Effect of light sterile neutrino on currently running long-baseline experiments

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Abstract

Recent $\nu_e$ appearance data from the Mini Booster Neutrino Experiment (MiniBooNE) are in support of the excess of events reported by the Liquid Scintillator Neutrino Detector (LSND), which provides an indirect hint for the existence of eV-scale sterile neutrino. As these sterile neutrinos can mix with the standard active neutrinos, in this paper, we explore the effect of such active-sterile mixing on the determination of various oscillation parameters by the currently running long-baseline neutrino experiments. We find that the existence of sterile neutrino can lead to new kind of degeneracies among these parameters which would deteriorate the mass hierarchy sensitivity of NO$\nu$A experiment. We also find that addition of data from T2K experiment helps in resolution of degeneracies.

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I. INTRODUCTION

Unlike other fundamental particles, neutrinos possess several unique features and are the only massless fermions within the Standard Model (SM). However, the experimental observation of neutrino oscillation by various experiments, wherein the neutrinos change their flavour as they propagate, provides strong evidence for neutrinos to have tiny but non-zero mass. In this regard, enormous attempts are being made to understand the origin of their masses, mixing phenomena, mass scale, whether they are Dirac or Majorana type in nature, etc. The three-flavour oscillation picture can successfully explain the experimental results from solar, atmospheric and reactor neutrino experiments [1]. In this framework, the phenomenon of neutrino oscillation is characterized by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$), two mass squared differences $\Delta m_{21}^2, \Delta m_{31}^2$ and one Dirac type CP phase $\delta_{\text{CP}}$. These oscillation parameters are measured very precisely, though there are few unknowns, which are yet to be determined, like the neutrino mass ordering, octant of the atmospheric mixing angle $\theta_{23}$ and the CP violating phase $\delta_{\text{CP}}$. The main physics goal of current and future generation neutrino oscillation experiments is to precisely determine all these unknowns. In this context, the long-baseline experiments play a major role in the determination of these unknown parameters due to the presence of enhanced matter effect [2]. However, the existence of parameter degeneracies among the oscillation parameters greatly affect the sensitivities of these experiments [3]. Therefore, the resolution of degeneracies among the oscillation parameters is the primary concern in neutrino oscillation studies.

Apart from these, another important aspect in the neutrino sector is the possible existence of additional eV-scale neutrino species, which has attracted a lot of attention in recent times, following some anomalies reported by various experiments. The first such anomaly was presented by the Liquid Scintillator Neutrino Detector (LSND) experiment [4], in the measurement of anti-neutrino flux in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation. An excess in the electron anti-neutrino ($\bar{\nu}_e$) events has been reported, which could be explained by incorporating at least one additional eV-scale neutrino. This result was further supported by the $\bar{\nu}_e$ appearance results at the MiniBooNE experiment [5]. Another hint for existence of light neutrinos has emerged from the deficit in the estimated anti-neutrino flux from reactor experiments [6, 7]. Similar anomalies have also been observed at GALLEX and SAGE Gallium experiments for solar neutrino observation, which also indicate the existence of additional light neutrino
species \[8, 9\]. Recently MiniBooNE collaboration \[10\], reported their new analysis with twice the data sample size used earlier, confirming the anomaly at the level of 4.8\(\sigma\), which becomes \(>6\sigma\), if combined with LSND data. Though an eV scale neutrino can explain all these anomalies, such a neutrino can’t have gauge interactions with the SM gauge bosons, to satisfy the precision measurement of \(Z\) boson decay width at LEP experiment. Hence, such a neutrino is known as a sterile neutrino, while the usual standard model neutrinos are known as active neutrinos. Though sterile neutrinos are blind to weak interactions, they can mix with active neutrinos. Therefore, in this paper we explore the effect of such active-sterile mixing on the determination of neutrino oscillation parameters by currently running long-baseline neutrino experiments. We, further investigate its effect on neutrino-less double beta decay process. The implications of light sterile neutrino on the physics potential of various long-baseline experiments, such as T2K, T2HK, NO\(\nu\)A and DUNE have been explored by several authors \[11–24\] for various possible combinations of run-period. However, in this work we would like to see in particular, whether the determination of mass-ordering by the currently running long-baseline experiments NO\(\nu\)A and T2K would be affected by the presence of light sterile neutrinos. Recently, NO\(\nu\)A \[25\] has performed the search for active-sterile neutrino mixing using neutral current interactions, though no evidence of \(\nu\)\(\mu\) \(\rightarrow\) \(\nu\)\(s\) has been found.

The paper is organised as follows. In the next section, we present the possible theoretical scenario for eV-scale sterile neutrino. In section III, we discuss the theoretical framework for (3+1) flavor oscillation case. Section IV covers the experimental set-up and details about the analysis adopted in this paper. The effect of sterile-neutrino on oscillation parameters is discussed in section V. Section VI deals with MH sensitivity analysis and section VII focused on the impact of sterile neutrino on neutrino-less double beta decay, prior to conclusion in section VIII.

