Mass Hierarchy sensitivity of Long Base Experiments

Jyotsna Singh [1], R. B. Singh [2]
[1,2]Assistant Professor,
Department of Physics,
University of Lucknow, India.

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ABSTRACT *Neutrino mass hierarchy is pattern of mass splitting amongst three active neutrino . The neutrino mixing angles and their mass splitting in vaccum are different from that in matter. Here the enhancement and suppression of oscillation probability with matter is manipulated to determine the neutrino mass hierarchy. In our work the long baseline experiment NOvA is used to study the neutrino mass hierarchy. In three years of running, 1.5 years in neutrino mode and 1.5 years in antineutrino mode we observe that for a specific range of* $\boldsymbol{\delta_{CP}}$ *values NOvA will be able to resolve heierarchy problem at 90% C.L.*

Key words: *mass hierarchy, matter effects, neutrino, oscillation probability.*

I. INTRODUCTION

Neutrino mass and neutrino oscillatory physics is an active research area of physics from past few decades. Neutrino can be used as one of the potential tool to resolve the mysteries of the Universe. In an attempt, that neutrino can be used as a new physics tool; its own parameters need to be determined with high accuracy. Neutrino oscillation experiments provide us an adequate platform to probe physics beyond the standard model. The observational feasibility through neutrino oscillation depends on six oscillation parameter, three mixing angles, two mass square difference and one delta CP phase. Out of these parameters the sign of one mass square difference (Δm_{31}^2) and value of the CP phase is still in research phase. Many observables that are planned to be determined by present and future neutrino experiment depends critically on the nature of sign of Δm_{31}^2 and value of delta CP. The mass ordering followed by the three active neutrino is an open question, which need to be answered by the community. Many groups from long baseline neutrino oscillation experiments [1] [2][3]to astroparticle studies [4] are putting their efforts together to unmask the mass ordering or mass hierarchy problem.

II. RELATED WORK

LONG BASE OSCILLATION NEUTRINO EXPERIMENTS

The relation between neutino flavor states and neutrino mass states is as

$$\nu_f = U_{PMNS}\nu_m \quad (1)$$

Where the Pontecorvo-Maki-Nakagawa_Sakata mixing matrix is parametrized as [5-7]

$$U_{PMNS}^{V} = U_{23}(\Theta_{23})I_\delta U_{13}(\Theta_{13})I_\delta U_{12}(\Theta_{12}) \quad (2)$$

in vaccum. In matter this unitary matrix have new effective mixing angles and is given as[6]

$$U_{PMNS}^{M} = U_{23}(\theta_{23})I_\delta U_{13}(\theta_{13})I_\delta U_{12}(\theta_{12}) \quad (3)$$

where the matrix $I_\delta \equiv diag\left(1,1,exp(i\delta)\right)$. This matrix contains CP phaseδ.
In vaccum the neutrino oscillation probability is given as

$$P_{\mu e}^{V} = sin^2\Theta_{23}sin^2 2\Theta_{13}sin^2\left(1.27\frac{\Delta M_{31}^2 L}{E}\right) \quad (4)$$

where $\Theta_{23}$and $\Theta_{13}$are the mixing angles, L is length in Km between the source and detector, E is the neutrino energy in GeV and $\Delta M_{31}^2$is the neutrino mass square splitting in ev^2.
When the neutrinos pass through the matter they feel some extra potential due to earth matter and their mixing angles and mass square difference splitting gets modified. The neutrino oscillation probability in matter can be written as

$$P_{\mu e}^{M} = sin^2\theta_{23}sin^2 2\theta_{13}sin^2\left(1.27\frac{\Delta m_{31}^2 L}{E}\right) \quad (5)$$

The θ_{23}in matter , due to approximation can be taken same as Θ_{23}in vaccum. Rest two neutrino mixing angles in matter can be correlated with the neutrino mixing angles in vaccum. One such correlation is expressed as:

$sin2\theta_{13} = sin2\Theta_{13}\Delta M_{31}^2/\Delta m_{31}^2$ (6)

and the mass splitting in matter and vaccum can be corellated

$\Delta m_{31}^2 = \sqrt{((\Delta M_{31}^2 cos2\Theta_{13} - A)^2 + (\Delta M_{31}^2 sin2\Theta_{13})^2)}$(7)

where$A = 2\sqrt{2}G_F N_e E = 0.76 \times 10^{-4}\rho(gm/cc)E(GeV)$

One possible way to address the neutrino mass hierarchy is by locating 13-resonance, we expect the probability in Equ. (5) will be maximum for a given neutino energy when$sin^2 2\theta_{13} \rightarrow 1$but from Equ. 7 we see that at this energyΔm_{31}^2will become minimum .

To summarize we can say that $P_{\mu e}^M$is maximum when $sin^2 2\theta_{13} = 1$and $sin^2(1.27\Delta m_{31}^2 \, L/E) = 1$. Using these two equalities for a given neutrino energy E we can find the baseline where the probability will be maximum [8].

