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NEW PHYSICS EFFECTS IN LONG BASELINE EXPERIMENTS*

Osamu Yasuda

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

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We discuss the implications of new physics, which modifies the matter effect in neutrino oscillations, to long baseline experiments, particularly the MINOS experiment. An analytic formula in the presence of such a new physics interaction is derived for $P(\nu_\mu \to \nu_e)$, which is exact in the limit $\Delta m^2_{21} \to 0$.

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1. Introduction

It has been suggested that future long baseline neutrino experiments such as so-called super-beams, beta-beams, neutrino factories will have great sensitivity to the third mixing angle θ_{13}, the CP phase δ and the mass hierarchy sign(Δm^2_{31}) (For a review, see, *e.g.*, [1]). Just like at the B factories, experiments of high precision measurements will allow us not only to measure precisely the parameters of the standard model, but also to probe new physics by looking at a deviation from the standard case. In this talk I would like to discuss the possible effects of new physics at long baseline experiments, particularly the MINOS experiment [2].

2. New physics in neutrino oscillations

A class of effective non-standard neutrino interactions with matter that would modify the neutrino oscillation probability are given by

$$\mathcal{L}^{\rm NSI}_{\rm eff} = \left\{ \begin{array}{ll} -2\sqrt{2}\,\varepsilon^{fP}_{\alpha\beta} G_{\rm F} (\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta)\,(\overline{f}\gamma^\mu P f')\,, & \text{(a)} \\ -2\sqrt{2}\,\varepsilon'^{fP}_{\alpha\beta} G_{\rm F} (\overline{\nu}_\alpha \gamma_\mu P_L \ell_\beta)\,(\overline{f}\gamma^\mu P f')\,, & \text{(b)} \end{array} \right. \tag{1}$$

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which are depicted in Fig. 1. In Eq. (1) f and f' stand for fermions (the only relevant ones here are electrons, u and d quarks), $G_{\rm F}$ is the Fermi coupling constant, P stands for a projection operator and is either $P_{\rm L} \equiv (1-\gamma_5)/2$ or $P_{\rm R} \equiv (1+\gamma_5)/2$. Since we are interested in the modification of the neutrino oscillation phenomena due to new physics here, the only relevant effective interactions are four Fermi interactions of type Fig. 1 (a) and (b), which are neutral and charged current interactions, respectively. The presence of the interaction of Fig. 1 (a) would modify the matter effect during propagation of neutrinos, while that of Fig. 1 (b) would change the process of production and detection of neutrinos.

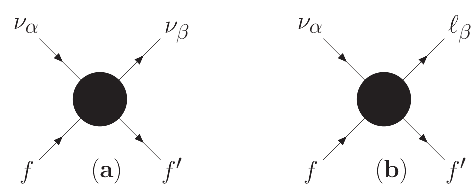

Fig. 1. Two types of the effective new interactions which are relevant to neutrino oscillations.

It has been shown [3] by taking into account various experimental constraints that the absolute value of the coefficient ${\varepsilon'}^{fP}_{\alpha\beta}$ of the interaction of type Fig. 1 (b) is small: $|{\varepsilon'}^{fP}_{\alpha\beta}| \lesssim \mathcal{O}(10^{-2})$. On the other hand, in the case of Fig. 1 (a), it is known [4,5] that the constraints on $\varepsilon^{fP}_{\alpha\beta}$ is relatively weak: $|\varepsilon^{fP}_{\alpha\beta}| \lesssim \mathcal{O}(1)$ for the flavor indices $\alpha, \beta = e, \tau$. So in this talk I will consider only new physics of type Fig. 1 (a) as a first step toward investigating new physics effects at long baseline experiments.

In the presence of the new interaction of Eq. (1) (a), by introducing the notation $\varepsilon_{\alpha\beta} \equiv \sum_P \left(\varepsilon^{eP}_{\alpha\beta} + 3\varepsilon^{uP}_{\alpha\beta} + 3\varepsilon^{dP}_{\alpha\beta}\right)$, and by making the approximation that the number density of electrons (N_e), protons and neutrons are equal, the 3×3 matrix of the matter potential becomes

$$A \left(\begin{array}{ccc} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{array} \right),$$