## II. POSSIBLE SCENARIO FOR eV-SCALE STERILE NEUTRINO

In this section, we briefly describe how one can accommodate an eV-scale sterile neutrino in the seesaw framework. In the standard canonical seesaw \[26, 27\], three heavy right-handed neutrinos \(\nu_{R_i} = (\nu_{R_1}, \nu_{R_2}, \nu_{R_3})\) are introduced, which gives rise the Lagrangian for neutrino
mass as

\[-\mathcal{L}_\nu = \bar{\nu}_L M_D \nu_R + \frac{1}{2} \bar{\nu}_R^c M_R \nu_R + \text{h.c.}, \quad (1)\]

where \( M_D \) is the Dirac mass matrix and \( M_R \) is the Majorana mass matrix for the right-handed neutrinos \( \nu_{R_i} \), which is symmetric. In the \((\nu_L, \nu_R^c)\) basis, the neutrino mass matrix can be represented as

\[ M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}. \quad (2)\]

For \( M_D \ll M_R \), the light neutrino masses are given as

\[ m_\nu \simeq -M_D M_R^{-1} M_D^T, \quad (3)\]

and the mixing between the light and heavy neutrinos can be obtained by diagonalizing \( M_\nu \) and is given by \( R \simeq M_D M_R^{-1} \). Assuming the Dirac mass \( M_D \) to be at the electroweak scale, i.e., \( \mathcal{O}(100) \) GeV, one required \( M_R \sim \mathcal{O}(10^{14}) \) GeV, for generating the light neutrino masses at the eV-scale. Hence, it is impossible to have an eV-scale sterile neutrino in this formalism. However, as discussed in [28], if one of the right-handed neutrinos \((\nu_s \equiv \nu_{R_3})\) is brought down to be eV-scale, while the other two \((\nu_{R_1}, \nu_{R_2})\) remained heavy, then the Lagrangian for the neutrino mass becomes

\[-\mathcal{L}_\nu = \bar{\nu}_L M_D \nu_R + \bar{\nu}_L M_S \nu_s + \frac{1}{2} \bar{\nu}_R^c M_R \nu_R + \frac{1}{2} \bar{\nu}_s^c \mu_s \nu_s + \text{h.c.}, \quad (4)\]

where \( M_D, M_R \) and \( M_s \) are the \( 3 \times 2, 2 \times 2 \) and \( 3 \times 1 \) mass matrices, respectively. Assuming the heavy right-handed neutrinos \( \nu_{R_j} \) \((j = 1, 2)\) to be at the TeV scale or higher, then at the energy scales much lower than \( M_R, \nu_{R_j} \) can be decoupled and one obtains the \( 4 \times 4 \) matrix for the active and sterile neutrinos as

\[ M_\nu^{4 \times 4} = \begin{pmatrix} -M_D M_R^{-1} M_D^T & M_S \\ M_D^T & \mu_s \end{pmatrix}. \quad (5)\]

For \( \mu_s \gg M_S \), one can obtain the light neutrino mass matrix as

\[ m_\nu \simeq -M_D M_R^{-1} M_D^T - M_S \mu_s^{-1} M_S^T, \quad (6)\]

and the sterile neutrino mass as

\[ m_s \simeq \mu_s. \quad (7)\]
As discussed in Ref. [28], one of the right-handed neutrinos can be made light, by starting with a flavor symmetry, which predicts one of the masses to be zero. Breaking of such symmetry, eventually generates a small but non-zero mass and thus, one can have a sterile neutrino in the eV-scale, as required to explain the observed anomalies in various short-baseline experiments.

Another interesting way to generate the eV scale sterile neutrino is by invoking the $A_4$ flavour symmetry [29–32]. We now proceed to discuss the realization of light sterile neutrinos in a modified discrete flavor symmetric $A_4$ model, where the SM has been extended $A_4 \times Z_3 \times Z_2$ along with an extra global symmetry $U(1)_X$. The basic set-up of the model depends on the construction of $A_4$ symmetric Lagrangian associated with the neutrino mass term. In this framework, the SM lepton doublets ($\ell_i$) transform as a triplet, while the singlet charged leptons $e_R, \mu_R$ and $\tau_R$ transform as $1, 1''$ and $1'$ under $A_4$ symmetry group. The particle content and their representations under flavour symmetries are presented in Table-I. The flavon fields $\phi_S, \phi_T$ and $\xi$ break the $A_4$ symmetry by acquiring vacuum expectation values (vevs) in suitable directions.

| Fields | $e_R$ | $\mu_R$ | $\tau_R$ | $\ell$ | $H$ | $N$ | $\phi_S$ | $\phi_T$ | $\xi$ | $\eta$ | $\rho$ | $\chi$ |
|--------|-------|---------|----------|-------|-----|-----|--------|--------|------|-------|-------|-------|
| $A_4$  | 1     | 1''     | 1'       | 3     | 1   | 1   | 3      | 3      | 1    | 1'    | 1     | 1     |
| $Z_3$  | $\omega$ | $\omega$ | $\omega$ | $\omega$ | 1   | $\omega^2$ | $\omega$ | 1 | $\omega$ | 1    | $\omega$ |
| $Z_2$  | -1    | -1      | -1       | 1     | 1   | 1   | 1      | -1     | 1    | 1     | 1     | 1     |
| $U(1)_X$ | 0     | 0       | 0        | 0     | 0   | 0   | 0      | 0      | $-x$ | $x$   | 0     |

TABLE I: The particle content and their charge assignments in the $A_4$ model.

The contribution to neutrino mass matrix arises from higher dimensional operators, can be expressed as

$$-\mathcal{L}_\nu = \frac{1}{\Lambda^2}(\ell H\ell H)(y_1 \xi - y_2 \phi_S),$$

(8)

where $\Lambda$ is the cut-off scale and $y_1, y_2$ are the respective coupling constants. When the scalar fields acquire their vevs along $\langle \phi_S \rangle = (v_S, 0, 0), \langle \phi_T \rangle = v_T (1, 1, 1), \langle \xi \rangle = v_\xi$ and $\langle H \rangle = (0, v)^T$, the flavor symmetry is broken, as a result one can obtain the neutrino mass
matrix as

\[
\mathcal{M}_\nu^{(0)} = \begin{pmatrix}
2a/3 + b & -a/3 & -a/3 \\
-a/3 & 2a/3 & -a/3 + b \\
-a/3 & -a/3 + b & 2a/3
\end{pmatrix},
\]

(9)

where \( a = y_1(v^2/\Lambda)\varepsilon \) and \( b = y_2(v^2/\Lambda)\varepsilon, \varepsilon = v_\xi/\Lambda = v_S/\Lambda \).

