Oscillation-enhanced search for new interaction with neutrinos

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We study how well we can observe the effect of new physics in neutrino oscillation experiments.

1. Introduction

Precision measurement on neutrino mass difference and mixing angles for lepton will be done in neutrino oscillation experiments of next generation (see, for example, [1]). According to those study we will know the mass square difference and the mixing angle relevant to the atomospheric neutrino anomaly with 3% and 1% accuracy, we can measure U_{e3} down to $O(10^{-2})$, and also we can observe the CP violation effect in near future.

Till today the main concern about the next generation experiments has been on these parameters, mixing angles and the mass square difference. Therefore there arise a question whether we can mesure only these parameters in those experiments. There are several suggestions that we may see the effect of flavor-violating new physics[2].

In this talk we consider the potential power of the next generation experiments to observe the effect of new interactions[3].

2. Measurement of Neutrino Oscillation

2.1. Idea

To see how the effect of new physics enter the oscillation phenomenon, first we remind ourselves what we really observe in oscillation experiments. Though we discuss only a neutrino factory to make the argument concrete, same discussion is followed in oscillation experiments with a conventional beam.

All we know in a neutrino factory is that the muons, say, with negative charge decay at an accumulate ring and wrong sign muons are observed in a detector located at a length L away just after the time L/c, where c is the light speed. This is depicted schematically in Fig.1.

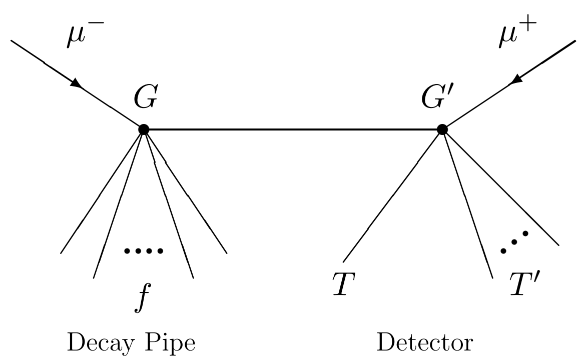

Figure 1. What we really see in a neutrino factory.

Since we know that there is the weak interaction process, we interpret such a wrong sign event as the evidence of the neutrino oscillation, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$, which is graphically represented in Fig.2.

Now if there is a flavor-changing exotic interaction, *e.g.*,

$$\epsilon(\bar{e}\gamma_\mu\mu)(\bar{\nu_\mu}\gamma^\mu\nu_\alpha), \quad \alpha \neq e, \tag{1}$$

then we will have the same signal of a wrong sign muon, whose diagram is shown in Fig.3, just like that caused by the weak interaction and the neutrino oscillation. We cannot distinguish these two kinds of contribution. The quantum mechanics tells us that in this case, to get a transition rate,

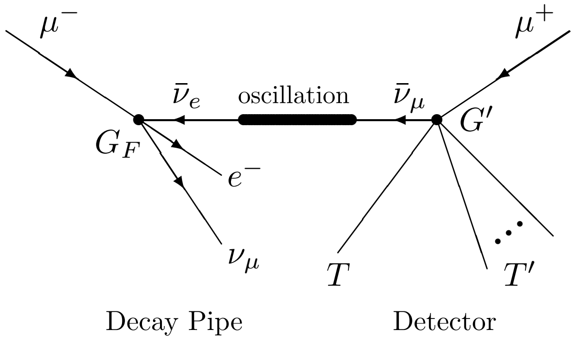

Figure 2. Standard interpretation of a wrong sign event.

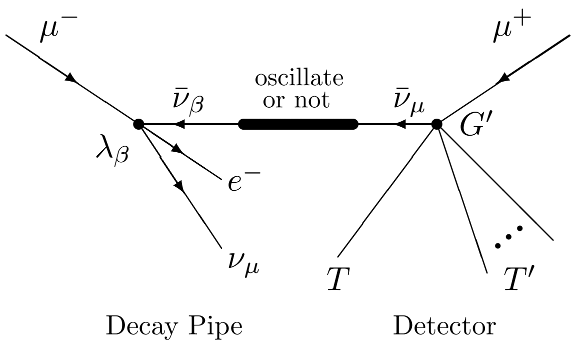

Figure 3. Diagram which gives same signal as that given by Fig.2.

we first sum up these amplitudes and then square the summation. In general, we have to calculate the graph fig.4 to get the transition rate.

