Research Article

Octant Degeneracy and Quadrant of Leptonic CPV Phase at Long Baseline ν Experiments and Baryogenesis

Kalpana Bora,¹ Gayatri Ghosh,¹ and Debajyoti Dutta²

¹Department of Physics, Gauhati University, Guwahati 781014, India

²Harish-Chandra Research Institute, Chhatnag Road, Jhansi, Allahabad 211019, India

Correspondence should be addressed to Kalpana Bora; kalpana.bora@gmail.com

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In a recent work by us, we have studied how CP violation discovery potential can be improved at long baseline neutrino experiments (LBNE/DUNE), by combining with its ND (near detector) and reactor experiments. In this work, we discuss how this study can be further analysed to resolve entanglement of the quadrant of leptonic CPV phase and octant of atmospheric mixing angle θ_{23} , at LBNEs. The study is done for both NH (normal hierarchy) and IH (inverted hierarchy), HO (higher octant), and LO (lower octant). We show how baryogenesis can enhance the effect of resolving this entanglement and how possible values of the leptonic CP violating phase δ_{CP} can be predicted in this context. With respect to the latest global fit data of neutrino mixing angles, we predict the values of δ_{CP} for different cases. In this context we present favoured values of δ_{CP} (δ_{CP} range at $\geq 2\sigma$) constrained by the latest updated BAU range and also confront our predictions of δ_{CP} with an up-to-date global analysis of neutrino oscillation data. We find that some region of the favoured δ_{CP} parameter space lies within the best fit values around $\delta_{CP} \approx 1.3\pi - 1.4\pi$. A detailed analytic and numerical study of baryogenesis through leptogenesis is performed in this framework within the nonsupersymmetric SO(10) models.

1. Introduction

Today, physics is going through precision era; this is more so for neutrino physics. With the measurement of reactor mixing angle θ_{13} [1–7] precisely by reactor experiments, the unknown quantities left to be measured in neutrino sector are leptonic CP violating phase [8–13], octant of atmospheric angle θ_{23} [14–20], mass hierarchy, nature of neutrino, and so forth. Long baseline neutrino experiments (LBNE [21, 22], NO ν A [23], T2K [24], MINOS [25], LBNO [26], etc.) may be very promising, in measuring many of these sensitive parameters.

Measuring leptonic CP violation (CPV) is one of the most demanding tasks in future neutrino experiments [27]. The relatively large value of the reactor mixing angle θ_{13} measured with a high precision in neutrino experiments [1–5] has opened up a wide range of possibilities to examine CP violation in the lepton sector. The leptonic CPV phase can be induced by the PMNS neutrino mixing matrix [28–30] which

holds, in addition to the three mixing angles, a Dirac-type CP violating phase in general as it exists in the quark sector and two extra phases if neutrinos are Majorana particles. Even if we do not yet have significant evidence for leptonic CPV, the current global fit to available neutrino data manifests nontrivial values of the Dirac-type CP phase [31–34]. In this context, possible size of leptonic CP violation detectable through neutrino oscillations can be predicted. Recently, [8], we have explored possibilities of improving CP violation discovery potential of newly planned long baseline neutrino experiments (earlier LBNE, now called DUNE) in USA. In neutrino oscillation probability expression $P(\nu_\mu \rightarrow \nu_e)$ relevant for LBNEs, the term due to significant matter effect changes sign when oscillation is changed from neutrino to antineutrino mode, or vice versa. Therefore in the presence of matter effects, CPV effect is entangled and hence one has two degenerate solutions, one due to CPV phase and another due to its entangled value. It has been suggested to resolve this issue by combining two experiments with different

baselines [35, 36]. But CPV phase measurement depends on value of reactor angle θ_{13} , and hence precise measurement of θ_{13} plays crucial role in its CPV measurements. This fact was utilized recently by us [8], where we have explored different possibilities of improving CPV sensitivity for LBNE (USA). We did so by considering LBNE with

- (1) its ND (near detector),
- (2) reactor experiments.

We considered both appearance ($\nu_\mu \rightarrow \nu_e$) and disappearance ($\nu_\mu \rightarrow \nu_e$) channels in both neutrino and antineutrino modes. Some of the observations made in [8] are as follows:

- (1) CPV discovery potential of LBNE increases significantly when combined with near detector and reactor experiments.
- (2) CPV violation sensitivity is more in LO (lower octant) of atmospheric angle θ_{23} , for any assumed true hierarchy.
- (3) CPV sensitivity increases with mass of FD (far detector).
- (4) When NH is true hierarchy, adding data from reactors to LBNE improves its CPV sensitivity irrespective of octant.

Aim of this work is to critically analyse the results presented in [8], in context of entanglement of quadrant of CPV phase and octant of θ_{23} , and hence study the role of baryogenesis in resolving this entanglement. Though in [8] we studied effect of both ND and reactor experiments on CPV sensitivity of the LBNEs, in this work we have considered only the effect of ND. But similar studies can also be done for the effect of reactor experiments on LBNEs as well. The details of LBNE and ND are same as in [8]. Following the results of [8], either of the two octants is favoured, and the enhancement of CPV sensitivity with respect to its quadrant is utilized here to calculate the values of lepton-antilepton symmetry. This is done considering two cases of the rotation matrix for the fermions, CKM only and CKM + PMNS. Then, this is used to calculate the value of BAU within the nonsupersymmetric SO(10) model [37], characterized by the presence of an intermediate mass scale where both the lepton number conservation and quark-lepton symmetry are broken. In the supersymmetric case, the two effects occur at the unification scale, and no intermediate scale is present.

