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Nonzero θ_{13} and CP violation from cobimaximal neutrino mixing matrix

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Abstract. The nonzero mixing angle θ_{13} have been reported and confirmed by many collaborations. If the mixing angle θ_{13} is nonzero, then the possiblity of the CP violation existence on neutrino sector become an attractive research subject both from experimental and theoretical sides. We evaluate the power predictions of cobimaximal neutrino mixing matrix on mixing angle θ_{13} and CP violation for neutrino sector by determining the Jarlskog invariant as a measure of CP violation.

1. Introduction

Now, we have confidence that neutrino have a tiny mass based on the experimental facts of neutrino oscillations. Neutrino oscillation is a term addressed to a changes of neutrino flavor from one flavor of neutrino to another flavor during its propogation in vacuum. From neutrino oscillation experiments, we have only got two squared-mass difference (not an absolute mass of neutrino) and three mixing angles. The problems of neutrino mass existence together with the process or mechanism to generate them and neutrino mass absolute values become an interesting research subject both from theoretical and experimental sides. The problem of absolute value of neutrino mass and the mechanism to generate them are still unsolved problems till today, another interesting challenge arise from the experimental fact i.e. the nonzero and relatively large mixing angle θ_{13} were reported by many collaborations [1-4].

The nonzero and relatively large mixing angle θ_{13} become an attractive subject to theorists because it give us a hint that CP violation could be exist in neutrino sector as well as in quark sector. There have been several attempts to explain the nonzero and relative large mixing angle θ_{13} and the possibility existence of CP violation in neutrino sector, see for example Ref. [5,6] and references there in. Most of the attempts are to modify the previously three well-known neutrino mixing matrix i.e. tribimaximal, bimaximal, and democratic. An alternative and interesting mixing angle, which is known as cobimaximal mixing, was introduced by Ma [7] that he claimed that cobimaximal mixing is achieve rigorously in a renormalizable model of radiative charged-lepton and neutrino masses. Authors in Ref. [8] used a scotogenic model i.e one loop neutrino mass model with dark right-handed neutrino gauge singlets and one inert dark scalar gauge doublet η which has symmetries that lead to cobimaximal mixing matrix.

In this paper we evaluate the power prediction of cobimaximal mixing matrix on mixing angle θ_{13} and CP violation in neutrino sector by determining the Jarlskog invariant as a measure of CP violation. The paper is organized as follow: in section 2, we discuss the cobimaximal neutrino mixing matrix and its brief formulation. In section 3, we evaluate the power prediction of cobimaximal mixing on mixing angle θ_{13} and Jarlskog invariant as a measure of CP violation. Finally, the section 4 is devoted for conclusions.

2. Cobimaximal neutrino mixing matrix

We have already known that neutrino come in three flavor eigenstates (ν_e, ν_μ, ν_τ) correspond to its charged partner (e, μ, τ) in the frame of weak interactions. When only using the flavor concept, we cannot explain the neutrino oscillation phenomena, then theorists formulated neutrino mass eigenstates (ν_1, ν_2, ν_3) concept which are different from neutrino flavor eigenstates. The flavor eigenstates are linked to neutrino mass eigenstates via a neutrino mixing matrix as follow

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \tag{1}$$

where V is neutrino mixing matrix. The standard parameterization of mixing matrix without Majorana phase read [9]

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{2}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and δ is the Dirac phase.

As stated in section 1, there are three already well-known of neutrino mixing matrix, i.e. bimaximal mixing (BM), tribimaximal mixing (TBM), and democratic mixing (DM). But, all of these mixing matrices predict the mixing angle $\theta_{13} = 0$ which are contrary to the recent experimental facts that mixing angle $\theta_{13} \neq 0$ and relatively large as reported by T2K Collaboration [2]

$$5^\circ \leq \theta_{13} \leq 16^\circ, \tag{3}$$

for neutrino masses in normal hierarchy (NH) and

$$5.8^\circ \leq \theta_{13} \leq 17.8^\circ, \tag{4}$$

for inverted hierarchy (IH) with Dirac phase $\delta = 0^\circ$. The reported results of T2K Collaboration on nonzero mixing angle θ_{13} was also confirmed by Daya Bay Collaboration [4]

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016\,(\text{stat.}) \pm 0.005\,(\text{syst.}). \tag{5}$$

Now, for a new mixing matrix which is known as cobimaximal mixing, one put the mixing angle $\theta_{23} = \pi/4$ and the Dirac phase $\delta = \pm\pi/2$ as suggested by authors of Ref. [7,8] and within this scenario the neutrino mixing matrix in Eq. (2) reads

$$V_{CBM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & \mp is_{13} \\ -\frac{\sqrt{2}}{2}(s_{12} \mp ic_{12}) & \frac{\sqrt{2}}{2}(c_{12} \mp is_{12}) & \frac{\sqrt{2}}{2}c_{13} \\ \frac{\sqrt{2}}{2}(s_{12} \mp c_{12}) & -\frac{\sqrt{2}}{2}(c_{12} \pm is_{12}) & \frac{\sqrt{2}}{2}c_{13} \end{pmatrix} \tag{6}$$

The cobimaximal neutrino mixing matrix may be achieved in the context of non-Abelian discrete symmetry by soft breaking A_4 to Z_3 and soft breaking of $S_3 \times Z_2$ to $Z_2 \times Z_2$ [10].

