Sensitivity of the T2HKK experiment to the non-standard interaction

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Abstract

If the flavor dependent non-standard interactions (NSI) in neutrino propagation exist, then the matter effect is modified and the modification is parametrized by the dimensionless parameter $\epsilon_{\alpha\beta}$ ($\alpha, \beta = e, \mu, \tau$). In this paper we discuss the sensitivity of the T2HKK experiment, whose possibility is now seriously discussed as a future extension of the T2K experiment, to such NSI. On the assumption that $\epsilon_{\alpha\mu} = 0$ ($\alpha = e, \mu, \tau$) and $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|/(1 + \epsilon_{ee})$, which are satisfied by other experiments to a good approximation, we find that, among the possible off-axis flux configurations of 1.3°, 1.5°, 2.0° and 2.5°, the case of the off-axis angle 1.3° gives the highest sensitivity to $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$. Our results show that the 1.3° off-axis configuration can exclude NSI for $|\epsilon_{ee}| \gtrsim 1$ or $|\epsilon_{e\tau}| \gtrsim 0.2$ at 3σ. We also find that in the presence of NSI, T2HKK (for the off-axis angle 1.3°) has better sensitivity to the two CP phases ($\delta_{CP}$ and $\text{arg}(\epsilon_{e\tau})$) than DUNE. This is because of the synergy between the two detectors i.e., one at Kamioka and one at Korea. T2HKK has better sensitivity to the CP phases than the atmospheric neutrino experiment at Hyperkamiokande in inverted hierarchy, but in normal hierarchy the atmospheric neutrino experiment has the best sensitivity to the CP phases.

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I. INTRODUCTION

It has been established by the successful experiments in the past that neutrinos have masses and mixings [1]. The three mixing angles \( \theta_{12}, \theta_{13}, \theta_{23} \) and two mass-squared differences \( \Delta m_{21}^2, \Delta m_{31}^2 \) in the standard three flavor neutrino oscillation framework are measured as: \( (\Delta m_{21}^2, \sin^2 2\theta_{12}) \simeq (7.5 \times 10^{-5}\text{eV}^2, 0.86) \), \( (|\Delta m_{31}^2|, \sin^2 2\theta_{23}) \simeq (2.4 \times 10^{-3}\text{eV}^2, 1.0) \), \( \sin^2 2\theta_{13} \simeq 0.09 \). The remaining unknowns are the value of the Dirac CP phase \( \delta_{\text{CP}} \), the sign of \( \Delta m_{31}^2 \) (the mass hierarchy i.e., normal or inverted) and the octant of \( \theta_{23} \) (the sign of \( \pi/4 - \theta_{23} \) i.e., lower or higher). It is expected that these unknowns will be determined by the future neutrino oscillation experiments, particularly the accelerator based long-baseline neutrino experiments [2, 3]. These experiments in the future can not only measure the oscillation parameters in the standard three flavor mixing scenario but also probe the new physics by looking at the deviation from the standard three flavor neutrino mixing framework.

Flavor-dependent neutral current neutrino Non-Standard Interactions (NSI) [4–6] have been studied as one of the new physics candidates which can be searched at the future neutrino experiments [7, 8]. In the presence of these NSI the neutrino propagation feels the extra contribution to the matter effect and hence long-baseline experiments with a longer baseline length \( L \) (typically \( L \gtrsim 1000 \text{ km} \)) and the atmospheric neutrino experiments are expected to have sensitivity to the neutral current NSI. Recent studies of neutral current NSI in long-baseline and atmospheric neutrino experiments can be found in Ref. [9–34].