The Yukawa Lagrangian for the charged lepton sector can be expressed as

\[
-\mathcal{L}_l = \frac{y_e}{\Lambda} (\bar{\ell} \phi_T) H e_R + \frac{y_\mu}{\Lambda} (\bar{\ell} \phi_T)' H \mu_R + \frac{y_\tau}{\Lambda} (\bar{\ell} \phi_T)'' H \tau_R,
\]

(10)

which yields the diagonal mass matrix for the charged leptons,

\[
\mathcal{M}_l = \begin{pmatrix}
y_e v v_T/\Lambda & 0 & 0 \\
0 & y_\mu v v_T/\Lambda & 0 \\
0 & 0 & y_\tau v v_T/\Lambda
\end{pmatrix}.
\]

(11)

It should be noted that the neutrino mass matrix (9) can be diagonalized by the tri-bimaximal (TBM) mixing matrix The immediate consequence of TBM mixing is that it implies vanishing reactor mixing angle (\( \theta_{13} = 0 \)), along with \( \sin^2 \theta_{23} = 1/2 \) and \( \sin^2 \theta_{12} = 1/3 \).

Now to explain the current experimental non-zero value of \( \theta_{13} \), we consider an operator of order \( 1/\Lambda^3 \), by including two other flavon fields \( \rho \) and \( \eta \), which transform as 1 and 1’ under \( A_4 \), with equal and opposite charges under \( U(1) \) as

\[
-\mathcal{L}_\nu^1 = \frac{1}{\Lambda^3} y_3 (\bar{\ell} H H^c) \rho \eta .
\]

(12)

This term contributes to the light neutrino mass matrix after symmetry breaking as

\[
\mathcal{M}_\nu^{(1)} = \begin{pmatrix}
0 & 0 & d \\
0 & d & 0 \\
d & 0 & 0
\end{pmatrix},
\]

(13)

where \( d = y_3(v^2/\Lambda)\varepsilon'^2 \) with \( \varepsilon' = \langle \rho \rangle/\Lambda \equiv \langle \eta \rangle/\Lambda \). By including the above additional contribution to the mass matrix (9), one can successfully explain the observed reactor mixing angle \( \theta_{13} \), as the modified mass matrix will no longer be diagonalized by the TBM matrix. However, to accommodate the anomalies associated with sterile neutrino sector, we further extend the model to include one sterile neutrino \( N \) and one more flavon field \( \chi \), with transformation properties as given in Table I, and write the interaction Lagrangian as

\[
\mathcal{L}_s = \frac{1}{\Lambda} y_s N N \chi \xi + \frac{1}{\Lambda^2} \bar{T} H N \chi \phi_S .
\]

(14)
Thus, with the inclusion of these terms, the neutrino mass matrix obtained as

\[
\mathcal{M}_\nu = \begin{pmatrix}
\frac{2a}{3} + b & -\frac{a}{3} & -\frac{a}{3} + d & e \\
-\frac{a}{3} & \frac{2a}{3} + d & -\frac{a}{3} + b & e \\
-\frac{a}{3} + d & -\frac{a}{3} + b & \frac{2a}{3} & e \\
e & e & e & m_s
\end{pmatrix},
\]

(15)

where \(m_s = y_s v_\chi v_\xi / \Lambda\) and \(e = y_\chi v_\chi v_s / \Lambda^2\). A similar form of mass matrix has been recently obtained in Ref. [33], by including one eV-scale sterile neutrino in an \(A_4\) flavour extended \(B - L\) model, which can successfully accommodate all the current oscillation data. In this framework the \(4 \times 4\) mass matrix can be analytically diagonalized with eigenvalues [33]:

\[
m_{\nu_1} = a + \sqrt{b^2 - bd + d^2},
\]

\[
m_{\nu_2} = \frac{1}{2} [b + d + m_s - \sqrt{12e^2 + (b + d - m_s)^2}],
\]

\[
m_{\nu_3} = a - \sqrt{b^2 - bd + d^2},
\]

\[
m_{\nu_4} = \frac{1}{2} [b + d + m_s + \sqrt{12e^2 + (b + d - m_s)^2}].
\]

(16)

and the mixing matrix constructed from the normalized eigenvectors takes the form

\[
U = \begin{pmatrix}
-\frac{p_+}{l_{p+}} & \frac{1}{6e} \frac{K_{p-}}{N_{p-}} & -\frac{1}{6e} \frac{K_{p+}}{N_{p+}} \\
\frac{q_+}{l_{p+}} & \frac{1}{6e} \frac{K_{q-}}{N_{q-}} & -\frac{1}{6e} \frac{K_{q+}}{N_{q+}} \\
\frac{1}{6e} \frac{1}{N_{p-}} & \frac{1}{6e} \frac{1}{N_{q-}} & \frac{1}{6e} \frac{1}{N_{p+}} \\
0 & \frac{1}{N_{p-}} & 0
\end{pmatrix},
\]

