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STUDY OF MATTER EFFECT WITH STERILE NEUTRINOS ON LONG BASELINE EXPERIMENTS

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Abstract: The three kinds of neutrino oscillation experiments can be described by three kinds of mass squared differences. However, there are also experimentally observed anomalies that cannot be described within the framework of the three neutrino mixing. Therefore, we consider the four-neutrino oscillation, where the fourth neutrino doesn't have the weak interaction. Three active neutrino flavors (ν_e, ν_μ, ν_τ) interact with leptons in the weak interaction and so, the fourth neutrino is called sterile neutrino (ν_s). In this paper, we study the effect of sterile neutrinos on long baseline experiments in the presence of matter.

Index terms: neutrino oscillation, long baseline experiments, sterile neutrino, CP violation, oscillation probabilities

I. INTRODUCTION

The standard model includes three massless neutrinos that participate in weak interactions. Measurement of the total decay cross section of a neutral Z boson imposes a limitation on the number of active neutrinos. At the moment, this limitation is N_ν =2.92±0.05 from the direct measurement of invisible Z width [1]. Experimentally observed neutrino oscillations require the introduction of nonzero neutrino mases and mixing matrix. The mixing parameters of the tree flavour states of the Standard Model art determined experimentally. However, there are also experimentally observed anomalies that cannot be described within the framework of the three neutrino mixing. The anomalies have been observed in several accelerator and reactor neutrino experiments; LSND [2], MiniBooNE [3], the Reactor antineutrino anomaly [4,5] and in the experiments with radioactive sources GALLEX/GNO and SAGE – gallium anomaly [6-8]. There is a direct way to expand the theory to explain these phenomena – adding sterile neutrinos to the theory of particles. One of the possible extension of the theory is the 3+1 model with one sterile state and one additional mass state of the order of several eV.

In this paper, we discuss the matter effect in the presence of these sterile neutrinos on accelerator based neutrino oscillation experiments. The paper is organised as follows. In section 2, we have given theoretical framework to calculate oscillation probabilities. Section 3 deals with results and discussions and concluding remarks are presented in section 4.

II. OSCILLATION PROBABILITIES IN MATTER

The oscillation probability, that is the probability for capturing neutrino as ν_β from the initial beam ν_α in vacuum is,

$$\mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 + 2\sum_{i<j}[Re(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i})cos\Delta_{ij} - Im(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i})sin\Delta_{ij}] \quad (1)$$

Where $\Delta_{ij} = \Delta m^2_{ij} L/2E$ and mass square differences $\Delta m^2_{ij} = m^2_i - m^2_j$. Here L is propagating distance, E is the energy carried by neutrinos and $U_{\alpha a}$ are the components of 4x4 unitary matrix

$$U = (U_{\alpha a}) = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \quad (2)$$

In (3+1) scheme, the full neutrino mixing is characterized by a 4× 4 matrix. To parameterize it, we need 6 rotation angles and three additional Dirac phase angles [9]. The Majorana phase angles are closed here because it doesn't involve in the oscillation process. The mixing matrix can be constructed by 6 two-dimensional rotations

$$U = R_{34}(\theta_{34}, \delta_{34}) \cdot R_{24}(\theta_{24}) \cdot R_{14}(\theta_{14}, \delta_{14}) \cdot R_{23}(\theta_{23}) \cdot R_{13}(\theta_{13}, \delta_{13}) \cdot R_{12}(\theta_{12})$$

where, R_{ij} is a four dimensional rotation matrix and its elements reads

$$R_{ij}(\theta_{ij}, \delta) = \begin{pmatrix} c_{ij} & s_{ij}e^{-i\delta} \\ -s_{ij}e^{i\delta} & c_{ij} \end{pmatrix} \quad (3)$$