It is clear from Eq. (6) that cobimaximal mixing matrix depend on the mixing angles θ_{12} and θ_{13} values. Thus, when concerning with the neutrino oscillation experiment, we need to make a precise measurement of mixing angles θ_{12} and θ_{13} in the experiment. It is also apparent from Eq. (6) that cobimaximal mixing is not an orthogonal matrix and the value of mixing angle θ_{13} can be arbitrary. Meanwhile, the recent value of mixing angle θ_{12} based on global analysis of neutrino oscillation experiments was reported in Ref. [11] as follow

$$\theta_{12} = 34.5 \pm 1.0\left({}^{+3.2}_{-2.8}\right)^{\circ} \tag{7}$$

at $1\sigma\,(3\sigma)$ level. We will use the mixing angle value in Eq. (7) as input for determining the cobimaximal mixing matrix predictions on mixing angle θ_{13} and CP violation.

3. Predictions of cobimaximal mixing on θ_{13} and J_{CP}

After introducing cobimaximal neutrino mixing as an alternative mixing angle and quote the recent experimental value of mixing angle θ_{12}, now we are in position to evaluate the power predictions of cobimaximal mixing on mixing angle θ_{13} and Jarlskog invariant (J_{CP}) as a measure of CP violation in neutrino sector.

From a cobimaximal neutrino mixing matrix in Eq. (6) we can see that the value of mixing angle θ_{13} can be arbitrary if the mixing matrix is a non-orthogonal matrix. But, if we put the mixing matrix to be an orthogonal matrix, then we must put mixing angle θ_{13} to be zero. Based on the cobimaximal mixing matrix, that the value of mixing angle θ_{13} can be arbitrary, we suggest the experimentalist to measure the precise value of mixing angle θ_{13} in the future experiments.

The Jarlskog invariant (J_{CP}) as a parameter for determining the CP violation is given by [12]

$$J_{CP} = \mathrm{Im}\left[(V_{CBM})_{11}(V_{CBM})_{22}(V_{CBM})^{*}_{12}(V_{CBM})^{*}_{21}\right]. \tag{8}$$

From Eqs. (6) and (8), for Dirac phase $\delta = \pi/2$, we have the Jarlskog invariant

$$J_{CP} = \tfrac{1}{2}\left(\left(1-s_{12}^{2}\right)^{3/2}\left(1-s_{13}^{2}\right)s_{12}s_{13}\right) - \tfrac{1}{2}\left(\left(1-s_{12}^{2}\right)^{1/2}\left(1-s_{13}^{2}\right)s_{12}^{3}s_{13}\right). \tag{9}$$

It is apparent from Eq. (9) that the value of Jarlskog invariant in the scheme of cobimaximal neutrino mixing matrix depend on the mixing angles θ_{12} and θ_{13}.

To get the qualitative prediction of the cobimaximal mixing on CP violation we can plot J_{CP} as function of s_{13} and s_{12}. If we plot J_{CP} as function of s_{13} and s_{12}, then we have a figure as shown in Figure 1.

