entire baryon asymmetry of the Universe.Since there can be more sources of CP violating phases in the leptonic sector which are not yet from experimentally determined, leptogenesis provides an indirect way of constraining these unknown phases from the requirement of producing the observed baryon asymmetry. The salient feature of this mechanism is the way it relates two of the most widely studied problems in particle physics: the origin of neutrino mass and the origin of matter-antimatter asymmetry. Before going to rigorous mathematical discussions of Leptogenesis, let us look at the basic picture behind the theory of leptogenesis. Till now we have learnt that there could be RH neutrino that is very heavy. A very heavy particle that could have been produced in early universe is the connection to the baryogenesis via leptogenesis. Presumably there may be one RH neutrino for each generation of neutrinos. One of them could be very long lived enough and once thay are produced, they hanging around the universe for a while, then eventually decay. But that will happen in out of equilibrium condition and because of this right handed neutrinos turn out to be Majorana fermions, which means that particles and antiparticles have no distinctions, when it decays it will have 50:50 probability to go into ordinary lepton ($\nu_R \rightarrow \nu_L + H$) and ordinary antilepton ($\nu_R \rightarrow \bar{\nu}_R + H^*$). That is given in the

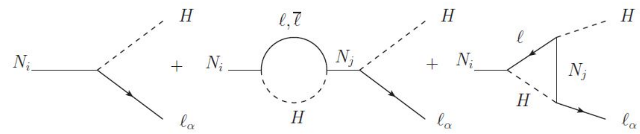

Figure 2. The CP asymmetry in type-I seesaw leptogenesis results from the interference between tree and 1-loop wave and vertex diagrams. For the 1-loop wave diagram, there is an additional contribution from L-conserving diagram to the CP asymmetry which vanishes when summing over lepton avours.

tree level lowest order diagram[1].
But if we look at the interference between the tree level lowest order diagram and higher order diagram at one loop level we can find a CP violation. That is decay into ordinary lepton may be supressed and decay into ordinary antilepton may be enhanced. So when these all decay we may end up with the net $-$ve lepton asymmetry.

2. Methodology

In our work we are considering CP-violating out of equilibrium decay of heavy right handed neutrinos into higgs and lepton within the framework type I seesaw mechanism.The neutrino mass matrix in type I seesaw mechanism can be written as

$$M_\nu = -m_{LR} M_{RR}^{-1} m_{LR}^T \tag{4}$$

where m_{LR} is the Dirac neutrino mass matrix and M_{RR} is the right handed singlet neutrino mass matrix. 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_lrespectively, as

$$U_{PMNS} = U_l^\dagger U_\nu \tag{5}$$

In the diagonal charged lepton basis, U_{PMNS} is same as the diagonalizing matrix U_ν of the
neutrino mass matrix given by

$$M_{\mathrm{RR}} = M_{\mathrm{LR}}^T . U_{\mathrm{PMNS}} . (M_\nu{}^{\mathrm{diag}})^{-1} U^T{}_{\mathrm{PMNS}} . M_{\mathrm{LR}} \tag{6}$$

The PMNS mixing matrix can be parametrized as

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)}) \tag{7}$$

Where, $c_{ij} = cos\theta_{ij}$, $s_{ij} = sin\theta_{ij}$,

δ is the Dirac CP phase. and, α, β are the Majorana phases.

The lepton asymmetry from the decay of right handed neutrino into leptons and Higgs scalar is given by-

$$\in N_K = \sum_i \frac{\Gamma(N_K \to L_i + H^*) - \Gamma(N_K \to \overline{L_i} + H)}{\Gamma(N_K \to L_i + H^*) + \Gamma(N_K \to \overline{L_i} + H)} \quad (8)$$

