Resolve the Neutrino Parameter Degeneracies with the T2K Off-axis Beam and the Large Detector in Korea 1

Naotoshi Okamura 2

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan.

Abstract. In this talk, we show the physics impacts of putting a large Water Čerenkov detector in Korea during the T2K experimental period. The T2K experiment which will start in 2009 plans to use the high intensity conventional neutrino beam from J-PARC at Tokai village, Japan. The center of this beam will reach the sea level between Japan and Korea, and an off-axis beam at 0.5° to 1.0° can be observed in Korea. For a combination of the 3° off-axis beam at SK with baseline length $L = 295$km and the 0.5° off-axis beam in the east coast of Korea, near Gyeongju, at $L = 1000$km, we find that the neutrino mass hierarchy (the sign of the larger mass-squared difference) can be resolved and the CP phase of the MNS unitary matrix can be constrained uniquely at 3-$\sigma$ level when $\sin^2 2\theta_{\text{rct}} > 0.06$.

The results of solar and atmospheric neutrino oscillation experiments are consistent with the 3 neutrino model, which has 6 observable parameters in neutrino oscillation experiments. They are 2 mass-squared differences, 3 mixing angles, and one CP phase. The atmospheric neutrino oscillation experiments determine the absolute value of the larger mass-squared difference ($\delta m^2_{\text{atm}} = \delta m^2_{13}$) and one mixing angle ($\theta_{\text{atm}}$) [2] as

$$1.5 \times 10^{-3} < |\delta m^2_{13}| = |m^2_3 - m^2_1| < 3.4 \times 10^{-3} \text{eV}^2,$$

$$0.92 < \sin^2 2\theta_{\text{atm}}$$

at the 90% confidence level. The K2K experiment [3] confirms the above results. The solar neutrino experiments [4] and the KamLAND experiment [5] determine the smaller mass-squared difference ($\delta m^2_{\text{sol}} = \delta m^2_{12}$) and another mixing angle ($\theta_{\text{sol}}$) as

$$\delta m^2_{12} \equiv m^2_2 - m^2_1 = 8.2^{+0.6}_{-0.5} \times 10^{-5} \text{eV}^2,$$

$$\tan^2 \theta_{\text{sol}} = 0.40^{+0.09}_{-0.07}. \quad (2)$$

The CHOOZ reactor experiment [6] gives the upper bound of the third mixing angle ($\theta_{\text{rct}}$) as

$$\sin^2 2\theta_{\text{rct}} < 0.16 \text{ for } |\delta m^2_{13}| = 2.5 \times 10^{-3} \text{eV}^2, \quad (3)$$

at the 90% confidence level. The CP phase ($\delta_{\text{MNS}}$) has not been constrained. In the future neutrino oscillation experiments, we should not only measure $\sin^2 2\theta_{\text{rct}}$ and $\delta_{\text{MNS}}$, but also resolve the parameter degeneracies [7–9], such as the sign of $\delta m^2_{13}$. These parameters are related to the MNS [13] matrix elements as $\sin^2 \theta_{\text{rct}} = |U_{e3}|^2$, $\sin^2 \theta_{\text{atm}} = |U_{\mu3}|^2$, $\sin^2 \theta_{\text{sol}} = 4|U_{e1}|^2|U_{e3}|^2$. The other elements are obtained from the unitary conditions [14, 15].

In this talk, we discuss the possibility of detecting in Korea the neutrino beam from J-PARC (Japan Proton Accelerator Complex) at Tokai village [10], that will be available during the period of the T2K (Tokai-to-Kamioka) experiment [11]. In the T2K experiment, the center of the neutrino beam will reach the sea level near the east coast of Korea. At the baseline length $L = 295$km away from J-PARC, the upper side of the beam at 0° to 3° off-axis angle is observed at Super-Kamiokande (SK), whose fiducial volume is 22.5kt, and the lower side of the same beam at 0.5° to 3.0° appears in the east coast of Korea [1, 12], at about $L = 1000$km; see Figs.1,2.

In order to quantify our investigation, we study physics impacts of putting a 100kt-level water Čerenkov detector, which allows us to distinguish clearly $e^\pm$ events from $\mu^\pm$ events, in Korea, during the T2K experiment period, which is for 5 years with $10^{21}$ POT per year. As of today, September 2005, there is no proposal to construct a huge water Čerenkov detector in Korea, but we investigate the prospect of the neutrino oscillation experiment with two detector putting the different baseline length.

