

CP Violation in Different Neutrino Experiments

Ng. K. Francis¹Assistant Professor, Department of Physics, Tezpur University, Tezpur, Assam, India ¹

ABSTRACT: We study CP violation originating from the phase of the neutrino mixing matrix in the long baseline neutrino oscillation experiments. The direct measurement of CP violation is the difference of the transition probabilities between CP conjugate channels. It is strongly dependent on the choice of CP phase and the reactor mixing angle as well as on the energy of neutrino and the distance it travel in vacuum and in the matter. Our results should give a clue in determining the CP violation in the upcoming long baseline neutrino oscillation experiments.

KEYWORDS: CP violation, vacuum and matter effects, long baseline neutrino experiments.

I. INTRODUCTION

2015 Nobel Prize in Physics was awarded jointly to T.Kajita and A.B McDonald, for the discovery of neutrino oscillations, which shows that neutrinos have mass. It was discovered experimentally in the two detectors: Super-Kamioka Neutrino Detection Experiment (SK) in Japan in 1998 and Sudbury Neutrino Observatory (SNO) in Canada in 2001 led by Professors Kajita and McDonald respectively. The long standing issues of solar neutrino deficit and the atmospheric neutrino anomaly were finally attributed to neutrino oscillations as showed by these two detectors. CP violation an unsolved problem in particle physics is expected to be observed in neutrino flavour oscillations. In the quark sector, CP violation has been intensively studied in the CKM standard model and found its value is too small [1, 2]. Leptonic CP violation is an important phenomenon because it relates directly to the CP violation phase parameter in the PMNS mixing matrix for the massive neutrinos [3,4]. If the neutrinos have the hierarchical mass spectrum, CP violating effect is suppressed in the short baseline accelerator experiments. However, the suppression is avoidable in the long baseline accelerator experiments, which are under operational now. The purpose of this paper is to present the numerical study of CP violation and test the theory in the long baseline atmospheric neutrino oscillations experiments. The long baseline experiments correspond to the atmospheric neutrino mass scale and we take $\Delta m^2 \approx 10^{-3} \text{ eV}^2$ as the lower mass scale in the three-flavour mixing scheme. The solar neutrino problem is not discussed in this paper. We also investigate the matter effect in the long baseline accelerator experiments since the background matter effect is not CP invariant. If the matter effect is not negligibly small compared to the CP violating effect in the vacuum, one should consider how to extract the matter effect from the data. It is found that the matter effect strongly depends on the hierarchical pattern of the neutrino masses and mixings. Neutrino oscillations occur because of a difference in phase between the wavepackets of each of the mass eigenstates. In vacuum, the phase difference can occur from wave packets which propagate with different velocities arising from mass differences. In matter, however, the phase difference is determined by the total energy of the mass eigenstate. If the neutrino is propagating in a potential, V , then the total energy of a state is $E+V$, and if the potential is different for different neutrino flavours (i.e. different flavours interact differently) then a phase difference can be introduced through the interaction potential and the neutrinos will oscillate through matter effects.

II. CP VIOLATION IN NEUTRINO FLAVOUR OSCILLATIONS

If we attribute both the solar deficit which implies a mass difference of $7.6 \times 10^{-5} \text{ eV}^2$ and the atmospheric anomaly indicates a mass difference of $2.4 \times 10^{-3} \text{ eV}^2$ to the neutrino oscillation [5,6], we find most reasonable solutions to satisfy $\Delta m_{21}^2 \ll \Delta m_{31}^2$ and $V \ll \Delta m_{31}^2$. Where V is a function of electron (n_e) and matter (ρ) densities. The assumption

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 7, July 2017

V , $\Delta m_{21}^2 \ll \Delta m_{31}^2$ is also the case of ongoing operational long baseline neutrino oscillation experiments NoVA, T2K, LBNE etc. Ignoring the majorana phases, the flavour and mass eigenstates for three flavour scheme are related by 3×3 PMNS unitary matrix as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)$$

$$\Delta m_{ij}^2 = m_j^2 - m_i^2; \Delta m_{21}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 \approx \Delta m_{32}^2, |\Delta m_{32}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\nu_e \rightarrow \nu_e, \nu_e \rightarrow \nu_\mu; \nu_e \rightarrow \nu_e, \nu_\mu \rightarrow \nu_e; \nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_\tau.$$

Solar and reactor; reactor and long baseline; atmospheric and long baseline

We are concerned with the ν_μ disappearance channel $\nu_\mu \rightarrow \nu_e$ only. This transition corresponds to MINOS(L=735km), MiniBOONE (L=500m), T2K (L=295km), Chooz (1.03km) neutrino flavour oscillations experiments.