The possibility of a second detector in Korea for the T2K [35] experiment was discussed in the past [36–51]. Recently there has been a renewed interest in the idea of placing the second detector in Korea as a part of the T2HK plan [2], and the plan with the second detector in Korea is now called the T2HKK project [52]. The original plan of the T2HK project is to build a large tank of water Čerenkov detector at the Kamioka site. Under the T2HKK project, there will be two tanks of equal volume instead of building a single tank and then one of the tanks will be built in Korea. Depending on the location of the second detector in Korea, one has different options for the flux in terms of the off-axis angle. According to the HK collaboration, there are various flux options between 1° to 3° off-axis configurations are under consideration at present [53]. In the T2HKK project, there are some discussions on which location is the most advantageous from the physics point of view. In this paper for the first time we study the sensitivity of T2HKK to NSI and discuss
the result of optimization for the NSI parameters $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ with respect to the different flux options. We also compare its sensitivity with that of DUNE [3] and the atmospheric neutrino experiment at Hyperkamiokande (HK) [54]. While a similar analysis was done in the past [47], the new points in the present paper are the optimization with respect to the location, which can be expressed in terms of the off-axis angle, and the comparison of the sensitivity with DUNE and the atmospheric neutrino at HK.

This paper is organized as follows. In Section II, we describe the constraints on NSI in propagation. In Section III, we study the sensitivity of the T2HKK experiment to NSI and compare our results with DUNE and HK. We will also compare our results with the T2HK configuration. In Section IV, we draw our conclusions.

II. PRELIMINARIES

A. Nonstandard interactions

Let us start with the effective flavor-dependent neutral current neutrino non-standard interactions in propagation given by

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\epsilon_{\alpha\beta}^{fP} G_F (\bar{\nu}_\alpha \gamma_\mu \nu_\beta L) (\bar{f}_P \gamma^\mu f'_P),$$  \hspace{1cm} (1)

where $f_P$ and $f'_P$ stand for fermions with chirality $P$ and $\epsilon_{\alpha\beta}^{fP}$ is a dimensionless constant which is normalized by the Fermi coupling constant $G_F$. The presence of NSI in Eq. (1) modifies the MSW potential in the flavor basis from

$$\sqrt{2}G_FN_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$  \hspace{1cm} (2)

to

$$\mathcal{A} \equiv \sqrt{2}G_FN_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix},$$  \hspace{1cm} (3)

where $\epsilon_{\alpha\beta}$ is defined by

$$\epsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \frac{N_f}{N_e} \epsilon_{\alpha\beta}^f.$$  \hspace{1cm} (4)
$N_f (f = e, u, d)$ stands for number densities of fermions $f$. Here we defined the NSI parameters as $\epsilon_{\alpha\beta}^{fF} \equiv \epsilon_{\alpha\beta}^{ffF}$ and $\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{ffL} + \epsilon_{\alpha\beta}^{ffR}$. In the three flavor neutrino oscillation framework with NSI, the neutrino evolution is given by the Schrodinger equation:

$$i \frac{d}{dx} \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = [U \text{diag}(0, \Delta E_{21}, \Delta E_{31}) U^{-1} + A] \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix},$$

(5)

where $U$ is the leptonic mixing matrix defined by

$$U \equiv \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix},$$

(6)

and $\Delta E_{jk} \equiv \Delta m_{jk}^2/2E \equiv (m_j^2 - m_k^2)/2E$, $c_{jk} \equiv \cos \theta_{jk}$, $s_{jk} \equiv \sin \theta_{jk}$.

As far as the neutrino oscillation on the Earth is concerned, we have the following limits on $\epsilon_{\alpha\beta}$ from the compilation of various neutrino data at 90% C.L.;[55, 56]

$$\begin{pmatrix} |\epsilon_{ee}| < 4 \times 10^0 & |\epsilon_{e\mu}| < 3 \times 10^{-1} & |\epsilon_{e\tau}| < 3 \times 10^0 \\ |\epsilon_{\mu\mu}| < 7 \times 10^{-2} & |\epsilon_{\mu\tau}| < 3 \times 10^{-1} & |\epsilon_{\tau\tau}| < 2 \times 10^1 \end{pmatrix}.$$  

(7)

It was pointed out in Refs. [58, 59] that the high-energy atmospheric neutrino data, where the matter effects are dominant, are consistent with NSI only when the following equality is approximately satisfied:

$$\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1 + \epsilon_{ee}}.$$  

(8)