III. Probing $\nu_\mu \rightarrow \nu_e$channel for mass hierarchy at NoVA

In long baseline experiments the matter effects are significant and to derive the exact expression for three flavor neutrino oscillation probability is complicated. The approximate expression of probability for three flavor neutrino oscillation developed by expanding the epression upto second order in perturbative terms $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$and θ_{13}[9][10]

$$P_{\mu e} \approx P_0 + P_1 sin\delta_{CP} + P_2 cos\delta_{CP} \quad (8)$$

$$P_{\mu e} \simeq sin^2\theta_{23} sin^2 2\theta_{13} \frac{sin^2(1-\hat{A})\Delta}{(1-\hat{A})^2} + \alpha^2 cos^2\theta_{23} sin^2 2\theta_{12} sin^2 \frac{(\hat{A}\Delta)}{\hat{A}}$$

$$\mp \alpha sin2\theta_{13} cos\theta_{13} sin2\theta_{12} sin2\theta_{23} sin\Delta sin\frac{(\hat{A}\Delta)}{\hat{A}} sin\frac{[(1-\hat{A})]}{(1-\hat{A})} sin\delta_{CP}$$

$$+\alpha sin2\theta_{13} cos\theta_{13} sin2\theta_{12} sin2\theta_{23} cos(\Delta) sin\frac{(\hat{A}\Delta)}{\hat{A}} sin\frac{[(1-\hat{A})\Delta]}{1-\hat{A}} cos\delta_{CP} \quad (9)$$

Where $\Delta = \frac{\Delta m_{31}^2 L}{4E}$,$\hat{A} = \frac{A}{\Delta m_{31}^2}$and matter potential A=$\pm 2\sqrt{2}G_F N_e E$

Amongst accelerator beam experiments NoVA and T2K are placed off axis to the neutrino beam, this makes their beam septra sharper [11]. In our analysis we have considered 3 years of running of NoVA experiment . The experiment runs for 1.5 years in neutrino mode and 1.5 years in antineutrino mode. The distance between the source and detector is 812 Km and the detector mass is 25 Kton. GloBES [12][13] simulation tool is used to check the sensitivity of NOvA experiment for mass hierarchy. The neutrino oscillation parameters considered in this work are: $\theta_{12} = 34.4^0; \theta_{13} = 8^0; \theta_{23} = 45^0; \Delta m_{21}^2 = 7.5 \times 10^{-5} ev^2; \Delta m_{31}^2 = 2.5 \times 10^{-3} ev^2$

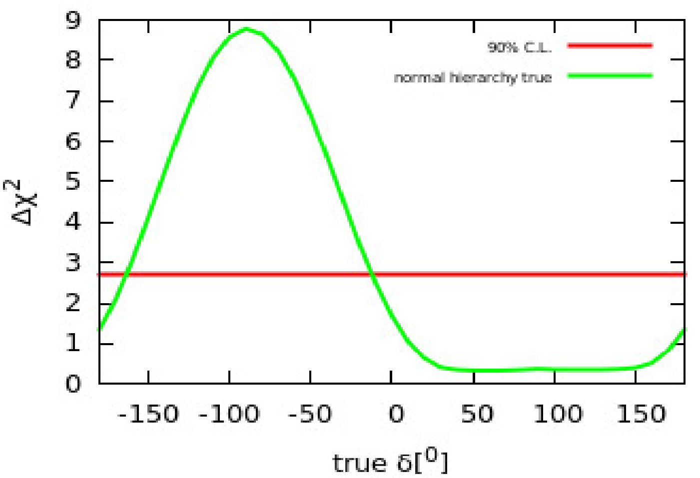

Fig. 1: Above plot showsχ^2as a function of δ_{CP}. Normal hierarchy is assumed to be true hierarchy.

In Fig. 1. we can observe the sensitivity of NoVA experiment to tag the neutrino mass hierarchy. The figure shows the value of dirac phase for which the NoVA experiment will be able to check the mass hierarchy at 90% C.L.

III. CONCLUSION

T2K observed that the electron neutrino appearance rate is significantally higher than rate which are expected while keeping CP conserve. At 95% CL allowed reigon for for CP phase $\delta_{CP}$is $[-167^0; -34^0]$for normal hierarchy and $[-88^0; -68^0]$for inverted hierarchy [14].In 2016 NoVA experiment also reported the 3.3σ excess of events in primary analysis, disfavors $0.1\pi < \delta_{cp} < 0.5\pi$in the inverted mass hierarchy at the 90% C.L.[15]. We find that the T2K experiment favours certain values ofδ_{CP}at 90% confidence level in three years of running for $\nu_\mu \rightarrow \nu_e$channel. In an attempt to resolve the neutrino mass hierarchy Its crucial to know the CP phase or vice-versa.

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