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{12}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \quad (2)$$

The mixing angles take values from 0 to π and phase δ is responsible for effects of the CP violation. The CP phase term δ can take values in the range $0 \leq \delta \leq 2\pi$. In the literature there are different hints of δ values: 306° (254°) NH (IH) [7]; 240° (266°) NH (IH) [8], and $-\pi/2$ [9]. The origin of mixing is not explained by the Standard Model (SM). If the mixing angles is zero, the flavour states are identical to the mass states and clearly oscillation cannot happen. However, if $\theta = \pi/4$ then the oscillations are said to be maximal. The amplitude of $\nu_\alpha \rightarrow \nu_\beta$ transition with the neutrino energy E after traversing the distance L can be written as

$$A(\nu_\alpha \rightarrow \nu_\beta) = e^{-iEL} \left\{ \delta_{\alpha\beta} + \sum_{k=2}^3 U_{\alpha\beta} U_{k\beta}^* \times \left[\exp\left(-i \frac{\Delta m_{k1}^2 L}{2E}\right) - 1 \right] \right\} \quad (3)$$

Where $U_{\alpha i}$ denote the elements in Eq. (2), in which α and i refer to the flavour eigenstate and mass eigenstate respectively. For antineutrino amplitude $A(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$, replace U by U^* in the right hand side in Eq. (3). The parameter L/E is within experimentalist control. The direct measurements of CP violation originating from the phase of the neutrino-mixing matrix are the differences of the transition probabilities between CP-conjugate channels [10,11]:

$$\Delta P \equiv P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) = P(\nu_\mu \rightarrow \nu_\tau) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau)$$

$$= 4 J_{CP}^v (\sin D_{12} \sin D_{23} \sin D_{13}) \quad [4]$$

$$\text{where } D_{ij} = 1.27 \Delta m_{ij}^2 \frac{L}{E}.$$

Unless the elements of the PMNS matrix are real

$$P(\nu_e \rightarrow \nu_\mu) \neq P(\nu_\mu \rightarrow \nu_e) \text{ and } P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e).$$

Hence, CP is violated in neutrino flavour oscillations. If any of the elements of the PMNS matrix are complex, neutrino oscillations are not invariant, $t \rightarrow -t$.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 7, July 2017

2.1 Vacuum: $\nu_\mu \rightarrow \nu_e$

Consider about the oscillation of muon neutrino (ν_μ) to electron neutrino (ν_e). The oscillation probability expression can be written as [12]

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \alpha \Delta - \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \alpha \Delta \sin[(\alpha - 2)\Delta - \delta_{cp}] + \sin \delta_{cp} \cos \alpha \Delta - \cos 2\theta_{12} \cos \delta_{cp} \sin \alpha \Delta + \frac{1}{4} \sin^2 2\theta_{13} \sin^2 \theta_{23} [2 - \sin^2 2\theta_{12} \sin^2 \alpha \Delta - 2 \cos^2 \theta_{12} \cos 2\Delta - 2 \sin^2 \theta_{12} \cos 2(\alpha - 1)\Delta] \dots \dots \dots (5)$$

where $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$ and $\Delta = \frac{\Delta m_{31}^2}{4E} L$

We can analysis the flavour changing probability with neutrino energy for different baselines experiment. Here we have used:

$$\Delta m_{31}^2 = 2.4 \times 10^{-3} eV^2; \Delta m_{21}^2 = 7.6 \times 10^{-5} eV^2; \theta_{13} = 8.3, \theta_{21} = 34, \theta_{23} = 45$$

and we can take CP violating phase term in between $0 \leq \delta \leq 2\pi$.