We use the Charged-Current-Quasi-Elastic (CCQE) events in our analysis, because they allow us to reconstruct the neutrino energy by measuring the strength and the orientation of the Čerenkov lights. Since the Fermi-motion effect of the target dominates the uncertainty of the neutrino energy reconstruction, about 80 MeV, in the following analysis we take the width of the energy bin as $\delta E_\nu = 200$ MeV for $E_\nu > 400$ MeV. The event
FIGURE 1. The off-axis angle of the neutrino beam from J-PARC on the sealevel when the beam center is 2.5° off at SK. The baseline length for \( L = 200, 400, 600, 800, 1000, 1200 \text{km} \) are shown by vertical lines, and closed curves stand for the off-axis angle between 0.5° and 4.0° with 0.5° step.

FIGURE 2. The magnified figures around Korea, when the beam center is 2.5° (left) and 3.0° (right) off at SK. The baseline length for \( L = 1000, 1100, 1200 \text{km} \) are shown by vertical contours, and the off-axis angles are shown by elliptic contours between 0.5° and 4.0°. The interval of each line is 0.5°.

numbers in the \( i \)-th energy bin, \( E_i^\nu < E_\nu < E_{i+1}^\nu \) where \( E_i^\nu = \delta E_\nu \times (i+1) \), are then calculated as

\[
N_i^\beta(\nu_\alpha) = N \int_{E_i^\nu}^{E_{i+1}^\nu} \Phi_{\nu_\alpha}(E) \cdot P_{\nu_\alpha \rightarrow \nu_\beta}(E) \cdot \sigma_{QE}^\beta(E) \, dE, \tag{4}
\]

where \( P_{\nu_\alpha \rightarrow \nu_\beta} \) is the neutrino oscillation probability including the matter effect, \( N \) is the number of target nucleons, \( \Phi_{\nu_\alpha} \) is the \( \nu_\alpha \) flux from J-PARC, and \( \sigma_{QE}^\beta \) is the CCQE cross section of \( \nu_\beta \) per nucleon in water. We include the contribution from the secondary neutrino flux of the \( \nu_\mu \) primary beam as the background events for the signal \( e^- \) and \( \mu^- \)-like events. After summing up the events from all flux, the \( e^- \)-like and \( \mu^- \)-like events for the \( i \)-th bin are obtained as

\[
N_i^{e,M} = N_i^{e}(\nu_\mu) + N_i^{e}(\nu_e) + N_i^{\mu}(\bar{\nu}_e) + N_i^{\mu}(\bar{\nu}_\mu), \tag{5}
\]

where \( \alpha = e \) and \( \mu \). In this analysis, we do not add the background from \( \tau \) pure leptonic decay because the beam intensity above the \( \tau \)-lepton production threshold is small, even for the 0.5° off-axis beam which has the hardest spectrum in our analysis. We also do not add the events from the Neutral Current interactions and from the Deep Inelastic Scattering which induce the misidentification for the signal event.

Since our concern is the possibility to distinguish the neutrino mass hierarchy and to measure \( \sin^2 2\theta_{\text{ext}} \) and \( \delta_{\text{MNS}} \), we study how the above “data”, to be gathered both at SK and a detector in Korea, can constrain the model parameters by using the \( \chi^2 \) function

\[
\chi^2 = \chi^2_{\text{SK}} + \chi^2_{\text{Kr}} + \chi^2_{\text{sys}} + \chi^2_{\text{para}}, \tag{6}
\]

Here the first two terms, \( \chi^2_{\text{SK}} \) and \( \chi^2_{\text{Kr}} \), measure the parameter dependence of the fit to the SK and the Korean detector data,

\[
\chi^2_{\text{SK,Kr}} = \sum_i \sum_{\alpha=e,\mu} \left( \frac{(N_i^\alpha(\nu_\alpha))^\text{fit} - (N_i^\alpha(\nu_\alpha))^\text{true}}{\sqrt{(N_i^\alpha(\nu_\alpha))^\text{true}}} \right)^2, \tag{7}
\]