The complete matrix elements are given by [10]

$$U_{e1} = c_{14}c_{13}c_{12} \quad (4.1)$$

$$U_{\mu 1} = (-s_{24}s_{14}c_{13}e^{i\delta_{14}} - c_{24}s_{23}s_{13}e^{i\delta_{13}})c_{12} - c_{24}c_{23}s_{12} \quad (4.2)$$

$$U_{\tau 1} = c_{12}[-s_{34}c_{24}s_{14}c_{13}e^{-i(\delta_{34}-\delta_{14})} - s_{13}e^{i\delta_{13}}(c_{34}c_{23} - s_{34}s_{24}s_{23}e^{i\delta_{34}})] + s_{12}(s_{34}s_{24}c_{23}e^{i\delta_{34}} + c_{34}s_{23}) \quad (4.3)$$

$$U_{s1} = c_{12}[-c_{34}c_{24}s_{14}c_{13}e^{i\delta_{14}} + s_{13}e^{i\delta_{13}}(s_{34}c_{23}e^{i\delta_{34}} + c_{34}s_{24}s_{23})] - s_{12}(-c_{34}s_{24}c_{23} + s_{34}s_{23}e^{i\delta_{34}}) \quad (4.4)$$

$$U_{e2} = c_{14}c_{13}s_{12} \quad (4.5)$$

$$U_{\mu 2} = c_{24}c_{23}c_{12} - s_{12}(s_{24}s_{14}c_{13}e^{i\delta_{14}} + c_{24}s_{23}s_{13}e^{i\delta_{13}}) \quad (4.6)$$

$$U_{\tau 2} = -c_{12}(s_{34}s_{24}c_{23}e^{-i\delta_{34}} + c_{34}s_{23}) - s_{12}[s_{34}c_{24}s_{14}s_{13}e^{-i(\delta_{34}-\delta_{14})} + s_{13}e^{i\delta_{13}}(c_{34}c_{23} - s_{34}s_{24}s_{23}e^{-i\delta_{34}})] \quad (4.7)$$

$$U_{s2} = c_{12}(-c_{34}s_{24}c_{23} + s_{34}s_{23}e^{i\delta_{34}}) - s_{12}[c_{34}c_{24}s_{14}c_{13}e^{i\delta_{14}} - s_{13}e^{i\delta_{13}}(s_{34}c_{23}e^{i\delta_{34}} + c_{34}s_{24}s_{23})] \quad (4.8)$$

$$U_{e3} = c_{14}s_{13}e^{-i\delta_{13}} \quad (4.9)$$

$$U_{\mu 3} = c_{24}s_{23}c_{13} - s_{24}s_{14}c_{13}e^{i(\delta_{14}-\delta_{13})} \quad (4.10)$$

$$U_{\tau 3} = c_{13}(c_{34}c_{23} - s_{34}s_{24}s_{23}e^{-i\delta_{34}}) - s_{34}c_{24}s_{14}s_{13}e^{-i(\delta_{34}-\delta_{14}+\delta_{13})} \quad (4.11)$$

$$U_{s3} = -c_{13}(s_{34}c_{23}e^{i\delta_{34}} + c_{34}s_{24}s_{23}) - c_{34}c_{24}s_{14}s_{13}e^{i(\delta_{14}-\delta_{13})} \quad (4.12)$$

$$U_{e4} = s_{14}e^{-i\delta_{14}} \quad (4.13)$$

$$U_{\mu 4} = s_{24}c_{14} \quad (4.14)$$

$$U_{\tau 4} = s_{34}c_{24}c_{14}e^{-i\delta_{34}} \quad (4.15)$$

$$U_{s4} = c_{34}c_{24}c_{14} \quad (4.16)$$

with $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$.

When passing through matter, active neutrinos interact with matter by weak interaction. More exactly ν_e interacts via both charged current and neutral current while ν_μ, ν_τ only receive neutral current interaction by exchanging Z bosons. Hence, the oscillation probability including matter effect having the same structure of the one in vacuum including sterile neutrino is given by

$$\widetilde{P}(\nu_\alpha \to \nu_\beta) = \sum_i |\widetilde{U}_{\alpha i}|^2 |\widetilde{U}_{\beta i}|^2 + 2\sum_{i<j}[Re(\widetilde{U}_{\alpha i}\widetilde{U}_{\beta j}\widetilde{U}^*_{\alpha j}\widetilde{U}^*_{\beta i})\, cos\widetilde{\Delta}_{ij} - \mathrm{Im}(\widetilde{U}_{\alpha i}\widetilde{U}_{\beta j}\widetilde{U}^*_{\alpha j}\widetilde{U}^*_{\beta j})\, sin\widetilde{\Delta}_{ij}] \quad (5)$$

With $\widetilde{\Delta}_{ij} \equiv \Delta\widetilde{m}^2_{ij}L/2E$, $\Delta\widetilde{m}^2_{ij} = \widetilde{m}^2_i - \widetilde{m}^2_j$. Hereafter, we denote $\widetilde{P}$ by P for simplicity.