This is an era of precision measurements in neutrino physics. We therefore consider variation of Δm_{31}^2 range at its 3σ CL versus δ_{CP} range at $\geq 2\sigma$ over the corresponding distribution of χ^2 -minima from Figure 2. We calculate baryon to photon ratio and compare with its experimentally known best fit value. As constrained by the latest updated BAU limits, $5.7 \times 10^{-10} < \text{BAU} < 6.7 \times 10^{-10}$, we plot θ_{13} range at its 3σ CL [6] from its central value versus δ_{CP} range at $\geq 2\sigma$ over χ^2 -minima distribution and find that for IH and LO case the allowed θ_{13} has a varied range altering within 8.7° to 9.4° in the upper quadrant (π to 2π) and 8.7° to 9.8° in the lower quadrant (0 to π). Similarly to IH and HO case

the allowed θ_{13} has a varied range differing within 8.7° to 9.8° . As shown in our results in Section 4, in IH and LO case the spectrum of δ_{CP} is mostly concentrated in the region 88° for θ_{13} around 9.09° to 9.2° , 9.25° , 9.35° to 9.5° , and 9.6° to 9.65° . Also $\delta_{CP} = 276.5^\circ$ exists for θ_{13} around 9.06° to 9.12° , 9.3° to 9.45° , 9.517° . $\delta_{CP} = 290^\circ$ survives for θ_{13} around, 9° , 9.15° to 9.3° , 9.35° to 9.5° in the higher quadrant (π to 2π). Similarly as shown in our results in Section 4, as allowed by the updated BAU limits in IH and HO case, the parameter space of δ_{CP} in the lower quadrant (0 to π) demands δ_{CP} to be around 69° , for $\theta_{13} \sim 8.86^\circ$ – 8.896° , 9.06° – 9.22° , 9.32° , and 9.61° . There also exists $\delta_{CP} = 95^\circ$ which constrains θ_{13} to be around 8.99° , 9.24° , 9.352° , 9.5 – 9.64° , and 9.79° . In the upper quadrant (π to 2π) for the present updated BAU constraint, the allowed region of δ_{CP} parameter space becomes constrained with $\delta_{CP} = 257.5^\circ$, for θ_{13} around 8.96° , 9.0974° to 9.22° , 9.5° , 9.6° , and 9.74° . Also the BAU constraint requires δ_{CP} to be equal to 288° , for θ_{13} around 9° , 9.06° to 9.35° , 9.5° , 9.69° , and 9.8° . Also $\delta_{CP} = 295^\circ$ survives for θ_{13} around 9.09° , 9.26° , 9.34° , 9.5° , 9.6° , and 9.69° . A part of the allowed δ_{CP} parameter space is found to lie within the best fit values of $\delta_{CP} \approx 1.3\pi$ – 1.4π . As constrained by the current BAU bounds we present the 3D variation of the favoured range of parameters: Δm_{31}^2 range within its 3σ C.L, θ_{13} range at its 3σ CL, and δ_{CP} range at $\geq 2\sigma$ varied within $[0, 2\pi]$ in Figure 2.

As can be seen from the results presented in Section 4, from Figures 3(a) and 3(b), we find that BAU can be explained most favourably for the following possible cases: $\delta_{CP} = 1.536\pi$, IH and LO of θ_{23} ; $\delta_{CP} = 1.611\pi$, IH and LO of θ_{23} ; $\delta_{CP} = 0.488\pi$, IH and LO of θ_{23} ; $\delta_{CP} = 1.638\pi$, IH and HO of θ_{23} ; $\delta_{CP} = 1.6\pi$, IH and HO of θ_{23} ; $\delta_{CP} = 1.43\pi$, IH and HO of θ_{23} ; $\delta_{CP} = 0.777\pi$, IH and HO of θ_{23} ; $\delta_{CP} = 0.5277\pi$, IH and HO of θ_{23} ; $\delta_{CP} = 1.436\pi$, NH and HO of θ_{23} . It is worth mentioning that the value of $\delta_{CP} = 1.43\pi$ and $\delta_{CP} = 1.436\pi$ is close to the central value of δ_{CP} from the recent global fit result [31, 34, 38–42]. It is fascinating to notice that a nearly maximal CP-violating phase $\delta_{CP} = (3/2)\pi$ has been reported by the T2K [43], NO ν A [44], and Super-Kamiokande experiments [45], even if the statistical significance of all these experimental results is below 3σ level. This accords with one of our calculated favoured solutions $\delta_{CP} = 1.536\pi$ which exactly holds with the current BAU constraints. Moreover, such hints of a nonzero δ_{CP} were already present in global analyses of neutrino oscillation data, such as the one in [31–33]. Our main aim in this work is to carry out a detailed analysis of the breaking of the entanglement of the quadrant of leptonic CPV phase and octant of θ_{23} by using the current data of ν mixing parameters and identify the CPV phase and θ_{13} spectrum required to get the breaking favourable with the current BAU constraint. These results could be important keeping in view that the quadrant of leptonic CPV phase and octant of atmospheric mixing angle θ_{23} are yet not fixed. Also, they are significant in context of precision measurements on neutrino oscillation parameters.

The paper is organized as follows. In Section 2, we discuss entanglement of quadrant of CPV phase and octant of θ_{23} . In Section 3, we present a review on leptogenesis and baryogenesis. In Section 4 we show how the baryon asymmetry (BAU)

FIGURE 1: CP asymmetry versus δ_{CP} at DUNE/LBNE, for both the hierarchies. Red and green solid (dotted) lines are for NH (IH) with types of curve to distinguish HO and LO as the true octant, respectively.

within the $SO(10)$ model, by using two distinct forms for the lepton CP asymmetry, can be used to break the entanglement. Finally in Section 5, we present our conclusions.