Therefore there is an interference phenomenon between several amplitudes in this process. Through this interference new physics effect gives a contribution to the transition rate of order of not $O(\epsilon^2)$ but $O(\epsilon)$. We get an enhancement of the effect of new physics, that is, we can make oscillation-enhanced search for new interactions with neutrinos.

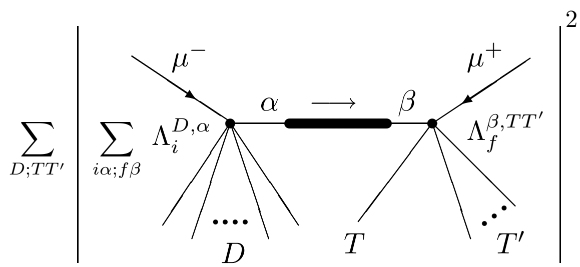

Figure 4. Transition rate for "$\bar{\nu}_e \to \bar{\nu}_\mu$".

2.2. Parameterization

Here we consider how to parameterize new physics effects.

First we note that the amplitude for "neutrino oscillation" can be divided into three pieces: (1) Amplitude relevant with decay of a parent particle denoted as A^C_α, here C describes the type of interactions. For μ decay, as we will see in eq.(3) and (4), there are two types of interactions, $C = L, R$ while for π decay we do not need this label. α distinguishes the particle species which easily propagates in the matter and make an interaction at a detector. (2) Amplitude representing a transition of these propagating particles, which are usually neutrinos, from one species α to another/same β , denoted as $T_{\alpha\beta}$. (3) Amplitude responsible for producing a charged lepton l from a propagated particle β at a detector, stood for by $D^I_{\beta l}$. Here I denotes an interaction type. Using these notations we get the probability to observe a charged lepton $l^\pm$ at a detector as

$$P_{\mu^- \to l^+(l^-)} = \left| \sum_{\alpha\beta CI} A^C_\alpha T_{\alpha\beta} D^I_{\beta l^\pm} \right|^2 . \qquad (2)$$

Therefore we can consider the effect of new physics separately for decay, propagation and detection processes.

First we consider the decay process of parent particles. For a neutrino factory, the exotic decays of muons which are $\mu^- \to e^- \nu_\alpha \bar{\nu}_e$ and $\mu^- \to e^- \nu_\mu \bar{\nu}_\beta$ can be amplified by the interference. This fact and Lorentz invariance allow only two kinds of new interactions in this process. For a wrong-sign mode, the allowed two interactions are the $(V-A)(V-A)$ type,

$$2\sqrt{2}\lambda_\alpha(\bar{\nu_\mu}\gamma^\rho P_L\mu)(\bar{e}\gamma_\rho P_L\nu_\alpha), \quad \alpha=\mu,\tau, \tag{3}$$

which has the same chiral property as the weak interaction but violates the flavor conservation, and the $(V-A)(V+A)$ type,

$$2\sqrt{2}\lambda'_\alpha(\bar{\nu_\mu}\gamma^\rho \nu_\alpha)(\bar{e}\gamma_\rho P_R\mu), \quad \alpha=e,\mu,\tau. \tag{4}$$

The latter has different chiral property from the former, so that it gives different energy dependence to the transition rate. However in the latter case there is a very strong chiral suppression for the interference and hence eventually there is no effect on the oscillation phenomena.

