Sensitivity of T2KK to non-standard interactions

Osamu Yasuda

Department of Physics, Tokyo Metropolitan University, Minami-Osawa, Hachioji, Tokyo 192-0397, Japan

Assuming only the non-zero electron and tau neutrino components $\epsilon_{ee}, \epsilon_{e\tau}, \epsilon_{\tau\tau}$ of the non-standard matter effect and postulating the atmospheric neutrino constraint $\epsilon_{e\tau} = |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee})$, the sensitivity to the non-standard interaction in neutrino propagation of the T2KK neutrino long-baseline experiment is estimated. It is found that T2KK can constrain the parameters $|\epsilon_{ee}| \lesssim 1$, $|\epsilon_{e\tau}| \lesssim 0.2$.

It is expected that the undetermined oscillation parameters such as $\theta_{13}$ and $\delta$ are expected to be measured in future neutrino long-baseline experiments (see, e.g., Ref. [2]). As in the case of B factories, such highly precise measurements will enable us to search for deviation from the standard three-flavor oscillations. One such possibility is the effective non-standard neutral current-matter interaction (NSI) with matter

$$L_{\text{eff}} = -2\sqrt{2} e f_{\alpha\beta} f'_{\mu\beta} \bar{\nu}_\alpha P_L \nu_\beta (\bar{f} \gamma^\mu f') ,$$

where $f$ and $f'$ stand for fermions (the only relevant ones are electrons, u, and d quarks), $G_F$ is the Fermi coupling constant, and $P$ stands for a projection operator that is either $P_L \equiv (1 - \gamma_5)/2$ or $P_R \equiv (1 + \gamma_5)/2$. In the presence of the interaction Eq. (1), the standard matter effect is modified. Using the notation $\epsilon_{\alpha\beta} \equiv \sum_P (\epsilon_{\alpha\beta} P + 3\epsilon_{u\alpha\beta} P + 3\epsilon_{d\alpha\beta} P)$, the hermitian $3 \times 3$ matrix of the matter potential becomes

$$A \equiv A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & 1 + \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & 1 + \epsilon_{\tau\tau} \end{pmatrix} ,$$

where $A \equiv \sqrt{2} G_F N_c$.

Constraints on $\epsilon_{\alpha\beta}$ from various neutrino experiments have been discussed by many people (see, e.g., Ref. [2] and references therein). Since $\epsilon_{\alpha\beta}$ in Eq. (2) are given by $\epsilon_{\alpha\beta} \sim \sum_P (\epsilon_{\alpha\beta} + 3\epsilon_{u\alpha\beta} + 3\epsilon_{d\alpha\beta})$ in the case of experiments on the Earth, we have the following constraints [2] at 90% CL:

$$|\epsilon_{ee}| < 4 \times 10^0, \quad |\epsilon_{e\mu}| < 3 \times 10^{-1}, \quad |\epsilon_{e\tau}| < 3 \times 10^0, \quad |\epsilon_{\mu\mu}| < 7 \times 10^{-2}, \quad |\epsilon_{\mu\tau}| < 3 \times 10^{-1}, \quad |\epsilon_{\tau\tau}| < 2 \times 10^1 .$$

On the other hand, it was shown in Ref. [3] that

$$|\epsilon_{e\tau}|^2 \sim \epsilon_{\tau\tau} (1 + \epsilon_{ee})$$

should be satisfied to be consistent with the high-energy atmospheric neutrino data. In the standard three-flavor scheme, the high-energy behavior of the disappearance oscillation probability is

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq \left( \frac{\Delta m_{31}^2}{2AE} \right)^2 \sin^2 2\theta_{23} \left( c_{13}^2 A_L \frac{2}{2} \right)^2$$

$$+ s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left( A_L \frac{2}{2} \right) .$$

In fact it was pointed out [4] that the generic matter potential [2] leads to the high-energy behavior of the disappearance oscillation probability

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq c_0 + c_1 \frac{1}{E} + O \left( \frac{1}{E^2} \right) ,$$

where $c_0$ and $c_1$ are functions of $\epsilon_{\alpha\beta}$, and that $|c_0| \ll 1$ and $|c_1| \ll 1$ implies $|\epsilon_{e\mu}|^2 + |\epsilon_{\mu\mu}|^2 + |\epsilon_{\mu\tau}|^2 \ll 1$ and $|\epsilon_{e\tau}|^2 - \epsilon_{\tau\tau} (1 + \epsilon_{ee}) | \ll 1$, respectively. Note that the terms of $O(E^0)$ and $O(E^{-1})$ are absent in Eq. (5) which is in perfect agreement with the experimental data [6]. So, taking into account the various constraints described

1 So far full three flavor analysis of the atmospheric neutrino data with the ansatz [2] has not been performed. In Refs. [7,8], the two-flavor analysis of the atmospheric
above, we will work with the ansatz
\[ A = A \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee}) \end{pmatrix} \]  
(7)
in the following discussions. The 90% CL allowed region for the parameters \( \epsilon_{ee} \) and \( |\epsilon_{e\tau}| \) is depicted in Fig. 1. The region \(|\tan\beta| \equiv |\epsilon_{e\tau}/(1 + \epsilon_{ee})| \geq 1\) is excluded in Fig. 1 because of the atmospheric neutrino data [7].

![Figure 1](image)

Figure 1. The 90% CL region which is constrained by the current experimental data in the \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) plane.