where $A \equiv \sqrt{2} G_{\rm F} N_e$. From the analysis in [4] the coefficients involving the μ flavor are small: $|\varepsilon_{e\mu}| < 3.8\times 10^{-4}$, $-0.05 < \varepsilon_{\mu\mu} < 0.08$, $|\varepsilon_{\mu\tau}| < 0.25$. So in the following discussions I will assume $\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0$ for simplicity and keep in the analysis the remaining three parameters, which have the values [4] $-4 < \varepsilon_{ee} < 2.6$, $|\varepsilon_{e\tau}| < 1.9$, $|\varepsilon_{\tau\tau}| < 1.9$. Furthermore, it was shown in [5] that the atmospheric neutrino and K2K data imply

$$|\varepsilon_{e\tau}|^2 \simeq \varepsilon_{\tau\tau}\,(1+\varepsilon_{ee})\,, \tag{2}$$

and $|\varepsilon_{e\tau}| \lesssim |1+\varepsilon_{ee}|$. Throughout the present talk I will assume that Eq. (2) holds exactly and eliminate $\varepsilon_{\tau\tau}$ by Eq. (2). Then we are left with the two unknown parameters ε_{ee} and $\varepsilon_{e\tau}$, in addition to those in the standard framework. Taking the constraints by [4] and [5] into account, the allowed region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane looks like Fig. 2. Below I will adopt the following reference values for the oscillation parameters in the standard three flavor framework: $\Delta m^2_{31} = 2.7\times 10^{-3}\mathrm{eV}^2$, $\Delta m^2_{21} = 8\times 10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1.0$, $\sin^2 2\theta_{12} = 0.8$.

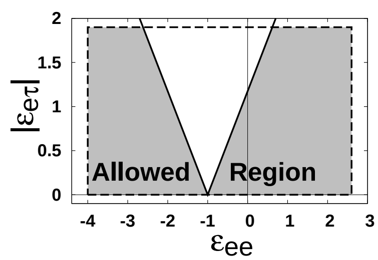

Fig. 2. The allowed region (the shaded area) in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane. Bounded by the dashed line is the region allowed by various experimental data [4] and below the solid thick line is the region allowed by the atmospheric neutrino and K2K data [5].

3. Analytic formula for the oscillation probability $P(\nu_\mu \to \nu_e)$

Before going into numerical analysis, it is instructive to have an analytical expression of the oscillation probability to see its behavior. It was shown in [7] by generalizing the exact analytical treatment on the oscillation probability by Kimura–Takamura–Yokomakura [8] that the oscillation probability $P(\nu_\mu \to \nu_e)$ in the presence of the new interaction of Eq. (1) (a) is obtained in the limit $\Delta m^2_{21} \to 0$ as follows:

$$\begin{aligned}P(\nu_\mu\to\nu_e) = &-4\mathrm{Re}(\tilde{X}_1^{\mu e}\tilde{X}_3^{\mu e*})\sin^2\left[\frac{(\Lambda_+-\Lambda_-)L}{2}\right]\\ &-4\mathrm{Re}(\tilde{X}_1^{\mu e}\tilde{X}_2^{\mu e*})\sin^2\left(\frac{\Lambda_- L}{2}\right) - 4\mathrm{Re}(\tilde{X}_2^{\mu e}\tilde{X}_3^{\mu e*})\sin^2\left(\frac{\Lambda_+ L}{2}\right)\\ &-8\mathrm{Im}(\tilde{X}_1^{\mu e}\tilde{X}_2^{\mu e*})\sin\left(\frac{\Lambda_- L}{2}\right)\sin\left(\frac{\Lambda_+ L}{2}\right)\sin\left[\frac{(\Lambda_+-\Lambda_-)L}{2}\right],\end{aligned} \tag{3}$$

where the energy eigenvalues $\Lambda_\pm$ and the quantities $\tilde{X}_j^{\mu e}$ are given by

$$\begin{aligned}
\Lambda_\pm &= (1/2)\left[\Delta E_{31} + A(1+\varepsilon_{ee})/\cos^2\beta\right] \\
&\quad \pm(1/2)\sqrt{\left[\Delta E_{31}\cos 2\theta''_{13} - A(1+\varepsilon_{ee})/\cos^2\beta\right]^2 + (\Delta E_{31}\sin 2\theta''_{13})^2}\,, \\
\tilde{X}_1^{\mu e} &= -[\xi + \eta e^{-i(\arg(\varepsilon_{e\mu})+\delta)} - \Lambda_+\zeta]/[\Lambda_-(\Lambda_+ - \Lambda_-)]\,, \\
\tilde{X}_2^{\mu e} &= [\xi + \eta e^{-i(\arg(\varepsilon_{e\mu})+\delta)} - (\Lambda_+ + \Lambda_-)\zeta]/(\Lambda_+\Lambda_-)\,, \\
\tilde{X}_3^{\mu e} &= [\xi + \eta e^{-i(\arg(\varepsilon_{e\mu})+\delta)} - \Lambda_-\zeta]/[\Lambda_+(\Lambda_+ - \Lambda_-)]\,.
\end{aligned}$$