In a hierarchical pattern of three right handed neutrinos $M_{2,3} \gg M_1$, it is sufficient to consider the lepton asymmetry produced by the decay of the lightest right handed neutrino N_1. Now following the notation of the literature [23] the lepton asymmetry arising from the decay of N_1 in the presence of type I seesaw only can be written as -

$$\begin{aligned}\in_1^{\alpha} = &\frac{1}{8\pi v^2} \frac{1}{\left(m_{LR}^{\dagger} m_{LR}\right)_{11}} \\ &\times \sum_{j=2,3} \mathrm{Im}\left[(m_{LR}^*)_{\alpha 1} \left(m_{LR}^{\dagger} m_{LR}\right)_{1j} (m_{LR})_{\alpha j}\right] g(x_j) \\ &+ \frac{1}{8\pi v^2} \frac{1}{\left(m_{LR}^{\dagger} m_{LR}\right)_{11}} \\ &\times \sum_{j=2,3} \mathrm{Im}\left[(m_{LR}^*)_{\alpha 1} \left(m_{LR}^{\dagger} m_{LR}\right)_{j1} (m_{LR})_{\alpha j}\right] \frac{1}{1-x_j}\end{aligned} \quad (9)$$

where v = 174 GeV is the vev of the Higgs bidoublets responsible for breaking the electroweak symmetry,

$$g(x) = \sqrt{x}\left(1 + \frac{1}{1-x} - (1+x)\ln\frac{1+x}{x}\right) \quad (10)$$

And, $x_j = \frac{M_j^2}{M_1^2}$. The second term in the expression for $\in_1^{\alpha}$above vanishes when summed over all the flavors α = e, μ, τ .
So, for the all summed over flavors is given by-

$$\in_1 = \frac{1}{8\pi v^2} \frac{1}{\left(m_{LR}^{\dagger} m_{LR}\right)_{11}} \sum_{j=2,3} Im[\left(m_{LR}^{\dagger} m_{LR}\right)_{ij}^2] g(x_j) \quad (11)$$

After determining the lepton asymmetry $\in_1$, the corresponding baryon asymmetry can be obtained by

$$Y_B = ck\frac{\in}{g^*}$$

through electroweak spheleron processes [24] Here, c is a measure of the fraction of lepton asymmetry being converted into baryon asymmetry and is approximately equal to -0.55, k is the dilution factor due to wash-out processes which erase the produced asymmetry and can be parametrized as

$$-k \cong \sqrt{0.1K}\exp\left[\frac{-4}{3\times(0.1K)^{0.25}}\right], \quad for\ K \geq 10^6 \quad (12)$$

$$\cong \frac{0.3}{K(\ln K)^{0.6}}, \qquad for\ 10 \leq K \leq 10^6 \quad (13)$$

$$\cong \frac{1}{2\sqrt{K^2+9}}, \qquad for\ 0 \leq K \leq 10 \quad (14)$$

Where K is given as

$$K = \frac{\Gamma_1}{H(T=M_1)} = \frac{\left(m_{LR}^{\dagger} m_{LR}\right)_{11} M_1}{8\pi v^2} \frac{M_{PL}}{1.66\sqrt{g^*} M_1^2} \quad (15)$$

For the calculation of baryon asymmetry, we first calculate the right handed singlet neutrino mass matrix M_{RR} as

$$U_R^* M_{RR} U_R^{\dagger} = diag(M_1, M_2, M_3) \quad (16)$$

In this diagonal M_{RR} basis, according to the type I seesaw formula , the Dirac neutrino mass matrix also changes to

$$m_{LR} = m_{LR}^o U_R \quad (17)$$

where, m_{LR}^o is the Dirac neutrino mass matrix. Numerical Analysis Using the parametric form of PMNS matrix shown in equation (18), the Majorana neutrino masscmatrix M_ν can be found as

$$M_\nu = U_{PMNS} M_\nu^{Diag} U_{PMNS}^T$$

where,

$$M_\nu^{Diag} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

where, m_1,m_2 and m_3 are the three neutrino mass eigenvalues. As mentioned earlier, here we assume that the diagonalizing matrix of the neutrino mass matrix is M_ν same as the PMNS mixing matrix due to the chosen charged lepton mass matrix in the diagonal form.
For Normal Hierachy:

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

For Inverted Hierachy:

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

For illustrative purposes, we consider two different order of magnitude values for the lightest neutrino mass m_1 for NH and m_3 for IH.In the first case we assume $m_{lightest}$ as large as possible so that the sum of the absolute neutrino mass lie just below the cosmological upper bound and it turns out to be 0.07 eV and 0.065 for NH and IH respectively.
Secondly we choose the lightest mass eigenvalue to be 10^{-6} for both NH and IH cases so that we have a hierarchical pattern of neutrino masses.

Table 1. Global fit 3σ values of neutrino oscillation parameters [25]

Parameters	NH	IH
$\Delta m^2_{21}/(10^{-5}\ \mathrm{eV}^2)$	7.02-8.09	7.02-8.09
$\Delta m^2_{31}/(10^{-5}\ \mathrm{eV}^2)$	2.317-2.607	2.307-2.590
$\sin^2\theta_{12}$	0.270-0.344	0.270-0.344
$\sin^2\theta_{23}$	0.382-0.643	0.389-0.644
$\sin^2\theta_{13}$	0.0186-0.0250	0.0188-0.0251
δ_{CP}	0-2π	0-2π

The PMNS matrix is evaluated from the best fit values of the neutriono mixing angles given in the Table 4.1.

After using the best fit values of two mass squared differences and three mixing angles, the most general neutrino mass matrix given by equation (18) contain four parameters: The lightest neutrino mass (m_1 or m_3), Dirac CP phase, δ, Majorana phase α and Majorana phase β. Our objective is to calculate the variation of the Baryogenesis with respect to the variation of the above four parameters, $m_1 or\ m_3$, δ, α and β separately.

3. Calculation

In this section we are just showing the calculation of Baryon asymmetry by taking some particular values of the four unknown parameters in the allowed range only for illustration purpose.In our actual work we have calculated Baryon asymmetry by varying all the parameters in the allowed range of values which is given in our next section "Results and Analysis".

After putting the best fit values of two mass squared difference and three mixing angles, the expression for U_{PMNS} becomes-

$$U_{\text{PMNS}} = \begin{pmatrix} 0.823347 & 0.54786e^{i\alpha} & 0.148155e^{-\frac{i\delta}{2}+i(\beta+\delta)} \\ -0.385239-0.0886364e^{i\delta} & e^{i\alpha}\left(0.578954-0.0589792e^{i\delta}\right) & 0.710682e^{i(\beta+\delta)} \\ 0.398092-0.0857747e^{i\delta} & e^{i\alpha}\left(-0.598269-0.057075e^{i\delta}\right) & 0.687737e^{i(\beta+\delta)} \end{pmatrix} \tag{18}$$

Now, we choose $\delta=\frac{\pi}{2}$, $\alpha=\frac{\pi}{2}$, $\beta=\pi/2$, m_1=0.001

$$U_{\text{PMNS}} = \begin{pmatrix} 0.823347+0.i & 0.+0.54786i & 0.+0.148155i \\ -0.385239-0.0886364i & 0.0589792+0.578954i & -0.710682+0.i \\ 0.398092-0.0857747i & 0.057075-0.598269i & -0.687737+0.i \end{pmatrix} \tag{19}$$

$$U^T{}_{\text{PMNS}} = \begin{pmatrix} 0.823347+0.i & -0.385239-0.0886364i & 0.398092-0.0857747i \\ 0.+0.54786i & 0.0589792+0.578954i & 0.057075-0.598269i \\ 0.+0.148155i & -0.710682+0.i & -0.687737+0.i \end{pmatrix} \tag{20}$$