The T2KK experiment is a proposal for the future extension of the T2K experiment (see, e.g., references in Ref. [4]). In this proposal, a water Cherenkov detector is placed both in Kamioka (at a baseline length \( L = 295 \) km) and in Korea (at \( L = 1050 \) km), whereas the power of the beam at J-PARC in Tokai Village is upgraded to 4 MW. To examine whether T2KK can tell the existence of NSI, we introduce the following quantity:

\[ \Delta \chi^2 = \min_{\text{param}} \left[ \sum_i \frac{\{N_i(\text{NSI}) - N_i(\text{std})\}^2}{\sigma_i^2} + \Delta \chi^2_{\text{prior}} \right], \]  
(8)

where the prior \( \Delta \chi^2_{\text{prior}} \) is given by

\[ \Delta \chi^2_{\text{prior}} = \frac{(\sin^2 2\theta_{23} - \sin^2 2\theta_{23}^{\text{best}})^2}{(\delta \sin^2 2\theta_{23})^2} + \frac{(\sin^2 2\theta_{13} - \sin^2 2\theta_{13}^{\text{best}})^2}{(\delta \sin^2 2\theta_{13})^2} + \frac{|\Delta m^2_{31}| - |\Delta m^2_{31}^{\text{best}}|^2}{(\delta |\Delta m^2_{31}|)^2}. \]

In Eq. (8) difference of the numbers of events, \( N_i(\text{NSI}) \) and \( N_i(\text{std}) \) with or without NSI, is compared with the error \( \sigma_i \) for each bin \( i \), while \( \Delta \chi^2 \) is minimized with respect to the oscillation parameters. If \( \Delta \chi^2 \) is larger than, e.g., 4.6 for 2 degrees of freedom, then significance for the existence of NSI at T2KK is more than 90% CL. In Fig 2 the contour of the excluded region in the \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) plane at 90% CL is plotted for various values of \( \sin^2 2\theta_{13}, \delta \) and \( \arg(\epsilon_{e\tau}) \). If the true point \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) is inside each contour, then T2KK cannot prove the existence of NSI.

![Figure 2](image)

Figure 2. The region which is expected to be constrained by T2KK at 90% CL in the \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) plane for various values of \( \sin^2 2\theta_{13} \), \( \delta \), and \( \arg(\epsilon_{e\tau}) \). If the true point \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) is inside each contour, then T2KK cannot prove the existence of NSI.

We found from detailed numerical calculations [4] that \(|\epsilon_{ee}| \leq 1, |\epsilon_{e\tau}| \leq 0.2\) will be obtained by the negative results of the T2KK experiment. Thus, the allowed region in the \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) plane will be updated from Fig 1 to Fig 2 after the T2KK experiment is completed with negative results.
On the other hand, if true point \((\epsilon_{ee}, |\epsilon_{e\tau}|)\) is outside each contour in Fig. 2, then T2K should be able to obtain some information on the parameters \(\epsilon_{ee}, |\epsilon_{e\tau}|\). In this case, it becomes important whether we can also determine the two phases \(\delta\) and \(\arg(\epsilon_{e\tau})\). The results at 90\% CL are shown in Fig. 4 for \((\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2), (2.0, 2.0)\). As in the standard three-flavor case, if \(\theta_{13}\) is very small, it is difficult to get any information on \(\delta\). For larger values of \(\theta_{13}\), the sensitivity to \(\arg(\epsilon_{e\tau})\) depends on the value of \(|\epsilon_{e\tau}|\). For larger (smaller) values of \(|\epsilon_{e\tau}|\), sensitivity to \(\arg(\epsilon_{e\tau})\) is good (poor). Qualitative understanding of these features using the analytic form of the oscillation probability \(P(\nu_{\mu} \rightarrow \nu_{e})\) is given in Ref. [4].

In conclusion, we have studied the sensitivity of the T2KK experiment to the non-standard interaction in propagation. If T2KK gets negative results, then we have constraints \(|\epsilon_{ee}| \lesssim 1\) and \(|\epsilon_{e\tau}| \lesssim 0.2\). If T2KK obtains affirmative results, then T2KK can determine the values of \(\epsilon_{ee}, |\epsilon_{e\tau}|,\) and \(\arg(\epsilon_{e\tau})\). In particular, if the values of \(\theta_{13}\) and \(|\epsilon_{e\tau}|\) are relatively large \((\sin^2 2\theta_{13} \gtrsim O(0.01), |\epsilon_{e\tau}| \gtrsim 0.2)\), then we can determine the two phases \(\delta, \arg(\epsilon_{e\tau})\) separately.

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REFERENCES
1. A. Bandyopadhyay et al. [ISS Physics Working Group], Rept. Prog. Phys. 72, 106201 (2009).
2. C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP 0908, 090 (2009).
3. A. Friedland, C. Lunardini and M. Maltoni, Phys. Rev. D 70, 111301 (2004).
4. H. Oki and O. Yasuda, Phys. Rev. D 82 (2010) 073009.
5. A. Friedland and C. Lunardini, Phys. Rev. D 74 (2006) 033012.
6. N. Fornengo, M. Maltoni, R. Tomas and J. W. F. Valle, Phys. Rev. D 65, 013010 (2002).
7. M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rev. D 70, 033010 (2004).
8. G. Mitsuka [Super-Kamiokande Collaboration], PoS NUFAC08, 059 (2008).
9. G. Mitsuka [Super-Kamiokande Collaboration], in these proceedings.