Here ξ, η, ζ, β, θ''_{13}, ΔE_{31} are given by

$$\begin{aligned}
\xi &\equiv [(\Delta E_{31})^2 + A(1+\varepsilon_{ee})\Delta E_{31}]U_{\mu 3}|U_{e3}|\,, \\
\eta &\equiv A\Delta E_{31}|\varepsilon_{e\tau}|U_{\mu 3}U_{\tau 3}\,, \\
\zeta &\equiv \Delta E_{31}U_{\mu 3}|U_{e3}|\,, \\
\tan\beta &\equiv |\varepsilon_{e\tau}|/(1+\varepsilon_{ee})\,, \\
\theta''_{13} &= \sin^{-1}|e^{-i\arg(\varepsilon_{e\mu})}U_{e3}\cos\beta + U_{\tau 3}\sin\beta|\,, \quad \Delta E_{31} \equiv \Delta m^2_{31}/2E\,.
\end{aligned}$$

Two remarks are in order. First, Eq. (3) indicates that the phases appear in the probability only through the combination of $\arg(\varepsilon_{e\mu}) + \delta$ in the limit $\Delta m^2_{21} \to 0$. It was found numerically in [6] that this property holds approximately even for nonvanishing Δm^2_{21}. Secondly, as is shown in Fig. 3, each term in Eq. (3) gives a relatively large contribution, and it is not easy to interpret the behavior of the probability unlike in the standard three flavor case, where the probability in the limit $\Delta m^2_{21} \to 0$ can be expressed by replacing the mixing angle θ_{13} and the difference of the energy eigenvalues ΔE_{31} in vacuum by those in matter, respectively [9].

4. Numerical analysis

In Fig. 4 the value of $P(\nu_\mu \to \nu_e)$ for the baseline L=730 km is plotted for various values of $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ in the allowed region depicted in Fig. 2, together with the value of the standard case with nearly the maximum possible value $\sin^2 2\theta_{13} = 0.1$. For some values of $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ the oscillation probability becomes so large that it cannot be explained by the standard three flavor framework. We have done numerical analysis for two cases at the MINOS experiments.

One is the case where MINOS has an affirmative result for the appearance channel $\nu_\mu \to \nu_e$. There exists a certain region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane in which the difference between the numbers of events with and without the new physics interaction (the latter being the standard case with the maximum value of $\sin^2 2\theta_{13}$) is so significant that we can establish the existence of new

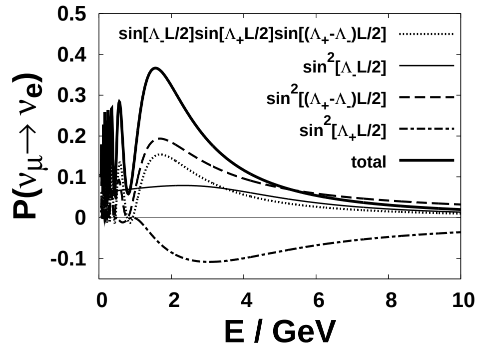

Fig. 3. Contribution of each term in Eq. (3) to the oscillation probability $P(\nu_\mu \to \nu_e)$ in matter at baseline L=730 km in the presence of new physics in the limit $\Delta m^2_{21} \to 0$. $\sin^2 2\theta_{13} = 0.16$, $\varepsilon_{ee} = 2.0$, $|\varepsilon_{e\tau}| = 1.5$, $\arg(\varepsilon_{e\tau}) + \delta = \pi/2$ are assumed.

