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STUDY OF STERILE NEUTRINO EFFECT ON OSCILLATION PROBABILITIES

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Abstract: The mass squared differences are the parameters showing the neutrino oscillations. In order to explain three kinds of neutrino experiments within one framework, three kinds of the mass squared differences are needed. 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). We have studied the effect of these sterile neutrinos on reactor neutrino experiments.

Index terms: neutrino oscillation, sterile neutrino, CP violation, oscillation probabilities, reactor neutrino experiments.

I. INTRODUCTION

Neutrinos are the most elusive particles in the universe and hence studying their properties remains a key challenge in particle physics. One of the most intriguing phenomena in the study of neutrinos is neutrino oscillation, which refers to how neutrinos can perform between different flavors as they travel through space. The study of neutrino oscillations has led to important insights into the properties of neutrinos and the fundamental laws of the universe.

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 $N_\nu = 2.92 \pm 0.05$ 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 study the effect of these sterile neutrinos on oscillation properties of three active neutrinos in reactor neutrino 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. CALCULATION OF OSCILLATION PROBABILITIES

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

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

The details of these matrix elements $U_{\alpha a}$ can be found in [9]. 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

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

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

Following eq. (2), the oscillation probability $P(\bar{\nu}_e \to \bar{\nu}_e)$ for reactor neutrino experiments can be written as

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4\sum_{i<j}\left(\left|\widetilde{U}_{ei}\right|^2\left|\widetilde{U}_{ej}\right|^2 \sin^2\frac{\tilde{\Delta}_{ij}}{2}\right) \qquad (3)$$

2.1 The oscillation probability $P(\bar{\nu}_e \to \bar{\nu}_e)$ for reactor neutrino experiments

Around a nuclear power plant (NPP), there are plenty of antielectron neutrinos produced via β decay in nuclear reactions. Detectors can be put in suitable places near to the nuclear plant to explore reactor neutrino events. Usually the baselines of such kind of experiments are in the range of short or medium baseline. Regarding to matter effect, whether the oscillation probability will change with or without matter effect, both in purely 3 flavor active neutrinos case and in the framework of active plus sterile neutrino case, is what we are concerned. Hence we have calculated the oscillation probability for Base line of 50 km as an example for short or medium baseline experiments to check it out.

The expansion of eq. (3) gives

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - 4\sum_{i<j}\left(\left|\widetilde{U}_{ei}\right|^2\left|\widetilde{U}_{ej}\right|^2 \sin^2\frac{\tilde{\Delta}_{ij}}{2}\right) \\ &= 1 - 4\left(\left|\widetilde{U}_{e1}\right|^2\left|\widetilde{U}_{e2}\right|^2 \sin^2\frac{\tilde{\Delta}_{12}}{2} + \left|\widetilde{U}_{e1}\right|^2\left|\widetilde{U}_{e3}\right|^2 \sin^2\frac{\tilde{\Delta}_{13}}{2}\right) + 4\left(\left|\widetilde{U}_{e1}\right|^2\left|\widetilde{U}_{e4}\right|^2 \sin^2\frac{\tilde{\Delta}_{14}}{2} + \left|\widetilde{U}_{e2}\right|^2\left|\widetilde{U}_{e3}\right|^2 \sin^2\frac{\tilde{\Delta}_{23}}{2}\right) \\ &+ 4\left(\left|\widetilde{U}_{e2}\right|^2\left|\widetilde{U}_{e4}\right|^2 \sin^2\frac{\tilde{\Delta}_{24}}{2} + \left|\widetilde{U}_{e3}\right|^2\left|\widetilde{U}_{e4}\right|^2 \sin^2\frac{\tilde{\Delta}_{34}}{2}\right) \qquad (4) \end{aligned}$$

where

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

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

and

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

III. RESULTS AND DISCUSSIONS

After expanding $\left|\widetilde{U}_{e1}\right|^2$, $\left|\widetilde{U}_{e2}\right|^2$, $\left|\widetilde{U}_{e3}\right|^2$ and $\left|\widetilde{U}_{e4}\right|^2$ and values of $\tilde{\Delta}_{ij}$, we have plotted the relative probability for $\bar{\nu}_e \to \bar{\nu}_e$ as a function of neutrino energy E for 4ν (3+1) and 3ν case in fig. 1-3. We have varied Dirac phases δ_{13} and δ_{14} from 0 to π/2 and kept $\delta_{34} = 0$.