where the summation is over all bins up to 5.0GeV for \( N_{\nu_\mu} \), 1.2GeV for \( N_e \) at SK, and 2.8GeV for \( N_e \) at Korea. We calculate \( (N_i^\alpha(\nu_\alpha))^\text{true} \) by assuming the following input
with the constant matter density, \( \rho_{\text{true}} = 2.8 \text{ g/cm}^3 \) for T2K and \( \rho_{\text{true}} = 3.0 \text{ g/cm}^3 \) for the Tokai-to-Korea experiments. Note that in eq. (8), we assume the normal hierarchy \( (\delta m^2_{13} > 0) \) as input (“true”) and examine several input values of \( \sin^2 2\theta_{\text{atm}} \) and \( \delta_{\text{MNS}} \). The fitting event number is calculated by allowing the model parameters to vary freely and by allowing for systematic errors. In our analysis, we assign 3% errors: i. the normalization of each neutrino flux, ii. the CCQE cross sections of the \( \nu_{\tau} \) and \( \bar{\nu}_\mu \) and \( \bar{\nu}_\tau \), the effective matter density along the each baseline, to SK and to Korea, and iv. the fiducial volume of SK and the Korean detector. These systematic errors make the third term of eq.(6), \( \chi^2_{\text{sys}} \). The last term in eq.(6), \( \chi^2_{\text{para}} \) accounts for the present constraints on the model parameters. Here we interpret the 90% CL lower bound on \( \sin^2 2\theta_{\text{atm}} \) in eq. (1) as the 1.96\( \sigma \) constraint from \( \sin^2 2\theta_{\text{atm}} = 1 \pm 0.04 \), and the asymmetric error for \( \tan^2 \theta_{\text{sol}} \) in eq. (2) has been made more symmetric for \( \sin^2 2\theta_{\text{sol}} = 0.84 \pm 0.07 \). The error of each mass-squared differences is \( 0.5 \times 10^{-3} \text{eV}^2 \) for \( |\delta m^2_{13}| \) and \( 0.6 \times 10^{-3} \text{eV}^2 \) for \( \delta m^2_{12} \). We do not include the bounds on \( \sin^2 2\theta_{\text{ct}} \) in eq. (3), in our \( \chi^2 \) function. In total, our \( \chi^2 \) function depends on 16 parameters, the 6 model parameters and the 10 normalization factors.

First, we search for the best place for the detector in Korea and the best combination of the off-axis angle for SK and the Korean detector to determine the sign of \( \delta m^2_{13} \). We show in Fig.3 the \( \delta \chi^2 \) as functions of the off-axis angle and the baseline length in Korea, when the data are generated for the normal hierarchy with eq. (8), and the fit has been performed by assuming the inverted hierarchy. We set \( \sin^2 2\theta_{\text{atm}}^{\text{true}} = 0.10 \) and \( \delta_{\text{MNS}}^{\text{true}} = 0^\circ \) in this analysis. The left hand figure shows the \( \delta \chi^2 \) for the 2.5\(^\circ\) off-axis beam at SK, and the right hand one is for the 3.0\(^\circ\) beam. The four symbols, solid circle, open circle, triangle, and square are for \( L = 1000\text{km}, 1050\text{km}, 1100\text{km}, \) and \( 1150\text{km} \), respectively. When the off-axis angle at SK is 2.5\(^\circ\), the 0.5\(^\circ\) beam does not reach the Korean coast; see Fig. 2. It is clear from these figures that the best discriminating power is obtained for the combination \( L = 1000\text{km} \) and 0.5\(^\circ\), which is available only when the off-axis angle at SK is 3.0\(^\circ\) (right figure). For this combination, we can distinguish the inverted hierarchy from the normal one at more than 4\( \sigma \) level. For the same baseline length, lower off axis angle beams give better discriminating power because the neutrino flux with smaller off-axis angle is harder [11, 16], and the stronger matter effect to help us distinguish the neutrino mass hierarchy [9, 15, 17].

We also examine the capability of the Tokai-to-Korea long baseline experiments for measuring the CP phase. We show in Fig. 4 regions allowed by this experiment in the plane of \( \sin^2 2\theta_{\text{ct}} \) and \( \delta_{\text{MNS}} \). The mean values of the inputs are calculated for the parameters of eq. (8). In each figure, the input points \( (\sin^2 2\theta_{\text{ct}}^{\text{true}} = 0.10, \delta_{\text{MNS}}^{\text{true}} = 0.06, \delta_{\text{MNS}}^{\text{true}} = 0^\circ, 90^\circ, 180^\circ, 270^\circ) \) (8)

\[
\begin{align*}
(\delta m^2_{13})^{\text{true}} &= 2.5 \times 10^{-3} \text{eV}^2 (> 0), \\
(\delta m^2_{12})^{\text{true}} &= 8.3 \times 10^{-5} \text{eV}^2, \\
(\sin^2 2\theta_{\text{atm}})^{\text{true}} &= 0.5, \\
(\sin^2 2\theta_{\text{sol}})^{\text{true}} &= 0.84, \\
(\sin^2 2\theta_{\text{ct}})^{\text{true}} &= 0.1, 0.06, \\
(\delta_{\text{MNS}})^{\text{true}} &= 0^\circ, 90^\circ, 180^\circ, 270^\circ,
\end{align*}
\]