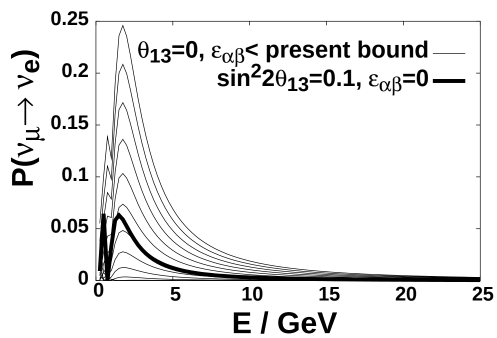

Fig. 4. The oscillation probability $P(\nu_\mu \to \nu_e)$ at the baseline $L = 730$ km with (the thin solid lines) or without (the thick solid line) the new interaction of Eq. (1) (a) for various values of $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ within the allowed region in Fig. 2.

physics. The region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane for such a case depends on the value of $\sin^2 2\theta_{13}$, and is given by Fig. 5 (a). The reason that a larger value of $\sin^2 2\theta_{13}$ gives a larger region is because the oscillation probability is roughly additive in θ_{13} and $\varepsilon_{\alpha\beta}$ so the larger value θ_{13} has, the larger the number of events, leading to the smaller statistical error and the larger deviation from the standard case. From Fig. 5 (a) we see that MINOS potentially has a chance to establish the existence of new physics, although the region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane is relatively small for smaller values of $\sin^2 2\theta_{13}$.

Another is the case where MINOS has a negative result for $\nu_\mu \to \nu_e$. In this case we can exclude a certain region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane whose prediction for the number of events is so large that we have contradiction with the negative assumption, irrespective of the value of θ_{13}. Such a region depends on the value of $\arg(\varepsilon_{e\tau}) + \delta$, and the case with $\arg(\varepsilon_{e\tau}) + \delta = 3\pi/2$ is the most pessimistic, *i.e.*, the excluded region becomes the smallest in this case. As we can see from Fig. 5 (b), again there is a little region in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane which can be excluded by the negative result of MINOS.

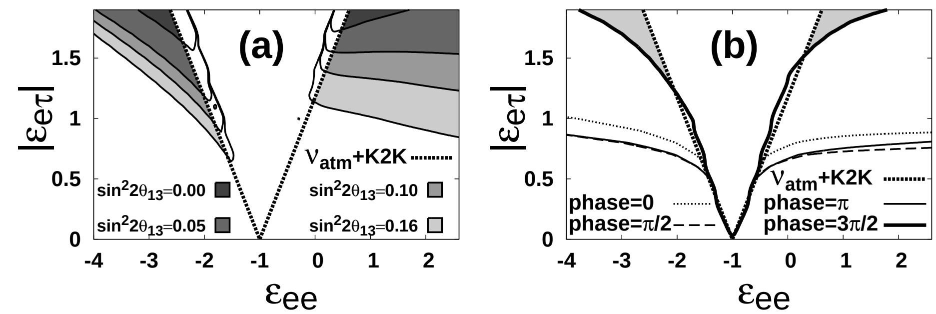

Fig. 5. Numerical results on sensitivity to new physics by the appearance channel $\nu_\mu \to \nu_e$ at MINOS with 16×10^{20} POT ($\simeq 5$ years of running). (a) The shaded areas are the regions in the $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$ plane in which we can establish the existence of new physics from the affirmative result of MINOS. The region varies, depending on the value of θ_{13}. (b) The shaded area is the region which can be excluded from the negative result of MINOS. The region depends on the value of the phase $\arg(\varepsilon_{e\tau}) + \delta$. Below the thick dashed line is the region allowed by the atmospheric neutrino and K2K data in both figures.

5. Conclusions

As a first step in probing new physics at long baseline experiments, I have discussed the new physics interaction given by Eq. (1) (a) and have examined the sensitivity to such an interaction by looking at the appearance channel $\nu_\mu \to \nu_e$ at the MINOS experiment. In the process of the analysis, I presented the analytical formula for $P(\nu_\mu \to \nu_e)$ which is exact in the limit $\Delta m^2_{21} \to 0$. As far as the interaction Eq. (1) (a) is concerned, an experiment with a longer baseline is more advantageous since the new effect appears only through the matter effect and roughly speaking it comes in the oscillation probability in the form of $\varepsilon_{\alpha\beta} AL \sim \varepsilon_{\alpha\beta}(L/2000\ \text{km})$ $(\alpha, \beta = e, \tau)$. A neutrino factory in the future [1] will have much more statistics and its baseline $L \gtrsim 3000$ km gives larger sensitivity to the matter effect, so it is expected that a neutrino factory has much better sensitivity to the new physics effect discussed here.

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