(17)

where

\[
K_{p\pm} = b + d - m_s \pm \sqrt{12e^2 + (b + d - m_s)^2},
\]

\[
N_{p\pm}^2 = 1 + \frac{\left(b + d - m_s \pm \sqrt{12e^2 + (b + d - m_s)^2}\right)^2}{12e^2},
\]

\[
p_\pm = \frac{b \pm \sqrt{b^2 - bd + d^2}}{b - d}, \quad q_\pm = \frac{d \pm \sqrt{b^2 - bd + d^2}}{b - d},
\]

\[
l_{p\pm}^2 = 1 + (p_\pm)^2 + (q_\pm)^2.
\]

(18)
The various mixing angles in this framework are given as

\[
\sin^2 \theta_{12} = \frac{|U_{e2}|^2}{1 - |U_{e4}|^2} \approx \frac{1}{3} \left[ 1 - \frac{2}{3} \left( \frac{e}{m_s} \right)^2 \right], \tag{19}
\]

\[
\sin^2 \theta_{23} = \frac{|U_{\mu3}|^2(1 - |U_{e4}|^2)}{1 - |U_{e4}|^2 - |U_{\mu4}|^2} \approx \frac{1}{2} \left[ 1 + \left( \frac{e}{m_s} \right)^2 \right], \tag{20}
\]

\[
\sin^2 \theta_{14} = |U_{e4}|^2 \approx \left( \frac{e}{m_s} \right)^2, \tag{21}
\]

\[
\sin \theta_{34} = \frac{|U_{\tau4}|^2}{1 - |U_{e4}|^2 - |U_{\mu4}|^2} \approx \left( \frac{e}{m_s} \right)^2, \tag{22}
\]

\[
\sin^2 \theta_{24} = \frac{|U_{\mu4}|^2}{1 - |U_{e4}|^2} \approx \left( \frac{e}{m_s} \right)^2, \tag{23}
\]

\[
\sin^2 \theta_{13} = \frac{|U_{e3}|^2}{(1 - \sin^2 \theta_{23})(1 - \sin^2 \theta_{14})} = \frac{d^2}{4b^2} \left( 1 + 2 \frac{e^2}{m_s^2} \right). \tag{24}
\]

It should be emphasized that, since the model considered here has similar structure of the mass matrix as that of Ref. [33], it can also explain the current oscillation data for suitable values of model parameters, and hence the detailed analysis will not be presented in this work. Rather we will focus on the implications of eV-sterile neutrino on the determination of oscillation parameters at the currently running long-baseline experiments.

### III. BRIEF DISCUSSION ABOUT 3+1 OSCILLATION MODEL

In presence of one sterile neutrino, the parametrization of neutrino mixing requires additional oscillation parameters, which includes three mixing angles (\(\theta_{14}, \theta_{24}, \theta_{34}\)), two phases (\(\delta_{14}, \delta_{34}\)), and one mass squared difference (\(\Delta m_{41}^2\)). Therefore, similar to the standard PMNS matrix, the four dimensional mixing matrix will have the form

\[
U^{3+1} = O(\theta_{34}, \delta_{34}) R(\theta_{24}) O(\theta_{14}, \delta_{14}) R(\theta_{23}) O(\theta_{13}, \delta_{13}) R(\theta_{12}), \tag{25}
\]

where \(R(\theta_{ij}) \ (O(\theta_{ij}, \delta_{ij}))\) is the real (complex) rotation matrix in the \(ij\) sector, represented with \(2 \times 2\) matrix form:

\[
R(\theta_{ij}) = \begin{pmatrix} \cos \theta_{ij} & \sin \theta_{ij} \\ -\sin \theta_{ij} & \cos \theta_{ij} \end{pmatrix}, \quad O(\theta_{ij}, \delta_{ij}) = \begin{pmatrix} \cos \theta_{ij} & \sin \theta_{ij} e^{-i\delta_{ij}} \\ -\sin \theta_{ij} e^{i\delta_{ij}} & \cos \theta_{ij} \end{pmatrix}, \tag{26}
\]

inside a \(4 \times 4\) matrix as \(ij\) sub-block. The oscillation probability for \(\nu_\mu \to \nu_e\) channel in terms of the effective mixing matrix elements (\(\tilde{U}_{ai}\)) and effective mass difference \(\Delta \tilde{m}_{ij}^2\) in
presence of matter is given as \[34\]

\[
P(\nu_\mu \rightarrow \nu_e) = \sum_i |\bar{U}_{\mu i}|^2 |\bar{U}_{ei}|^2 + 2 \sum_{i<j} \left[ \text{Re}(\bar{U}_{\mu i} U_{ej} U_{\mu j}^* U_{ei}^*) \cos \Delta_{ij} - \text{Im}(\bar{U}_{\mu i} U_{ej} U_{\mu j}^* U_{ei}^*) \sin \Delta_{ij} \right]
\]

(27)

where \(\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}\), \(L\) and \(E\) are baseline and energy of neutrino beam, respectively.