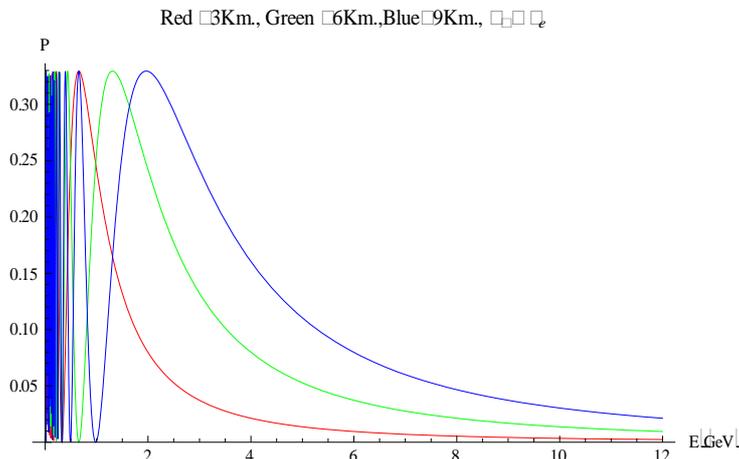


Fig. 1 Profile of oscillation probability of muon neutrino to electron neutrino with respect to energy (GeV) for different baselines. The plot shows that the probability of observing CP phase is better for larger distance from the source.

2.2 Matter: $\nu_\mu \rightarrow \nu_e$

The presence of matter can change drastically the pattern of neutrino oscillations. Neutrinos can interact with the particles forming the matter. Accordingly, the Hamiltonian of the neutrino system in matter H_m , differs from the Hamiltonian in vacuum H_0 , $H_m = H_0 + H_{int}$, where H_{int} describes the interaction of neutrinos with the particles of matter. When for instance, ν_e and ν_μ propagate in matter, they can scatter (due to H_{int}) on the electrons (e^-), protons (p) and neutrons (n) present in matter. The incoherent elastic and the quasi-elastic scattering, in which the states of the

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 7, July 2017

initial particles change in the process (destroying the coherence between the neutrino states), are not of interest they have a negligible effect on the solar neutrino propagation in the Sun and on the solar, atmospheric and reactor neutrino propagation in the Earth. Let us consider the earth matter effect on the above ν_e appearance probability. The charged current interaction of ν_e with electrons resulting in a potential energy term $V = \sqrt{2}G_F N_e \cong 1.13 \times 10^{-13} eV$. Where G_F is the Fermi coupling and N_e the electron number density in the terrestrial matter. For ν_e passing through the earth's crust one can write this in terms of a nearly constant matter density $\rho \cong 3g/cm^3$. In order to calculate the neutrino oscillation probability in matter, we have to solve the Schrodinger equation for the neutrino state vector in the flavour basis

$$i \frac{d}{dt} |v(t)\rangle = H |v(t)\rangle \quad (6)$$

with the effective Hamiltonian

$$H \approx \frac{1}{2E_\nu} U \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^\dagger + \text{diag}(V, 0, 0) \quad (7)$$

For antineutrino we have to replace U by U^* and V by $-V$. The oscillation probability can be expressed as [13]

$$P(\nu_\mu \rightarrow \nu_e) \cong (c_{23}s_{12}c_{12}(\delta/\omega)\sin\omega L)^2 + 2(s_{23}s_{13})^2(1 - \cos\bar{\Delta}L) + 2s_{13}s_{12}c_{12}s_{23}c_{23}(\delta/\omega) \sin\omega L (\cos(\bar{\Delta}L + \delta_{CP})\sin\bar{\Delta}L + \sin(\bar{\Delta}L + \delta_{CP})(1 - \cos\bar{\Delta}L)) \quad (8)$$

Where

$$\delta = \frac{\delta m_{12}^2}{2E}$$

$$\Delta = \frac{\delta m_{13}^2}{2E}$$

$$2\omega = \sqrt{\delta^2 + V^2 - 2\delta V \cos(2\theta_{12})}$$

$$\bar{\Delta} = \Delta - \left(\frac{V + \delta}{2} \right)$$

We can use different values of s_{13} at a constant CP phase and also different values of CP phase at a constant s_{13} to study the effect of these two unknown parameters on neutrino oscillation probability.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 7, July 2017