III. THE LONG BASE LINE ACCELERATOR NEUTRINO EXPERIMENTS: $\nu_\mu \to \nu_e$

Using the expressions for effective mass difference and effective mixing matrix entries, we can write the oscillation probabilities as [10],

$$P(\nu_\mu \to \nu_e) = \sum_i |\widetilde{U}_{\mu i}|^2 |\widetilde{U}_{ei}|^2 + 2\sum_{i<j}[Re(\widetilde{U}_{ei}\widetilde{U}_{\mu j}\widetilde{U}^*_{ej}\widetilde{U}^*_{\mu i})\cos\widetilde{\Delta}_{ij} - Im(\widetilde{U}_{ei}\widetilde{U}_{\mu j}\widetilde{U}^*_{ej}\widetilde{U}^*_{\mu i})\sin\widetilde{\Delta}_{ij}], \quad (6)$$

Here L is the baseline of a particular neutrino experiment,

with $$|\widetilde{U}_{ei}|^2 = \frac{1}{\prod_{k\neq i}\Delta\widetilde{m}^2_{ik}}(X_e + C_e) \tag{7}$$

In which $X_e = \sum_j F_e^{ij}\,|U_{ej}|^2$, $F_e^{ij} = \prod_{k\neq i}(A + \hat{\Delta}m^2_{jk})$

$$C_e = -A\sum_{i<j}(\Delta m^2_{ij})^2|U_{ei}|^2\left|U_{ej}\right|^2 - A'\sum_{i<j}(\Delta m^2_{ij})^2 Re(U_{ei}\,U^*_{ej}U^*_{si}U_{sj}) \tag{8}$$

Where $$\left|\widetilde{U}_{\mu i}\right|^2 = \frac{1}{\prod_{k\neq i}\Delta\widetilde{m}^2_{ik}}\left(X_\mu + C_\mu\right)$$

With the associated functions

$$X_\mu = \sum_j F_\mu^{ij}\left|U_{\mu j}\right|^2, \quad F_\mu^{ij} = \prod_{k\neq i}\hat{\Delta}m^2_{jk}$$

$$C_\mu = -A\sum_{i<j}\left(\Delta m^2_{ij}\right)^2 Re(U_{\mu i}U^*_{\mu j}U^*_{ei}U_{ej}) - A'\sum_{i<j}\left(\Delta m^2_{ij}\right)^2 Re\left(U_{si}U^*_{sj}U^*_{\mu i}U_{\mu j}\right) \tag{9}$$

Where

$$\widetilde{U}_{ei}\widetilde{U}^*_{\mu i} = \frac{1}{\prod_{k\neq i}\Delta\widetilde{m}^2_{ik}}\left[\sum_j F^{ij}_{e\mu}U_{ej}U^*_{\mu j} + C_{e\mu}\right] \tag{10}$$

Also $$\left(\widetilde{U}_{ei}\widetilde{U}^*_{\mu i}\right)^* = \left\{\frac{1}{\prod_{k\neq i}\Delta\widetilde{m}^2_{ik}}\left[\sum_j F^{ij}_{e\mu}U_{ej}U^*_{\mu j} + C_{e\mu}\right]\right\}^* \tag{11}$$

$$\widetilde{U}_{\mu i}\widetilde{U}^*_{ei} = \frac{1}{\prod_{k\neq i}\Delta\widetilde{m}^2_{ik}}\left[\sum_j F^{ij}_{e\mu}U_{\mu j}U^*_{ej} + C^*_{e\mu}\right] \tag{12}$$