In this paper we assume the relation (8) exactly. It may seem that the condition (8) forces $|\epsilon_{e\tau}|$ to be smaller than it should be, near the region $|1 + \epsilon_{ee}| \ll 1$. However, Eq. (8) turns out to be a reasonable condition even in the region $|1 + \epsilon_{ee}| \ll 1$ because of the following arguments. The constraint from the high energy atmospheric neutrino data is that the smaller eigenvalue in the matter potential (3) with $\epsilon_{\alpha\mu} = 0$ should be smaller than 0.2$\sqrt{2}G_FN_e$ (See Eq. (13) in Ref. [31]). For $|1 + \epsilon_{ee}| \ll 1$, this implies $\sqrt{4|\epsilon_{e\tau}|^2 + \epsilon_{\tau\tau}^2} - \epsilon_{\tau\tau} < 0.4$. This condition in principle allows us to take a large value of $|\epsilon_{e\tau}|$. However, we have

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1 See Ref. [57] for the constraints on NSI at production and detection.
checked explicitly that such a large value of \(|\epsilon_{e\tau}|\) gives a very bad fit to the HK atmospheric neutrino data assuming the standard scenario, and therefore \(|\epsilon_{e\tau}| \ll 1\) should be satisfied near the region \(|1 + \epsilon_{ee}| \ll 1\).\(^2\) This result is consistent with the discussion in Ref. [47] based on an analytic formula on the disappearance probability. Namely, the high energy atmospheric neutrino data is perfectly consistent with its behavior \(1 - P(\nu_\mu \rightarrow \nu_\mu) \propto 1/E^2\) inferred from the standard oscillation scenario, while in the presence of NSI with \(\epsilon_{\mu\alpha} = 0\), it has the behavior \(1 - P(\nu_\mu \rightarrow \nu_\mu) \sim c_1/E + O(1/E^2)\) where \(c_1\) satisfies \(c_1 \propto \epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee})\) in the case of \(|\epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee})| \ll 1\) (See Eq.(9) in Ref. [47]). Therefore, the condition (8) is a good approximation also in the region \(|1 + \epsilon_{ee}| \ll 1\), and the ansatz (8) is justified.

If Eq. (8) is satisfied, then \(\epsilon_{\tau\tau}\) can be eliminated. Furthermore, we have

\[
\frac{|\epsilon_{e\tau}|}{1 + \epsilon_{ee}} \lesssim 0.8 \quad \text{at 3}\sigma\text{C.L.},\]

(9)

from the atmospheric neutrino data of Superkamiokande [17].

From the above two constraints (7) and (8), the following ansatz is a good approximation to analyze the sensitivity to NSI:

\[
\mathcal{A} = \sqrt{2}G_F N_e \begin{pmatrix}
1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\
0 & 0 & 0 \\
\epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee})
\end{pmatrix}.
\]

(10)

The allowed region in the \((\epsilon_{ee},|\epsilon_{e\tau}|)\) plane at 90\% C.L., is given by the following:

\[
-4 \lesssim \epsilon_{ee} \lesssim 4, \quad |\epsilon_{e\tau}| \lesssim 3, \quad \left|\frac{\epsilon_{e\tau}}{1 + \epsilon_{ee}}\right| \lesssim 0.6.
\]

(11)

B. The T2HKK experiment

The T2HKK experiment is a proposal for the future extension of the T2K experiment. In this proposal, a water Čerenkov detector is placed not only in Kamioka (at a baseline length \(L = 295\) km) but also in Korea (at \(L \simeq 1100\) km), whereas the power of the beam at J-PARC in Tokai Village is upgraded to 1.3 MW. As in the T2K experiment, it is assumed that T2HKK uses an off-axis beam at a 2.5° angle between the directions of the decaying

\(^2\) At present we have only the very weak bound on \(|\epsilon_{e\tau}|\). If we find \(|1 + \epsilon_{ee}| \ll 1\) experimentally in the future, however, then by combining \(|1 + \epsilon_{ee}| \ll 1\) and the high energy atmospheric neutrino data, we will obtain the very strong bound on \(|\epsilon_{e\tau}|\).
FIG. 1: The flux (dashed curves) at different off-axis angles and the appearance oscillation probabilities (solid curves) at Kamioka \((L=295\text{ km})\) and in Korea \((L=1100\text{ km})\) in the standard oscillation scenario in normal hierarchy. The left (right) panel is for neutrinos (antineutrinos). The baseline length \(L=1088\text{ km}\) at an angle 1.3° is slightly different from \(L=1100\text{ km}\), but the difference between the oscillation probabilities at \(L=1088\text{ km}\) and at \(L=1100\text{ km}\) is invisibly small.

