Will MINOS see new physics?

Noriaki Kitazawa,† Hiroaki Sugiyama,‡ and Osamu Yasuda

1Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan
2Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan

The effect of non-standard neutrino interactions with matter at long baseline neutrino experiments is examined in a model independent way, taking into account the constraints from all the experiments. It is found that such a non-standard interaction can enhance the flavor transition probability so significantly that the ongoing experiment MINOS may see the signal of $\nu_\mu \rightarrow \nu_e$ which is much more than the prediction by the standard scenario. It is also found that the silver channel $\nu_\mu \rightarrow \nu_\tau$ at a neutrino factory could have a huge enhancement.

It has been shown from the measurements of the atmospheric, solar, reactor, and accelerator neutrinos, that neutrinos have masses and mixings \[1\]. Furthermore it is expected that precise measurements of the neutrino oscillation parameters will be performed at future long baseline neutrino oscillation experiments with intense neutrino beams, such as T2K \[2\], a next generation experiment which is now under construction, and a neutrino factory \[3\], a beta-beam experiment \[4\], etc. Just like the goal of the B physics \[1\] has shifted from measuring the mixing angle and such as $T_2K \[2\]$, a next generation experiment which is now under construction, and a neutrino factory \[3\], a beta-beam experiment \[4\], etc. Just like the goal of the B physics \[1\] has shifted from measuring the mixing angle and such as $\tau$.

In the past a class of non-standard neutrino interactions with matter were considered to explain the flavor transitions of the solar \[2\] or atmospheric neutrinos \[3\] without the standard oscillations due to masses. While the scenarios without the standard oscillations have been disfavored, the non-standard interactions themselves can still exist as perturbation to the standard oscillations. This class of the non-standard interactions offers us an interesting possibility which can be tested at the future long baseline experiments because existence of such interactions would give us some clue about the new physics beyond the standard model.

In this Letter, we investigate the effect of the non-standard interaction with matter upon the oscillation probabilities in long baseline experiments by taking into account the constraints in \[2\], \[2\], which showed that some terms of the non-standard interactions can have size of $O(1)$ relative to the standard interaction with matter.

Here we consider the following four-fermi interactions:

$$L_{\text{eff}}^\text{NSI} = -2\sqrt{2}\epsilon_{\alpha\beta}^{fP}G_F(\gamma\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{f}\gamma^\mu P f),$$

where only the interactions with $f = e, u, d$ are relevant to the flavor transition of neutrino due to the matter effect. $G_F$ denotes the Fermi coupling constant, $P$ stands for a projection operator and is either $P_L \equiv (1 - \gamma_5)/2$ or $P_R \equiv (1 + \gamma_5)/2$. \[1\] is the most general form of the interactions which conserve electric charge, color, and lepton number \[3\]. \[1\] is supposed to arise from certain new physics, but we do not specify any particular dynamics which produces \[1\], so our approach is model-independent in this sense \[1\]. There can be also interactions that predict flavor transitions at production or detection of neutrinos \[1\] but here we will discuss only the effect in propagation of neutrinos for simplicity. Many people \[1\], \[1\] have discussed the effects of the non-standard interactions in propagation of neutrinos at future long baseline oscillation experiments, but the present work is the first to consider potentially large effects of the new physics terms, which are comparable in magnitude to the standard matter term, at the long baseline experiments.

