NON-STANDARD NEUTRINO PHYSICS PROBED BY TOKAI-TO-KAMIIOKA-KOREA TWO-DETECTOR COMPLEX

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Abstract. The discovery potentials of non-standard physics (NSP) which might be possessed by neutrinos are examined by taking a concrete setting of Tokai-to-Kamioka-Korea (T2KK) two detector complex which receives neutrino superbeam from J-PARC. We restrict ourselves into $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance measurement. We describe here only the non-standard interactions (NSI) of neutrinos with matter and the quantum decoherence. It is shown in some favorable cases T2KK can significantly improve the current bounds on NSP. For NSI, for example, $\varepsilon_{\mu\tau} < 0.03$, which is a factor 5 severer than the current one.

1 Introduction

The primary objective of the future neutrino oscillation experiments is of course to determine the remaining lepton mixing parameters, most notably CP violating phase and the neutrino mass hierarchy. Nonetheless, it is highly desirable that such facilities possesses additional physics capabilities such as exploring possible non-standard interactions (NSI) of neutrinos with matter. It will give us a great chance of discovering or constraining the extremely interesting new physics beyond neutrino mass incorporated Standard Model. Such additional capabilities are highly desirable because such projects would inevitably be rather costly, and it would become the necessity if a smoking gun evidence of new physics beyond the Standard Model is discovered in $\sim$TeV range.

Some of the present authors have proposed Tokai-to-Kamioka-Korea (T2KK) identical two detector complex which receives neutrino superbeam from J-PARC as a concrete setting for measuring CP violation and determining the mass hierarchy [1, 2]. In this manuscript we report, based on [3], discovery reach to the possible non-standard interactions of neutrinos and the quantum decoherence by the T2KK setting. See [3] for the sensitivities to the Lorentz invariance violation as well as the cases which are not treated in this report.

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2 Non-Standard Interactions (NSI) of Neutrinos

2.1 NSI; General feature

It has been suggested [4,5] that neutrinos might have non-standard interactions (NSI) which reflect physics outside Standard Model of electroweak interactions. The possibility of exploring physics beyond the neutrino mass incorporated Standard Model is so charming that the sensitivity reach of NSI would be one of the most important targets in the ongoing as well as future neutrino experiments. The latter include neutrino superbeam experiments, reactor $\theta_{13}$ experiments [6], beta beam, and neutrino factory [7]. See these references for numerous other references on hunting NSI. In this sense it is natural to investigate sensitivity reach of NSI by T2KK.

As a first step we examine the sensitivity to NSI by using $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance modes of T2KK. We of course make a comparison between discovery potentials of T2KK and Kamioka only (T2K II [8]) as well as Korea only settings. Our primary concern, however, is not to propose to use NSI sensitivity as a criterion of which setting is the best, but rather to understand how the sensitivity to NSI in T2KK is determined. (The real decision between various settings would require many other considerations.)

As is now popular, the effects of NSI are parametrized in a model independent way by $\varepsilon_{\alpha\beta}$ parameters ($\alpha, \beta = e, \mu, \tau$) in the matter sensitive term in the effective Hamiltonian in the flavor basis, $H_{\alpha\beta} = a(\delta_{\alpha e}\delta_{\beta e} + \varepsilon_{\alpha\beta})$, where $a \equiv \sqrt{2}G_F N_e$ with $G_F$ being the Fermi constant and $N_e$ electron number density in the earth. The existing constraints on $\varepsilon_{\alpha\beta}$ are worked out in [9].

When we restrict ourselves into the disappearance channel we can safely truncate the system into the $2 \times 2$ subsystem [3] as

$$
\frac{d}{dt} \begin{bmatrix} \nu_\mu \\ \nu_\tau \end{bmatrix} = \left[ U \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m_{32}^2}{2E} \end{pmatrix} U^\dagger + a \begin{pmatrix} 0 & \varepsilon_{\mu\tau} \\ \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} \end{pmatrix} \right] \begin{bmatrix} \nu_\mu \\ \nu_\tau \end{bmatrix},
$$

(1)

where $U$ is the flavor mixing matrix and $a \equiv \sqrt{2}G_F N_e$. Because of the form of the 2-2 element of the NSI term in the Hamiltonian, we set $\varepsilon_{\mu\mu} = 0$ and simply discuss the constraint on $\varepsilon_{\tau\tau}$ and $\varepsilon_{\mu\tau}$.

2.2 Sensitivity reach to NSI

We describe analysis results by skipping the details of the procedure by referring the readers [3] for it. The input values $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ are taken to be vanishing. The important point in correctly estimating the sensitivities is to marginalize over the lepton mixing parameters, in particular, $\Delta m_{32}^2$ and $\theta_{23}$.

To understand competition and synergy between the detectors in Kamioka and in Korea, and in particular, between the neutrino and the anti-neutrino
channels we present Fig. 1. We see from the figure that the Kamioka detector is more sensitive to NSI than the Korean detector, probably because of the higher event rate by a factor of $\simeq 10$. The synergy between the neutrino and the anti-neutrino channels is striking; Neither neutrino only nor anti-neutrino only measurement has sensitivity comparable to that of $\nu$ and $\bar{\nu}$ combined.