charged pions and neutrinos, and the neutrino energy spectrum has a peak approximately at 0.6 GeV. This off-axis beam at an angle 2.5° reaches Korea and the corresponding off-axis angle on the surface in Korea ranges from 1.3° to 2.5° with the baseline 1088 km (for 1.3°) to 1100 km (for 1.5°, 2.0° and 2.5°), depending on the location of the detector in Korea \(^3\). The flux and the appearance oscillation probabilities for neutrinos and antineutrinos at various off-axis angles in normal hierarchy are shown in Fig. 1. The label in the \(y\) axis corresponds to the value of \(P_{\mu e}\) whereas the the unit of the fluxes are arbitrary. As we can see from Fig. 1, the first oscillation maximum occurs at \(E \simeq 1.8\) (2.6) GeV, whereas the second one appears at \(E \simeq 0.7\) (0.8) GeV for neutrinos (antineutrinos). From Fig. 1 we observe the following:

- Among the different off-axis fluxes, the flux corresponding to the lowest off-axis angle (i.e., OA 1.3) peaks at 0.8 GeV and the flux at the highest off-axis angle (i.e., OA 2.5) peaks at 0.6 GeV.

\(^3\) The other flux options which are also under consideration are: 1.8°, 1.9° and 2.2° \([53]\) which are not considered in this work.
• The relative heights of the peak of the fluxes is maximum for OA 2.5 and minimum for OA 1.3.

• The off-axis fluxes corresponding 2.5° and 2.0° can mainly probe the physics at the second oscillation maxima for $L = 1100$ km while the off-axis fluxes corresponding to 1.3° and 1.5° can also cover a part of the first oscillation maxima for the Korean baseline.

III. SENSITIVITY OF T2HKK TO $\epsilon_{ee}$ AND $|\epsilon_{e\tau}|$

In this section we discuss the sensitivity of the T2HKK experiment to the non-standard interaction in propagation with the ansatz (10). For comparison, we also study sensitivity of the DUNE [3] and the atmospheric neutrino experiment at HK [54]. Since $\epsilon_{e\tau}$ is expressed in terms of $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$, the only new degrees of freedom are $\epsilon_{ee}$, $|\epsilon_{e\tau}|$ and arg($\epsilon_{e\tau}$). First of all, in sect. III.A, assuming that the Nature is described by the standard three-flavor scheme, we discuss the bounds on $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$. In our analysis we assume that the true numbers of events are those of the standard three-flavor scenario, and the test numbers of events are those with NSI. We discuss the region of the ($\epsilon_{ee}$, $|\epsilon_{e\tau}|$) plane in which T2HKK can exclude the hypothesis with NSI. Secondly, in sect. III.B, assuming that NSI exists, we consider whether the two complex phases $\delta_{CP}$ and arg($\epsilon_{e\tau}$) can be determined separately.

The neutrino flux of the T2HKK experiment in Korea is taken from Ref. [60]. To calculate the event rates for the T2HKK setup we proceed in the following way. First we have matched the number of events corresponding to the T2HK setup as given in Ref. [2] taking the 2.5° off-axis flux. The detector volume in this case is 560 kt. Then we scale these number of events for the Korean baseline corresponding to different off-axis configurations. For T2HKK project we have taken 280 kt detector both at Kamioka and Korea. Note that as we have taken the backgrounds corresponding to the T2HK setup and scale them down for the Korean baseline, the neutral current $\pi^0$ backgrounds at the high energies are ignored and thus our results of T2HKK may be optimistic. For T2HKK setup we have taken a total integrated beam-power of $15.6 \times 10^{21}$ pot (protons on target) with $10^{21}$ pot/year. Thus it corresponds to 15.6 years running of the beam. For T2HKK we have taken an overall systematic error of 3.3% for both appearance and disappearance channel in neutrino mode and 6.2% (4.5%) for appearance (disappearance) channel in antineutrino mode. The
TABLE I: The numbers of appearance events for neutrino and antineutrinos expected at the second detector in Korea. $\theta_{23} = \pi/4$, $\delta = -\pi/2$ with normal hierarchy is assumed.