$$F^{ij}_{e\mu} = \left[A^2\Delta m^2_{j1} + A\Delta m^2_{j1}\left(\Delta m^2_{j1} - \sum_{k\neq i}\hat{\Delta}m^2_{k1}\right) + (\Delta m^2_{j1})^3 - \sum_{k\neq i}(\Delta m^2_{j1})^2\hat{\Delta}m^2_{k1} + \sum_{k,l;k\neq l\neq i}\Delta m^2_{j1}\hat{\Delta}m^2_{k1}\hat{\Delta}m^2_{l1}\right] \tag{13}$$

$$C_{e\mu} = A'\sum_{k,l}\Delta m^2_{k1}\Delta m^2_{l1}U_{ek}U^*_{\mu l}U_{sk}U^*_{sl} + A\sum_{k,l}\Delta m^2_{k1}\Delta m^2_{l1}|U_{ek}|^2U_{el}U^*_{\mu l} \tag{14}$$

IV. RESULTS AND DISCUSSIONS

Neutrino beam produced from accelerators usually carries higher energy and can be detected in a long distance from source. Hence we have calculated the oscillation probability $P\left(\nu_\mu \to \nu_e\right)$ of appearance mode for base line of 300, 900 and 1300 km as example to illustrate the properties of long baseline experiments. Due to matter effects, the effective mass square difference in matter $\Delta\widetilde{m}^2_{21}$, $\Delta\widetilde{m}^2_{31}$and $\Delta\widetilde{m}^2_{41}$ depend on Dirac phases and 6 neutrino mixing angle and matter density. In eqn. (13), we have taken $A = 2\sqrt{2}G_F N_e E$ and $A' = -2\sqrt{2}G_F N_n E$, with matter density for electron and neutron, $N_e = N_n = 2.6 g/cm^3$ [11]. We choose mixing angle $\theta_{12} = 34.3^0$, $\theta_{13} = 8.58^0$, $\theta_{23} = 48.8^0$ and ignore the majorana phases. Also, the sterile neutrino mixing angles are considered as $\theta_{14} = 5.7^0$, $\theta_{24} = 5^0$, $\theta_{34} = 20^0$ [12]. The details to calculate $\Delta\widetilde{m}^2_{ij}$ from Δm^2_{ij} can be found in [10]. In present analysis, we have taken mass square difference $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2, $\Delta m^2_{31} = 2.56 \times 10^{-3}$ eV^2 and $\Delta m^2_{41} = 1.3$ eV^2 [13].

To calculate $P\left(\nu_\mu \to \nu_e\right)$, we solve the eqn. (6) which gives

$$\begin{aligned} P\left(\nu_\mu \to \nu_e\right) = {} & \left|\widetilde{U}_{\mu 1}\right|^2\left|\widetilde{U}_{e1}\right|^2 + \left|\widetilde{U}_{\mu 2}\right|^2\left|\widetilde{U}_{e2}\right|^2 + \left|\widetilde{U}_{\mu 3}\right|^2\left|\widetilde{U}_{e3}\right|^2 + \left|\widetilde{U}_{\mu 4}\right|^2\left|\widetilde{U}_{e4}\right|^2 \\ & + 2\left[\mathrm{Re}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 2}\widetilde{U}^*_{e2}\widetilde{U}^*_{\mu 1}\right)\cos\widetilde{\Delta}_{12} - \mathrm{Im}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 2}\widetilde{U}^*_{e2}\widetilde{U}^*_{\mu 1}\right)\sin\widetilde{\Delta}_{12}\right] \\ & + \left[\mathrm{Re}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 3}\widetilde{U}^*_{e3}\widetilde{U}^*_{\mu 1}\right)\cos\widetilde{\Delta}_{13} - \mathrm{Im}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 3}\widetilde{U}^*_{e3}\widetilde{U}^*_{\mu 1}\right)\sin\widetilde{\Delta}_{13}\right] \\ & + \left[\mathrm{Re}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 1}\right)\cos\widetilde{\Delta}_{14} - \mathrm{Im}\left(\widetilde{U}_{e1}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 1}\right)\sin\widetilde{\Delta}_{14}\right] \\ & + \left[\mathrm{Re}\left(\widetilde{U}_{e2}\widetilde{U}_{\mu 3}\widetilde{U}^*_{e3}\widetilde{U}^*_{\mu 2}\right)\cos\widetilde{\Delta}_{23} - \mathrm{Im}\left(\widetilde{U}_{e2}\widetilde{U}_{\mu 3}\widetilde{U}^*_{e3}\widetilde{U}^*_{\mu 2}\right)\sin\widetilde{\Delta}_{23}\right] \\ & + \left[\mathrm{Re}\left(\widetilde{U}_{e2}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 2}\right)\cos\widetilde{\Delta}_{24} - \mathrm{Im}\left(\widetilde{U}_{e2}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 2}\right)\sin\widetilde{\Delta}_{24}\right] \\ & + \left[\mathrm{Re}\left(\widetilde{U}_{e3}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 3}\right)\cos\widetilde{\Delta}_{34} - \mathrm{Im}\left(\widetilde{U}_{e3}\widetilde{U}_{\mu 4}\widetilde{U}^*_{e4}\widetilde{U}^*_{\mu 3}\right)\sin\widetilde{\Delta}_{34}\right] \end{aligned} \tag{15}$$