2. CPV Phase and Octant of θ_{23}

As discussed above, from Figure 3 of [8], we find that by combining with ND and reactor experiments, CPV sensitivity of LBNE improves more for LO (lower octant) than HO (higher octant), for any assumed true hierarchy. In Figure 1 we plot CP asymmetry,

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (1)$$

as a function of leptonic CPV phase δ_{CP} , for $0 \leq \delta_{CP} \leq 2\pi$. CP asymmetry also depends on the mass hierarchy. For NH, CP asymmetry is more in LO than in HO. For IH, CP asymmetry is more in LO than in HO. In this work we have used above information to calculate dependence of leptogenesis on octant of θ_{23} and quadrant of CPV phase. From Figure 1 we see that

$$A_{CP}(\text{LO}) > A_{CP}(\text{HO}). \quad (2)$$

For a given true hierarchy, there are eight degenerate solutions

$$\begin{aligned} &\delta_{CP}(\text{first quadrant})-\theta_{23}(\text{lower octant}) \\ &\delta_{CP}(\text{second quadrant})-\theta_{23}(\text{lower octant}) \end{aligned}$$

$$\begin{aligned} &\delta_{CP}(\text{third quadrant})-\theta_{23}(\text{lower octant}) \\ &\delta_{CP}(\text{fourth quadrant})-\theta_{23}(\text{lower octant}) \\ &\delta_{CP}(\text{first quadrant})-\theta_{23}(\text{higher octant}) \\ &\delta_{CP}(\text{second quadrant})-\theta_{23}(\text{higher octant}) \\ &\delta_{CP}(\text{third quadrant})-\theta_{23}(\text{higher octant}) \\ &\delta_{CP}(\text{fourth quadrant})-\theta_{23}(\text{higher octant}). \end{aligned} \quad (3)$$

This eight-fold degeneracy can be viewed as

$$\text{Quadrant of CPV phase-Octant of } \theta_{23} \quad (4)$$

entanglement. Out of these eight degenerate solutions, only one should be true solution. To pinpoint one true solution, this entanglement has to be broken. We have shown [8] that sensitivity to discovery potential of CPV at LBNEs in LO is improved more, if data from near detector of LBNEs or from reactor experiments is added to data from FD of LBNEs as shown in Figure 3 of [8]. Therefore 8-fold degeneracy of 2 gets reduced to 4-fold degeneracy, with our proposal [8]. Hence, following this 4-fold degeneracy still remains to be resolved:

$$\begin{aligned} &\delta_{CP}(\text{first quadrant})-\theta_{23}(\text{LO}) \\ &\delta_{CP}(\text{second quadrant})-\theta_{23}(\text{LO}) \\ &\delta_{CP}(\text{third quadrant})-\theta_{23}(\text{LO}) \\ &\delta_{CP}(\text{fourth quadrant})-\theta_{23}(\text{LO}). \end{aligned} \quad (5)$$

The possibility of $\theta_{23} > 45^\circ$, that is, HO of θ_{23} , is also considered in this work. In this context the degeneracy is

$$\begin{aligned} &\delta_{CP}(\text{first quadrant})-\theta_{23}(\text{HO}) \\ &\delta_{CP}(\text{second quadrant})-\theta_{23}(\text{HO}) \\ &\delta_{CP}(\text{third quadrant})-\theta_{23}(\text{HO}) \\ &\delta_{CP}(\text{fourth quadrant})-\theta_{23}(\text{HO}). \end{aligned} \quad (6)$$

In this work, we propose that leptogenesis can be used to break above-mentioned 4-fold degeneracy of (5) and (6). It is known that observed baryon asymmetry of the universe (BAU) can be explained via leptogenesis [46–50]. In leptogenesis, the lepton-antilepton asymmetry can be explained, if there are complex Yukawa couplings or complex fermion mass matrices. This in turn arises due to complex leptonic CPV phases, δ_{CP} , in fermion mass matrices. If all the other parameters except leptonic δ_{CP} phase in the formula for lepton-antilepton asymmetry are fixed, for example, then observed value of BAU from experimental observation can be used to constrain quadrant of δ_{CP} , and hence 4-fold entanglement of (5) and (6) can be broken. An experimental signature of CP violation associated with the Dirac phase δ_{CP} , in PMNS matrix [51] can in principle be obtained, by searching for CP asymmetry in ν flavor oscillation. To elucidate this proposal, we consider nonsupersymmetric $SO(10)$ models, in which

FIGURE 2: In (a) and (b) δ_{CP} versus χ^2 sensitivity corresponding to CP discovery potential at LBNEs, for both the hierarchies and octant shown.

BAU arises due to leptogenesis, and this lepton-antilepton asymmetry [52] is generated by the out of equilibrium decay of the right handed, heavy Majorana neutrinos, which form an integral part of seesaw mechanism for neutrino masses and mixing. We consider type I seesaw mechanism, just for simplicity.

3. Leptogenesis and Baryogenesis Using Type I Seesaw in SO(10) Models

In grand unified theories like SO(10), one right-handed heavy Majorana neutrino per generation is added to standard model and they couple with left-handed ν via Dirac mass matrix m_D . When the neutrino mass matrix is diagonalised, we get two eigenvalues, light neutrino $\sim m_D^2/M_R$ and a heavy neutrino state $\sim M_R$. This is called type I seesaw mechanism (it may be noted that type I seesaw may be obtained in other theories). Here, decay of the lightest of the three heavy RH Majorana neutrinos, M_1 , that is $M_3, M_2 \gg M_1$, will contribute to $l - \bar{l}$ asymmetry [53–58] (for leptogenesis), that is, ϵ_l^{CP} . It may be noted that some results on leptogenesis in the context of SO(10) models have been discussed earlier in [59–65]. In the basis where RH ν mass matrix is diagonal, the type I contribution to ϵ_l^{CP} is given by decay of M_1

$$\epsilon_l^{\text{CP}} = \frac{\Gamma(M_1 \rightarrow lH) - \Gamma(M_1 \rightarrow \bar{l}\bar{H})}{\Gamma(M_1 \rightarrow lH) + \Gamma(M_1 \rightarrow \bar{l}\bar{H})}, \quad (7)$$

where $\Gamma(M_1 \rightarrow lH)$ means decay rate of heavy Majorana RH ν of mass M_1 to a lepton and Higgs. We assume