In the case of the $(V-A)(V-A)$ type exotic interaction, we can introduce the interference effect by treating the initial state of oscillating neutrino as the superposition of all flavor eigenstates. On the $\mu^- \to \mu^+$ process, we can take initial neutrino $\bar{\nu}$ as

$$\bar{\nu}=\bar{\nu}_e+\epsilon_\mu\bar{\nu}_\mu+\epsilon_\tau\bar{\nu}_\tau, \tag{5}$$

where $\epsilon_\alpha=\lambda_\alpha/G_F$. This simple treatment is allowed only for the $(V-A)(V-A)$ type interaction because of the same interaction form as the weak interaction except for difference of the coupling constant and the flavor of antineutrino. In this case we can generalize the initial neutrino for any flavor, using Y. Grossman's source state notation [4], as, [1]

$$\begin{aligned} \nu^s_\beta &= U^s_{\beta\alpha}\nu_\alpha, \quad \alpha,\beta=e,\mu,\tau, \\ U^s &\equiv \begin{pmatrix} 1 & \epsilon^s_{e\mu} & \epsilon^s_{e\tau} \\ \epsilon^s_{\mu e} & 1 & \epsilon^s_{\mu\tau} \\ \epsilon^s_{\tau e} & \epsilon^s_{\tau\mu} & 1 \end{pmatrix}. \end{aligned} \tag{6}$$

We can include the total exotic effect into the oscillation probability as

$$P_{\nu^s_\alpha\to\nu_\beta}=\left|\langle\nu_\beta|e^{-iHL}U^s_{\alpha\gamma}|\nu_\gamma\rangle\right|^2. \tag{7}$$

This treatment is also valid for the effect on the ν_μ oscillation.

[1] U^s is not necessarily unitary.

For π decay the situation is much simpler. In the presence of new physics there may be a flavor violating decay of π such as $\pi^- \to \mu^-\nu_\alpha(\alpha=e,\tau)$. This effect changes the initial ν state;

$$\nu_\mu \longrightarrow \nu^s_\mu=\epsilon^s_{\mu e}\nu_e+\nu_\mu+\epsilon^s_{\mu\tau}\nu_\tau. \tag{8}$$

In this case we do not have to worry about the type of new physics which gives a flavor changing π decay at a low energy scale. Due to kinematics, the energy and the helicity of the decaying particles, μ and ν are fixed.

Next we consider the propagation process. Exotic interactions also modify the Hamiltonian for neutrino propagation as [5],

$$\begin{aligned} H_{\beta\alpha} = \frac{1}{2E_\nu}\Bigg\{ & U_{\beta i}\begin{pmatrix} 0 & & \\ & \delta m^2_{21} & \\ & & \delta m^2_{31}\end{pmatrix}U^\dagger_{i\alpha} \\ & + \begin{pmatrix} \bar{a}+a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}{}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}{}^* & a_{\mu\tau}{}^* & a_{\tau\tau}\end{pmatrix}_{\beta\alpha}\Bigg\}, \end{aligned} \tag{9}$$

where $\bar{a}$ is the ordinary matter effect given by $2\sqrt{2}G_F n_e E_\nu$, $a_{\alpha\beta}$ is the extra matter effect due to new physics interactions, that is defined by $a_{\alpha\beta}=2\sqrt{2}\epsilon^m_{\alpha\beta}G_F n_e E_\nu$. Note that to consider the magnitude of the matter effect, the type of the interaction is irrelevant since in matter particles are at rest and hence the dependence on the chirality is averaged out.[6]

Finally we make a comment about new physics which affect a detection process. To consider this process we need the similar treatment to that at the decay process, that is, we have to separate contribution of new interactions following the difference of the chirality dependence. However to take into account new physics at a detector, the parton distribution and a knowledge about hadronization are necessary. Though we may wonder whether we can parameterize the effect of new physics at the detector g/G_T as ϵ^d like ϵ^s. It is expected that ϵ^d has a complicated energy dependence due to the parton distribution for example in a energy region of a neutrino factory. Consider the case that there is an elementary process from lepton flavor violating new physics including strange quark. To parameterize its effect we need both its magnitude and the distribution function of strange quark in nucleon which will show the dependence on the neutrino energy (more exactly, the transfered momentum from neutrino to strange quark). They are beyond our ability and hence we do not consider them further in this paper, though new physics which can affect the decay process have contribution to the detection process too.