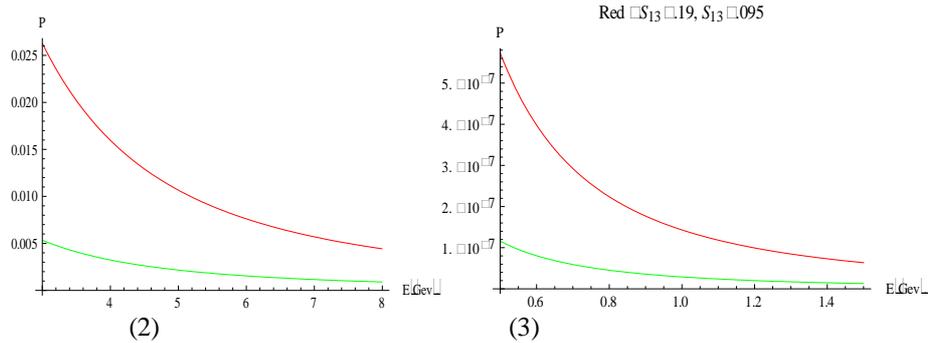


Fig. (2) Variation of $P(\nu_\mu \rightarrow \nu_e)$ w.r.t energy for MINOS (L=735Km.), here $\delta_{CP} = \pi/4$.

Fig. (3) Variation of $P(\nu_\mu \rightarrow \nu_e)$ w.r.t energy for MiniBooNE (L=500m.), here $\delta_{CP} = \pi/4$.

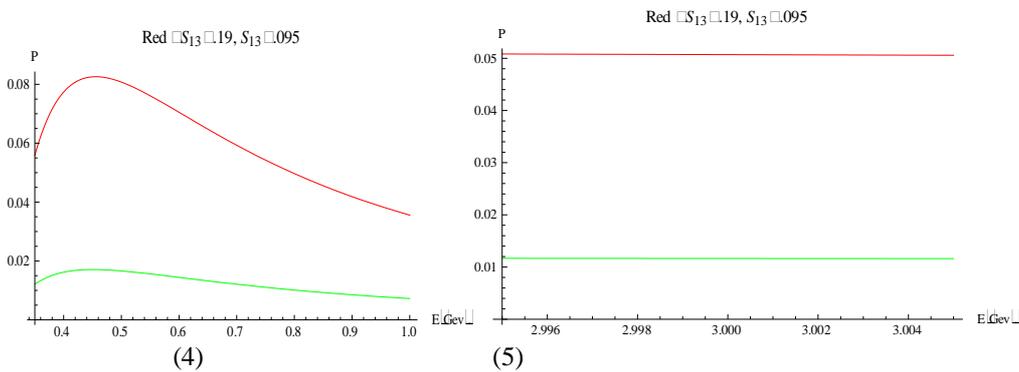


Fig. (4) Variation of $P(\nu_\mu \rightarrow \nu_e)$ w.r.t energy for T2K (L=295km.), here $\delta_{CP} = \pi/4$.

Fig. (5) Variation of $P(\nu_\mu \rightarrow \nu_e)$ w.r.t energy for CHOOZ (L=1.03km.), here $\delta_{CP} = \pi/4$.

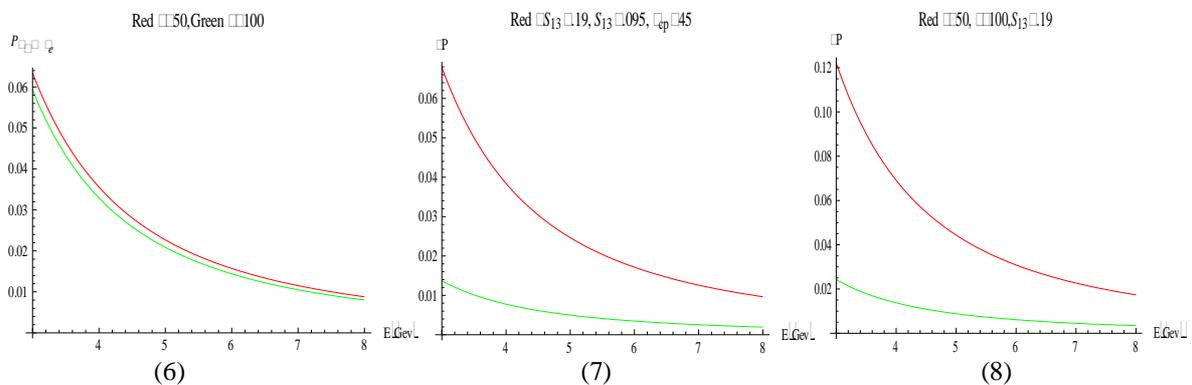


Fig. (6) Variation of $P(\nu_\mu \rightarrow \nu_e)$ w.r.t energy for long baseline experiment at two different CP phases and at a constant θ_{13} value.