We present in Fig. 2 the sensitivity to NSI by T2KK and its dependence on $\theta_{23}$. The approximate $2 \sigma$ CL (2 DOF) sensitivities of the Kamioka-Korea setup for $\sin^2 \theta = 0.45$ ($\sin^2 \theta = 0.5$) are: $|\varepsilon_{\mu\tau}| < 0.03$ (0.03) and $|\varepsilon_{\tau\tau}| < 0.3$ (1.3). Here, we neglected a barely allowed region near $|\varepsilon_{\tau\tau}| = 2.3$, which is already excluded by the current data. Notice that T2KK has potential of (almost) eliminating the island regions. The disparity between the sensitivities to $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ can be understood by using the analytic formula as discussed in [3]. The figure also contain the comparison between discovery reach of NSI by the Kamioka-only setting, the Korea-only setting, and T2KK.
Figure 2: The allowed regions in $\varepsilon_{\mu\tau} - \varepsilon_{\tau\tau}$ space for 4 years neutrino and 4 years anti-neutrino running. The upper, the middle, and the bottom three panels are for the Kamioka-only setting, the Korea-only setting, and the Kamioka-Korea setting, respectively. The left and the right panels are for cases with $\sin^2 \theta \equiv \sin^2 \theta_{23} = 0.45$ and 0.5, respectively. The red, the yellow, and the blue lines indicate the allowed regions at 1$\sigma$, 2$\sigma$, and 3$\sigma$ CL, respectively.

The input value of $\Delta m^2_{32}$ is taken as $2.5 \times 10^{-3}$ eV$^2$. The figure is taken from [3].

3 Quantum Decoherence

Though there is really no plausible candidate mechanism for quantum decoherence, people talk about it mainly because it can be one of the alternative models for “neutrino deficit”, namely, a rival of the neutrino oscillation. It is well known that quantum decoherence modifies the neutrino oscillation probabilities. The two-level system in vacuum in the presence of quantum decoherence can be solved to give the $\nu_\mu$ survival probability [10, 11]:

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2} \sin^2 2\theta \left[1 - e^{-\gamma(E)L} \cos \left(\frac{\Delta m^2_{32} L}{2E} \right)\right], \quad (2)$$
with $\gamma(E) > 0$, the parameter which controls the strength of decoherence effect.

The most stringent constraints on decoherence obtained to date are by atmospheric neutrino observation ($\gamma = \gamma_0 (E/\text{GeV})^2 < 0.9 \times 10^{-27} \text{ GeV}$, energy-independent $\gamma < 2.3 \times 10^{-23} \text{ GeV}$, [10], and solar and KamLAND experiments ($\gamma = \gamma_0 (E/\text{GeV})^{-1} < 0.8 \times 10^{-26} \text{ GeV}$) [12]. (A particular underlying mechanism for decoherence, if any, may have some characteristic energy dependence.) Yet, such study is worth pursuing in various experiments and in varying energy regions because of different systematic errors, and for unknown energy dependence of $\gamma$. That was our motivation for investigating the sensitivity to quantum decoherence achievable in T2KK.

In Fig. 3 presented is the allowed region of the decoherence parameter $\gamma$ as a function of true values of $\sin^2 2\theta_{23}$ (left panel) and $\Delta m^2$ (right panel). This is the case of energy independent $\gamma$. In this case T2KK can improve the current bound on decoherence by a factor of 3. It is also obvious that the sensitivity to decoherence reachable by the T2KK setting far exceeds those of Kamioka-only setting, though the sensitivity by Korea-only setting is not so bad.

For cases with alternative energy dependences of $\gamma$ and for other additional non-standard physics, see [3]. Most notably, more than 3 orders of magnitude improvement is expected in Lorentz-CPT violating parameter.
4 Conclusion

In searching for additional physics potential of the Kamioka-Korea two-detector setting which receives an intense neutrino beam from J-PARC, we have investigated its sensitivities to non-standard physics of neutrinos. It was shown that T2KK can significantly improve the current bounds on quantum decoherence and NSI in some favorable cases.

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References

[1] M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, Phys. Rev. D 72, 033003 (2005) [arXiv:hep-ph/0504026].
[2] T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, Phys. Rev. D 75, 013006 (2007) [arXiv:hep-ph/0609286].
[3] N. Cipriano Ribeiro, T. Kajita, P. Ko, H. Minakata, S. Nakayama and H. Nunokawa, arXiv:0712.4314 [hep-ph].
[4] L. Wolfenstein, Phys. Rev. D 17, 2369 (1978).
[5] Y. Grossman, Phys. Lett. B 359, 141 (1995) [arXiv:hep-ph/9507344].
[6] J. Kopp, M. Lindner, T. Ota and J. Sato, arXiv:0708.0152 [hep-ph].
[7] N. Cipriano Ribeiro, H. Minakata, H. Nunokawa, S. Uchimani and R. Zukanovich Funchal, JHEP 12, 002 (2007) arXiv:0709.1980 [hep-ph].
[8] Y. Itow et al., arXiv:hep-ex/0106019. For an updated version, see: http://nucl-ex.kek.jp/jhfnu/loi/loi.v2.030528.pdf
[9] N. Fornengo, M. Maltoni, R. T. Bayo and J. W. F. Valle, Phys. Rev. D 65, 013010 (2002) [arXiv:hep-ph/0108043]. S. Davidson, C. Penag-Garay, N. Rius and A. Santamaria, JHEP 0303, 011 (2003) [arXiv:hep-ph/0302093]. J. Abdallah et al. [DELPHI Collaboration], Eur. Phys. J. C 38, 395 (2005) [arXiv:hep-ex/0406019].
[10] E. Lisi, A. Marrone and D. Montanino, Phys. Rev. Lett. 85, 1166 (2000) [arXiv:hep-ph/0002053]. G. L. Fogli, E. Lisi, A. Marrone and D. Montanino, Phys. Rev. D 67, 093006 (2003) [arXiv:hep-ph/0303064];
[11] F. Benatti and R. Floreanini, JHEP 0002, 032 (2000) [arXiv:hep-ph/0002221]; Phys. Rev. D 64, 085015 (2001) [arXiv:hep-ph/0105303].
[12] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, Phys. Rev. D 76, 033006 (2007) [arXiv:0704.2568 [hep-ph]].