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The sensitivity of the T2HKK experiment to the flavor-dependent non-standard interactions

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I discuss the possibility to test a hypothesis, in which the tension between the mass-squared differences obtained from the solar neutrino and KamLAND experiments may be solved by introducing the Non-Standard flavor-dependent Interaction in neutrino propagation, by the future long baseline neutrino experiments T2HKK as well as DUNE.

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Scenario	Experimental indication	Phenomenological constraint on the relative deviation
Light sterile ν [5]	Maybe	$O(10\%)$
NSI in propagation [6, 7, 8]	Maybe	$O(100\%)$ (for ν_e,ν_τ), $O(1\%)$ (for ν_μ)
NSI at production / detection [9]	None	$O(1\%)$
Unitatiry violation due to ν_R [10]	None	$O(0.1\%)$

Table 1: Various scenarios beyond the standard model with massive three neutrinos.

1. Introduction

By the successful neutrino experiments in the past, all the mixing angles and the mass squared differences have been measured [1], and the only unknown quantities which can determined by neutrino oscillation experiments are the mass hierarchy pattern, the octant of the mixing angle of the atmospheric neutrino oscillation and the CP violating phase. It is believed that these unknown quantities will be determined in the future neutrino experiments, including those with intense accelerator neutrino beams [2, 3, 4]. It is also expected that these future experiments with intense accelerator neutrino beams will enable us to probe new physics beyond the standard model with three massive neutrinos, by looking for the deviation from the standard scenario. The scenarios of new physics, which can be searched at the future neutrino experiments, include light sterile neutrinos [5], the Non-Standard flavor-dependent Interaction (NSI) in neutrino propagation [6, 7, 8], NSI at production / detection [9], Unitatiry violation due to right handed neutrinos [10]. As is indicated in table 1, the first two scenarios offer stronger phenomenological motivation because (i) there are experimental hints which may suggest these scenarios, (ii) the deviation of the oscillation probability for these scenarios could be potentially larger than those for the other scenarios and therefore it is encouraging for experimentalists to look for the effects of these scenarios.

Here I would like to consider NSI in neutrino propagation, which comes from the flavor-dependent nonstandard four-fermi interactions

$$\mathscr{L}_{\mathrm{eff}}^{\mathrm{NSI}} = -2\sqrt{2}\,\varepsilon_{\alpha\beta}^{fP} G_F \left(\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right)\left(\overline{f}\gamma^\mu P f\right), \tag{1.1}$$

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 $P_R \equiv (1+\gamma_5)/2$. (1.1) is the most general form of the interactions which conserve electric charge, color, and lepton number [11]. In the presence of these interactions (1.1), the flavor eigenstate $\Psi^T \equiv (\nu_e, \nu_\mu, \nu_\tau)$ of neutrino in matter satisfies the following equation of motion:

$$i\frac{d\Psi}{dt} = \left[U \mathrm{diag}\left(E_1, E_2, E_3\right) U^{-1} + \mathscr{A}\right]\Psi \quad \text{with} \quad \mathscr{A} = A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}, \tag{1.2}$$

where $\varepsilon_{\alpha\beta}$ are defined as $\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d}(n_f/n_e)\varepsilon^f_{\alpha\beta}$, 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.

In Refs. [12, 13] it was pointed out that there is a tension between the two mass squared differences extracted from the KamLAND and solar neutrino experiments. The mass squared difference Δm^2_{21} $(= 4.7 \times 10^{-5}\mathrm{eV}^2)$ extracted from the solar neutrino data is 2σ smaller than that from the KamLAND data Δm^2_{21} $(= 7.5 \times 10^{-5}\mathrm{eV}^2)$. The authors of Refs. [13] discussed the tension can be removed by introducing NSI in propagation. To discuss the effect of NSI on solar neutrinos, we reduce the 3×3 Hamiltonian in the Dirac equation Eq. (1.2) to an effective 2×2 Hamiltonian to get the survival probability $P(\nu_e \to \nu_e)$ because solar neutrinos are approximately driven by one mass squared difference Δm^2_{21} [13]. The survival probability $P(\nu_e \to \nu_e)$ can be written as

$$P(\nu_e \to \nu_e) = c^4_{13} P_{\mathrm{eff}} + s^4_{13}\,. \tag{1.3}$$

P_{eff} can be calculated by using the effective 2×2 Hamiltonian H^{eff} written as