Using these expansions, we have calculated the oscillation probabilities and plotted them in fig. 1-9. Here we have varied Dirac phases δ_{13} and δ_{14} from 0 to π/2 and kept $\delta_{34} = 0$. We have varied the neutrino energy from 0 to 5 GeV. The brown and yellow lines denote 4ν and 3ν matter oscillations respectively while blue dot and green lines show 4ν and 3ν oscillations in vacuum.

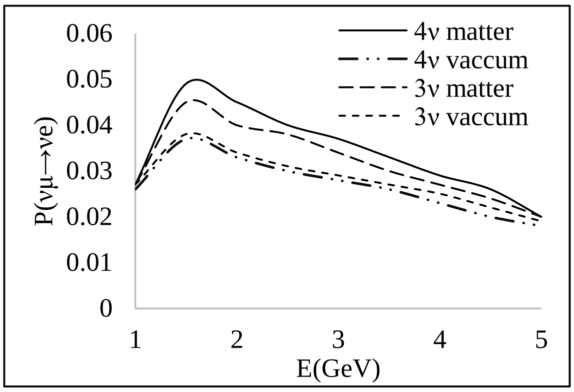

Fig. 1: Neutrino oscillation probability for $\nu_\mu \rightarrow \nu_e$ in L = 300 km long base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = 0$, $\delta_{14} = 0$ and $\delta_{34} = 0$.

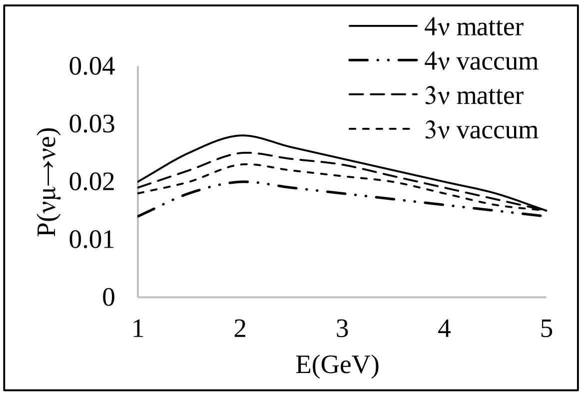

Fig. 2: Same as Fig. 1 but with Dirac phases $\delta_{13} = 0$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

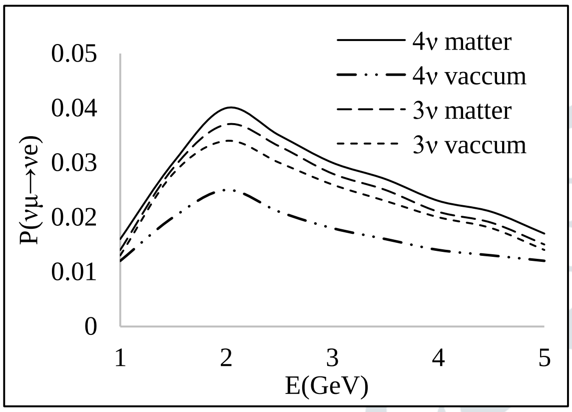

Fig. 3: Same as Fig. 1 but with Dirac phases $\delta_{13} = \pi/2$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