These operators introduce a new potential for the neutrino propagation in the matter, and the evolution equation
in the flavor basis \((\alpha, \beta = e, \mu, \tau)\) is given by \(^2\)

\[
\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2}{2E} \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix},
\]

where \(\Delta m^2_{jk} \equiv m_j^2 - m_k^2\) is the mass squared difference, \(E\) is the neutrino energy, \(A \equiv \sqrt{2}G_F n_e \simeq 1.0 \times 10^{-13}\text{eV} (\rho/2.7g \cdot \text{cm}^{-3})\) stands for the magnitude of the standard matter effect, \(n_e\) is the number density of the electron in the matter, \(\rho\) stands for the matter density, and \(U\) is the Maki-Nakagawa-Sakata matrix in the standard parametrization \(^1\). \(\epsilon_{\alpha\beta}\) are defined as

\[
\epsilon_{\alpha\beta} \equiv \sum_{f,P} n_f \frac{m^P}{G_F} \epsilon_{\alpha\beta}^P \simeq \sum_{P} \left( \epsilon_{\alpha\beta}^{eP} + 3 \epsilon_{\alpha\beta}^{uP} + 3 \epsilon_{\alpha\beta}^{dP} \right),
\]

where \(n_f\) is the number density of \(f\) in matter, and we have taken into account the fact that the number density of \(u\) quarks and \(d\) quarks are three times as that of electrons. The striking feature of \(^2\) is that the flavor transition is possible even at high energy because the last term in \(^2\) is not diagonal, while the transition vanishes at high energy in the standard case.

\(\epsilon_{\alpha\beta}^{fP}\) is a dimensionless parameter normalized by \(G_F\), and theoretically it is expected that \(\epsilon_{\alpha\beta}^{fP}\) is suppressed by a factor \((W\text{ boson mass})^2/(\text{new physics scale})^2\). Experimentally, however, it is known \(^2\) that some of \(\epsilon_{\alpha\beta}^{fP}\) have a very weak bound. The result in \(^5\) is given by

\[
\begin{pmatrix}
-4 < \epsilon_{ee} < 2.6 \\
|\epsilon_{e\mu}| < 3.8 \times 10^{-4} \\
-0.05 < \epsilon_{\mu\mu} < 0.08 \\
|\epsilon_{e\tau}| < 1.9 \\
|\epsilon_{\mu\tau}| < 0.25 \\
|\epsilon_{\tau\tau}| < 18.6
\end{pmatrix}
\]

Furthermore, it was shown \(^3\) that the measurements of the atmospheric and accelerator neutrinos give non-trivial constraints on \(\epsilon_{ee}, \epsilon_{e\tau}\) and \(\epsilon_{\tau\tau}\). It was found in \(^3\) that a strong constraint applies to the channel \(\nu_\mu \to \nu_\mu\) in the high energy atmospheric neutrino data while there is some freedom left in the channel \(\nu_e \leftrightarrow \nu_\tau\) because neither electron nor tau events are observed at high energy. From Fig.6 of \(^3\), we can read off the following two approximate constraints:

\[
|\epsilon_{e\tau}| \lessgtr |1 + \epsilon_{ee}|, \tag{4}
\]

\[
\epsilon_{e\tau} \simeq \epsilon_{\tau\tau} (1 + \epsilon_{ee}). \tag{5}
\]

\(^5\) is the condition for which the survival probability \(P(\nu_\mu \to \nu_\mu)\) of the high energy atmospheric neutrinos in the presence of the new physics is reduced to that in the standard case.

Thus, combining \(^3\), \(^4\) and \(^5\), the region for \(\epsilon_{\alpha\beta}\) that we will use in the following analysis can be summarized as

\[
\begin{pmatrix}
-4 < \epsilon_{ee} < 2.6 \\
\epsilon_{e\mu} = 0 \\
|\epsilon_{e\tau}| < 1.9 \\
\epsilon_{\mu\mu} = 0 \\
\epsilon_{\mu\tau} = 0 \\
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\end{pmatrix}
\]

\(^6\)

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\end{pmatrix}
\]

\(^6\)

\[
\begin{pmatrix}
\Delta m^2_{21}L \\ \left(\frac{\Delta m^2_{31}}{4E}\right)^2
\end{pmatrix} = \left(\frac{\Delta m^2 L}{4E} \cos 2\theta - \frac{AL}{2} (1 + \epsilon_{ee} - \epsilon_{\tau\tau}) \right)^2
\]