The general form of M_{LR} is given by-

$$M_{\text{LR}} = \begin{pmatrix} \lambda^m & 0 & 0 \\ 0 & \lambda^n & 0 \\ 0 & 0 & 1 \end{pmatrix} * m_f \tag{21}$$

where, λ is the standard Wolfenstein parameter(=0.22) and (m,n) are positive integers. To calculate the baryon asymmetry in the appropriate flavor regime, we choose the diagonal Dirac neutrino mass matrix in such a way that the lightest right handed singlet neutrino mass lies in the same flavor regime.We choose m_f = 82.43 GeV in the Dirac neutrino mass matrix. For one flavour regime i.e. leptogenesis occur at very high temperature T ¿ 10^{12} GeV, we choose (m, n) = (1, 1) to keep the lightest right handed neutrino mass in one flavor regime.

$$M_{\text{LR}} = \begin{pmatrix} 0.22 & 0 & 0 \\ 0 & 0.22 & 0 \\ 0 & 0 & 1 \end{pmatrix} * 82.43 * 10^9 eV \tag{22}$$

i.e.

$$M_{LR} = \begin{pmatrix} 1.81346\times 10^{10} & 0. & 0. \\ 0. & 1.81346\times 10^{10} & 0. \\ 0. & 0. & 8.243\times 10^{10} \end{pmatrix} eV \tag{23}$$

Now,

$$M_{\text{RR}} = M^T_{\text{LR}}.U_{\text{PMNS}}.(M_\nu{}^{\text{diag}})^{-1} U^T{}_{\text{PMNS}}.M_{\text{LR}} \tag{24}$$

$$= \begin{pmatrix} 2.1164\times 10^{23}+0.i & -1.1616\times 10^{23}-2.31985\times 10^{22}i & 5.45614\times 10^{23}-1.02043\times 10^{23}i \\ -1.1616\times 10^{23}-2.31985\times 10^{22}i & 3.57766\times 10^{22}+2.50101\times 10^{22}i & -1.72671\times 10^{23}-3.73158\times 10^{21}i \\ 5.45614\times 10^{23}-1.02043\times 10^{23}i & -1.72671\times 10^{23}-3.73158\times 10^{21}i & 7.90712\times 10^{23}-5.16737\times 10^{23}i \end{pmatrix} \tag{25}$$

The diagonalizing matrix of U_{RR} is found out to be-

$$U_R = \begin{pmatrix} 0.456028+0.14776i & 0.869439+0.i & -0.0705614+0.19253i \\ -0.141544-0.0912156i & 0.162591-0.13429i & 0.952037+0.i \\ 0.861307+0.i & -0.419392-0.154004i & 0.226843+0.010992i \end{pmatrix} \tag{26}$$

$$M_{\text{LR}} = M^0{}_{\text{LR}} \cdot U_R$$

$$= \begin{pmatrix} 3.37995\times 10^{20}+0.i & -1.26309\times 10^{18}+1.05478\times 10^{20}i & 2.13084\times 10^{19}+4.56842\times 10^{20}i \\ -1.26309\times 10^{18}-1.05478\times 10^{20}i & 3.22023\times 10^{20}+0.i & 6.95725\times 10^{19}-1.14652\times 10^{19}i \\ 2.13084\times 10^{19}-4.56842\times 10^{20}i & 6.95725\times 10^{19}+1.14652\times 10^{19}i & 6.74739\times 10^{21}+0.i \end{pmatrix}$$

(27)

The eigenvalues of M_{RR} are

$$\{1.21483\times10^{24}, 1.00774\times10^{23}, 7.98593\times10^{21}\} \tag{28}$$

And,

$$x_2 = {M_2}^2/{M_1}^2 = 159.237 \tag{29}$$

$$x_3 = {M_3}^2/{M_1}^2 = 23140.9. \tag{30}$$

Now,

$$g(x) = \sqrt{x}\left(1+\frac{1}{1-x}-(1+x)\ln\frac{1+x}{x}\right) \tag{31}$$

$$g(x_2) = \sqrt{x_2}\left(1+\frac{1}{1-x_2}-(1+x_2)\ln\frac{1+x_2}{x_2}\right) = -0.119287 \tag{32}$$

$$g(x_3) = \sqrt{x_3}\left(1+\frac{1}{1-x_3}-(1+x_3)\ln\frac{1+x_3}{x_3}\right) = -0.00986079 \tag{33}$$