3. Analysis

Let us discuss the feasibility to observe the signal induced by new physics. We will deal with a neutrino factory. For details see ref[3]. For the numerical calculation we use the parameters,

$$\begin{aligned}
&\sin\theta_{12} = \frac{1}{2}, \quad \sin\theta_{23} = \frac{1}{\sqrt{2}}, \quad \sin\theta_{13} = 0.1, \\
&\delta m_{21}^2 = 5\times 10^{-5}, \quad \delta m_{31}^2 = 3\times 10^{-3}, \\
&\delta = \frac{\pi}{2},
\end{aligned} \tag{10}$$

and take $|\epsilon| = 3\times 10^{-3}$, which is a reference value for the feasibility to observe the effect by using the method of the oscillation enhancement. Except for $\epsilon_{e\mu}^{s,m}$ and $\epsilon_{\mu e}^{s}$, the constraints of the processes of charged lepton have not forbidden this magnitude of ϵ's.

Here, we consider the case that there are only $(V-A)(V-A)$ type new interactions in the lepton sector. In this case the "oscillation probability" is given by eq.(7) in this situation.

The analytic expression of the probability for $\nu_e \to \nu_\mu$ given in the Appendix A of ref.[3]. It shows that the effect due to $\epsilon_{\mu\tau}^{m}$ and $\epsilon_{\alpha\alpha}^{s,m}$ are irrelevant since these terms are proportional to $\sin^2 2\theta_{13}\times\epsilon$ in the high energy region, so it is difficult to observe their effects. Therefore here as an example we consider the contribution of $\epsilon_{e\mu}^{s,m}$[2]. It can be represented analytically in the high energy region as

$$\begin{aligned}
&\Delta P_{\nu_e^s\to\nu_\mu}\{\epsilon_{e\mu}\} = 2 s_{23} s_{2\times 13} \\
&\times \Bigg[\left(s_\delta \mathrm{Re}[\epsilon_{e\mu}^s] - c_\delta \mathrm{Im}[\epsilon_{e\mu}^s]\right) \\
&\times \left\{ 1 - \frac{2}{3}\left(\frac{\bar a}{4E_\nu}L\right)^2 + \frac{2}{3}\left(2c_{2\times 13} - 3c_{23}^2 c_{13}^2\right) \right. \\
&\left. \times \left(\frac{\bar a}{4E_\nu}L\right)\left(\frac{\delta m_{31}^2}{4E_\nu}L\right)\right\}\left(\frac{\delta m_{31}^2}{4E_\nu}L\right) \qquad \text{(11a)} \\
&- \left(c_\delta \mathrm{Re}[\epsilon_{e\mu}^s] + s_\delta \mathrm{Im}[\epsilon_{e\mu}^s]\right) \\
&\times \left[\left\{ 1 - \frac{1}{3}\left(\frac{\bar a}{4E_\nu}L\right)^2 \right\}\left(\frac{\bar a}{4E_\nu}L\right) \right. \\
&- \left\{ 1 - 2s_{23}^2 c_{13}^2 - \left(1 - c_{13}^2\left(2 - \frac{4}{3}c_{23}^2\right)\right) \right. \\
&\left.\left. \times \left(\frac{\bar a}{4E_\nu}L\right)^2 \right\}\left(\frac{\delta m_{31}^2}{4E_\nu}L\right)\right]\left(\frac{\delta m_{31}^2}{4E_\nu}L\right) \\
&\qquad \text{(11b)} \\
&+ 2c_{23}^2\left(s_\delta \mathrm{Re}[\epsilon_{e\mu}^m] + c_\delta \mathrm{Im}[\epsilon_{e\mu}^m]\right) \\
&\left(\frac{\bar a}{4E_\nu}L\right)\left(\frac{\delta m_{31}^2}{4E_\nu}L\right)^2 \qquad \text{(11c)} \\
&+ 2\left(c_\delta \mathrm{Re}[\epsilon_{e\mu}^m] - s_\delta \mathrm{Im}[\epsilon_{e\mu}^m]\right) \\
&\times \left\{ 1 - \frac{1}{3}\left(\frac{\bar a}{4E_\nu}L\right)^2 \right. \\
&+ \left(c_{23}^2 s_{13}^2 + \frac{2}{3}s_{23}^2 c_{2\times 13}\right)\left(\frac{\bar a}{4E_\nu}L\right) \\
&\left. \times \left(\frac{\delta m_{31}^2}{4E_\nu}L\right)\right\}\left(\frac{\bar a}{4E_\nu}L\right)\left(\frac{\delta m_{31}^2}{4E_\nu}L\right)\Bigg]. \\
&\qquad \text{(11d)}
\end{aligned}$$

where $s_{2\times ij} \equiv \sin 2\theta_{ij}$. Since we can suppose that E_ν is proportional to E_μ in a neutrino factory, E_μ and L dependence of the sensitivity to each term