Effective mass squared difference can be written in terms of two arbitrary effective mass squared difference as

\[
\hat{\Delta} m^2_{ij} = \hat{\Delta} m^2_{i1} - \hat{\Delta} m^2_{j1},
\]

\[
\hat{\Delta} m^2_{ij} = \hat{m}^2_i - \hat{m}^2_j.
\]

(28)

Exact analytical expressions for \(\hat{\Delta} m^2_{\alpha 1}(\alpha = 1, 2, 3, 4)\) can be found in \[34\]. The effective mixing elements can be related to the \(4 \times 4\) mixing matrix elements \((U_{\alpha \beta})\) as

\[
\bar{U}_{\text{ei}} U_{\mu j}^* = \prod_{k \neq i} \frac{1}{\Delta m^2_{ik}} \left[ \sum_j F_{e\mu}^{ij} U_{ej} U_{\mu j}^* + C_{e\mu} \right],
\]

(29)

where

\[
F_{e\mu}^{ij} = A^2 \Delta m^2_{j1} + A \Delta m^2_{j1} (\Delta m^2_{j1} - \sum_{k \neq i} \hat{\Delta} m^2_{k1}) + (\Delta m^2_{j1})^3 - \sum_{k \neq i} (\Delta m^2_{j1})^2 \hat{\Delta} m^2_{k1}
\]

\[+ \sum_{k,l:k \neq l \neq i} \Delta m^2_{j1} \hat{\Delta} m^2_{k1} \hat{\Delta} m^2_{l1},\]

\[C_{e\mu} = A' \sum_{k1} \Delta m^2_{k1} \Delta m^2_{l1} U_{ek} U_{\mu l}^* U_{sl} + A \sum_{k,l} \Delta m^2_{k1} \Delta m^2_{l1} |U_{ek}|^2 U_{el} U_{\mu l}^*,\]

(30)

with \(A = 2\sqrt{2} G_F N_e E\), \(A' = -\sqrt{2} G_F N_n E\) and \(N_e, N_n\) is the electron (neutron) densities.

One can get the oscillation of three neutrino in the presence of matter, from the 3+1 case by assuming \(U_{\alpha 4} = 0, U_{sl} = 0, A' = 0\) and \(A \neq 0\).

Long-baseline experiments are primarily designed to observe the \(\nu_\mu \rightarrow \nu_e\) and \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\) oscillation channel. So, first and foremost the impact of sterile can be shown by defining a quantity, which is the absolute deviation of the above mentioned channels in the presence of a sterile neutrino from the standard three flavor scenario in matter \((\Delta P_{\alpha \beta} = |P^\text{sterile}_{\alpha \beta} - P^\text{SI}_{\alpha \beta}|)\).

Analogously, one can also obtain the corresponding parameter for anti-neutrino case as \(\overline{\Delta P}_{\alpha \beta}\). In Fig.1, we show the graphical representation of oscillograms for \(\Delta P_{\mu e}\) \((\Delta P_{\mu \mu})\) in left (right) panel, as function of baseline \((L)\) and energy \((E)\) for neutrino beam. In the
calculation for obtaining the oscillograms, we have assumed the maximal atmospheric mixing
\((\sin^2 \theta_{23} = 0.5)\) and used the values of other parameters as in the Table II. In the plots, dark red regions represent large deviation between the oscillation probabilities. Moreover, it is clear from \(\Delta P_{\mu e}\) plot that, one can probe sterile neutrino in long-baseline experiments like T2K \((L = 295 \text{ km}, E=0.6 \text{ GeV})\), NO\(\nu\)A \((L=810 \text{ km}, E=2 \text{ GeV})\) and DUNE \((L= 1300 \text{ km}, E= 2.5 \text{ GeV})\). Hence, sterile neutrinos may play prominent role in the determination of the oscillation parameters in long baseline neutrino oscillation experiments.

IV. SIMULATION DETAILS

As we are interested in exploring the impact of an eV-scale sterile neutrino on currently running long baseline experiments NO\(\nu\)A and T2K, we simulate these experiments using GLoBES software package along with snu plugin [36, 37]. The auxiliary files and experimental specification of these experiments that we use in our analysis are taken from [38]. T2K and NO\(\nu\)A are complementary accelerator-based experiments with similar capabilities and goals, but differ only on their baselines. NO\(\nu\)A experiment is optimised to study the
FIG. 2: The neutrino (anti-neutrino) oscillation probability as a function of $\delta_{CP}$ is shown in the left (right) panel. The upper panel is for 3-flavor case and lower panel is for 3+1 case with $\delta_{14} = -90^\circ$.

appearance of $\nu_e (\bar{\nu}_e)$ from a beam of $\nu_\mu (\bar{\nu}_\mu)$, consists of two functionally identical detectors, each located 14.6 mrad off the central-axis of Fermilab’s neutrino beam, to receive a narrow band neutrino beam with peak energy near 2 GeV, corresponding to $\nu_\mu \to \nu_e$ oscillation maximum. Its near detector (ND) of mass 280 ton is located about 1 km downstream (100 m underground) from the source to measure un-oscillated beam of muon-neutrinos and estimate backgrounds at the far detector (FD). Oscillated neutrino beam is observed by 14 kton far detector, situated in Ash River, 810 km away from Fermilab. In order to simulate NO$\nu$A, we consider 120 GeV proton beam energy with $6 \times 10^{20}$ POT per year. We assume signal efficiencies for both electron (muon) neutrino and anti-neutrino as 45% (100%). The
TABLE II: Values of oscillation parameters considered in our analysis [11]. Values for the sterile mixing angles and their allowed ranged are calculated from the 3σ ranges of the matrix elements $|U_{\alpha 4}|$ as discussed in [35].

background efficiencies for mis-identified muons (anti-muons) at the detector are considered as 0.83% (0.22%). The neutral current background efficiency for $\nu_\mu$ ($\bar{\nu}_\mu$) is assumed to be 2% (3%). We further assume the intrinsic beam contamination, i.e., the background contribution coming from the existence of electron neutrino (anti-neutrino) in the beam to be about 26% (18%). Apart from these, we also consider 5% uncertainty on signal normalization and 10% on background normalization.