| Off-axis degree | 1.3° | 1.5° | 2.0° | 2.5° |
|-----------------|------|------|------|------|
| Neutrinos       | 515  | 438  | 368  | 309  |
| Antineutrinos   | 39   | 34   | 25   | 17   |

systematic error is the same for both the signal and the background\(^4\). For DUNE we have taken a flux of beam-power 1.2 MW with $10^{21}$ pot/year and 34 kt liquid argon detector. In our analysis we have considered a 10 years running of DUNE unless otherwise mentioned. The number of events are taken from Ref. [3]. The systematic error for DUNE is 2% (10%) for appearance channel and 5% (15%) for disappearance channel corresponding to the signal (the background). The systematic errors in neutrino and antineutrino mode are the same for DUNE. The simulations of T2HKK and DUNE have been performed with the softwares GLoBES [61, 62] and MonteCUBES [63].

Assuming the operation with $\nu:\bar{\nu} = 1:1$, as well as the oscillation parameters $\theta_{23} = \pi/4$, $\delta_{CP} = -\pi/2$ with normal hierarchy, the expected numbers of appearance events in Korea, are shown in Table I, while those at Kamioka are 3219 neutrinos and 420 antineutrinos. The expected numbers of appearance events at DUNE are 1897 neutrinos and 229 antineutrinos. Thus we understand that among all the off-axis configurations, the number of events are maximum for 1.3°. This is because the 1.3° off-axis configuration covers the major portion of the first oscillation maxima where the appearance channel probability has a significant contribution (c.f Fig. 1). From the above discussion it is also clear that the number of events at the Kamioka detector is almost 1.8 times that of the number of events for DUNE.

Simulation of the atmospheric neutrino at HK is done with the codes which were used in Refs. [17, 64–66] and is described in detail in Ref. [17]. We assume here the data size from the HK atmospheric neutrino experiment for 15 years with 560 kt fiducial volume.

\(^4\) Note that in our work we followed the configuration of T2HK as given in [2]. According to the T2HKK report [53] (which appeared on the same day as our paper appeared in arXiv), the total detector volume is around 380 kt which will be split into 190 kt for each Kamioka and Korea. The total exposure in this report is $2.7 \times 10^{22}$ pot with 10 years of running.
A. Bounds on $e_{ee}$ and $|e_{e\tau}|$

Firstly, let us discuss the case of the region $(e_{ee}, |e_{e\tau}|)$, in which we can test the difference between NSI with ansatz (10) and the standard three-flavor scheme. Here, we take the best-fit values for most of the standard oscillation parameters as the reference values:\(^5\)

\[
\begin{align*}
\sin^2(2\bar{\theta}_{12}) &= 0.87 \\
\sin^2(2\bar{\theta}_{23}) &= 1.0 \\
\sin^2(2\bar{\theta}_{13}) &= 0.085 \\
\Delta \bar{m}_{21}^2 &= 7.9 \times 10^{-5} \text{eV}^2 \\
\Delta \bar{m}_{32}^2 &= 2.4 \times 10^{-3} \text{eV}^2 \\
\delta_{\text{CP}} &= -90^\circ
\end{align*}
\]

\(\text{(12)}\)