\(^2\) Throughout this Letter, we assume that the number of light neutrinos is three and there is no unitarity violation.
The enhancement depends mainly on $\epsilon_{\text{MINOS}}$, NOvA, T2KK and a neutrino factory, since $P_{\text{AL}}$ reactor experiment has advantage of having no backgrounds due to the new physics in measurements of the standard $\epsilon_{\nu\tau}$ the signal of $\nu\tau$ is set to be zero. Thus, the nonstandard $\rho_{\alpha\beta}$ changes the oscillation probabilities in long baseline experiments. Since the analytical treatment of the three flavor $\nu$ oscillation and the subsequent $\alpha\beta$ interaction, because the signal is much larger than the standard prediction with the maximum possible value of $\theta_{13}$, $\Delta m_{31}^2$, and this effect will be taken into account in the following analysis. The reference values of $\theta_{12}$, $\theta_{13}$, and $\Delta m_{23}^2$ for the atmospheric neutrino measurement are given in Table I. As is explained in [8], the best fit values for $\sin 2\theta_{23}$ and $\Delta m_{23}^2$ for the atmospheric neutrino measurement are changed by the nonzero values of $\epsilon_{\alpha\beta}$, and this effect will be taken into account in the following analysis.

The ongoing MINOS experiment [14] has the baseline length $L = 735$km and the $\nu_{\mu}$ beam has a peak at several GeV. The appearance probability $P(\nu_{\mu} \rightarrow \nu_{e})$ at MINOS is shown in Fig. 4. We see that the non-standard matter effect due to $\epsilon_{\alpha\beta}$ can give much larger probability than that by the standard oscillation with allowed value of $\theta_{13}$. The enhancement depends mainly on $\epsilon_{\tau\tau}$, $\sin 2\theta_{23}$, and $\Delta m_{31}^2$, and it almost disappears if one of these parameters is set to be zero. Thus, the nonstandard $\nu_{\mu}-\nu_{e}$ oscillation can be understood very roughly by the standard $\nu_{\mu}-\nu_{e}$ oscillation and the subsequent $\nu_{\tau}-\nu_{\tau}$ transition with $\epsilon_{\tau\tau}$. The sets (b), (c), and (h) in Table I which have $\epsilon_{\tau\tau} = 0$, give the almost same line that vanishes for $E \gtrsim 2$GeV. The sets (a), (e), (g), and (i), which have large $|\epsilon_{\tau\tau}|$, give large values of the probability. If the MINOS experiment observes the probability $P(\nu_{\mu} \rightarrow \nu_{e})$ that is given by the set (g) in Table I which is the most extreme case, then it would be a clear signal of the existence of the non-standard interaction, because the signal is much larger than the standard prediction with the maximum possible value of $\theta_{13}$.

| set | (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\epsilon_{\alpha\beta}$ | -4 | -4 | -4 | 0 | 0 | 0 | 2.6 | 2.6 | 2.6 |
| $\epsilon_{e\tau}$ | -1.9 | 0 | 1.9 | -1 | 0 | 1 | -1.9 | 0 | 1.9 |
| $\epsilon_{e\tau}$ | -1.2 | 0 | -1.2 | 1 | 0 | 1 | 1 | 0 | 1 |

TABLE I: The table shows nine sets of the reference values of $\epsilon_{\alpha\beta}$ used in the figures. These sets are consistent with the bounds 4, 5, and 6.

$$ + \left( \frac{\Delta m^2 L}{4E} \sin 2\theta + A \epsilon_{e\tau} \right)^2, $$

$$ \tan 2\theta_M = \frac{\Delta m^2/2E \sin 2\theta + 2A \epsilon_{e\tau}}{\Delta m^2/2E \cos 2\theta - A(1 + \epsilon_{ee} - \epsilon_{e\tau})}, $$

$$ P(\nu_e \rightarrow \nu_\tau) = \sin^2 2\theta_M \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right). $$

