

Low Energy CP Violation and Its Relation with Leptogenesis

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ABSTRACT: In this work we have tried to explore the sign and magnitude of leptogenesis with the help of low energy CP violation experimental results. For our studies we have selected a framework with two heavy Majorana neutrinos and three light neutrinos. In minimal seesaw model, the CP violating phases which contributes to leptogenesis are identified. The low energy experimentally determined parameters are correlated with high energy parameters to quantify the leptogenesis.

KEYWORDS: Leptogenesis, Baryogenesis, Majorana Neutrino, Mass Matrix, CP Violation.

I. INTRODUCTION

After the landmark discovery of neutrino masses and neutrino mixing in the past, current attention in neutrino physics is shifting towards the observance of physics beyond the standard model [1]. Neutrinos are the potential candidate to unmask some of the deepest and long standing mysteries of cosmology and astrophysics, such as origin of matter, Baryogenesis, dark matter and many more. Due to neutrino mixing, CP violation naturally arises in the leptonic sector and in principle can be measured through neutrino oscillations [2, 3]. Here in this paper we intend to establish a relationship between CP violation at low energies and CP breaking necessary, to generate leptogenesis [4, 5, 6]. The leptogenesis process proposed by Fukugita and Yanagida [7], demands heavy right handed neutrinos. The presence of these heavy right handed neutrinos are indirectly hinted by the observed small mass square difference of left handed neutrinos at the superkamioka. The see-saw model can be a natural explanation to explain the smallness of neutrino masses. If the mass hierarchy of the right handed neutrinos is assumed to be similar to the mass hierarchy of left handed neutrinos then the decay of the lightest right handed majorana neutrino can be responsible for the generation of lepton asymmetry. Lep-tonic CP violation will play a crucial role in the generation of observed baryogenesis.

II. RELATED WORK

In conventional form, the seesaw mechanism [8, 9, 10] comprise of three heavy singlet, right handed neutrinos, N_I , where $I = 1,2,3$. These right handed neutrinos transform as complete singlets under the standard model gauge group. The minimal seesaw model, which is compatible with the solar and atmospheric neutrinos invokes only two heavy right-handed neutrinos. In this case the SM lagrangian needs to be supplemented with the following Yukawa and mass terms at higher energies.

$$-L = \overline{\psi}_{Li}(Y_v)_{ij}\tilde{\phi}N_{Rj} + \overline{\psi}_{Li}(Y_l)_{ij}\phi L_{Rj} + \frac{1}{2}\overline{(N_{Ri})^c}(M_R)_{ij}N_{Rj} \quad (1)$$

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Where $i = 1,2,3; j = 1,2$. N_R denote the right-handed neutrino fields and f is the SU(2) higgs doublet with $\tilde{\phi} = i\sigma_2\phi^+, \psi_{Li}$, is the lepton doublet of flavor i , and L_{Rj} are the right handed charged lepton singlet. The Yukawa coupling constants Y_n and Y_l are the complex valued matrices. After the electroweak symmetry breaking one gets the charged mass matrix $m_l = vY_l$ and the Dirac mass matrix for the neutrino as $m_D = vY_\nu$, where v is the vacuum expectation value of the neutral component of the higgs doublet ϕ .

After the see-saw diagonalization the seesaw formula for Majorana mass matrix for light neutrino is given by [11, 12]

$$m_\nu = m_D^T M_R^{-1} m_D \quad (2)$$

The above formula is valid, only when the Eigen values of M_R are much greater than the elements of m_D . In flavor basis $(\nu_e, \nu_\mu, \nu_\tau)$ the mass matrix m_ν can be written in terms of the observables as

$$m_\nu = U_{PMNS} m_\nu^{diag} U_{PMNS}^\dagger \quad (3)$$

In the basis where the mass matrix of Right handed Majorana M_R is diagonal, the Dirac mass matrix can be written as

$$m_D = U_L^\dagger m_D^{diag} U_R \quad (4)$$

Here U_L and U_R are unitary matrices and $m_D^{diag} \equiv \text{diag}(m_u, m_c, m_d)$, the Eigen-values of m_D is in analogy with up-type quark masses. The selection of Eigen values reflects the strong hierarchy in Eigen values of m_D . U_L is the leptonic analogue of quark CKM matrix.