For the parameters $\theta_{12}$, $\theta_{13}$, $\Delta m_{21}^2$ and $\Delta m_{32}^2$, our choice of true parameters are consistent with the best-fit values as obtained by the global analysis of the world neutrino data [67–69]. The status of $\theta_{23}$ at this moment is quite intriguing. The latest T2K data favours maximal mixing [70] whereas the NO$\nu$A data disfavours maximal mixing at $2.5\sigma$ [71]. Thus one needs more data from both the experiments to resolve this issue. For our work we have taken $\theta_{23}$ to be maximal in the true spectrum and marginalized from $40^\circ$ to $50^\circ$ in the test spectrum. Regarding $\delta_{\text{CP}}$ both the experiments obtain a best-fit value of $-90^\circ$ which we also take as true value in our analysis. We have marginalized $\delta_{\text{CP}}$ in the test spectrum from $-180^\circ$ to $180^\circ$. For the NSI parameters we have taken $\bar{e}_{ee} = |\bar{e}_{e\tau}| = \arg(\bar{e}_{e\tau}) = 0$. In the test spectrum we have marginalized over $\arg(e_{e\tau})$ from $-180^\circ$ to $180^\circ$. The results are shown in Fig. 2, where the curves are drawn at $3\sigma$ ($\Delta \chi^2 = 11.83$ for 2 degrees of freedom). NSI with the ansatz (10) can be distinguished from the standard three-flavor scheme outside the curves. For comparison, we have also showed the excluded regions by the long-baseline experiment DUNE, the atmospheric neutrino experiment HK and T2HK with the detector of volume 560 kt at Kamioka only. From Fig. 2, we observe that the case at off-axis angle 1.3$^\circ$ has the highest sensitivity to $(e_{ee}, |e_{e\tau}|)$. This is because (i) the number of events is the largest at off-axis angle 1.3$^\circ$, as we can see from Table I and (ii) due to the relatively

\(^5\) The oscillation parameters with bars (without bars) stands for the true (test) value throughout this paper.
TABLE II: The bounds on $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ at 90% C.L., (3$\sigma$) by each experiment in the case of normal hierarchy.

| Experiment | $\epsilon_{ee}$ 90% C.L. (3$\sigma$) | $|\epsilon_{e\tau}|$ 90% C.L. (3$\sigma$) |
|------------|----------------------------------|-----------------------------------|
| T2HK       | -4 to +4 (-4 to +4)              | < 0.9 (< 1.1)                     |
| T2HKK(OA1.3$^\circ$) | -0.2 to 0.2 (-1.4 to 1.1)     | < 0.02 (< 0.24)                   |
| T2HKK(OA1.5$^\circ$) | -0.2 to 0.2 (-1.4 to 1.1)     | < 0.02 (< 0.24)                   |
| T2HKK(OA2.0$^\circ$) | -1.2 to 0.6 (-3.5 to 1.4)    | < 0.03 (< 0.44 )                  |
| T2HKK(OA2.5$^\circ$) | -1.4 to 1.0 (-3.5 to 1.8)    | < 0.2 (< 0.5)                     |
| DUNE       | -0.1 to 0.4 (-1.2 to 1.4)       | < 0.04 (< 0.23)                   |
| atm(HK)    | -0.05 to 0.1 (-0.1 to 0.2)      | < 0.035 (< 0.1)                   |

broad band nature of the flux, the 1.3$^\circ$ off axis configuration covers the wider energy range in the probability spectrum among the other off-axis configurations. The sensitivity at the 1.5$^\circ$ off-axis is similar as that of 1.3$^\circ$ while the sensitivities at 2.0$^\circ$ and 2.5$^\circ$ are worse than sensitivities at 1.3$^\circ$ and 1.5$^\circ$. If we compare the sensitivity of the T2HKK with T2HK, then we find that T2HKK is far more powerful than T2HK in terms of constraining the value of the NSI parameters. These results are true for both normal and inverted hierarchies. The sensitivity of DUNE to NSI is comparable to T2HKK at 1.3$^\circ$ for normal hierarchy and better in inverted hierarchy. The sensitivity of HK atmospheric neutrino experiment is the highest for both the hierarchies. In Table II we have given the 90% C.L., as well as 3$\sigma$ bounds on $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ for the different experimental setups which are considered in our analysis. From the table we see that the sensitivity of the 1.3$^\circ$ configuration in constraining ($\epsilon_{ee}$, $|\epsilon_{e\tau}|$) is one order of magnitude higher than the configuration of 2.5$^\circ$.