a normal mass hierarchy for heavy Majorana neutrinos. In this scenario the lightest of heavy Majorana neutrinos is in thermal equilibrium while the heavier neutrinos, M_2 and M_3 , decay. Any asymmetry produced by the out of equilibrium decay of M_2 and M_3 will be washed away by the lepton number violating interactions mediated by M_1 . Therefore, the final lepton-antilepton asymmetry is given only by the CP-violating decay of M_1 to standard model leptons (l) and Higgs (H). This contribution is [66]

$$\epsilon_l = -\frac{3M_1}{8\pi} \frac{\text{Im} [\Delta m_{\odot}^2 R_{12}^2 + \Delta m_A^2 R_{13}^2]}{v^2 \sum |R_{1j}|^2 m_j}, \quad (8)$$

where v is the vev of the SM Higgs doublet that breaks the SM gauge group to $U(1)_{em}$. R is a complex orthogonal matrix with the property that $RR^T = 1$. R can be parameterized as [67]

$$R = D_{\sqrt{M^{-1}}} Y_\nu U D_{\sqrt{K^{-1}}}, \quad (9)$$

where Y_ν is the matrix of neutrino Yukawa couplings. v is the vacuum expectation value of ν Dirac masses. In the flavour basis, where the charged lepton Yukawa matrix, Y_e , and gauge interactions are flavour-diagonal, $D_K = U^T K U$, where $K = Y_\nu^T M_R^{-1} Y_\nu$. U is the PMNS matrix and M_R is the RH neutrino Majorana scale. On the basis of right-handed neutrinos, $D_M = \text{Diag}(M_1, M_2, M_3)$, where $M_3, M_2 \gg M_1$. Equation (8) relates the lepton asymmetry to both the solar (Δm_{21}^2) and atmospheric (Δm_A^2) mass squared differences. Thus the magnitude of the matter-antimatter asymmetry can be predicted in terms of low energy oscillation parameters,

FIGURE 3: Allowed region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP}, θ_{13} for the case when R matrix consists of both V_{CKM} and U_{PMNS} . The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from Figure 2 and θ_{13} with its experimental values varied within 3σ . In Figure (a) (Figure (b)) we show the plot for the IH and LO case (IH and HO case). The blue (cyan) horizontal line represents $\delta_{CP} = 1.3\pi$ (1.4π) around which the best fit values of CPV phase δ_{CP} are assumed to lie.

Δm_{21}^2 , Δm_{A}^2 , and a CPV phase. In SO(10) models, the right-handed neutrino M_R is generated from the Yukawa coupling of right-handed neutrinos with the Higgs field that breaks the unification or intermediate symmetry down to the standard model [68]. When such a Higgs field takes a VEV, the right-handed neutrinos get a Majorana mass. This happens because lepton number is broken at that scale. It has been discussed in [65] that in the supersymmetric case the mass scale of the right-handed neutrino is similar to the unification scale, $M_R \sim M_U \sim 10^{16}$ GeV, while in the nonsupersymmetric case the scale of M_R is about the intermediate scale, $M_R \sim M_I \sim 10^{11}$ GeV [69, 70], M_I being the scale of the quark-lepton symmetry [71].

As has been discussed in [66], the lepton-antilepton asymmetry gets connected to both the solar and the atmospheric mass difference square. Following [72], in this work we choose a basis where the complex orthogonal matrix R takes the form, $R = V_{CKM} \times U_{PMNS}$, where V_{CKM} is the CKM matrix containing the quark mixing angles, and U_{PMNS} is the PMNS matrix containing neutrino mixing parameters. In equations (9) and (15) of [72], if V is taken as quark mixing matrix (where, in SO(10) theories, as quarks and leptons appear in same representation, neutrino mixing matrix can be taken to be same as quark mixing matrix at high scales) and U is taken as PMNS matrix at low energies, then we get the relation $R = V_{CKM} \times U_{PMNS}$. This assumption can also be justified, as it is well known that quark mixing CKM phase alone is not sufficient to explain the BAU, and leptonic CPV phase is needed to generate the observed BAU. Here, the matrix R is orthogonal since $R^\dagger R = U^\dagger V^\dagger V U = 1$ (because $U^\dagger U = V^\dagger V = 1$). Thus both the quark sector (quark mixing

angles, phase) and the neutrino sector (ν mixing angles and the leptonic CPV phase) appear in the expression for R and in that case R can be parameterized as

$$\begin{aligned} \text{Im } R_{13}^2 &= -s(2\delta_q) c^2 23_l c^2 13_l s^2 13_q \\ &\quad - 2s(\delta_q) c 13_q c 23_l c^2 13_l s 12_q s 13_q s 23_l \\ &\quad + 2s(-\delta_l - \delta_q) c 12_q c 13_q c 23_l c 13_l s 13_q s 13_l \\ &\quad - 2s(\delta_l) c 12_q c^2 13_q c 13_l s 12_q s 23_l s 13_l \\ &\quad - s(2\delta_l) c^2 12_q c^2 13_q s^2 13_l \\ &\quad - 2s(\delta_l) c^2 12_q c^2 13_q s^2 13_l \end{aligned}$$

$$\begin{aligned} \text{Im } R_{12}^2 &= 2s(\delta_q) c 13_q c^2 12_l c 23_l s 12_q s 13_q s 23_l \\ &\quad + 2s(\delta_q) c 12_q c 13_q c 12_l c 13_l s 13_q s 12_q s 23_l \\ &\quad - s(2\delta_q) c^2 12_l s^2 13_q s^2 23_l \\ &\quad - 2s(\delta_l - \delta_q) c 13_q c 12_l c^2 23_l s 12_q s 13_q s 12_l s 13_l \\ &\quad - 2s(\delta_l - \delta_q) c 12_q c 13_q c 23_l c 13_l s 13_q s^2 12_l s 23_l \\ &\quad - 2s(\delta_l) c^2 13_q c 12_l c 23_l s^2 12_q s 12_l s 23_l s 13_l \end{aligned}$$