To have a large value of the oscillation probability $P(\nu_e \rightarrow \nu_\tau)$, we need large values for both $\sin^2 2\theta_M$ and $\sin^2 (\Delta m_{31}^2 L/4E)$. From (10) we observe the two things. First of all, the effect of the new physics in $\sin^2 (\Delta m_{31}^2 L/4E)$ appears in a form $AL(\epsilon_{ee} - \epsilon_{e\tau})$ or $AL\epsilon_{e\tau}$, so large deviation of $\Delta m_{31}^2 L/4E$ from the standard one $\Delta m_{31}^2 L/4E$ requires $AL\epsilon_{e\tau}$ be nonnegligible irrespective of the neutrino energy $E$. Secondly, for the experiments with $|\Delta m^2|/E \sim O(1)$, we see by multiplying $L$ both the numerator and the denominator of 7 that the condition for nontrivial contribution of the new physics to the mixing angle $\theta_M$ again demands that $AL\epsilon_{e\tau}$ be nonnegligible. These imply that the baseline length has to be relatively large for the new physics effect to affect both of the factors in the oscillation probability, since $A$ can be roughly estimated as $A \simeq 1/(2000$km) with $\rho \simeq 3$g/cm$^3$. Although it is difficult to treat the three flavor case analytically, these features hold also in the case with three flavors, and they are important to understand the sensitivity of the long baseline experiments to the new physics. Typical ongoing and future long baseline experiments and their baseline length $L$ are: a reactor experiment [12] ($L \sim 2$km), the T2K experiment [2] ($L = 295$km), the MINOS experiment [14] ($L = 735$km), the NOvA experiment [13] ($L \simeq 800$km), the T2KK experiment [16] ($L \sim 1000$km), a neutrino factory [8] ($L \sim 3000$km). All these experiments are designed mainly to probe neutrino oscillations with the atmospheric neutrino mass squared difference $|\Delta m_{\text{atm}}^2| \simeq 2.5 \times 10^{-3}$eV$^2$ and the typical neutrino energy $E$ of each experiment satisfies $|\Delta m_{\text{atm}}^2| L/E \simeq O(1)$. The baseline lengths $L$ of these experiments, however, are quite different, and when $\epsilon_{e\tau} \sim O(1)$, only the experiments with nonnegligible value of $AL$ have sensitivity to the new physics. A reactor experiment satisfies $AL \ll 1$, so that it has no hope to see the signal due to $\epsilon_{e\tau}$. On the other hand, a reactor experiment has advantage of having no backgrounds due to the new physics in measurements of the standard oscillation parameters. For the T2K experiment, $AL \simeq 3/20$, so it has potential to see the new physics effect. For MINOS, NOvA, T2KK and a neutrino factory, since $AL$ is larger, they have in principle even more potential to see the signal of $\epsilon_{e\tau}$. Let us now investigate the three flavor case and see how much the non-standard matter effect with $\epsilon_{e\tau} = O(1)$ changes the oscillation probabilities in long baseline experiments. Since the analytical treatment of the three flavor case is difficult, we will evaluate the oscillation probability numerically. In the present analysis we use the following values of the parameters: $\rho = 2.7g \cdot cm^{-3}$, $Y_e = 0.5$, $0 < \Delta m_{12}^2 = 2.5 \times 10^{-3}$eV$^2$, $\Delta m_{21}^2 = 8 \times 10^{-5}$eV$^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{13} < 0.16$, $\delta = 0$. The reference values of $\epsilon_{e\tau}$ that will be used are given in Table I. As is explained in [8], the best fit values for $\sin 2\theta_{23}$ and $\Delta m_{23}^2$ for the atmospheric neutrino measurement are changed by the nonzero values of $\epsilon_{e\tau}$, and this effect will be taken into account in the following analysis.
FIG. 1: The figure shows $P(\nu_\mu \rightarrow \nu_e)$ in MINOS experiment with the non-standard matter effect. Solid lines are obtained with the non-standard effect for $\sin^2 2\theta_{13} = 0$. A dashed line is for $\sin^2 2\theta_{13} = 0.16$ without the non-standard effect. The set (g) of Table II gives the line whose value is the largest among the nine solid lines at the peak near $E \approx 2$GeV. The sets (b), (e), and (h) give almost the same lines which vanish for $E > \sim 2$GeV, where (e) is the case with $\theta_{13} = 0$ and $\epsilon_{\alpha\beta} = 0$.