The muon neutrino beam of T2K experiment is produced at Tokai and is directed towards the water Cherenkov detector of fiducial mass 22.5 kt kept 295 km far away at Kamioka [39]. The neutrino flux peaks around 0.6 GeV as the detector is kept 2.5° off-axial to the neutrino beam direction. In order to simulate T2K experiment, we consider a proton beam power of 750 kW and with a proton energy of 30 GeV which corresponds to a total exposure of 7.8
×10^{21} protons on target (POT) with 1:1 ratio of neutrino to anti-neutrino modes. We match the signal and background event spectra and rates as given in the recent publication of the T2K collaboration [40]. We consider an uncorrelated 5\% normalization error on signal and 10\% normalization error on background for both the appearance and disappearance channels as given in Ref. [40] to analyse the prospective data from the T2K experiment. We assume that the set of systematics for both the neutrino and anti-neutrino channels are uncorrelated.

We simulate the true \( \left( N_{\text{true}} \right) \) and test \( \left( N_{\text{test}} \right) \) event rates and compare them by using binned \( \chi^2 \) method defined in GLoBES, i.e.,

\[
\chi^2_{\text{stat}}(\vec{p}_{\text{true}}, \vec{p}_{\text{test}}) = \sum_{i \in \text{bins}} 2 \left[ N_{i,\text{test}} - N_{i,\text{true}} - N_{i,\text{true}} \ln \left( \frac{N_{i,\text{test}}}{N_{i,\text{true}}} \right) \right],
\]

where \( \vec{p} \) stands for the array of standard neutrino oscillation parameters. However, for numerical evaluation of \( \chi^2 \), we also incorporate the systematic errors using pull method, which is generally done with the help of nuisance parameters as discussed in the GLoBES manual. Suppose \( \vec{q} \) denotes the oscillation parameter in presence of sterile neutrino, then the Mass Hierarchy (MH) sensitivity is given by

\[
\chi^2_{\text{MH}}(\vec{q}) = \chi^2_{\text{NH}}(\vec{q}) - \chi^2_{\text{IH}}(\vec{q}) \quad \text{(for true Normal Hierarchy)}
\]

\[
\chi^2_{\text{MH}}(\vec{q}) = \chi^2_{\text{IH}}(\vec{q}) - \chi^2_{\text{NH}}(\vec{q}) \quad \text{(for true Inverted Hierarchy)}
\]

Further, we obtain minimum \( \chi^2_{\text{min}} \) by doing marginalization over all oscillation parameter spaces.

V. DEGENERACIES AMONG OSCILLATION PARAMETERS

In this section, we discuss the degeneracies among the oscillation parameters in presence of an eV-scale sterile neutrino. Here, we focus only on NO\( \nu \)A experiment.

In order to analyse degeneracies among the oscillation parameters at probability level, we show \( \nu_e \) (\( \bar{\nu}_e \)) appearance oscillation probability as a function of \( \delta_{\text{CP}} \) in the left (right) panel of Fig. 2. The upper panel of the figure corresponds to oscillation probability in standard paradigm and that for 3+1 case is given in lower panel. The green, orange, blue and red bands in the figure represent the oscillation probabilities for possible hierarchy-octant combinations: NH-HO, NH-LO, IH-HO and IH-LO respectively. From the upper panel of the figure, it can be seen that the bands for NH-HO and IH-LO are very well
separated in neutrino channel, whereas the NH-LO and IH-HO bands are overlapped with each other, which results degeneracies among the oscillation parameters. Also it should be noted that, in the anti-neutrino channel, the case is just opposite. Therefore, a combined analysis of neutrino and anti-neutrino data helps in the resolution of degeneracies and also improves the sensitivity of long-baseline experiments to precisely determine the unknowns of standard oscillation paradigm. From the bottom panel of the figure, it can be seen that there emerged new types of degeneracies among the oscillation parameters in the presence of sterile neutrino even for a single value of both sterile phases $\delta_{14}$ ($= -90^\circ$) and $\delta_{34}$ ($= -90^\circ$), which can worsen the sensitivity of the unknowns.

![Bi-probability plots for NO$\nu$A in 3 years in neutrino and 3 years in anti-neutrino mode.](image)

FIG. 3: Bi-probability plots for NO$\nu$A in 3 years in neutrino and 3 years in anti-neutrino mode.

Another way of representing these degeneracies among oscillation parameters is by using the bi-probability plot. In this case, we calculate the oscillation probabilities for neutrino and anti-neutrino for a fixed hierarchy-octant combination for all possible values of $\delta_{\text{CP}}$ and display it in a neutrino-antineutrino probability plane in Fig. 3. The ellipses in the figure correspond to 3 flavor case, whereas the bands represent the oscillation probabilities in presence of sterile neutrino with all possible values of new phases $\delta_{14}$ and $\delta_{34}$. From the figure, it can be seen that the ellipses for LO and HO are very well separated for both hierarchies, whereas the ellipses for NH and IH for both LO and HO are overlapped with
FIG. 4: The allowed parameter space in $\theta_{23} - \delta_{CP}$ plane.

each other and give rise to degeneracies. Therefore, NO\textnu A experiment is more sensitive to octant of $\theta_{23}$ than that of mass hierarchy. While in 3 + 1 paradigm, the bands are overlapped with each other for all combinations, which gives rise to new degeneracies. The additional degeneracies between lower and higher octants along with the standard ones, indicates that experiment is loosing its sensitivity in presence of sterile neutrino.

