

Leptogenesis and low energy CP violation

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Received Nov. 25, 2015

Accepted Dec. 12, 2015

ABSTRACT

In this work the low energy neutrino parameters, which are determined experimentally in neutrino oscillation experiments are correlated with the high energy neutrino parameters in order to estimate the magnitude of leptogenesis. Here we have examined the minimal seesaw mechanism of 3 X 2 Dirac matrix. By selecting the appropriate texture of the Dirac matrix and starting our analysis with the light neutrino masses we have tried to establish the bound on phase coming from high energy neutrino physics.

Key words: Leptogenesis, low energy, Dirac matrix, high energy, Phase.

I. INTRODUCTION

After the discovery of small but finite neutrino masses, neutrino physics has opened the door for the observance of physics beyond the standard model [1]. Neutrinos are the potential candidate to unmask some of the deepest and long standing mysteries, such as origin of matter, Baryogenesis, dark matter, puzzles of cosmology and astrophysics, and many more. Due to the mixing of neutrinos, CP violation naturally occurs in the leptonic sector and in principle can be measured through neutrino oscillations [2, 3]. The Seesaw mechanism is the most potential mechanism to explain the smallness of neutrino masses. Here in this paper we intend to derive a relationship between CP violation at low energies and new CP phase at high energy necessary to generate leptogenesis [4, 5, 6]. The leptogenesis process proposed by Fukugita and Yanagida [7], requires heavy right handed neutrinos. The presence of experimentally observed small mass square difference of left handed neutrinos at the Super-Kamioka gave an indirect hint to the presence of these heavy right handed Majorana neutrinos. 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. Leptonic CP violation will play a crucial role in the generation of observed baryogenesis.

II. SEESAW MECHANISM

In its 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 neutrino fields transform as complete singlets under the standard model gauge group. The minimal seesaw model, which is compatible with two non zero light neutrino mass invokes only two heavy right-handed neutrinos [11]. In this case the SM Lagrangian needs to be supplemented with the following Yukawa and mass terms at higher energies.

$$-L = \overline{\psi_{Li}} (Y_{\nu})_{ij} \varphi N_{Rj} + \overline{\psi_{Li}} (Y_l)_{ij} \varphi L_{Rj} + \frac{1}{2} (\overline{N_{Ri}})^c (M_R)_{ij} N_{Rj} \quad (1)$$

Where $i = 1, 2, 3$; $j = 1, 2$. N_R denotes the right-handed neutrino fields and φ is the SU(2) Higgs doublet with $= i\sigma_2 \varphi$, ψ_{Li} is the lepton doublet of flavor i , and L_{Rj} are the right handed charged lepton singlet.

The complex valued matrices, Yukawa coupling are denoted by Y_{ν} and Y_l .

After the electroweak symmetry breaking we can write $\frac{m_D}{v} = Y_l$ and $\frac{m_D}{v} = Y_{\nu}$, 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 mass matrix of light neutrino is given by [12, 13]

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

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 matrix M_R is diagonal, the Dirac mass matrix can be written as

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

Here U_L and U_R are unitary matrices and $m_D^{diag} = \text{diag}(m_w, m_c, m_d)$.

The Eigen-values of m_D are in analogy with up-type quark masses. This selection reflects the strong hierarchy in Eigen values of m_D . U_L is the leptonic analogue of quark CKM matrix.

In this work the selection of the three mass matrix are as follows:

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

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

(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 $\delta_3 = \varphi$, hence

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

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

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

using equation the above selected form of mass matrix in equation (2),

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

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

Leptogenesis is a natural consequence of the seesaw mechanism. In the very hot early universe , the right handed heavy neutrinos N_i were produced. The lepton asymmetry is generated by out of equilibrium decays of heavy N_i (m Tev), electroweak singlet neutrinos. CP violation always come through phases. 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 [14]. The lepton asymmetry so produced can be converted to Baryon asymmetry through the sphaleron processes [15]. The experimental value of baryon to photon ratio is given as, FF