$$\begin{aligned}
& + 2s(\delta_l - 2\delta_q) c_{12_l} c_{23_l} s_{13_q}^2 s_{12_l} s_{23_l} s_{13_l} \\
& - 2s(\delta_l) c_{12_q} c_{13_q}^2 s_{13_l} s_{12_q}^2 s_{23_l} s_{13_l} \\
& + 2s(\delta_l - \delta_q) c_{13_q} c_{12_l} s_{12_q} s_{12_l} s_{23_l} s_{13_l} \\
& + 2s(2\delta_l - 2\delta_q) c_{23_l}^2 s_{13_q}^2 s_{12_l}^2 s_{13_l} \\
& + 2s(2\delta_l - \delta_q) c_{13_q} c_{23_l} s_{12_q} s_{13_q}^2 s_{12_l} s_{23_l} s_{13_l} \\
& + s(2\delta_l) c_{13_q}^2 s_{12_q}^2 s_{12_l}^2 s_{23_l}^2 s_{13_l} \\
R_{11} & = c_{12_q} c_{13_q} c_{12_l} c_{13_l} + e^{-i\delta_q} s_{13_q} s_{12_l} s_{23_l} \\
& - e^{-i\delta_l} e^{-i\delta_q} s_{13_l} c_{12_l} c_{23_l} s_{13_l} - c_{13_q} s_{12_q} c_{23_l} s_{12_l} \\
& - e^{-i\delta_l} c_{13_q} s_{12_q} c_{12_l} s_{23_l} s_{13_l} \\
R_{12} & = c_{12_q} c_{13_q} c_{13_l} s_{12_l} - e^{-i\delta_q} s_{13_q} c_{12_l} s_{23_l} \\
& - e^{-i\delta_l} e^{-i\delta_q} c_{23_l} s_{12_l} s_{13_l} s_{13_q} - c_{13_q} s_{12_q} c_{12_l} c_{23_l} \\
& - e^{-i\delta_l} c_{13_q} s_{12_q} s_{12_l} s_{23_l} s_{13_l} \\
R_{13} & = e^{-i\delta_q} c_{23_l} c_{13_l} s_{13_q} - c_{13_q} c_{13_l} s_{12_q} s_{23_l} \\
& - e^{-i\delta_l} c_{12_q} c_{13_q} s_{13_l}.
\end{aligned} \tag{10}$$

Here, c_{23_l} , s_{12_l} , c_{13_l} , and so forth represent the cosine of atmospheric mixing angle, sine of solar mixing angle, and cosine of reactor mixing angle, respectively. Similarly 23_q , 12_q , and 13_q are the quark mixing angles. δ_l and δ_q are the leptonic CPV phase and quark CPV phase, respectively. Here the R equation presumably holds at the GUT scale but weak scale values can be used in the calculations since it is well known that quark mixing parameters do not change much under renormalization group (RG) evolution in hierarchical mass spectrum of SO(10) theories. Hence CKM matrix at high scales can be used at low energies also and U is taken as PMNS matrix at low energies. We also consider $R = U_{\text{PMNS}}$, where R matrix consists of ν mixing angles and the leptonic CPV phase. Thus when left-right symmetry is broken at high intermediate mass scale M_R in SO(10) theory, CP asymmetry in this case is given by

$$\epsilon_l = -\frac{3M_1}{8\pi} \frac{\text{Im}[\Delta m_A^2 R_{13}^2]}{v^2 \sum |R_{ij}|^2 m_j}, \tag{11}$$

where

$$\begin{aligned}
|R_{11}|^2 &= \cos^2(\theta_{12}^l) \cos^2(\theta_{13}^l), \\
|R_{12}|^2 &= \sin^2(\theta_{12}^l) \cos^2(\theta_{13}^l),
\end{aligned}$$

$$|R_{13}|^2 = \cos^2(\delta_l) \sin^2(\theta_{13}^l) + \sin^2(\delta_l) \sin^2(\theta_{13}^l),$$

$$\text{Im } R_{13}^2 = -\sin^2(2\delta_l) \sin^2(\theta_{13}^l). \tag{12}$$

The neutrino oscillation data used in our numerical calculations are summarised as follows [31, 38–42]:

$$\begin{aligned}
\Delta m_{21}^2 [10^{-5} \text{ eV}^2] &= 7.60_{-0.18}^{+0.19} \\
|\Delta m_{31}^2| [10^{-3} \text{ eV}^2] &= 2.48_{-0.07}^{+0.05} (2.38_{-0.06}^{+0.05}) \\
\sin^2 \theta_{12} &= 0.323 \pm 0.016 \\
\sin^2 \theta_{23} &= 0.567_{-0.124}^{+0.032} (0.573_{-0.039}^{+0.025}) \\
\sin^2 \theta_{13} &= 0.0226 \\
&\pm 0.0012 (0.0229 \pm 0.0012).
\end{aligned} \tag{13}$$

For Δm_{31}^2 , $\sin^2 \theta_{23}$, and $\sin^2 \theta_{13}$, the quantities inside the bracket correspond to inverted neutrino mass hierarchy and those outside the bracket correspond to normal mass hierarchy. The errors are within the 1σ range of the ν oscillation parameters. It may be noted that some results on neutrino masses and mixing using updated values of running quark and lepton masses in SUSY SO(10) have also been presented in [73]. Though we consider 3-flavour neutrino scenario, 4-flavour neutrinos with sterile neutrinos as fourth flavour are also possible [74]. It is worth mentioning that ν masses and mixing can lead to charged lepton flavor violation in grand unified theories like SO(10) [75].