Figs. (7 & 8) ΔP variation w.r.t. energy for two different values of θ_{13} with δ_{CP} fixed.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 7, July 2017

For the anti-neutrino part we have to change $V \rightarrow -V$ and $\delta \rightarrow -\delta$ in the above expression. We can plot $\Delta P = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with respect to energy to see the variation in probability at different CP phase as well as at different θ_{13} also.

III. RESULTS AND ANALYSIS

We have estimated the dependence of CP violating phase and value of s_{13} on neutrino oscillation probability. We have used two different values for s_{13} at fixed δ_{CP} and also two different values δ_{CP} at fixed s_{13} to determine their dependence on oscillation probability. The plots shows that the probability $P(\nu_\mu \rightarrow \nu_e)$ is strongly dependent on s_{13} i.e. on θ_{13} and is essentially independent of δ_{cp} and therefore the measurement of $P(\nu_\mu \rightarrow \nu_e)$ should determine the value of the s_{13} parameter but can predict only few information about the δ_{cp} . So many experiments are now going on which are basically based on this technique for precise determination of θ_{13} and δ_{CP} .

IV. CONCLUSIONS

The CP violating probability $\Delta P_{\mu e}^{CP}$ is strongly dependent on both θ_{13} and δ_{CP} , and the correction is less for longer baselines as shown by our plots. Such type of experiments can provides information about the CP phase term also. The plots shows δ_{CP} to be higher than $\pi/4$. Till date no experiments are possible to test CPV via neutrino oscillations. In extension of this work, we plan to study next generation long baselines neutrino oscillation experiments like T2K, NoVA, LBNE, LBNO, and Hyper-SK for better determination of leptonic CP violation and mass hierarchy.

ACKNOWLEDGEMENTS

The author is grateful to the SERB-DST, Govt. of India for the financial support through the major research project "Neutrino Mass Ordering, Leptonic CP Violation and Matter-Antimatter Asymmetry," File No: EMR/2015/001683.

REFERENCES

- [1] N. Cabibbo, "Unitary symmetry and leptonic decays," Phys. Rev. Lett. Vol.10, No.531, 1963.
- [2] M. Kobayashi and T. Maskawa, "CP Violation in the renormalization theory of weak interaction," Prog. Theor. Phys. Vol.49, no.652, 1973.
- [3] V. Barger, K. Whisnant and R.J.N. Phillips, "CP nonconservation in three neutrino oscillations," Phys. Rev. Lett. Vol.45, no.2084, 1980.
- [4] S.M. Bilenky and F. Nidermaler, "Some comments on high precision study of neutrino oscillations," Sov. J. Nucl. Phys. 34 (1981) 606.
- [5] G. L. Fogli, E. Lisi, D. Montanino and G.Scioscia, "Three-flavour atmospheric neutrino anomaly," (hep-ph/9607251).
- [6] G. L. Fogli, E. Lisi and D. Montanino, "Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme," Phys. Rev. D Vol.49, pp.3626, 1994.
- [7] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, "Updated fit to three neutrino mixing: status of leptonic CP violation," JHEP Vol.1411, No.052, 2014.
- [8] D. V. Forero, M. Tortola and J. W. F. Valle, "Neutrino oscillations refitted," Phys. Rev. D Vol.90, No.093006, 2014.
- [9] K. Abe et al., "[T2K Collaboration]," Phys. Rev. D Vol.91, No.072010, 2015.
- [10] S. Pakvasa, "In Proc of the XX International Conference of High Energy Physics," Madison, Wisconsin, USA, Part2, pp.1165, 1980, edited by L. Durand and L.G. Pondrom, AIP, New York.
- [11] V. Barger, K. Whisnant and R.J.N. Phillips, "CP Nonconservation in Three-Neutrino Oscillations," Phys. Rev. Lett. Vol.45, No.2084, 1980.
- [12] Joachim Kopp, "Phenomenology of three-flavour neutrino oscillation" thesis, 2006.
- [13] Leonard S. Kisslinger, "Improved Theory of Neutrino Oscillations in Matter," Mod.Phys.Lett.A, Vol.30, No.1550014, 2015. [arXiv:1408.0310].