Implication of a large $\theta_{13}$ for the Tokai to Kamioka and Korea setup

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Abstract. In this paper, I present the implications of the large value of $\theta_{13}$ on the Tokai to Kamioka and Korea setup (T2KK). I study the sensitivity of T2KK when using a 750 kW beam (the design luminosity of T2K planned to be achieved by 2017) and a potential 1.66 MW upgraded beam. In addition I compare the capability of the T2KK setup with the T2HK letter of intent.

Keywords: t2kk, neutrino, theta13, mass hierarchy, CP phase

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INTRODUCTION

Previous studies [1, 2] have shown the potential of placing two very large Water Cherenkov detectors in the T2K beam. By placing one Mton detector at 295 km (in Kamioka) and another one at about 1000 km (in Korea), one is able to observe the first and the second oscillation maxima in Kamioka and Korea respectively. In addition if the Korean detector is located approximately on-axis (1 degree is the smallest angle available in Korea), then the beam is wide-band and the Korean detector will be able to observe the first and the second oscillation maxima, as it can be seen in Figure 1. Therefore with a detector at 2.5 degree off-axis in Kamioka and a detector at 1 degree off-axis in Korea, it is possible to measure three types of oscillation maxima (the first maximum at two baselines, and the second in Korea) [2]. Such a redundancy is an excellent tool to measure the mass hierarchy and the CP phase. Previous studies have shown this potential, but in this paper, I update the study to account for the large value of $\theta_{13}$ measured in 2011-2012 and present its implications [3, 4, 5, 6]. In addition, I compare my results with those presented in the Hyper-K letter of intent [7].

EXPERIMENTAL SETUPS

For this study I assumed two Mton size water Cherenkov detectors. It was shown previously that a photo-coverage of 20% is equivalent to a photo-coverage of 40%. The capability for rejecting neutral current background was shown to be around 68% in both cases [2]. In Table 1 I present the experimental parameters that were chosen for this study. In addition to the experimental parameters, I have assumed that $\sin^2 2\theta_{13} = 0.1$ when showing event spectra and I have assumed that the remaining oscillation parameters are: $\Delta m^2_{21,31} = 8.0 \times 10^{-5}, 2.5 \times 10^{-3} \text{eV}^2$, and $\sin^2 2\theta_{12,23} = 0.86, 1.0$. We take the earth density to be constant and equal to 2.8 g/cm$^3$.

FIGURE 1. (Color online) Neutrino flux as a function of energy for several off-axis angles, and a 0.75 MW beam at 1050 km from the target. For comparison, the $\nu_{\mu} \rightarrow \nu_e$ probability, for two baselines considered for T2KK (295km and 1050km). Neutrino mixing parameters are: normal hierarchy, $\Delta m^2_{21,31} = 8.0 \times 10^{-5}, 2.5 \times 10^{-3} \text{eV}^2$, and $\sin^2 2\theta_{12,23} = 0.86, 1.0$. We take the earth density to be constant and equal to 2.8 g/cm$^3$. 
TABLE 1. List of experimental parameters

|                | T2HK                | T2KK                |
|----------------|---------------------|---------------------|
| Volume         | 0.56 Mton           | 2 × 0.28 Mton       |
| Baseline       | 295 km              | 295 km + 1050 km    |
| Off-axis angle | 2.5°                | 2.5°+1.0°           |
| Time (ν + ¯ν)  | 3+7 years           | 5+5 years           |
| POT equivalent | Beam power          | Proton energy       |
|                | 0.75 or 1.66 MW     | 30 GeV              |
|                | One year            | 10^7 seconds        |

### POTENTIAL OF A 750 KW BEAM VERSUS A 1.66 MW BEAM

In previous studies, the major concern was always the value of θ_{13} and therefore we always envisioned that a very high power beam was necessary. With the large value of θ_{13} measured in 2012, this is not true anymore and in the case of T2KK, the 750 kW beam designed for T2K is enough to measure the mass hierarchy and the CP phase. Of course, if a 1.66 MW beam was built, the same sensitivity would be achieved twice as fast or a detector twice as small could be used. Figure 2 shows the event spectra in Kamioka (2.5 degree off-axis) and Korea (1 degree off-axis) for a 750 kW beam and a 1.66 MW beam. The rest of the parameters are the ones presented in Table 1. On these figures, we can clearly see that the first oscillation maximum is visible in Kamioka and both the first and second oscillation maxima are visible at the Korean location.