The origin of the baryon asymmetry in the universe (baryogenesis) is a very interesting topic of current research. A well known mechanism is the baryogenesis via leptogenesis, where the out of equilibrium decays of heavy right-handed Majorana neutrinos produce a lepton asymmetry which is transformed into a baryon asymmetry [72] by electroweak sphaleron processes [76–79]. Lepton asymmetry is partially converted to baryon asymmetry through B + L violating sphaleron interactions [80]. As proposed in [65], a baryon asymmetry can be generated from a lepton asymmetry. The baryon asymmetry is defined as

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B - n_{\bar{B}}}{7n_\gamma} = \frac{\eta_B}{7}, \tag{14}$$

where n_B , $n_{\bar{B}}$, and n_γ are number densities of baryons, antibaryons, and photons, respectively, s is the entropy density, η is the baryon to photon ratio, and $5.7 \times 10^{-10} \leq \eta_B \leq 6.7 \times 10^{-10}$ (95% CL) [81]. The lepton number is converted into the baryon number through electroweak sphaleron process [76–79]:

$$Y_B = \frac{a}{a-1} Y_L, \quad a = \frac{8N_F + 4N_H}{22N_F + 13N_H}, \tag{15}$$

where N_F is the number of families and N_H is the number of light Higgs doublets. In case of SM, $N_F = 3$ and $N_H = 1$. The lepton asymmetry is as follows:

$$Y_L = d \frac{\epsilon_l}{g^*}. \quad (16)$$

d is a dilution factor and $g^* = 106.75$ in the standard case [65] is the effective number of light degrees of freedom in the theory. The dilution factor d [65] is $d = 0.24/k(\ln k)^{0.6}$ for $k \geq 10$ and $d = 1/2k$, $d = 1$ for $1 \leq k \leq 10$, and $0 \leq k \leq 1$, respectively, where the parameter k [65] is $k = (M_P/1.7v^2 32\pi\sqrt{g^*})((M_D^\dagger M_D)_{11}/M_1)$; here M_P is the Planck mass. We have used the form of Dirac neutrino mass matrix M_D from [37].

4. Calculations, Results, and Discussion

For the purpose of calculations, we use the current experimental data for three neutrino mixing angles as inputs, which are given at 1σ – 3σ C.L., as presented in [31, 38–42]. Here, we perform numerical analysis for both the hierarchies and octants. We explore the baryon asymmetry of the universe within nonsupersymmetric SO(10) models [37] using (7)–(16) of the two hierarchies (NH and IH), two octants LO and HO, w ND, w/o ND (with and without near detector), and δ_{CP} range at $\geq 2\sigma$ over the corresponding distribution of χ^2 -minima (for maximum sensitivity from Figures 2(a) and 2(b), for which the CP discovery potential of the DUNE is maximum). For our purpose, we shall carry out general scanning of the parameters: δ_{CP} range at $\geq 2\sigma$ (from Figures 2(a) and 2(b)), θ_{13} at its 3σ CL, and Δm_{31}^2 at its 3σ CL using the data given by the oscillation experiments [1–6, 31, 38–42]. In this calculation, we have chosen $M_1 \sim 2.154 \times 10^{11}$ GeV. Also we note that, for values of $M_1 < 2.154 \times 10^{11}$ GeV, the baryon asymmetry becomes lower than the observed value. We scan the parameter space for IH and HO/LO in the light of recent ratio of the baryon to photon density bounds, $5.7 \times 10^{-10} \leq \eta_B \leq 6.7 \times 10^{-10}$ (CMB) [81] in the following ranges:

$$\begin{aligned} \delta_{CP} &\in [0, 2\pi] \\ \theta_{13} &\in [7.8^\circ, 9.9^\circ] \\ \Delta m_{31}^2 &\in [-2.54 * 10^{-3}, -2.20 * 10^{-3}] \text{ eV}^2. \end{aligned} \quad (17)$$

Similarly constrained by the present BAU bounds we perform random scans for the following range of parameters in NH, HO/LO case:

$$\begin{aligned} \delta_{CP} &\in [0, 2\pi] \\ \theta_{13} &\in [7.7^\circ, 9.9^\circ] \\ \Delta m_{31}^2 &\in [2.30 * 10^{-3}, 2.65 * 10^{-3}] \text{ eV}^2. \end{aligned} \quad (18)$$

We find that the updated BAU limit [81] together with a large θ_{13} [1–7] puts significant constraints on the δ_{CP} – θ_{13} parameter space in the IH and LO case. As can be seen from Figure 3(a), a part of the parameter space survives for $\delta_{CP} \approx 1.3$ – 1.4π in the IH and LO case as allowed by the current BAU constraint

$5.7 \times 10^{-10} \leq \eta_B \leq 6.7 \times 10^{-10}$ (CMB), corresponding to θ_{13} around 8.9° – 9.5° . This leads to the conclusion that the parameter space for the best fit values of $\delta_{CP} \approx 1.3$ – 1.4π is allowed by the present BAU constraint. The allowed regions in Figure 3(a) for the lower quadrant (0 to π) require δ_{CP} spectra, that is, δ_{CP} to be equal to 88° for θ_{13} around 9.09° to 9.2° , 9.25° , 9.35° to 9.5° , and 9.6° to 9.65° . Almost continuous values of δ_{CP} ranging from 50° to 140° are allowed for θ_{13} , 9.3° to 9.5° . For θ_{13} around 9.7° , the values of δ_{CP} mostly favoured are 50° , 69° , 88° , 90° , 95° , 99° , 120° , and 130° . The allowed region in the upper quadrant (π to 2π) necessitates δ_{CP} to be around 276.5° , for θ_{13} around 9.06° to 9.12° , 9.3° to 9.45° , and 9.517° as allowed by the current BAU bounds. Also $\delta_{CP} = 290^\circ$ exists for θ_{13} around 9° , 9.15° to 9.3° , and 9.35° to 9.5° . Almost continuous δ_{CP} ranging from 230° to 340° are allowed for θ_{13} around 9.4° .