In Fig. 3, $\chi^2$ to exclude a particular choice $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ is plotted as a function of the running time. Here for comparison we have extended the DUNE runtime to 15 years. From the figures we see that the sensitivity in normal hierarchy is better than inverted hierarchy. This is because in inverted hierarchy the MSW effect enhances the antineutrino probabilities and the cross section of the antineutrinos are almost one third of the neutrinos. Thus the number of events in the IH are less as compared to the normal hierarchy. Similar as that of Fig. 2, the sensitivity of 1.5$^\circ$ is comparable with 1.3$^\circ$ and the sensitivities at 2.0$^\circ$ and 2.5$^\circ$ are poor. The significance to exclude NSI is the best for the HK atmospheric
FIG. 2: The excluded region in the \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) plane. The hypothesis with NSI is excluded at 3\(\sigma\) outside each curve. The thin solid diagonal straight line stands for the bound \(|\tan \beta| \equiv |\epsilon_{e\tau}/(1 + \epsilon_{ee})| \lesssim 0.8\) at 3\(\sigma\) from the current atmospheric data by Superkamiokande. Upper left pane: Normal mass hierarchy. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector of volume 560 kt at Kamioka only.

FIG. 3: \(\chi^2\) to exclude \((\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)\) as a function of the running time. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector at Kamioka only.

neutrino experiment and it is followed by DUNE. Notice that the sensitivity of T2HK with the detector at Kamioka only has poor sensitivity, and therefore the second detector in Korea greatly improves its sensitivity at all the off-axis angles. From the figure we notice that T2HKK at off-axis angle 1.3\(^\circ\) can exclude the case with \((\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)\) at 2\(\sigma\) within its proposed run-time for both the hierarchies. Whereas DUNE and HK can exclude the same by more than 3\(\sigma\) in for NH. For IH the sensitivity of DUNE is similar that of the 1.3\(^\circ\) configuration of T2HKK and the sensitivity of HK is around 2.5\(\sigma\) in 15 years of running. The sensitivity of the T2HK experiment is less than 1\(\sigma\) for both the hierarchies.
FIG. 4: The correlation between $\delta_{\text{CP}}$ and $\phi_{31} \equiv \text{arg}(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel). The true value is $(\bar{\delta}_{\text{CP}}, \bar{\phi}_{31}) = (\pi/2, 0)$.

**B. CP violating phases**

Next let us consider the implication to the T2HKK experiment in the case with an affirmative result of NSI. As a reference value for NSI we take $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$, which lies outside each exclusion curve in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane at 90% C.L.\(^6\)

The ansatz (10) contains the two phases $\delta_{\text{CP}}$ and $\text{arg}(\epsilon_{e\tau})$. In the presence of NSI, it is important how precisely we can determine these two phases. So we study the correlation between $\delta_{\text{CP}}$ and $\text{arg}(\epsilon_{e\tau})$ around a certain set of the two phases. Here we assume that the true oscillation parameters are

\begin{align*}
\bar{\epsilon}_{ee} &= 0.8, \\
|\bar{\epsilon}_{e\tau}| &= 0.2, \\
\bar{\phi}_{31} &\equiv \text{arg}(\bar{\epsilon}_{e\tau}) = 0, \\
\bar{\delta}_{\text{CP}} &= -\frac{\pi}{2}.
\end{align*}

The allowed regions at 90% C.L., around the true value $(\bar{\delta}_{\text{CP}}, \text{arg}(\bar{\epsilon}_{e\tau}))$ are shown in Fig. 4 for $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$. In these plots we have marginalized over $\epsilon_{ee}$ from $-4$ to $+4$ and $|\epsilon_{e\tau}|$ from 0 to 2. To clarify the roles of the two detectors, in the case of the off-axis angle $1.3^\circ$, \(^6\) Notice that Fig. 2 is depicted for $3\sigma$ and the allowed region at 90% C.L., is smaller than that at $3\sigma$.\(^6\)
FIG. 5: The correlation between $\delta_{CP}$ and $\phi_{31} \equiv \arg(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel) at the off-axis angle $1.3^\circ$. The true value are $\bar{\phi}_{31} = 0$ and $\bar{\delta}_{CP} = -\pi/2$. The dotted curves, which are given for the detector at Kamioka without marginalizing over $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$, are also shown to show the contribution of these two parameters.