In our work the selection of three mass matrix are as follows-

(1) $m_\nu^{diag} = \text{diag}(0, m_2, m_3)$

Where $m_2 = \sqrt{\Delta m_{12}^2}$ and $m_3 = \sqrt{\Delta m_{12}^2 + \Delta m_{23}^2}$

(2) The texture of dirac mass matrix can be written as

$$m_D = \begin{bmatrix} c_1 e^{i\delta_1} & c_2 e^{i\delta_2} & c_3 e^{i\delta_3} \\ c_4 & c_5 & c_6 \end{bmatrix}$$

In our analysis $c_1 = 0; \delta_2 = 0$ and $\delta_3 = \phi$, hence

$$m_D = \begin{bmatrix} 0 & c_2 & c_3 e^{-i\phi} \\ c_4 & c_5 & c_6 \end{bmatrix}$$

(3) The Right handed Majorana mass matrix is given as

$$M_R^{-1} = \begin{bmatrix} \frac{1}{M_1} & 0 \\ 0 & \frac{1}{M_2} \end{bmatrix}$$

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using equation (2) we get,

$$m_\nu = m_D^T M_R^{-1} m_D = \begin{bmatrix} \frac{c_4^2}{M_2} & \frac{c_4 c_5}{M_2} & \frac{c_4 c_6}{M_2} \\ \frac{c_4 c_5}{M_2} & \frac{c_2^2}{M_1} + \frac{c_5^2}{M_2} & \frac{c_2 c_3 e^{-i\phi}}{M_1} + \frac{c_5 c_6}{M_2} \\ \frac{c_4 c_6}{M_2} & \frac{c_2 c_3 e^{-i\phi}}{M_1} + \frac{c_5 c_6}{M_2} & \frac{c_3^2 e^{-2i\phi}}{M_1} + \frac{c_6^2}{M_2} \end{bmatrix} \quad (5)$$

Six parameters of Dirac matrix and two parameter of Majorana mass matrix can be related to low energy neutrino physics. The relationship between low energy CP violating parameters and high energy leptogenesis parameter can be established using $m_\nu^{diag} = U_{TB}^T m_\nu U_{TB}$ where U_{TB} is tri bimaximal mixing matrix.

III. BARYOGENESIS AND LEPTOGENESIS

The lepton asymmetry is generated by out of equilibrium decays of heavy (m Tev) electroweak singlet neutrinos. The decay of heavy right handed Majorana neutrinos into light leptons and Higgs bosons can give rise to CP violation, if the Yukawa coupling involved have unremovable phases, then it can lead to the excess of antileptons over leptons in the final state [13]. The lepton asymmetry so produced can be converted to Baryon asymmetry through the sphaleron processes [14]. The experimental value of baryon to photon ratio is given as,

$$\eta_B = \frac{n_B - \bar{n}_B}{n_\gamma} (6.21 \pm 0.16) \times 10^{-10} \quad (6)$$

The lepton number asymmetry, ϵ_i , produced by the decay of a heavy electroweak singlet with mass M_i is given as [15].

$$\epsilon_i = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i} = \frac{-3}{4\pi v^2} \left[\frac{1}{m_D m_D^\dagger} \right]_{11} \text{Im} (m_D m_D^\dagger)_{12}^2 F \left(\frac{M_i^2}{M_1^2} \right) \quad (7)$$

Where, $v = 246$ GeV, is the vacuum expectation value of the higgs field, and the function F is defined as

$$F(x) = \sqrt{x} \left[\frac{2}{x-1} + \ln \left(\frac{1+x}{x} \right) \right] \quad (8)$$

And $F(x) \approx \frac{3}{\sqrt{x}}$ for $x \gg 1$, where $x = \frac{M_i^2}{M_1^2}$; in case of only two heavy right handed neutrino we can approximate

$$F \left(\frac{M_2^2}{M_1^2} \right) \approx 3 \frac{M_1}{M_2}$$

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In two heavy right handed neutrino case $\Gamma_1 = \Gamma_2$ is an excellent approximation. The contribution decay mode of $N_i \rightarrow l + H^c$ and its complex conjugate process $N_i \rightarrow l^c + H$ at tree level and at one loop is checked. Lepton asymmetry can be converted into baryon asymmetry.

