More on Non-standard Interaction at MINOS

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Abstract. We discuss about effects of the non-standard interaction of neutrinos with matter on the \( \nu_e \) appearance search in the MINOS experiment. We consider the effects of the complex phase of the interaction and of the uncertainty on \( \theta_{23} \) also. We show that the oscillation probability can be so large that cannot be explained by the ordinary oscillation. We show also how much constraints on the non-standard effects can be improved if the experiment does not observe \( \nu_e \) appearance signal.

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INTRODUCTION

Oscillations of three generation neutrinos are parametrized by two mass squared differences, three mixing angles, and one CP violating phase. Among these parameters, a tiny mixing angle \( \theta_{13} \) and the phase \( \delta \) have not been measured yet. Measuring tiny effects of \( \theta_{13} \) and \( \delta \) is the main purpose of future oscillation experiments. On the other hand, such precision measurements will be sensitive to effects of new physics also. In this talk, we investigate possibilities to see new physics effects on the \( \nu_e \) appearance search with \( \nu_\mu \) beam in the MINOS experiment [1]. This talk is based on [2].

We consider the non-standard interaction (NSI) of neutrinos with matter as an example of new physics. The interaction is introduced in a model-independent way by the following effective Lagrangian

\[
\mathcal{L}_{\text{eff}} = \epsilon_{\alpha \beta} F_\alpha \left( \sum \gamma \nu \right) \left\{ \frac{1}{2} \gamma^\mu P_f \right\};
\]

where \( \alpha = e, \mu, \tau \) and \( \beta \) stand for flavors, \( F_\alpha \) is the Fermi coupling constant, \( P = (P_L, P_R) \) denotes the projection operator onto the left-handed one or the right-handed one, and \( f \) (e, \( \mu, \tau \)) represents the fermions existing in matter. Then, the Hamiltonian in the flavor basis is modified from the standard one and it is given by

\[
H = \frac{1}{2E} U_{\text{MNS}} \left( \begin{array}{ccc}
0 & 0 & 0 \\
0 & \Delta m^2_{31} & 0 \\
0 & 0 & \Delta m^2_{21}
\end{array} \right) U_{\text{MNS}}^\dagger + \epsilon_{\alpha \beta} \left( \begin{array}{ccc}
\epsilon_{e\mu} & \epsilon_{e\tau} & \epsilon_{\mu\tau} \\
\epsilon_{\mu\tau} & \epsilon_{\mu\mu} & \epsilon_{\tau\tau} \\
\epsilon_{\tau\tau} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}
\end{array} \right),
\]

where \( \epsilon_{\alpha \beta} = 2G_{\nu} n_e \) with the electron number density \( n_e \), and \( \epsilon_{\alpha \beta} = \sum \epsilon_{\alpha \beta} \). The first term of the right-hand-side of (2) is for the oscillation in vacuum and the second term is the matter potential with NSI.

\[ 4 < \epsilon_{ee} < 2.6, \quad \epsilon_{e\tau} < 19; \]

The constraint on \( \epsilon_{ee} \) in (3) is rather loose but it is improved by the atmospheric neutrino measurement and the K2K experiment [4]. In order to reproduce the observed \( \nu_\mu \) disappearance for \( \Delta m^2_{21} = 0 \) and \( \theta_{13} = 0 \), which is 1 \( P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 2\theta_{23}^{\text{obs}} \sin^2 \left( \Delta m^2_{31}^{\text{obs}} L/4E \right) \), the parameters in vacuum (\( \theta_{23}, \Delta m^2_{31} \)) and non-standard in-

\[ 1 \] Actually, constraints on \( \epsilon_{\alpha \beta}^{IP} \) are obtained by experiments with muon through loop effects.
Interactions should satisfy
\[ \epsilon_{\tau\tau} = \frac{\bar{\epsilon}_{\tau\tau}}{1 + \epsilon_{ee}}; \] (4)
\[ \cos 2\theta_{23} = \frac{s_{\beta}^2 (1 + c_{\beta}^2) + 4 c_{\beta}^2 \cos 2\theta_{13} \text{obs}}{1 + \cos^2 2\theta_{23} \text{obs}}; \] (5)
\[ \Delta m^2_{31} = \frac{2 \Delta m^2_{31} \text{obs}}{\epsilon (1 + c_{\beta}) \cos 2\theta_{23} s_{\beta}^2 + 4 c_{\beta}^2 \sin^2 2\theta_{23}}; \] (6)
where \( \tan \beta \) \( \epsilon_{\tau\tau} \) \( \epsilon_{ee} \) \( c_{\beta} \) and \( s_{\beta} \) denote \( \cos \beta \) and \( \sin \beta \), respectively. Furthermore, in order to be consistent with the sub-GeV data of atmospheric \( \nu_\mu \), where the matter effect is suppressed, the parameters in vacuum should satisfy
\[ \cos 2\theta_{23} < 0.5; \quad \Delta m^2_{31} \leq 5 \times 10^{-3} \text{ eV}^2; \] (7)
The conditions give an upper-bound on \( \tan \beta \) \( j \) and then we can constrain \( \epsilon_{\tau\tau} \) also as \( \epsilon_{\tau\tau} \leq \frac{\tan \beta}{\tan \beta + \max \epsilon_{\tau\tau}} \). We use the conditions (4)-(7) for also the case with \( \Delta m^2_{31} \leq 0 \) and \( \theta_{13} \leq 0 \) for simplicity.