Now we calculate the lepton asymmetry for Type I seesaw,

$$\begin{aligned}\in_1^\alpha = &\frac{1}{8\pi v^2}\frac{1}{\left(m_{LR}^\dagger m_{LR}\right)_{11}}\sum_{j=2,3} Im[(m_{LR}^*)_{\alpha 1}\left(m_{LR}^\dagger m_{LR}\right)_{1j}(m_{LR})_{\alpha j}]\\ &\frac{1}{8\pi v^2}\frac{1}{\left(m_{LR}^\dagger m_{LR}\right)_{11}}\sum_{j=2,3} Im[(m_{LR}^*)_{\alpha 1}\left(m_{LR}^\dagger m_{LR}\right)_{j1}(m_{LR})_{\alpha}\end{aligned} \tag{34}$$

$$\in_1 = -3.11625*10^{-7} \tag{35}$$

$$K = \frac{\Gamma_1}{H(T=M_1)} = \frac{\left(m_{LR}^\dagger m_{LR}\right)_{11}M_1}{8\pi v^2}\frac{M_{PL}}{1.66\sqrt{g^*}M_1^2} = 19.4998 \tag{36}$$

Where, Plank mass,$M_{PL} = 1.22*10^{19}$Gev
Since, for $10 \le K \le 10^6$

$$-k = \cong \frac{0.3}{K(\ln K)^{0.6}} = 0.00800575 \tag{37}$$

Now we calculate the baryon asymmetry of the universe

$$Y_B = ck\frac{\in}{g^*} = 1.24739*10^{-11}$$

where, $g^* = 110$, c=-0.55

This tenth order of this calculated result fit with the observed baryon asymmetry seen by Plank's experiment [26], which was

$$Y_B = (8.58\pm0.22)*10^{-11} \tag{38}$$

4. Results And Analysis

4.1 Analysis of Baryon Asymmetry Varying Parameters δ, m_1, α and β

4.1.1 For Normal Hierarchy($m_1 \ll m_3, m_2$)

- **Varying the Dirac phase, δ**

  Here, we have taken δ = 0- 2π (in Radian 0 - 6.28) with step size 0.001 and alculated the Baryon Asymmetry Y_B for 6281 number of values of δ and plot the results for Baryon asymmetry Y_B vs Dirac phase, δ.

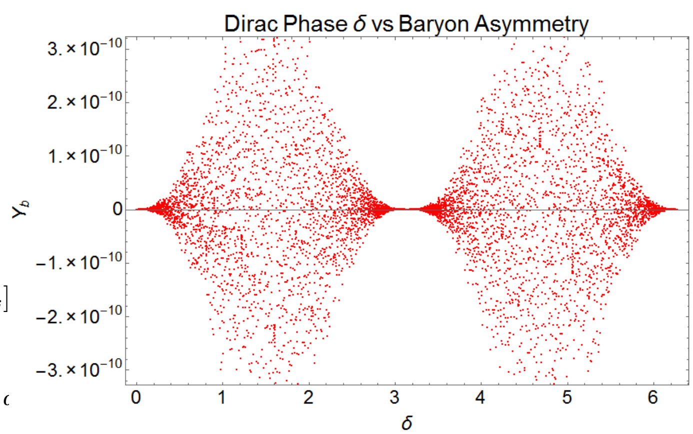

Figure 3. Variation of Baryon Asymmetry with respect to Dirac phase for Normal Hierarchy

- **Varying the Lightest Neutrino Mass, m_1**

  Here, we have taken the lower limit for the lightest neutrino mass to be 10^{-6}eV and upper limit to be 0.07eV. Now taking the step size 0.0001 we have calculated the Baryon Asymmetry Y_B for 7000 number of values of m_1 and plot the results for Baryon asymmetry Y_B vs Lightest neutrino mass m_1.