$$H^{\mathrm{eff}} = \frac{\Delta m^2_{21}}{4E}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} c^2_{13}A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^{f*}_N & \varepsilon^f_D \end{pmatrix},$$

where ε^f_D and ε^f_N are linear combinations of the standard NSI parameters:

$$\begin{aligned} \varepsilon^f_D =&\; c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\mathrm{CP}}}\left(s_{23}\varepsilon^f_{e\mu} + c_{23}\varepsilon^f_{e\tau}\right)\right] - \left(1+s^2_{13}\right)c_{23}s_{23}\mathrm{Re}\left[\varepsilon^f_{\mu\tau}\right] \\ &- \frac{c^2_{13}}{2}\left(\varepsilon^f_{ee} - \varepsilon^f_{\mu\mu}\right) + \frac{s^2_{23} - s^2_{13}c^2_{23}}{2}\left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}\right) \qquad (1.4) \\ \varepsilon^f_N =&\; c_{13}\left(c_{23}\varepsilon^f_{e\mu} - s_{23}\varepsilon^f_{e\tau}\right) + s_{13}e^{-i\delta_{\mathrm{CP}}}\left[s^2_{23}\varepsilon^f_{\mu\tau} - c^2_{23}\varepsilon^{f*}_{\mu\tau} + c_{23}s_{23}\left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}\right)\right]. \qquad (1.5) \end{aligned}$$

Ref. [13] discussed the sensitivity of solar neutrino and KamLAND experiments to ε^f_D and real ε^f_N for one particular choice of $f = u$ or $f = d$ at a time. The best fit values from the solar neutrino and KamLAND data are $(\varepsilon^u_D, \varepsilon^u_N) = (-0.22, -0.30)$ and $(\varepsilon^d_D, \varepsilon^d_N) = (-0.12, -0.16)$ and that from the global analysis of the neutrino oscillation data are $(\varepsilon^u_D, \varepsilon^u_N) = (-0.140, -0.030)$ and $(\varepsilon^d_D, \varepsilon^d_N) = (-0.145, -0.036)$. These results give us a hint for the existence of NSI.

In the analysis of the long-baseline experiments and the atmospheric neutrino experiments, the dominant oscillation comes from the larger mass squared difference Δm^2_{31} and the oscillation probabilities are expressed in terms of $\varepsilon_{\alpha\beta}$ in addition to the standard oscillation parameters. While the results in Ref. [13] may suggest the existence of NSI, the parametrizations for the NSI parameters $(\varepsilon_D, \varepsilon_N)$ in Ref. [13] are different from the one with $\varepsilon_{\alpha\beta}$ and it is not clear how the allowed region in Ref. [13] will be tested or excluded by the future experiments. In Ref. [14], assuming the standard oscillation scenario, the excluded region in the $(\varepsilon_D, \varepsilon_N)$-plane by the atmospheric neutrino measurements at Hyper-Kamiokande was given. In this talk I discuss the sensitivity of the accelerator based neutrino measurements T2HKK [3] and DUNE [4] to NSI using the same parametrization as in Ref. [13]. This talk is based on the work [15] and the readers are referred to Ref. [15] for details.

2. Results

Assuming that Nature is described by the standard oscillation scheme and that the mass hierarchy is known, we have obtained χ^2 at each point in the $(\varepsilon^f_D, \varepsilon^f_N)$-plane for T2HKK and DUNE.