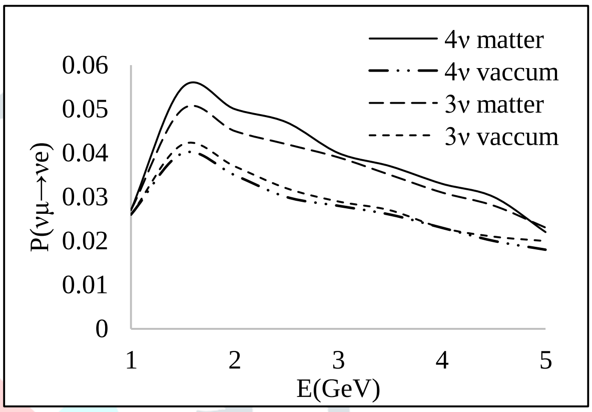

Fig. 4: Neutrino oscillation probability for $\nu_\mu \rightarrow \nu_e$ in L = 900 km long base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = 0$, $\delta_{14} = 0$ and $\delta_{34} = 0$.

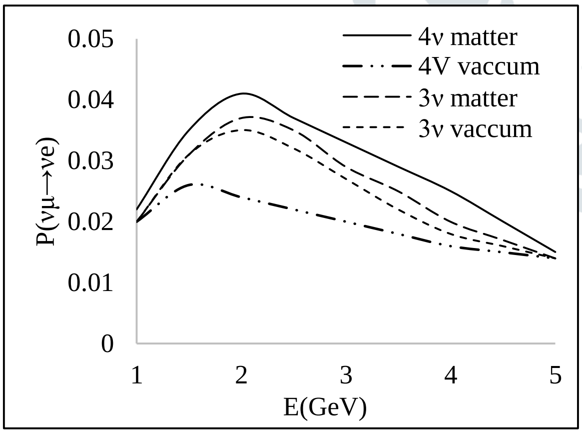

Fig. 5: Same as Fig. 4 but with Dirac phases $\delta_{13} = 0$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

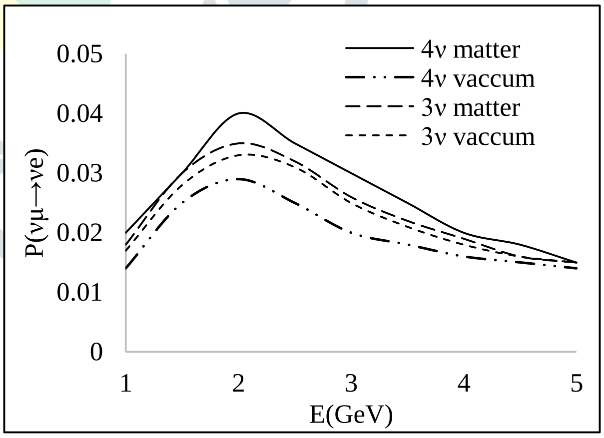

Fig. 6: Same as Fig. 4 but with Dirac phases $\delta_{13} = \pi/2$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

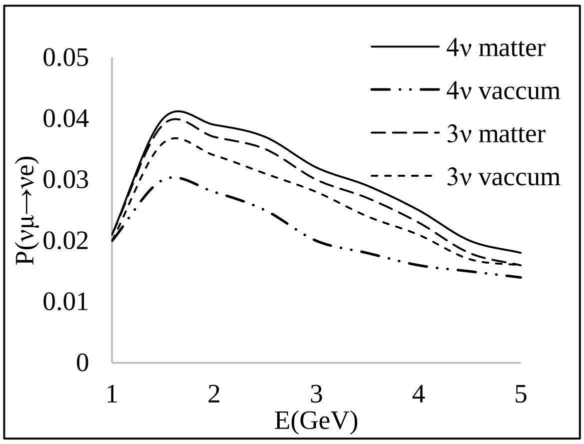

Fig. 7: Neutrino oscillation probability for $\nu_\mu \rightarrow \nu_e$ in L = 1300 km long base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = 0$, $\delta_{14} = 0$ and $\delta_{34} = 0$.