[2]The flavor changing processes between muon and electron, *e.g.*, $\mu\to e\gamma$, $\mu\leftrightarrow e$ conversion, are strictly constrained from experiments, and these constraints are related to $\epsilon_{e\mu}^s$[7]. Therefore, the magnitude of $\epsilon_{e\mu}^s$ has very severe bound. However here we ignore these constraints.

can be approximated as

$$\begin{aligned} \chi^2(11a) &\propto \left\{1 - \frac{2}{3}\left(\frac{\bar{a}}{4E_\mu}L\right)^2\right\}^2 \times E_\mu^2/L, \\ \chi^2(11b, 11d) &\propto \left\{1 - \frac{1}{3}\left(\frac{\bar{a}}{4E_\mu}L\right)^2\right\}^2 \times E_\mu^2, \\ \chi^2(11\mathrm{c}) &\propto E_\mu, \end{aligned} \tag{12}$$

In Fig.5 we see that the sensitivity is indeed understood by the high energy behavior of the transition rate.

In the realisitic situation, we probably do not exactly know the value of the theoretical parameters. Once the uncertainties for those values are introduced, the sensitivities shown in Figs.5 may be spoiled completely. The $\epsilon_{e\mu}^{s,m}$ effect can be absorbed easily into the main (unperturbed) part of the oscillation by adjusting the theoretical parameters since the effects have the same energy dependence as the main part has.

Indeed, taking into account these uncertainties, some of the sensitivities to $\epsilon_{e\mu}^{s,m}$ are completely washed out. Therefore, we have to look for the terms whose energy dependence differ from that of the main oscillation term in the high energy region. Contribution for the transition probability labeled (11a), (11b) and (11d) depends on $1/E_\mu$. Consequently, the sensitivities to the terms must be robust against the uncertainties of the theoretical parameters. Since in the high energy region there is no $1/E_\mu$ dependence of the oscillation probability they can be distinguished from the main oscillation part by observing the energy dependence. The claim mentioned above are confirmed numerically by Fig.5 and 6. By comparison of these graphs, we can see that the sensitivities to observe the contribution of (11a), (11b) and (11d) do not suffer from the uncertainties. Incidentally, we note that though the uncertainties wreck the sensitivity to (11c) since it is proportional to $1/E_\mu^2$, the $\epsilon_{e\mu}^{m}$ second order term brings constant contribution for energy and this signal does not vanish.

4. Summary

In this talk we study how well we can reach the flavor changing interaction in neutrino oscillation experiments. In general, we can summarize it as follows.

For a neutrino factory:

- In $\nu_\alpha \to \nu_\beta$, $(\alpha = e, \mu,\ \beta = e, \mu, \tau)$ appearance channel, the observable effects of new $(V-A)(V-A)$ interactions come only from $\epsilon_{\alpha\beta}^{s,m}$. The others are too small or too vulnerable against the adjustment of the theoretical parameters. Note that δ and ϵ's phase are correlated. Namely the measured values are a certain combination of δ and ϵ.

- In $\nu_\mu \to \nu_\mu$ disappearance channel, we can measure $\epsilon_{\mu\tau}^{s,m}$ depending on their phase. In other words, the signal includes information of the phase. Furthermore, there is no correlation between δ and ϵ, so the measurement tells us directly the phase concerning the lepton-flavor violating process. In $\nu_e \to \nu_e$ disappearance channel, we can not get anything for new interactions in the oscillation enhanced way.

- The χ^2 is proportional to $|\epsilon|^2$. The expected sensitivity is to $|\epsilon| \geq \mathcal{O}(10^{-4})$ by using this methodology.