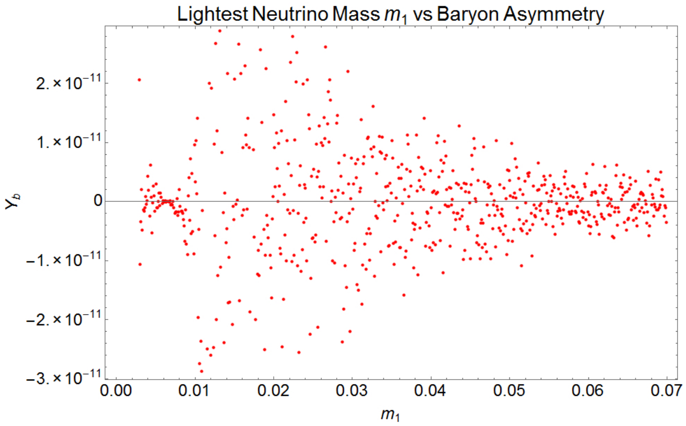

Figure 4. Variation of Baryon Asymmetry with respect to lightest Neutrino Mass For Normal Hierarchy

- **Varying the Majorana Phase , α**

  Here, we have taken $\alpha = 0\text{-}\ 2\pi$ (in Radian 0 - 6.28) with step size 0.001 and calculated the Baryon Asymmetry Y_B for 6281 number of values of α and plot results for Baryon asymmetry Y_B vs Majorana Phase(α).

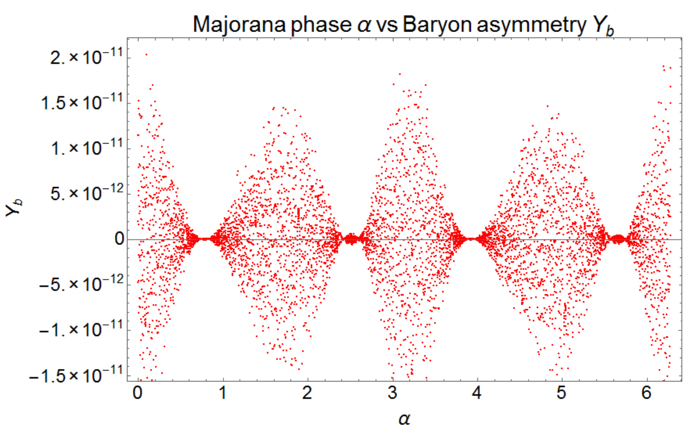

Figure 5. Variation of Baryon Asymmetry with respect to Majorana Phase For Normal Hierarchy

- **Varying the Majorana Phase , β**

  Here, we have taken $\beta = 0\text{-}\ 2\pi$ (in Radian 0 - 6.28) with step size 0.001 and calculated the Baryon Asymmetry Y_B for 6281 number of values of β and plot results for Baryon asymmetry Y_B vs Majorana Phase(β).

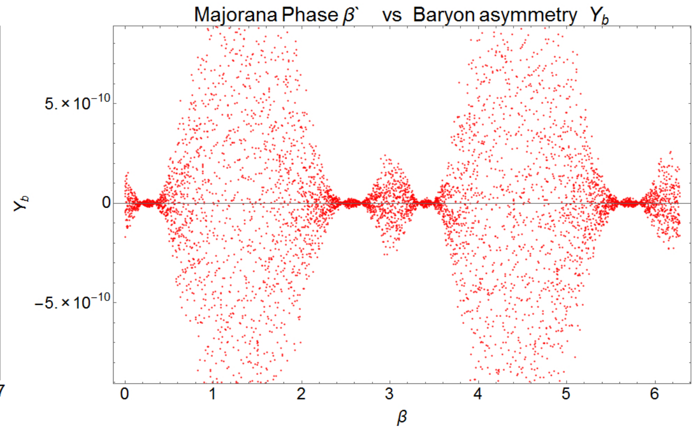

Figure 6. Variation of Baryon Asymmetry with respect to Majorana Phase For Normal Hierarchy