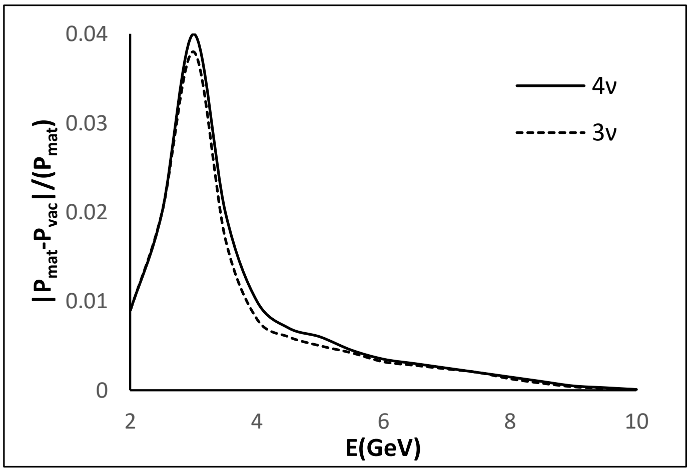

Fig. 1: Relative probability for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ in L = 50 km base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = 0$, $\delta_{14} = 0$ and $\delta_{34} = 0$.

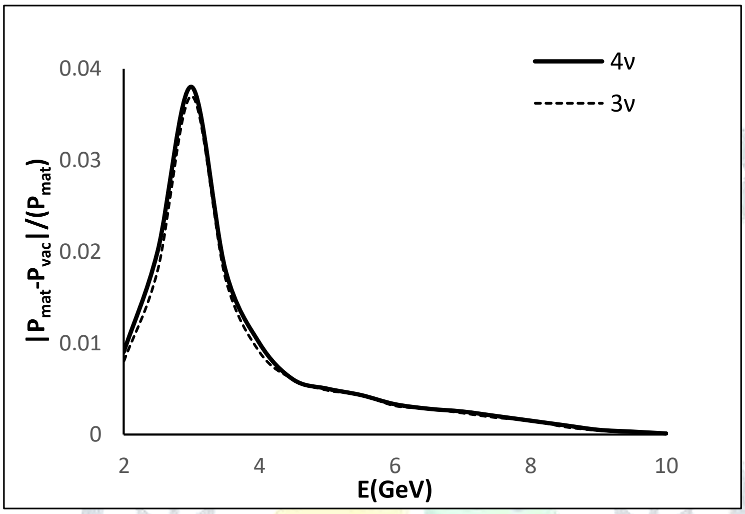

Fig. 2: Relative probability for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ in L = 50 km base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = 0$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

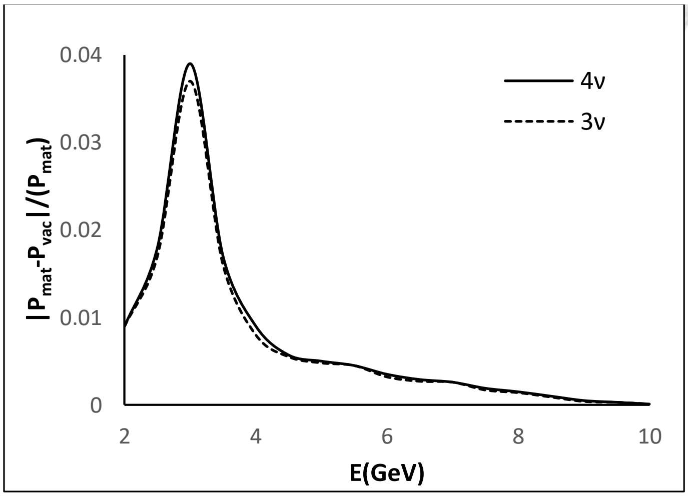

Fig. 3: Relative probability for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ in L = 50 km base line experiment as a function of neutrino energy E for 4ν (3+1) and 3ν case. Here Dirac phases $\delta_{13} = \pi/2$, $\delta_{14} = \pi/2$ and $\delta_{34} = 0$.

From the plots, it is observed that

1. the sterile neutrino contribution does not affect probability curve very much, that is to say for short/medium baseline experiment, sterile neutrino effect is quite limited.

2. The effect from Dirac phase seems bleak, no distinction can be reflected from different phase combinations.

IV. CONCLUSIONS

we have plotted the relative probability for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ as a function of neutrino energy E for 4ν (3+1) and 3ν case. From the observations of the plot, it is concluded that the short and medium baseline experiments are not sensitive to the matter effect of sterile neutrino, as well as the CP-violating Dirac phases.

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