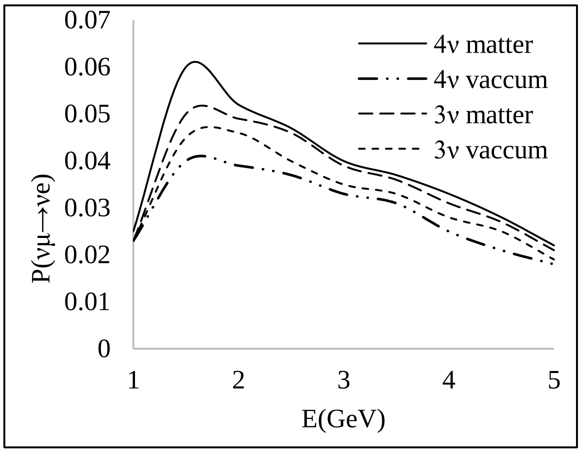

Fig. 8: Same as Fig. 7 but with Dirac phases $\delta_{13} = 0$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

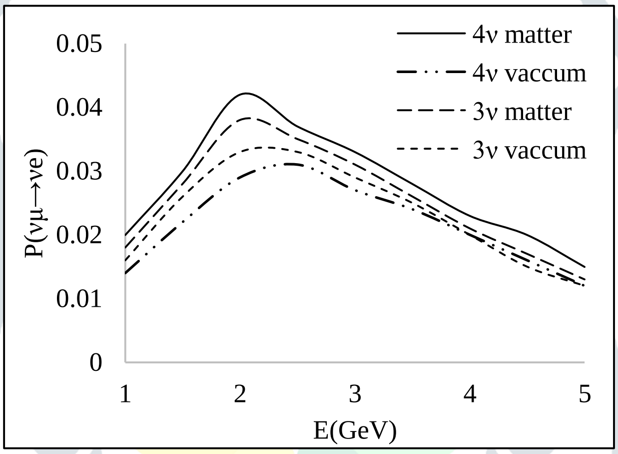

Fig. 9: Same as Fig. 7 but with Dirac phases $\delta_{13} = \pi/2$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

It is observed from these figures that,

1. The matter effect is important in both 4ν and 3ν case. At energy range 1-2 GeV, the relative difference between probabilities is maximum in each case.
2. The matter oscillation probability is more in each case than their vacuum counterpart.
3. Sterile neutrino gives non negligible contribution to oscillation probability, no matter whether propagating in vacuum or in matter. In each of these plots, the brown and yellow lines has clear deviation from green and blue lines.
4. The CP violating phases also show their role in these plots. The brown lines have maximum distinction from blue dot lines in the scenario of $(\delta_{13}, \delta_{14}) = (\pi/2, \pi/2)$ while in the case $(\delta_{13}, \delta_{14}) = (0,0)$ and $(0, \pi/2)$, that much deviation is not observed. The lines are very close to each other and a litter overlap is seen in these cases.

V. FUTURE PROSPECTS

Currently there are three proposed long base line experiments, which are T2HK [14] in Japan, DUNE [15] in USA and ESSnuSB [16] in Sweden. In the first phase, T2HK in Japan, which is basically the upgrade of T2K experiment, will use a water Cherenkov detector of volume 187 kt located at a distance of 295 km from the neutrino source at J – PARC to study the oscillation of muon neutrinos. For DUNE, a time projection chamber detector of 40 kt will be located at a distance of 1300 km from the neutrino source at Fermilab, whereas ESSnuSB will use a water Cherenkov far detector of mass 540 kt located at a distance of 360 km from the neutrino source at the ESS facility. The baseline of these experiments are within the reach of current analysis and hence, it will be interesting to consider the output of these experiments for further analysis.

VI. CONCLUSIONS

In the present work, we have calculated the matter oscillation probabilities for sterile neutrinos and plotted them for some particular Dirac angles for baseline of 300, 900 and 1300 km long baseline experiments. From the observations, it is concluded that in the long baseline experiment, in the presence of sterile neutrino, the matter effect can-not be ignored. The CP-violating Dirac phases in the mixing matrix may play an important role in sterile neutrino's matter effect.

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