Next, we show the allowed parameter space in $\theta_{23} - \delta_{CP}$ plane for each hierarchy-octant combination as given in Fig. 4. In order to obtain the allowed parameter space, we simulate the true event spectrum with oscillation parameters given in Table I and compare it with test event spectrum by varying test values of $\theta_{23}$, $\delta_{CP}$ in their allowed ranges and doing
marginalization over $|\Delta m_{31}|^2$ for standard paradigm. In the 3+1 case, we also do marginalization over new phases $\delta_{14}$ and $\delta_{34}$. The solid blue (red) curve in the figure is for standard paradigm (3+1 case) for NO$\nu$A experiment, whereas the dashed curve is for the combined analysis of T2K and NO$\nu$A experiments. The left (right) panel corresponds to lower (higher) octant. From the top panels of the figure, it can be seen that the allowed parameter space in the presence of sterile neutrino is enlarged which indicates that the degeneracy resolution capability is decreased significantly. However, the synergy of T2K and NO$\nu$A improves the degeneracy resolution capability.

**FIG. 5:** MH sensitivity as a function of true values of $\delta_{CP}$. The left (right) panel is for inverted (normal) hierarchy and the upper (bottom) panel is for LO (HO).
VI. MH SENSITIVITY

In this section, we discuss how MH sensitivity of NOνA experiment gets modified in presence of sterile neutrino. In order to obtain the MH sensitivity, we simulate the event spectrum by assuming true hierarchy as normal (inverted) and test hierarchy as inverted (normal). We obtain $\chi^2$ by comparing true and test event spectra. While doing the calculation, we do marginalization over $\delta_{CP}$, $\theta_{23}$, $|\Delta m^2_{31}|$ for standard paradigm and in addition to this, we also do marginalisation over $\delta_{14}$ and $\delta_{34}$ for (3+1) case, in the range as shown in Table II. In Fig. 5 we present the hierarchy determination sensitivity of NOνA. The left (right) panel corresponds to inverted (normal) hierarchy as true hierarchy, while lower (upper) panel corresponds to lower (higher) octant. From the figure, one can see that the wrong mass hierarchy can be ruled out significantly above 2$\sigma$ in the favourable regions, i.e., lower half-plane (upper half-plane) for NH (IH) in the standard paradigm. Whereas, in presence of sterile neutrino the $\delta_{CP}$ coverage for the mass hierarchy sensitivity is significantly reduced. At the same time the combined analysis of T2K with NOνA shows a significant increase in MH sensitivity due to increase of $\delta_{CP}$ coverage as shown in Fig. 5 by magenta lines.

VII. IMPLICATIONS ON NEUTRINO-LESS DOUBLE BETA DECAY

In this section, we would like to see the implication of the eV scale sterile neutrino on some low-energy phenomena, like neutrino-less double beta decay ($0\nu\beta\beta$). One of the important features of $0\nu\beta\beta$ process is that it violates the lepton number by two units and hence, its experimental observation would not only ascertain the Majorana nature of light neutrinos, but also can provide the absolute scale of lightest active neutrino mass. Various neutrino-less double beta decay experiments like KamLAND-Zen [41], GERDA [42], EXO-200 [43] etc., have provided bounds on the half-life ($T_{1/2}$) of this process on various isotopes, which can be translated as a bound on effective Majorana mass parameter $|M_{ee}|$ [44, 45] as,

$$T_{1/2} = Q \left| \frac{M_\nu}{m_e} \right|^2 |M_{ee}|^2,$$

where $Q$ is the phase space factor, $M_\nu$ is the nuclear matrix element (NME) and $m_e$ is the electron mass. Recently $0\nu\beta\beta$ experiments involving $^{76}$Ge, GERDA [42], $^{136}$Xe EXO-200 [43] provided the upper limit on $|M_{ee}|$ as $\sim (0.2 - 0.4)$ eV, using the available results on
nuclear matrix elements (NME) from literature. The current best upper limit on $|M_{ee}|$ has been reported by KamLAND-Zen Collaboration [41] as $|M_{ee}| < (0.061 - 0.165)$ eV at 90% CL. The next generation experiments are planning to probe towards $|M_{ee}| < (10^{-3} - 10^{-2})$ eV regime, and hopefully, they can cover the inverted mass hierarchy region of parameter space.

The effective Majorana mass, which is the key parameter of $0\nu\beta\beta$ decay process is defined in the standard three neutrino formalism as

$$|M_{ee}| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta} \right|,$$

(35a)

where $U_{ei}$ are the PMNS matrix elements and $\alpha$, $\beta$ are the Majorana phases. In terms of the lightest neutrino mass $m_l$ and the atmospheric and solar mass-squared differences, it can be expressed for NH and IH as

$$|M_{ee}|_{\text{NH}} = \left| U_{e1}^2 m_l + U_{e2}^2 \sqrt{\Delta m^2_{\text{sol}} + m_l^2} e^{i\alpha} + U_{e3}^2 \sqrt{\Delta m^2_{\text{atm}} + m_l^2} e^{i\beta} \right|,$$

(36)

and

$$|M_{ee}|_{\text{IH}} = \left| U_{e1}^2 \sqrt{\Delta m^2_{\text{atm}} - \Delta m^2_{\text{sol}} + m_l^2} + U_{e2}^2 \sqrt{\Delta m^2_{\text{atm}} + m_l^2} e^{i\alpha} + U_{e3}^2 m_l e^{i\beta} \right|.$$

(37)

Analogously, one can obtain the expression for $|M_{ee}|$ in the presence of an additional sterile neutrino as

$$|M_{ee}| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta} + U_{e4}^2 m_4 e^{i\gamma} \right|.$$