### COMPARISON BETWEEN T2KK AND T2HK

It was shown in the Hyper-Kamiokande Letter of Intent that the best results are obtain when running with three years of neutrinos and seven years of anti-neutrinos so I kept this running ratio for the Hyper-Kamiokande simulation. For the T2KK simulation I used five years of neutrinos and five years of anti-neutrinos as it was shown to be the best previously [1]. Figures 3 and Figures 4 show the capability of T2KK versus T2HK for a 750 kW beam and a 1.66 MW beam. Note that I assumed an unknown mass hierarchy when measuring the CP phase. In Figures 3 we can see that T2KK is able to solve the mass hierarchy at 5σ regardless of the value of δ_{CP} and even for a 750 kW beam. In Figures 4, we see that the T2KK setup can also determine whether CP violation exists for a larger fraction of the δ_{CP} phase space than T2HK. T2KK covers 60% of the phase space at 5σ for a 750 kw beam and 70% for a 1.66 MW beam. However let me remind that in this study it was assumed that the mass hierarchy is not known even when trying to measure the CP phase. If the mass hierarchy is known the results for T2HK are much better as can be seen in the Hyper-Kamiokande Letter Of Intent [7].

### CONCLUSIONS

Given the large value of θ_{13} measured in 2012, the Tokai to Kamioka and Korea (T2KK) setup with a 750 kW beam is able to solve the mass hierarchy at σ, for any value of the CP phase. It also tells us if there is CP violation in the lepton sector for 60% of the values of the CP phase. It is important to note that as long as the mass hierarchy is unknown, T2HK alone cannot achieve this. This is because the longer baseline to Korea is needed to solve the mass hierarchy and solve the degeneracies of the parameter space. However if the mass hierarchy is known then T2HK is equivalent to T2KK for the measurement of the CP phase.

### REFERENCES

1. M. Ishitsuka, T. Kajita, H. Minakata, and H. Numokawa, *Phys. Rev.* **D72**, 033003 (2005), hep-ph/0504026.
2. F. Dufour, T. Kajita, E. Kearns, and K. Okumura, *Phys. Rev.* **D81**, 093001 (2010), 1001.5165.
3. K. Abe, et al., *Phys. Rev. Lett.* **107**, 041801 (2011), 1106.2822.
4. P. Adamson, et al., *Phys. Rev. Lett.* **107**, 1108.0015.
5. J. Ahn, et al., *Phys. Rev. Lett.* **108**, 191802 (2012), 1203.1669.
6. F. An, et al., *Phys. Rev. Lett.* **108**, 171803 (2012), 1109.3262.
FIGURE 2. (Color online) Reconstructed energy spectra at Kamioka (top) and Korea 1.0° off-axis (bottom) for a 750 kW beam (left) and a 1.66 MW beam (right) for \( \sin^2(2\theta_{13}) = 0.1 \) and normal hierarchy. The remaining oscillation parameters are: \( \Delta m^2_{21,31} = 8.0 \times 10^{-5}, 2.5 \times 10^{-3} \text{eV}^2 \) and \( \sin^2 2\theta_{13,23} = 0.86, 1.0 \). Each plot is normalized to 5 years of running with neutrino, with 40 GeV protons and in a 0.27 Mton (FV) detector (i.e. \( 5 \times 1.17 \times 10^{21} \text{ POT} \)).
FIGURE 3. **Left:** Region of CP phase and $\theta_{13}$ where the mass hierarchy can be solved. **Right:** Fraction of $\delta_{CP}$ phase space in which the mass hierarchy can be solved. (Plain lines = normal hierarchy, dashed lines = inverted hierarchy)

FIGURE 4. **Left:** Region of CP phase and $\theta_{13}$ where CP violation can be found. **Right:** Fraction of $\delta_{CP}$ phase space in which CP violation can be found. (Plain lines = normal hierarchy, dashed lines = inverted hierarchy)