Separate contours are given in Fig. 5 for the result from the detector in Kamioka (purple curve), for that from the detector in Korea (blue curve), and for that from the combination of the two (green curve). As we can see from Fig. 4, T2HKK at the off-axis angles $1.3^\circ$ and $1.5^\circ$ has good sensitivity also in the sensitivity to the CP phases. In the case of off-axis angle $1.3^\circ$, the sensitivity of T2HKK is better than that of DUNE. This can be explained as follows. The detector at Kamioka, which has a shorter baseline length, has poor sensitivity to the matter effect and therefore to $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$. This is why the allowed region of the Kamioka detector is large in Fig. 5 (purple contour) since the uncertainty in $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ increases the uncertainty in the CP phases. However, from the result of the detector in Korea, we have stronger constraint on $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$. If we use this information, then the detector at Kamioka gives better sensitivity to $\delta_{CP}$ because of its high statistics. To confirm this, in Fig. 5, we also draw the contours for the Kamioka detector assuming $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ is known (the red dotted contours where we do not marginalize over $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$) and we see that the allowed region shrinks profoundly. So sensitivity of the combined T2HKK detector complex to the CP phases is better than that of DUNE. This synergy of the detectors at Kamioka and in Korea in the determination of the CP phases is the striking advantage of the T2HKK experiment. On the other hand, the HK atmospheric neutrino experiment has...
disjoint allowed regions particularly in the inverted mass hierarchy. If one assumes that
HK could separate neutrinos and antineutrinos, then we have confirmed that these disjoint
regions disappear. Thus as far as sensitivity to the CP phases is concerned, its performance
is not as good the T2HKK experiment in inverted hierarchy. But for normal hierarchy the
sensitivity of HK in constraining the CP phases is best among all the other setups because
of the huge earth matter effects.

IV. CONCLUSION

We have studied the sensitivity of the T2HKK experiment to the non-standard interaction
in propagation with the ansatz (10). With the ansatz (10), we obtained the region in the \((\epsilon_{ee},
|\epsilon_{e\tau}|)\) plane in which T2HKK can distinguish NSI from the standard three-flavor scenario.
As far as the sensitivity to NSI is concerned, T2HKK at the off-axis angle 1.3° is the best
option, and with this option T2HKK can discriminate NSI at 3σ from the standard case
for approximately \(|\epsilon_{ee}| \gtrsim 1\) and \(|\epsilon_{e\tau}| \gtrsim 0.2\). The sensitivity of DUNE is comparable as that
of T2HKK with 1.3° off-axis flux configuration in normal hierarchy but it is better in the
inverted hierarchy. We find that the sensitivity of the HK atmospheric experiment is the
highest among the other setups considered in this work.

On the other hand, if the value of \(|\epsilon_{e\tau}|\) is relatively large \(|\epsilon_{e\tau}| \gtrsim 0.2\), then we can determine
the two phases \(\delta_{CP}, \arg(\epsilon_{e\tau})\) separately by T2HKK or DUNE. As far as the sensitivity to
the CP phases is concerned, T2HKK is the better than DUNE. The powerful feature of
determination of the two CP phases is the remarkable advantage of the T2HKK experiment.
The atmospheric neutrino experiment at HK is inferior to the two long-baseline experiments
in inverted hierarchy but superior in normal hierarchy.

Since the matter effect \(A\) and the baseline length \(L\) appears in the form of \(AL/2 \sim L/4000\)
km in the oscillation probability, long-baseline neutrino experiments with longer baseline
lengths \((L \gtrsim 1000\ km)\) are sensitive to the matter effect. Hence they are also sensitive to
NSI. The nice feature of the T2HKK experiment is that while the detector at Kamioka with
a shorter baseline length is advantageous to measure \(\delta_{CP}\) because of its high statistics, the
one in Korea with a longer baseline length has better sensitivity to the matter effect as well
as \(\epsilon_{ee}\) and \(|\epsilon_{e\tau}|\). We have seen that the sensitivity to \(\epsilon_{ee}\) and \(|\epsilon_{e\tau}|\) is the best at the off-axis
angle 1.3°. Thus we conclude that T2HKK at the off-axis angle 1.3° is expected to be the
best option to make the synergy of the two detectors effective determine the NSI parameters $\epsilon_{ee}$ and $|\epsilon_{e\tau}|$ as well as the CP phases $\delta_{\text{CP}}$ and $\arg(\epsilon_{e\tau})$.

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