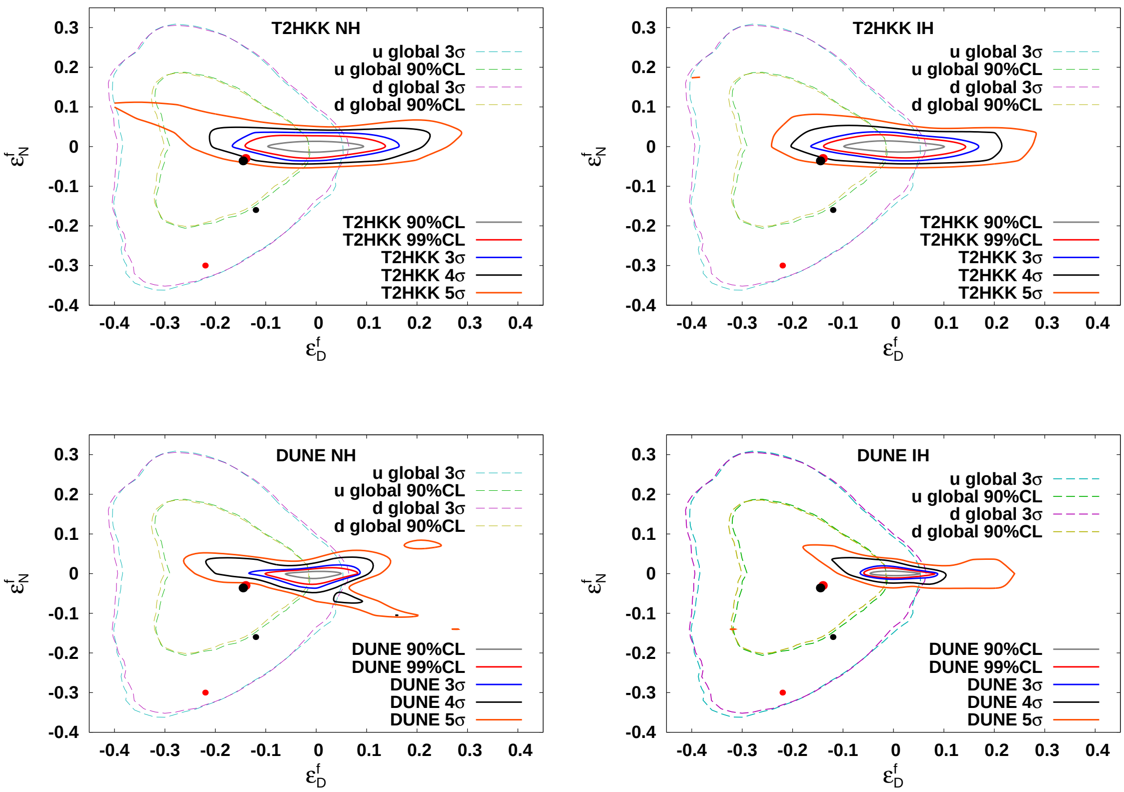

Figure 1: The excluded regions in the $(\varepsilon_D, \varepsilon_N)$ plane in the case of T2HKK and DUNE for $\delta_{CP} = -90^\circ$ and $\theta_{23} = 45^\circ$ (outside of the curves). The allowed regions at 90%CL and 3σ suggested by the global analysis [13] are also shown in dashed curves (inside of the curves). The large (small) red and black circles stand for the best fit points for the case of $f = u$ and $f = d$ from the global (solar + KamLAND) analysis [13], respectively.

The excluded regions at 90%CL, 99%CL, 3σ, 4σ, 5σ are shown in Fig. 1. The true oscillation parameters are $\sin^2 2\theta_{12} = 0.84$, $\Delta m^2_{21} = 7.8 \times 10^{-5}\mathrm{eV}^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2$, $\theta_{23} = 45^\circ$, $\sin^2 2\theta_{13} = 0.09$, $\delta_{CP} = -90^\circ$. For comparison, the allowed regions at 90%CL and 3σ suggested by the global analysis in Ref. [13] are also depicted. The large (small) red and black circles stand for the best fit points for the case of $f = u$ and $f = d$ from the global (solar + KamLAND) analysis respectively. The left column is for normal hierarchy ($\Delta m^2_{31} > 0$: NH) and the right column is for inverted hierarchy ($\Delta m^2_{31} < 0$: IH) whereas the first row is for T2HKK and the second row is for DUNE.

In general the sensitivity of DUNE is better than that of T2HKK. We observe that the both experiments will exclude some of the regions suggested by the global analysis, although it is difficult for the both experiments to exclude the region near the origin (the standard scenario). The best fit point of the combined analysis of the solar neutrino and KamLAND data by Ref. [13] can be excluded at more than 10σ, while the best fit point of the global analysis in Ref. [13] can be excluded at 3σ, by both T2HKK and DUNE. For T2HKK the sensitivity is same for both NH and IH whereas for DUNE the sensitivity in IH is slightly better than NH. It is remarkable that the ex-