4.1.2 For Inverted Hierarchy($m_3 \ll m_1, m_3$)

- **Varying the Dirac phase, δ**

  Here, we have taken $\delta = 0\text{-}\ 2\pi$ (in Radian 0 - 6.28) with step size 0.001 and calculated the Baryon Asymmetry Y_B for 6281 number of values of δ and plot results for Baryon asymmetry Y_B vs Dirac phase, δ.

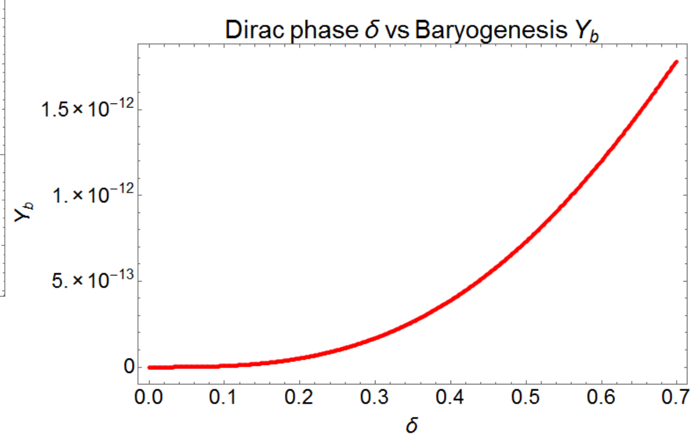

Figure 7. Variation of Baryon Asymmetry with respect to Dirac phase for Inverted Hierarchy

- **Varying the Lightest Neutrino Mass, m_3**

  Here, we have taken the lower limit for the lightest neutrino mass to be 10^{-6}eV and upper limit to be 0.065eV. Now taking the step size 0.0001 we have calculated the Baryon Asymmetry Y_B for 6500 number of values of m_3 and plot the results for Baryon asymmetry Y_B vs Lightest neutrino mass m_3.

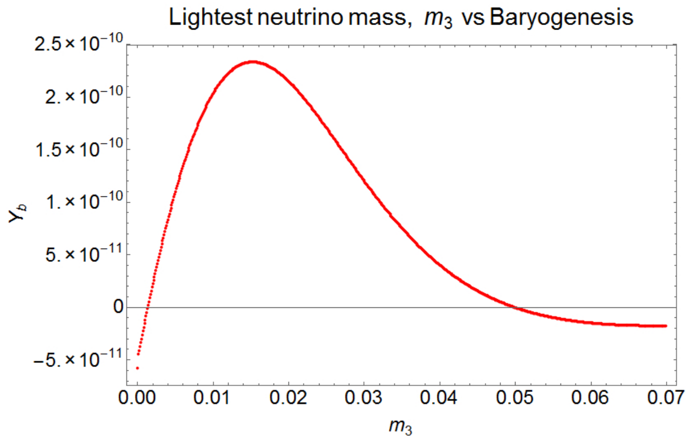

Figure 8. Variation of Baryon Asymmetry with respect to lightest Neutrino Mass For Inverted Hierarchy

- **Varying the Majorana Phase , α**

  Here, we have taken $\alpha = 0\text{-}\ 2\pi$ (in Radian 0 - 6.28) with step size 0.001 and calculated the Baryon Asymmetry Y_B for 6281 number of values of α and plot results for Baryon asymmetry Y_B vs Majoran Phase(α).