FIGURE 3. \( \delta \chi^2 \) as functions of the off-axis angle and the baseline length from J-PARC, when the normal hierarchy \( (\delta m^2_{13} = 2.5 \times 10^{-3} \text{eV}^2 > 0) \) with \( \sin^2 2\theta_{\text{ct}} = 0.10 \) and \( \delta_{\text{MNS}} = 0^\circ \) is assumed in generating the data events, and the inverted hierarchy \( (\delta m^2_{13} < 0) \) is assumed in the fit. The left hand figure is for the 2.5\(^\circ\) off-axis beam at SK, and the right hand one is for the 3.0\(^\circ\) beam.

constrained to $\pm 30^\circ$ at $1\sigma$ level, when $\sin^2 2\theta^\text{true}_{\text{osc}} > 0.06$. It is remarkable that we can distinguish between $\delta^\text{true}_{\text{MNS}} = 0^\circ$ and $180^\circ$, which has been found difficult in previous studies [7, 9, 18].

In this talk, we present the possibility of solving the degeneracy of the neutrino mass hierarchy and constraining $\sin^2 2\theta^\text{osc}$ and $\delta^\text{true}_{\text{MNS}}$ uniquely by measuring the T2K off-axis beam in Korea.

ACKNOWLEDGMENTS

I thank our colleagues Y. Hayato, A.K. Ichikawa, T. Ishii, I. Kato, T. Kobayashi and T. Nakaya, learn about the K2K and T2K experiments.

REFERENCES

1. K. Hagiwara, N. Okamura, K. Senda, hep-ph/0504061.
2. The Super-Kamiokande Collaboration (Y. Ashie et al.), Phys. Rev. Lett. 93, 101801 (2004) [hep-ex/0404034]; hep-ex/0501064.
3. K2K Collaboration (E. Aliu et al.), Phys. Rev. Lett. 94, 081802 (2005) [hep-ex/0411038].
4. B. Kayser, in Review of Particle Physics, Phys. Lett. B592 (145) 2004, and references therein.
5. The KamLAND Collaboration (T. Araki et al.), Phys. Rev. Lett. 94, 081801 (2005) [hep-ex/0406035].
6. The CHOOZ Collaboration (M. Apollonio et al.), Eur. Phys. J. C27, 331 (2003) [hep-ex/0301017].
7. M. Koike, T. Ota, J. Sato, Phys. Rev. D65, 053015 (2002) [hep-ph/011387]; J. Burguet-Castell, M.B. Gavela, J.J. Gomez-Cadenas, P. Hernandez, O. Mena, Nucl. Phys. B608, 301 (2001) [hep-ph/0103258].
8. H. Minakata, H. Nonokawa, JHEP 0110, 001 (2001) [hep-ph/0108085].
9. V. Barger, D. Marfatia, K. Whisnant, Phys. Rev. D65, 073023 (2002) [hep-ph/0112119].
10. I-PARC home page, http://i-parc.jp/.
11. Y. Itow et al. (JHF-Kamioka neutrino Project), hep-ex/0106019; see also the JHF Neutrino Working Group’s home page, http://neutrino.kek.jp/jhfnu/.
12. K. Hagiwara, Nucl. Phys. Proc. Suppl. 137, 84 (2004) [hep-ph/0410229].
13. Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).
14. K. Hagiwara and N. Okamura, Nucl. Phys. B548, 60 (1997).
15. M. Aoki et al., Phys. Rev. D67, 093004 (2003) [hep-ph/0112338].
16. A.K. Ichikawa, private communication.
17. P. Lipari, Phys. Rev. D61, 113004 (2000) [hep-ph/9903481]; V. Barger, S. Geer, R. Raja, K. Whisnant, Phys. Lett. B485, 379 (2000) [hep-ph/0004208].
18. M. Aoki, K. Hagiwara, N. Okamura, Phys. Lett. B606 (371) 2005 [hep-ph/0311324].