ANALYSES AND RESULTS

In our analysis, we calculate numbers of \( \nu_e \) events (signal and background) for 13 bins of 0.5GeV width within 1-7.5GeV of the reconstructed energy. We assume 16 \( 10^{30} \text{POT} \) which corresponds to about 5 years of running. Systematic errors are ignored for simplicity. Two parameters are fixed as \( \sin^2 2\theta_{12} = 0.8, \Delta m^2_{31} = 8 \times 10^{-5} \text{ eV}^2 \) throughout this talk.

First, we investigate the possibility to see the effect of NSI in the MINOS experiment. “Data” are generated with NSI and we try to fit the “data” without NSI. If the \( \Delta \chi^2 \) that corresponds to the fitting is larger than 4.6, it means that the MINOS experiment can exclude the case with \( \epsilon_{ee} = \epsilon_{\tau\tau} = 0 \) and see the NSI effect at 90%CL. For the generation of the “data” with NSI, we use
\[ \delta_{\text{true}} = \arg (e^{\text{true}_{\tau\tau}}) = 0; \] (8)
\[ s_{23} = 1; \quad \Delta m^2_{31} = 2.7 \times 10^{-3} \text{ eV}^2; \] (9)
We fix \( \sin^2 2\theta_{13} \) also but take several values for that. On the other hand, the values of parameters for fitting without NSI are
\[ 0 < \sin^2 2\theta_{13} < 0.16; \] (10)
\[ \delta = \pi/2; \quad s_{23} = 0.8 \quad (\sin^2 2\theta_{23} = 0.92); \] (11)
\[ \Delta m^2_{31} = 2.7 \times 10^{-3} \text{ eV}^2; \] (12)
\( \Delta \chi^2 \) is minimized with respect to \( \theta_{13} \) within the region. Note that the choice of (11) is for large \( P(\nu_\mu \to \nu_e) \) in the standard oscillation, and hence it is a pessimistic one for the search of the NSI effect. The result is shown in Fig. 1. The region above the dash-dotted line has the dotted line has been excluded by the atmospheric neutrino measurement and the K2K experiment.

\[ \text{FIGURE 1.} \quad \text{Thin dashed, thin solid, bold dashed, and bold solid curves are obtained for} \quad \sin^2 2\theta_{13} = 0 \quad \theta_{13} = 0, \quad \text{and} \quad 0.16, \quad \text{respectively. If true values exist above these curves, the MINOS experiment can see the NSI effect. The region above the dash-dotted line has been excluded by the atmospheric neutrino measurement and the K2K experiment.} \]
been excluded by \( \tan \beta \lesssim 1 \) obtained with (7) and (8). The thin dashed, thin solid, bold dashed, and bold solid curves are results for \( \sin^2 2\theta_{13} = 0.05, 0.1, \) and 0.16, respectively; If nature chooses true values above the curves, the number of \( \nu_e \) appearance signal becomes so large that cannot be explain with \( \theta_{13} \) only. Then, it is possible to see the NSI effect in the MINOS experiment.

Next, let us consider the case without \( \nu_e \) appearance signal. In this case, bounds on \( \varepsilon \) will be obtained by the search for \( \delta \). We have investigated possibilities to obtain information about NSI effect with the search of \( \nu_\mu \to \nu_e \) oscillation in the MINOS experiment. We have shown that it is possible to find the effect in the experiment. Even if the experiment does not find \( \nu_e \) appearance signal, some part of \( \varepsilon_{ee} - \varepsilon_{\tau\tau} \) space can be excluded by the result. Therefore, ongoing and future oscillation experiments are very interesting not only for the precise determination of the mixing parameter in the lepton sector but also for the new physics search.

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**CONCLUSIONS**

We have investigated possibilities to obtain information about NSI effect with the search of \( \nu_\mu \to \nu_e \) oscillation in the MINOS experiment. We have shown that it is possible to find the effect in the experiment. Even if the experiment does not find \( \nu_e \) appearance signal, some part of \( \varepsilon_{ee} - \varepsilon_{\tau\tau} \) space can be excluded by the result. Therefore, ongoing and future oscillation experiments are very interesting not only for the precise determination of the mixing parameter in the lepton sector but also for the new physics search.