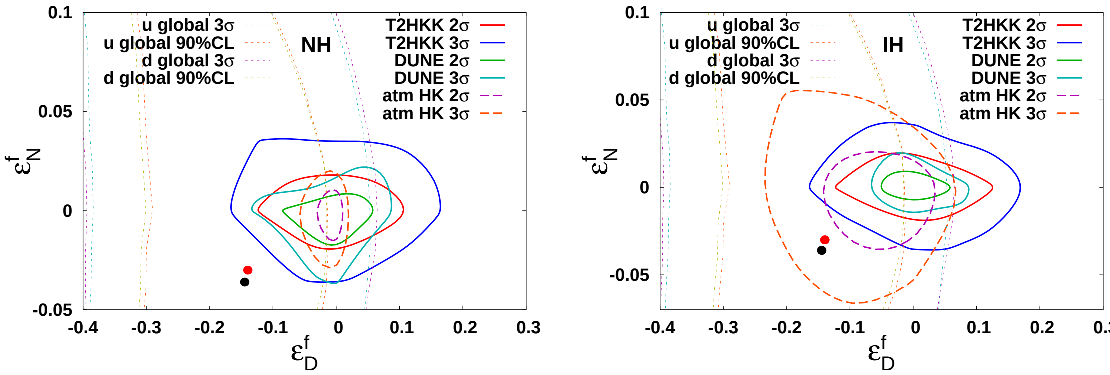

Figure 2: The excluded regions in the (ε_D, ε_N) plane in the case of T2HKK and DUNE for $\delta_{CP} = -90°$ and $\theta_{23} = 45°$ (outside of the curves). The allowed regions at 90%CL and 3σ suggested by the global analysis [13] are also shown in dashed curves (inside of the curves). The large (small) red and black circles stand for the best fit points for the case of $f = u$ and $f = d$ from the global (solar + KamLAND) analysis [13], respectively.

cluded region is relatively horizontal, i.e., the constraint is stronger in the direction of ε^f_N compared to the one of ε^f_D. This is because the appearance probability $P(\nu_\mu \to \nu_e)$ is sensitive to $|\varepsilon_{e\tau}| \sim |\varepsilon^f_N|$ while $\varepsilon^f_D \sim \varepsilon_{ee}$ changes the magnitude of the matter effect and the accelerator based long baseline experiments with energy $E_\nu \sim$ a few GeV and with baseline lengths $L \sim$(1000km) are not very sensitive to the matter effect.

For comparison with the HK atmospheric neutrino observation, which is analyzed in Refs. [14] and [16], in Fig. 2 we show the excluded regions at 2σ and 3σ for T2HKK, DUNE and the HK atmospheric neutrino observation. In the case of normal hierarchy, we can see from Fig. 2 that the sensitivity of the HK atmospheric neutrino experiment is better than that of the accelerator based experiments particularly with respect to ε_D. This is because the atmospheric neutrino experiment has information from a wide range of the baseline lengths up to the diameter of the Earth ($\sim$ 13000km) and it is more sensitive to the matter effect. On the other hand, in the case of inverted hierarchy, the sensitivity of the HK atmospheric neutrino experiment is inferior. This is because atmospheric neutrino experiments with water Čerenkovdetectors measure only the sum of neutrinos and antineutrinos, and there is a destructive phenomenon in which the deviations of the neutrino and antineutrino modes are averaged out [17]. In the case of the accelerator based experiments, which separately measure the neutrino and antineutrino modes, such a destructive phenomenon does not occur and the sensitivity for inverted hierarchy is almost the same as that for normal hierarchy.

3. Conclusion

In this talk I have discussed the sensitivity of the future accelerator based neutrino long baseline experiments, T2HKK and DUNE, to NSI which is suggested by the tension between the mass squared differences from the solar neutrino and KamLAND data. We have given the excluded regions in the in the (ε_D, ε_N) plane, and it turned out that the sensitivity of DUNE is slightly better than that of T2HKK. We found that the both experiments will exclude some of the regions suggested by the global analysis, although it is difficult for the both experiments to exclude the region near the standard scenario point. If there are no non-standard interactions in nature, then the best fit point of the combined analysis of the solar neutrino and KamLAND data by Ref. [13] can be excluded at more than 10σ, while the best fit point of the global analysis in Ref. [13] can be excluded at 3σ, by T2HKK and DUNE for most of the parameter space.

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