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Sterile neutrino oscillation at a neutrino factory

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We have investigated a neutrino factory potential to look for sterile neutrinos. We point out that the golden and the silver channels are not optimal to study (3+1) sterile neutrino models and the relevant channels are $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$. We have studied the sensitivity to θ_{13} and to the active-sterile mixing angles θ_{14}, θ_{24} and θ_{34} using both $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ channels at a neutrino factory. In this preliminary analysis, we have found that sensitivity limits in θ_{24} and θ_{34} are improved from the present bounds ($\theta_{24} \sim 12^\circ$ and $\theta_{34} \sim 30^\circ$) to about 1° and about 4°, respectively.

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1. Introduction

There have been a lot of effort to interpret the LSND data in terms of neutrino oscillations. Particularly after the negative result by MiniBooNE, however, it has become difficult to explain the anomaly by oscillations. Despite this situation, there still remains a possibility of a sterile neutrino scenario whose mixing angles are so small that it is consistent with all the present experimental data. It is therefore worth-while to study whether the present or future neutrino experiments can investigate the existence of sterile neutrinos. The CNGS potential to look for sterile neutrinos has been investigated in [1]. We will investigate a neutrino factory potential to look for sterile neutrinos.

2. Analytic formulae of oscillation probabilities

We will consider a (3+1) sterile neutrino model. In this model, we will make use of the following parametrization for the leptonic mixing matrix [1]:

$$U = R_{34}(\theta_{34})R_{24}(\theta_{24})R_{23}(\theta_{23},\ \delta_3)R_{14}(\theta_{14})R_{13}(\theta_{13},\ \delta_2)R_{12}(\theta_{12},\ \delta_1). \tag{2.1}$$

The mixing angle θ_{13} and the active-sterile mixing angle θ_{14} and θ_{24} are strongly bound [1]. On the other hand, the angle θ_{34} is weakly bound. The values of $\sin\theta_{13}$, $\sin\theta_{14}$, $\sin\theta_{24}$ and $\sin^2\theta_{34}$ are of the same order and we will expand the oscillation probabilities in powers of the four parameters. We only concentrate on heavy neutrinos, such that if m_4 is the mass of the neutrino eigenstate with a dominant sterile component, $\Delta m^2_{41} \approx \Delta m^2_{42} \approx \Delta m^2_{43} \gtrsim 0.1\mathrm{eV}^2$. Neglecting $\Delta m^2_{sol}/\Delta m^2_{41}$ and $\Delta m^2_{atm}/\Delta m^2_{41}$, we get the following difference of oscillation probabilities (3+1) sterile models from the three flavor ones in the first order expansion:

$$\begin{aligned}
\delta P_{ee} &\sim \delta P_{e\mu} \sim \delta P_{e\tau} \sim \delta P_{es} \sim O(s^2_{13}),\\
\delta P_{\mu\mu} &= -2(A_nL)s_{24}s_{34}\sin^2 2\theta_{23}\cos\delta_3 \sin\frac{\Delta m^2_{atm}L}{2E},\\
\delta P_{\mu\tau} &= -\sin^2 2\theta_{23}s^2_{34}\sin^2\frac{\Delta m^2_{atm}}{4E} + \{s_{24}s_{34}\sin\delta_3 + 2(A_nL)s_{24}s_{34}\cos\delta_3\}\sin\frac{\Delta m^2_{atm}L}{2E},\\
\delta P_{\mu s} &= \sin^2 2\theta_{23}s^2_{34}\sin\frac{\Delta m^2_{atm}L}{4E} - s_{24}s_{34}\sin\delta_3\sin\frac{\Delta m^2_{atm}L}{2E}.
\end{aligned} \tag{2.2}$$

where s_{ij} (i, j=1, 2, 3, 4) stands for $\sin\theta_{ij}$ and $A_n = G_F N_n/\sqrt{2}$, G_F is the Fermi constant and N_n is the number density of neutron. Because the differences of the δP_{ee}, $\delta P_{e\mu}$, $\delta P_{e\tau}$ and δP_{es} in eq.(2.2) are of the second order in the small parameters, $\nu_e \to \nu_x$ ($x = e, \mu, \tau, s$) and $\nu_x \to \nu_e$ channels are not suitable to distinguish (3+1) sterile neutrino models from three flavor ones. Thus, the golden and silver channels are not optimal to study (3+1) sterile neutrino models. On the contrary, because the difference of $P_{\mu\mu}$, $P_{\mu\tau}$ and $P_{\mu s}$ in eq.(2.2) are of the first order, these channels are suitable to distinguish a (3+1) sterile neutrino model from the three flavor one. Therefore, we will study (3+1) sterile neutrino oscillation using $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ channels.