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

The CP-violation asymmetry between N decay rates [16] can be given as

$$\varepsilon_i = \frac{\Gamma(N \rightarrow lH) - \Gamma(N \rightarrow \bar{l}H)}{\Gamma(N \rightarrow lH) + \Gamma(N \rightarrow \bar{l}H)} = \frac{-3}{4\pi v^2} \frac{1}{[m_D m_D^\dagger]_{11}} \text{Im} (m_D m_D^\dagger)_{12}^2 F \left(\frac{M_1^2}{M_2^2} \right) \tag{7}$$

this will produce nonzero lepton number. Here $v = 246$ GeV, is the vacuum expectation value of the higgs field, and the function F is defined as

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

And $F(x) \approx \frac{3}{\sqrt{x}}$ for $x \gg 1$, where $x = \frac{M_1^2}{M_2^2}$; in case of only two heavy right handed neutrino we can approximate

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

From the seesaw relation the heavy right handed neutrino mass should be of the order of

$$10^{(9-10)} \text{ GeV}$$

These heavy neutrinos are out of reach with LHC experiment, hence the possibility of the leptogenesis requires a method which do not depend on its production.

Lepton asymmetry can be converted into baryon asymmetry.

$$\eta_B = 0.96 \times 10^{-2} (-\varepsilon) k \tag{9}$$

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

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

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

Now the baryon asymmetry h_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 [17]

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

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 $M_1 \sim 10^9 - 10^{14}$ GeV allows for the neutrino oscillation by see-saw formula and can be responsible for the leptogenesis for normal mass hierarchy.

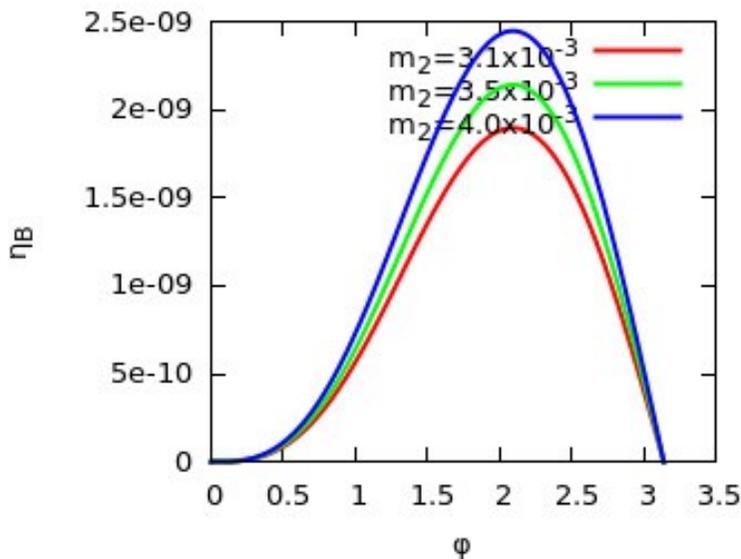


Fig. 1 Relation between baryon asymmetry η_B and $\sin\varphi$ for two values of M_1 ; the red line is for $M_1 = 5 \times 10^{13} \text{MeV}$ and the black line is for $M_1 = 1 \times 10^{13} \text{MeV}$

In our work we have used :

$$m_2 = 3.1 \times 10^{-3}, 3.5 \times 10^{-3}, 4.0 \times 10^{-3} \text{eV}, m_3 = 4.56 \times 10^{-2} \text{eV}, M_1 = 10^{14} \text{GeV}$$

we have explored bounds on phase φ .

The higher energy phenomenon phase is φ constrained for observed value of Baryogenesis. Hence we can say that the value of higher energy CP phase present in dirac matrix depends on the choice of mass of M_1 and lower energy mass m_2 . To conclude we can quantify leptogenesis with lower energy phenomenon.

Acknowledgements: This work is financially supported by government of India, DST project no-SR/MF/PS02/2013. One of the author Jyotsna Singh is thankful to D.S.T .

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