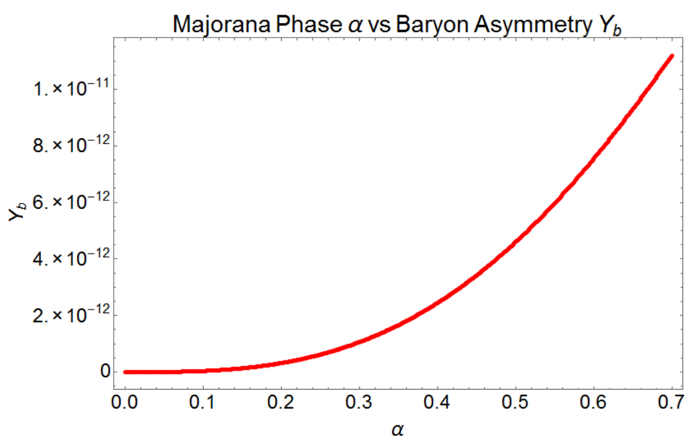

Figure 9. Variation of Baryon Asymmetry with respect to Majorana Phase For Inverted Hierarchy

- **Varying the Majorana Phase , β**

  Here, we have taken $\beta = 0\text{-}\ 2\pi$ (in Radian 0 - 6.28) with step size 0.001 and calculated the Baryon Asymmetry Y_B for 6281 number of values of β and plot results for Baryon asymmetry Y_B vs Majoran Phase(β).

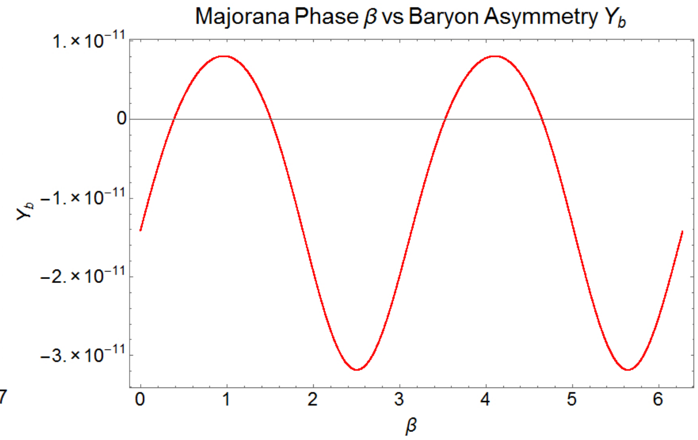

Figure 10. Variation of Baryon Asymmetry with respect to Majorana Phase For Inverted Hierarchy

5. Conclusion

We have studied the possibility of producing the observed baryon asymmetry in the Universe within the framework of Type I seesaw model by considering both hierarchical type light neutrino mass spectra.We use the generic parametrization of neutrino mixing matrix and find the numerical value of these parameters using the global fit neutrino oscillation data.Then we have calculated corresponding baryon to photon ratio taking each parameter of the four unknown parameters appear in the mass matrix, $\delta, m_1/m_3, \alpha, \beta$ as variable.
Our main conclusion can be summarized as-

- For single flavor scenario that is $T > 10^{12}$ GeV, observed baryon asymmetry can be successfully reproduced for both inverted and normal hierarchies and all the choices of lightest neutrino mass eigenvalue and Dirac CP phase.

- At around 290 -330 degrees of the Dirac phase we get a very good result for the baryon asymmetry which fit with the experimental value of baryon asymmetry.in between 120-220 degrees of Dirac phase no considerable number of baryon asymmetry found.

- For the both Majorana phases α and β we have got a considerabe baryon asymmetry at around 31-54 degrees and 320-354 degrees.

- In between 0.04 and 0.06 ev of lightest neutrino mass, (m_1 for NH m_3 for IH), we found a very less numbers which give the desired baryon asymmetry.

In view of above, we see that the neutrino mass model considered in our study can survive in nature and can very well predict the observed baryon asymmetry within the framework of type I seesaw mechanism. So we can conclude that decay of right handed neutrino may be the strong hint for the obeserved matter-antimatter asymmetry of the universe.

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