(38)

Now varying the PMNS matrix elements as well as the Dirac CP phase within their $3\sigma$ range [46] and the Majorana phases $\alpha$ and $\beta$ between $[0, 2\pi]$, we show the variation of $|M_{ee}|$ for three generation of neutrinos in the top panel of Fig. 6. Including the contributions from the eV scale sterile neutrino the corresponding plots are shown in the bottom panel, where the left plot is for NH and the right one for IH. In all these plots, the horizontal regions represent the bounds on effective Majorana mass from various $0\nu\beta\beta$ experiments, while the vertical shaded regions are disfavored from Planck data on the sum of light neutrinos, where the current bound is $\Sigma_i m_i < 0.12$ eV from Planck+WP+highL+BAO data at 95% C.L. [47]. It should be noted that with the inclusion of a eV scale sterile neutrino, part of the the parameter space of $|M_{ee}|$ (for IH) is within the sensitivity reach of KamLAND-Zen experiment. Furthermore, there is also some overlap regions between NH and IH cases.
Thus, the future 0νββ decay experiments may shed light on several issues related the nature of neutrinos.

**Comment on sensitivity reach of future experiments:**

Here, we present a brief discussion on the sensitivity of eV-scale sterile neutrino in the future 136Xe experiment. The discovery sensitivity of an experiment is characterized by the value of half-life ($T_{1/2}$) for which it has 50% probability of measuring a $3\sigma$ signal, above the background, defined as [48, 49]

$$T_{1/2} = \frac{\ln 2 N_A \epsilon}{m_a S_{3\sigma}(B)} ,$$

where $N_A$ is the Avogadro’s number, $m_a$ denotes the atomic mass of the Xe isotope, $B = \beta \epsilon$ ($\beta$ and $\epsilon$ stand for the background and exposure sensitivity), and $S_{3\sigma}$ signifies the value for which 50% of the measurements would give a signal above $B$, which can be calculated assuming a Poisson distribution

$$1 - CDF_{\text{Poisson}}(C_{3\sigma}|S_{3\sigma} + B) = 50%.$$
Here $C_{3\sigma}$ indicates the number of counts for which $CDF_{\text{Poisson}}(C_{3\sigma}|B) = 3\sigma$ and the continuous Poisson distribution can be defined in terms of incomplete gamma function as

$$CDF_{\text{Poisson}}(C|\mu) = \frac{\Gamma(C + 1, \mu)}{\Gamma(C + 1)}.$$  \hspace{1cm} (41)

Thus, with Eqns. (39) and (41), we show in Fig. 7 the discovery sensitivity of $T_{1/2}$ for $^{136}Xe$ as a function of $\varepsilon$ for various values of $\beta$. The red band corresponds to a representative value of $|M_{e\bar{e}}| = 10^{-2}$ eV in the presence of a sterile neutrino (expressed in terms of the half-life $T_{1/2}$ using Eqn.(35)), and varying the parameters in the PMNS matrix within their $3\sigma$ allowed ranges and also taking into account the uncertainty in the nuclear matrix element ($M_\nu$).

In Fig. 7 the dotted black line represents the future $3\sigma$ sensitivity of nEXO [50], which is $T_{1/2} = 5.7 \times 10^{27}$ years. The black, blue, red, and magenta lines correspond to different values of the sensitive background levels of $0, 10^{-5}, 10^{-4}$ and $10^{-3}$ cts/(kg$_{\text{iso}}$ yr) respectively. From the figure, we can see that for a sensitive background level of $10^{-4}$ cts/(kg$_{\text{iso}}$ yr), the $10^{-2}$ region could be probed with a sensitive exposure of $\sim 10^4$ kg$_{\text{iso}}$ yr.

FIG. 7: $^{136}Xe$ discovery sensitivity as a function of sensitivity exposure for a representative set of sensitive background levels. The black, blue, red and magenta lines correspond to the values of sensitive background levels of $0, 10^{-5}, 10^{-4}$ and $10^{-3}$ cts/(kg$_{\text{iso}}$ yr) respectively.
VIII. CONCLUSION

The various short baseline anomalies hint towards existence of an eV scale sterile neutrino. If such neutrino exists, it can mix with active neutrinos and affect the sensitivities of long-baseline experiments. As one of the main objectives of currently running long-baseline experiments is to determine mass hierarchy of neutrinos, in this paper, we discussed the effect of active-sterile mixing on the degeneracy resolution capability and MH sensitivity of NO$\nu$A experiment. We found that introduction of sterile neutrino gives rise to new kind of degeneracies among the oscillation parameters which results in reduction of $\delta_{\text{CP}}$ coverage for MH sensitivity of NO$\nu$A experiment. We also found that addition of T2K data helps in resolving the degeneracies among the oscillation parameters and for MH sensitivity analysis, results a significant increase in $\delta_{\text{CP}}$ coverage for one additional sterile neutrino. We have also studied the effect sterile neutrino on neutrinoless double beta decay process and shown that the inclusion of an eV scale sterile neutrino can enhance the value of the effective mass parameter $|M_{ee}|$, and for IH it could be within the sensitivity reach of KamLAND-Zen experiment. We also comment on the sensitivity reach of future $^{136}\text{Xe}$ experiments for exploring the presence of eV-scale sterile neutrino and found that for a sensitive background level of $10^{-4}$ cts/(kg$\text{iso}$yr), the $10^{-2}$ region of effective Majorana mass parameter ($|M_{ee}|$) could be probed with a sensitive exposure of $\sim 10^4$ kg$\text{iso}$yr.

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