3. Sensitivity to (3+1) sterile neutrinos at a neutrino factory

In this section, we will study the sensitivity to θ_{13} and to the active-sterile mixing angles θ_{14}, θ_{24} and θ_{34} using both $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ channels at a neutrino factory. The mixing angles have been fixed to $\theta_{12} = 34^\circ$ and $\theta_{23} = 45^\circ$. And the mass square differences have been fixed to $\Delta m^2_{21} = 8.0 \times 10^{-5}\mathrm{eV}^2$ and $\Delta m^2_{31} = 2.4 \times 10^{-3}\mathrm{eV}^2$. The CP-violating phases have been fixed $\delta_1 = \delta_2 = \delta_3 = 0$ for simplicity. In this preliminary analysis, we have assumed a neutrino factory with a 50 GeV muon beam directed at two ideal (no background and no systematic error) 50 kton far hybrid-MIND detectors [2] at 3000 km and 7500km away [1]. The number of muons in the storage ring is taken to be $2 \times 10^{20}/yr$ and we have assumed four years of running.

The first panel of fig1 from the left shows the sensitivity limits in θ_{13} and θ_{14}. This result consistent with eq.(2.2). The second panel of fig.1 shows the sensitivity limits in θ_{24} and θ_{34}. This result shows that the combination of the $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ channels has high sensitivity in both θ_{24} and θ_{34}. The sensitivity limits in θ_{24} and θ_{34} are improved from the present bounds ($\theta_{24} \sim 12^\circ$ and $\theta_{34} \sim 30^\circ$) to about 1° and about 4°, respectibely. The third and the fourth panels of fig.1 show the sensitivity limits for $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ channels at baseline lengths L=3000km and 7500km, respectively. These results show that the sensitivity limits in θ_{24} and θ_{34} at 3000km are improved to about 1° and 4° at 90% CL using the $\nu_\mu \to \nu_\tau$ channel, only, whereas the sensitivity limits in θ_{24} and θ_{34} at 7500km are improved to about 3° and 5° at 90% CL using the $\nu_\mu \to \nu_\mu$ channel.

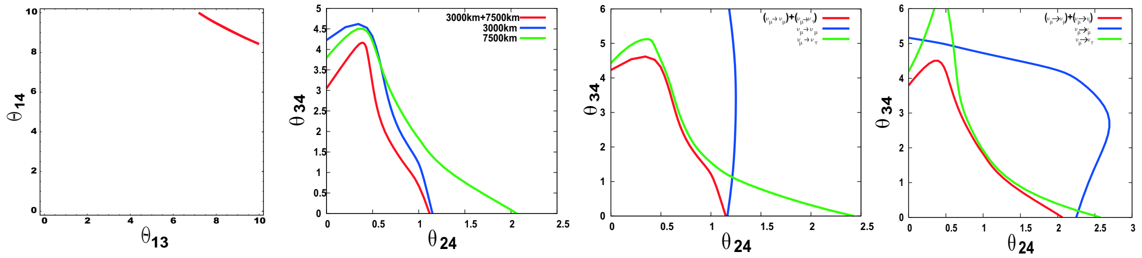

Figure 1: The first panel shows the sensitivity limit in θ_{13} and θ_{14}; The second panel shows the sensitivity limits in θ_{24} and θ_{34}: the blue curve corresponds to L=3000km. The green curve corresponds to L=7500km. The red curve corresponds to a result combining 3000km and 7500km; The third and the fourth panels show the sensitivity limits in θ_{24} and θ_{34} at 3000km and 7500km, respectively: The blue curve corresponds to the $\nu_\mu \to \nu_\mu$ channel. The green curve corresponds to the $\nu_\mu \to \nu_\tau$ channel. The red curve corresponds to a result combining both the channels.

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[1] After this workshop we have improved our analysis including the backgrounds, the efficiencies and the systematic errors at a Neutrino Factory for stored muon energies 50 GeV and 20 GeV [3].