$$\eta_B = 0.96 \times 10^{-2} (-\varepsilon) k$$

Here k is the efficiency factor which estimates the washout effects of out of equilibrium decays of N_1 and N_2

$$k = 2 \times 10^{-2} \left(\frac{0.01 \text{ eV}}{\tilde{m}} \right)^{1.1 \pm 0.1} \tag{11}$$

$$\tilde{m} = \frac{(m_D m_D^\dagger)_{ii}}{M_i} \tag{12}$$

Now the baryon asymmetry η_B can be parametrized as a function of m_2, m_3 (low energy scale parameter) and M_1, M_2 and phase ϕ (high energy scale parameter). In the hierarchical case, the baryogenesis can be given as [16]

$$\eta_B \approx 2.5 \times 10^{-8} \left(\frac{M_1}{10^{-13} \text{ GeV}} \right) \left(\frac{m_2}{0.01 \text{ eV}} \right) \left(\frac{0.01}{m_3} \right)^{1.1} (1 - \cos \phi) (\sin \phi) \tag{13}$$

In our studies we have tried to establish bound on phase ϕ for experimentally observed value of Baryogenesis. These bounds will help to correlate low energy neutrino parameter with high energy leptogenesis.

IV. CONCLUSION

Neutrino physics opens the door, towards the era of new physics. While looking at physics beyond the standard model heavy Majorana neutrinos enter in many scenarios. Natural explanation of small masses of neutrino can be provided by the see-saw mechanism which depends on the presence of heavy right handed majorana neutrinos. The minimal see-saw model consist of two heavy right handed Majorana neutrinos which follows the same hierarchal spectrum as light neutrinos. In order to quantify the observed baryogenesis a careful study of leptogenesis is required. The right handed neutrino masses $M_1 \sim 10^9 - 10^{14} \text{ GeV}$ allows for the neutrino oscillation by see-saw formula and can be responsible for the leptogenesis for normal mass hierarchy.

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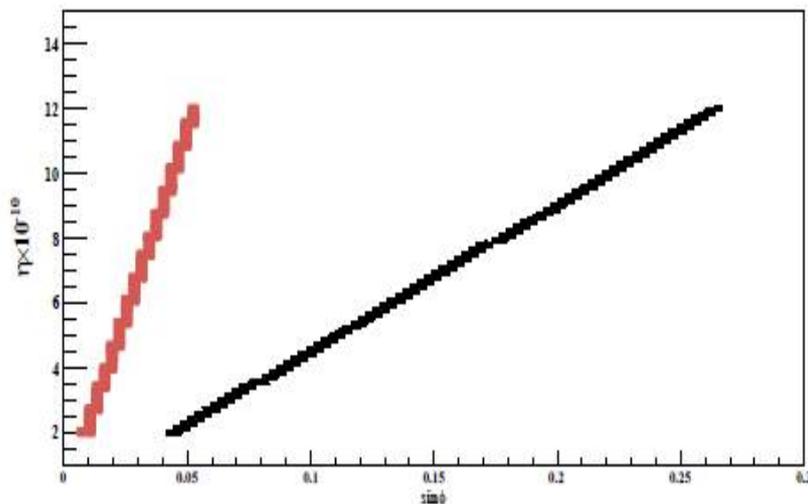


Fig. 1 Relation between baryon asymmetry η_B and $\sin \phi$ for two values of M_1 ; the red line is for $M_1 = 5 \times 10^{13}$ MeV and the black line is for $M_1 = 1 \times 10^{13}$ MeV

In our work we have used $m_2 = 9.59 \times 10^{-3}$ eV, $m_3 = 4.56 \times 10^{-2}$ eV and we have explored bounds on phase f for two values of M_1 , (1) $M_1 = 10^{13}$ GeV, and (2) $M_1 = 5 \times 10^{13}$ GeV.

The higher energy phenomenon phase f is constrained for observed value of Baryo-genesis as $\sin \phi = 0.13$ for $M_1 = 10^{13}$ GeV and $\sin \phi = 0.034$ for $M_1 = 5 \times 10^{13}$ GeV. Hence we can say that the value of CP phase present in dirac matrix depends on our choice of mass of M_1 and in attempt to correlate low energy CP physics we must check the effect of phase ϕ on the CP at low energies.

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