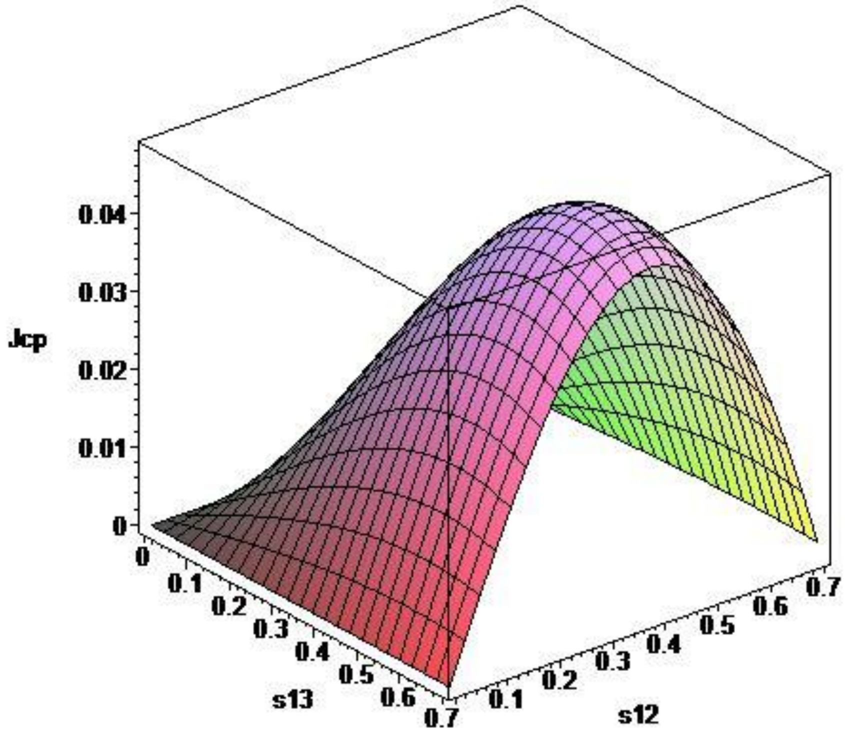

Figure 1. Plot of Jarlskog invariant (J_{CP}) as function of $\sin\theta_{13}$ and $\sin\theta_{12}$

From Fig. 1 we can see that the parameter J_{CP} has a maximun value when $\sin\theta_{13} = 0.55$ and $\sin\theta_{12} = 0.4$ that give the value of $J_{CP} \approx 0.05$. But, if we insert the center experimental value of mixing angles $\theta_{12} = 34.5^\circ$ and $\theta_{13} = 10^\circ$, then we have $J_{CP} \approx 0.013$.

4. Conclusions

We have evaluate the power predictions of cobimaximal neutrino mixing matrix on mixing angle θ_{13} and the Jarlskog invariant as a parameter of CP violation by using the central value of the experimental data of neutrino mixing angle $\theta_{12} = 34.5^\circ$ as input. It is also apparent that the value of mixing angle θ_{13} in the cobimaximal neutrino mixing matrix can be arbitrary. The Jarlskog invariant can be put as function of mixing angle θ_{13} and θ_{12} and its has a maximum value around $J_{CP} \approx 0.013$. When the central value of mixing angles $\theta_{12} = 34.5^\circ$ is inserted into the Jarlskog invariant we have $J_{CP} \approx 0.05$.

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References

[1] Adamsom P et al. (MINOS Collab.) 2011 Measurement of neutrino mass splitting and flavor mixing by MINOS *Phys. Rev. Lett.* **107** 181801 (*Preprint* arXiv: 1103.0340 [hep-ex])

[2] Abe K et al. (T2K collab.) 2011 Indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam *Phys. Rev. Lett.* **107** 041801 (*Preprint* arXiv: 1106.2822 [hep-ex])

[3] Ahn J K et al. (RENO Collab.) 2012 Observation of reactor electron antineutrino disappearance in the RENO experiment *Phys. Rev. Lett.* **108** 191802 (*Preprint* arXiv: 1204.0626 [hep-ex])

[4] An F P et al. (Daya Bay Collab.) 2012 Observation of electron-antineutrino disappearance at Daya Bay *Phys. Rev. Lett.* **108** 171803 (*Preprint* arXiv: 1203.1669 [hep-ex])

[5] Damanik A 2012 Nonzero θ_{13} and neutrino masses from modified neutrino mixing matrix *Int. J. Mod. Phys.* A **27** 1250091 (*Preprint* arXiv: 1201.2747 [hep-ph])

[6] Damanik A 2014 *Chinese J. Phys.* **52** 1439

[7] Ma E 2016 Soft $A_4 \rightarrow Z_3$ symmetry breaking and cobimaximal neutrino mixing *Phys. Lett.* B **755** 348 (*Preprint* arXiv: 1601.00138 [hep-ph])

[8] Ferreira P M, Grimus W, Jurciukonis D and Lavoura L 2016 Scotogenic model for co-bimaximal mixing *J. High Energy Phys.* JHEP07(2016) 010

[9] Harrison P F, Perkins D H, and Scott W G 2002 Tri-bimaximal mixing and neutrino oscillation data *Phys. Lett.* B **530** 167 (*Preprint* hep-ph/0202074)

[10] Ma E 2017 Cobimaximal neutrino mixing from $S_3 \times Z_2$ *Preprint* arXiv: 1707.03352v1 [hep-ph]

[11] Gonzales-Garcia M C, Maltoni M and Salvado J 2010 Updated global fit to three neutrino mixing: status of the hints of $\theta_{13} > 0$ *J. High Energy Phys.* JHEP04(2010)056

[12] Branco C G, Gonzales Felipe R, Joaquim F R, Masina I, Rebelo M N and Savoy C A 2002 Minimal scenarios for leptogenesis and CP violation *Phys. Rev.*D **67** 073025 (*Preprint* hep-ph/0211001v2)