even if we take into consideration the 30% uncertainty in $\sin^2 \theta_{23}$. On the other hand, even if MINOS does not see any signal of $\nu_\mu \rightarrow \nu_e$ within its sensitivity, it would still give us new information on the allowed region of $\epsilon_{\alpha\beta}$, which will be reported elsewhere [18]. NOvA experiment [15] at $L \approx 800$km will have better sensitivity to the non-standard interaction because of fewer backgrounds with the off-axis beam.

We have also considered the case of a neutrino factory [3] with a baseline length $L = 3000$km and the muon energy $E_\mu = 50$GeV and the neutrino beam has a peak at around 30GeV. For the so-called golden channel $P(\nu_e \rightarrow \nu_\mu)$ [19], the qualitative behavior is similar to that in MINOS: There is a large enhancement of the probability for neutrinos of a few GeV. On the other hand, for the so-called silver channel $P(\nu_e \rightarrow \nu_\tau)$ [20], the probability has a huge enhancement at high energy as is shown in Fig. 2 and the probability becomes independent of the energy in the region. It is because the terms of $|\Delta m^2_{jk}|/E$ in (2) disappear at high energy and $\epsilon_{\alpha\beta}$ gives the energy independent transition of flavors. In fact, the oscillation probability $P(\nu_e \rightarrow \nu_\tau)$ at high energy is approximately given by the two flavor formula (10), since $\nu_\mu$ decouples from $\nu_e$ or $\nu_\tau$ with the Hamiltonian (2) at high energy.

In this Letter, we discussed the effects of the non-standard interaction with matter upon the long baseline oscillation experiments, with only the terms whose sizes have a very weak bound from other neutrino experiments. Taking into account all the constraints on the non-standard interactions including the atmospheric neutrino data, the $ee$, $e\tau$, $\tau\tau$ components of the non-standard matter effect can be comparable in magnitude to the standard matter interaction. Possibility of detecting such a potentially large effect was examined for the first time in the ongoing and future long baseline experiments. It was found that $\epsilon_{\alpha\beta}$ can give a large oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ in the ongoing MINOS experiment. In the most optimistic case, the oscillation probability is so large that it cannot be explained by the

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3 If the value of $\theta_{13}$ is close to the current bound given by the CHOOZ experiment [15], then the oscillation probability for $\nu_\mu \rightarrow \nu_e$ is proportional to $\sin^2 \theta_{23} \sin^2 2\theta_{13}$.\[3}
standard oscillation with $\theta_{13}$. Thus, it is a clear signal of the non-nonstandard interaction if MINOS observes such a large number of $\nu_e$ appearance events. It was also shown that the oscillation probability $P(\nu_e \rightarrow \nu_\tau)$ of the silver channel at a neutrino factory can be very large at high energy due to $\epsilon_{\alpha\beta}$ of $O(1)$; Amazingly, even $P(\nu_e \rightarrow \nu_\tau) \simeq 1$ is possible. Therefore, the silver channel is a very promising way to look for the effect of the non-standard interaction. Once such signals are found, it would be necessary to separate the effects due to the standard oscillations and those due to the new physics. In that case, as was explained in the text, combination with a reactor experiment or long baseline experiments with different baseline lengths would be important.

In conclusion, there remains a possibility to find the large effect of the non-standard interaction in the long baseline oscillation experiments. More detailed analyses as well as other discussions on the subject will be given elsewhere.

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