- When the situations that new interactions exist not only in the source but also in the matter effect are considered, we can easily understand the sensitivity by simply adding each effect.

- Oscillation-enhanced effects for the $(V-A)(V+A)$ type interactions are strongly suppressed by m_e/m_μ, so we can not get an advantage over a direct measurement.

For an upgraded conventional beam:

- We do not have to care the types of new interactions in the source. The analyses for the feasibility are similar to that of $(V-A)(V-A)$ type for a neutrino factory. In the assumed energy and baseline region, there is no sensitivity to the new effect in matter.

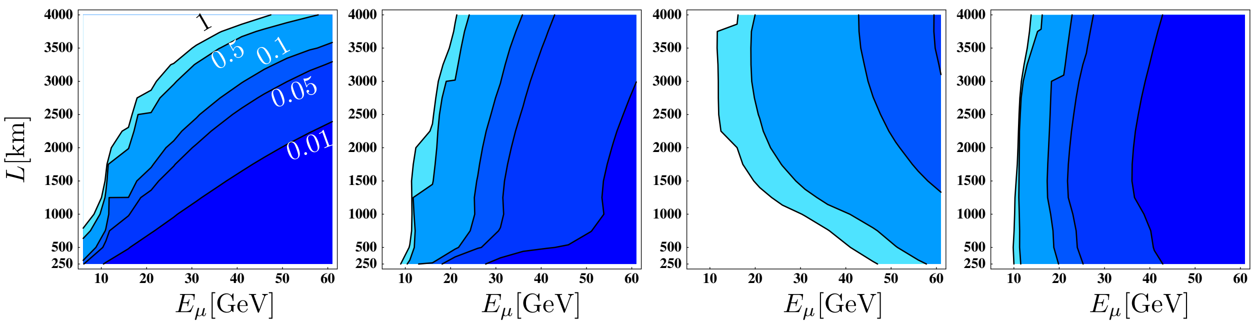

Figure 5. Contour plots of the required $N_\mu M_{\rm det}$ to observe the new physics effects concerning $\epsilon^{s,m}_{e\mu}$ at 90% C.L. in $\nu_e \to \nu_\mu$ channel when there is no uncertainty for theoretical parameters. From left to right: $(\epsilon^s_{e\mu}, \epsilon^m_{e\mu}) = (3.0\times 10^{-3}, 0)$, $(3.0 \times 10^{-3} i, 0)$, $(0, 3.0\times 10^{-3})$, $(0, 3.0\times 10^{-3} i)$. Each plot corresponds to the sensitivities to eq.(11a)$\sim$eq.(11d) respectively.

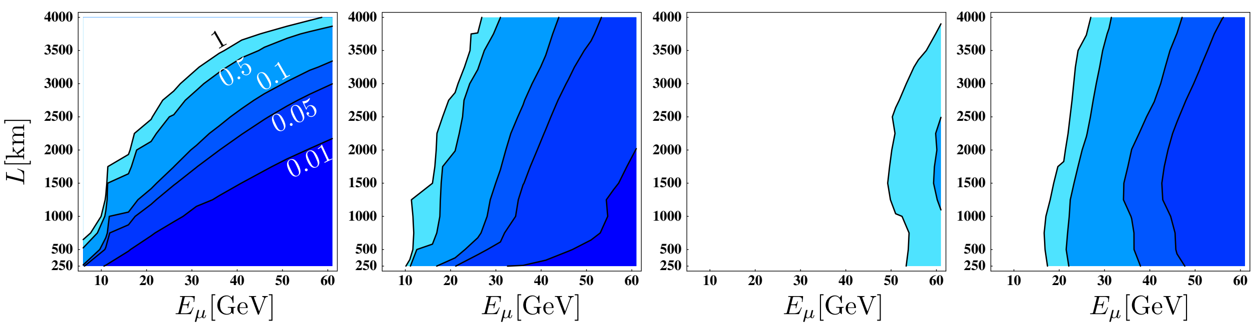

Figure 6. Same as Fig.5, but here each parameter has 10% uncertainty.

- The ϵ's for a conventional beam have different dependence from those for a neutrino factory on new interactions. Therefore, the comparison between two methods makes clear the species of new physics.

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