For IH and HO case in Figure 3(b), a part of the δ_{CP} – θ_{13} parameter space exists for $\delta_{CP} \approx 1.3$ – 1.4π constrained by the current BAU limits for θ_{13} around 9° , 9.097° , 9.1° , 9.2° , 9.3° , 9.5° , 9.55° , 9.6° , and 9.7° . Thus the parameter space for the best fit values of $\delta_{CP} \approx 1.3$ – 1.4π is allowed by the present BAU constraint [81]. Figure 3(b) reveals that the allowed regions for the lower quadrant (0 to π) require δ_{CP} to be around 69° , for $\theta_{13} \sim 8.86^\circ$ – 8.896° , 9.06° – 9.22° , 9.32° , and 9.61° . There also exists $\delta_{CP} = 88^\circ$ which constrains θ_{13} to be around 9.0° to 9.1° . Also $\delta_{CP} = 95^\circ$ survives for θ_{13} around 8.99° , 9.24° , 9.352° , 9.5° – 9.64° , and 9.79° . Almost continuous values of δ_{CP} ranging from 50° to 140° are allowed for θ_{13} varying from 8.75° to 9.75° . In the upper quadrant (π to 2π) for the present updated BAU constraint, the allowed region of δ_{CP} parameter space becomes constrained with $\delta_{CP} = 257.5^\circ$, for θ_{13} around 8.96° , 9.0974° to 9.22° , 9.5° , 9.6° , and 9.74° . Also the BAU constraints necessitate δ_{CP} to be around 288° , for θ_{13} around 9° , 9.06° to 9.35° , 9.5° , 9.69° , and 9.8° as allowed by the current BAU bounds. Also $\delta_{CP} = 295^\circ$ survives for θ_{13} around 9.09° , 9.26° , 9.34° , 9.5° , 9.6° , and 9.69° . Almost continuous δ_{CP} ranging from 232° to 340° are allowed for θ_{13} around 8.9° and 9.65° .

The constraints imposed on the δ_{CP} and θ_{13} parameter in NH, HO/LO space are found to be more severe as compared to IH and HO/LO space. For, NH and LO only a particular value of CP violating phase, $\delta_{CP} = 258.5^\circ$ corresponding to $\theta_{13} = 9.02375^\circ$, is consistent with the BAU constraint. From our analysis we find that for NH and HO case we are unable to resolve the entanglement of the quadrant of δ_{CP} and octant of θ_{23} since no point in the parameter space (δ_{CP}, θ_{13}) is consistent with the recent ratio of baryon to photon density bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$. Therefore, this indicates that IH is the most favoured hierarchy for breaking the 4-fold degeneracy of (5) and (6). All of the analysis presented above is for the case when R matrix consists of both V_{CKM} and U_{PMNS} .

No points in the δ_{CP} – θ_{13} parameter space, consistent with the BAU constraint, are able to break the entanglement of the quadrant of δ_{CP} and octant of θ_{23} , when R matrix consists of U_{PMNS} only.

In Figures 4 and 5 we display the allowed 3D space (δ_{CP} , θ_{13} , and Δm_{31}^2) for breaking the 4-fold degeneracy of (5) and

TABLE 1: The summary of our calculated values of δ_{CP} , θ_{13} , and Δm_{31}^2 in case of IH and LO for R_{1j} elements of R matrix comprising U_{PMNS} and V_{CKM} .

Serial number	Leptonic CPV phase δ_{CP}	$[\Delta m_{31}^2] \text{ eV}^2$	θ_{13}	Quadrant of δ_{CP}
1	$\delta_{CP} = 88^\circ$	$[-2.54 * 10^{-3}, -2.21 * 10^{-3}]$	$9.0417^\circ, 9.0697^\circ, 9.0974^\circ, 9.3917^\circ, 9.4417^\circ, 9.6167^\circ, 9.6417^\circ$	I
2	$\delta_{CP} = 276.5^\circ$	$[-2.45 * 10^{-3}, -2.21 * 10^{-3}]$	$9.0667^\circ, 9.0974^\circ, 9.3167^\circ - 9.4417^\circ, 9.5167^\circ$	IV
3	$\delta_{CP} = 290^\circ$	$[-2.42 * 10^{-3}, -2.54 * 10^{-3}]$	$9^\circ, 9.1817^\circ, 9.2667^\circ, 9.3667^\circ - 9.4417^\circ$	IV

FIGURE 4: Allowed region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP} , θ_{13} , and Δm_{31}^2 for the case when R matrix consists of both V_{CKM} and U_{PMNS} . The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from Figure 2 and θ_{13} with its experimental values varied within 3σ and Δm_{31}^2 at its 3σ C.L. The results of our calculation are presented for IH and LO case.

FIGURE 5: Allowed 3D region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP} , θ_{13} , and Δm_{31}^2 for the case when R matrix consists of both V_{CKM} and U_{PMNS} . The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from Figure 2, θ_{13} with its experimental values varied within 3σ from its central values, and Δm_{31}^2 at its 3σ CL. The results of our calculation are presented for IH and HO case.

(6) by varying the leptonic δ_{CP} phase in all of its possible range $[0-2\pi]$ at $\geq 2\sigma$ (from Figure 2), the mixing parameter θ_{13} within its 3σ level, and Δm_{31}^2 at its 3σ C.L [6].

From Figure 4 one can easily see the favoured values of δ_{CP} , θ_{13} , and Δm_{31}^2 for IH and LO case, allowed by the updated recent ratio of photon density to baryon density bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ (shown in Table 1).

For IH and HO case, the results of our numerical analysis are shown in Figure 5 which shows allowed $(\delta_{CP}, \theta_{13}, \Delta m_{31}^2)$ space as allowed by the current BAU bounds. The values of δ_{CP} , θ_{13} , and Δm_{31}^2 which are favoured simultaneously consistent with η_B constraints, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ [81], are shown in Table 2. For NH case we get only one point as shown in

$$\begin{aligned} &\text{NH, HO, III quadrant of Leptonic } \delta_{CP} \text{ phase } \delta_{CP} \\ &= 258.4^\circ \text{ or } 1.436\pi. \end{aligned} \quad (19)$$

5. Conclusion

Measuring CP violation in the lepton sector is one of the most challenging tasks today. A systematic study of the CP sensitivity of the current and upcoming LBNE/DUNE is done in our earlier work [8] which may help a precision measurement of leptonic δ_{CP} phase. In this work, we studied how the entanglement of the quadrant of leptonic CPV phase and octant of atmospheric mixing angle θ_{23} at LBNE/DUNE can be broken via leptogenesis and baryogenesis. Here, we have considered the effect of ND only in LBNE, on sensitivity of CPV phase measurement, but similar conclusions would hold for the effect of reactor experiments as well. This study is done for both the octants and hierarchies. We considered two cases of fermion rotation matrix, PMNS only and CKM + PMNS. Following the results of [8], the enhancement of CPV sensitivity with respect to its quadrant is utilized here to calculate the values of lepton-antilepton symmetry. Then, this is used to calculate the value of BAU. This is an era of precision measurements in neutrino physics. We therefore

TABLE 2: The summary of our calculated values of δ_{CP} , θ_{13} , and Δm_{31}^2 in case of IH and HO for R_{1j} elements of R matrix comprising U_{PMNS} and V_{CKM} .

Serial number	δ_{CP}	$[\Delta m_{31}^2] \text{ eV}^2$	θ_{13}	Quadrant of δ_{CP}
1	95°	$[-2.54 * 10^{-3}, -2.21 * 10^{-3}]$	8.9917°, 9.2417°, 9.352°, 9.5167°, 9.567°, 9.6417°, 9.7917°	II
2	69°	$[-2.54 * 10^{-3}, -2.38 * 10^{-3}]$	8.8667°, 8.8917°, 8.9667°, 9.0667°, 9.0917°, 9.1667°, 9.2167°, 9.3167°, 9.6167°	I
3	140°	$[-2.54 * 10^{-3}, -2.21 * 10^{-3}]$	8.7667°, 8.8667°, 8.9167°, 8.9667°, 9.1167°, 9.1417°, 9.1917°–9.2417°, 9.3167°, 9.3417°, 9.5667°, 9.6917°	II
4	257.5°	$[-2.54 * 10^{-3}, -2.21 * 10^{-3}]$	8.9667°, 9.0974°, 9.1417°, 9.1667°, 9.2167°, 9.4917°, 9.5917°, 9.6167°, 9.7417°	III
5	295°	$[-2.3 * 10^{-3}, -2.21 * 10^{-3}]$	8.4917°, 8.8167°, 9.0917°, 9.2667°, 9.4917°, 9.6167°	IV
6	288°	$[-2.44 * 10^{-3}, -2.28 * 10^{-3}]$	8.7817°, 8.9917°, 9.0667°, 9.1167°, 9.1417°, 9.1917°, 9.2417°, 9.3167°, 9.3417°, 9.5167°, 9.6917°, 9.7917°	IV

considered variation of Δm_{31}^2 and θ_{13} within its 3σ range from their central values. We calculated baryon to photon ratio and compared with its experimentally known best fit value.

It has been found [65] that, in SUSY theories, Y_B does not lie in the allowed range of the order of 10^{-10} . Nonsupersymmetric SO(10) model is favoured for baryogenesis with respect to the supersymmetric model. In the nonsupersymmetric model [37], we find that the baryon asymmetry is around the required order of magnitude $Y_B \sim 10^{-10}$. We have made a complete numerical analysis of the 3-dimensional parameters, δ_{CP} , θ_{13} , and Δm_{31}^2 , that encode the breaking of the entanglement of the quadrant of CPV phase and octant of θ_{23} in the presence of the latest constraints on $|\eta_B|$, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$, by taking neutrino oscillation mixing and mass scales as indicated by the experiments. By allowing δ_{CP} range to vary within $[0-2\pi]$ interval at $\geq 2\sigma$ over the χ^2 -minima distribution from Figure 2, we have studied the absolute values of both θ_{13} and δ_{CP} parameters in order to break the 4-fold degeneracy of (5) and (6).

The current data shows a preference of δ_{CP} towards 1.5π . From our analysis, one of the leptonic CPV phases determined in IH and LO of θ_{23} case is $\delta_{CP} = 276.5^\circ$ or 1.536π corresponding to $\theta_{13} \sim 9.0667^\circ, 9.0974^\circ, 9.3167^\circ-9.4417^\circ, 9.5167^\circ$, and $\Delta m_{31}^2 \in [-2.45 * 10^{-3}, -2.21 * 10^{-3}] \text{ eV}^2$ which is near the preferred data $\delta_{CP} = (3/2)\pi$ reported in [43–45]. The current analysis reveals that our calculated value of $\delta_{CP} = 1.43\pi$ of IH and HO of θ_{23} case is close to the best fit value of $\delta_{CP} = 1.48\pi$ for inverted ordering from global fit results [31, 38–42] and also $\delta_{CP} = 1.436\pi$ of NH and HO of θ_{23} case is favoured with the recent hint of $\delta_{CP} = 1.41\pi$ for normal hierarchy [31, 38–42].

The main results of this work are presented in Tables 1 and 2 and (19) which show that leptonic CPV phases in all the four quadrants are allowed which lie within the constraints of present BAU. These values also contain the best fit values of leptonic CPV phase as discussed earlier.

These results could be important, as the quadrant of leptonic CPV phase and octant of atmospheric mixing angle θ_{23} are yet not fixed experimentally. Also, they are significant in context of precision measurements of neutrino oscillation parameters, specially the leptonic CPV phase, Δm_{31}^2 , and the reactor angle θ_{13} .

Future experiments like DUNE/LBNEs and Hyper-Kamiokande [82] looking for the leptonic CPV phase δ_{CP} together with an improvement in the precision determination on the mixing angles would certainly provide worthy information to support or rule out the scenario presented in this work for breaking the entanglement of quadrant of CPV phase and octant of θ_{23} .

Competing Interests

The authors declare that they have no competing interests.

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