Future neutrino oscillation experiment with 2 detectors at Kamioka and Korea

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Abstract.
The J-PARC neutrino facility will produce a very intense neutrino beam. The neutrinos can be detected at Korea as well as at Kamioka. We explore a possibility of two identical detectors at Kamioka and Korea exposed to the same neutrino beam. We show that this setup can be a promising experiment to measure the yet unknown neutrino parameters.

1. Introduction: Initial studies of T2KK
T2K is the next generation neutrino oscillation experiment [1]. The neutrino beam is produced by the J-PARC facility. The neutrinos are detected in Super-Kamiokande, which is located 295 km away from J-PARC. T2K plans to proceed to Phase-2 of the experiment once \(\theta_{13}\) is found to be non-zero. In Phase-2, it is planned to upgrade the beam power to about 4 MW. In addition, a much larger detector than Super-Kamiokande is planned. It is called Hyper-Kamiokande, and will have the fiducial mass of 0.54 Mton. We refer this setup as T2K-II.

The T2K experiment will use an off-axis beam. The 2.5 degree off-axis beam in Kamioka and Korea (which is more than 1,000 km away from the target) is simultaneously available with the present T2K beam-line configuration. Therefore, we consider a setup with two identical detectors in Kamioka and Korea, both of which will have the fiducial mass of 0.27 Mton, i.e., half of the full Hyper-Kamiokande fiducial volume. The peak energy is about 0.7 GeV for the 2.5 degree off-axis beam. We refer this setup as T2KK in this paper.

Throughout this paper, we assume \(\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2\), \(\sin^2 \theta_{12} = 0.29\), and \(\Delta m_{31}^2 = \pm 2.5 \times 10^{-3} \text{ eV}^2\). We take the baseline length of 1050 km as a typical distance to the Korean detector. We also assume that both the neutrino and anti-neutrino runs will be for 4 years.

Since both the detectors will be exposed to the same 2.5 degree off-axis beam, the background must be almost identical if the trivial flight-length correction is made. On the other hand, the neutrino and anti-neutrino oscillation probabilities, which depend on the CP phase and mass hierarchy, must be different due to the different baseline length and the different amount of matter traversed. When we move from the first to the second oscillation maxima, the size of CP phase effects become larger by about a factor of 3. In order to compare the sensitivities for T2K-II and T2KK, a detailed \(\chi^2\) analysis was carried out [2, 5] taking into account various detector effects, such as background contamination, detection efficiency, and their systematic errors. Figure 1 shows the contours for the sensitivity to the mass hierarchy at 2 and 3
standard deviations on the $\delta$-$\sin^2 2\theta_{13}$ plane. The 2 and 3 standard deviations are defined to be $\chi^2_{\text{min}}(\text{wrong hierarchy}) - \chi^2_{\text{min}}(\text{true hierarchy}) > 4$ and 9, respectively. As expected, better sensitivity to the mass hierarchy is obtained for T2KK. Also shown in Fig. 1 is the sensitivity to the leptonic CP violation. For large $\sin^2 2\theta_{13}$, T2KK gives the better sensitivity. It is due to the fact that in T2KK, the mass hierarchy can be resolved for large $\sin^2 2\theta_{13}$, and therefore the value of $\delta$ is uniquely measured in the case of T2KK [2].

Figure 1. 2(thin lines) and 3(thick lines) $\sigma$ sensitivities to the mass hierarchy (left) and the CP violation (right) for T2K-II and T2KK.

2. Further studies of the T2KK sensitivities

2.1. Baseline Length dependence of the Sensitivity

The baseline length to the Korean detector has been assumed to be 1050 km. However, we notice that the 2.5 degree off-axis beam can be available across the Korean peninsula. Therefore the possible baseline length can be between 1000 and 1250 km. A study was carried out to understand the baseline length dependence of the sensitivities to the mass hierarchy and CP violation [3]. It was found that the sensitivities do not depend on the baseline length strongly. This is good, since the selection of the Korean detector site could have many possibilities.

2.2. Higher Energy Option for the Korean Detector

Since the matter effect is proportional to the neutrino energy, higher energy beam must be useful to determine the sign of $\Delta m^2$. The higher energy beam is available near the on-axis in Korea. (The Kamioka detector is always exposed to the 2.5 degree beam.) However, higher energy beam might have more background for the electron appearance search, especially in the lower energy part of the spectrum. Therefore, a careful analysis should be carried out to understand the relative merit and demerit of the higher energy beam for the Korean detector. A maximum likelihood analysis was carried out to search for electron appearance signal in the higher energy beam [4]. Figure 2 shows the expected signal and background for 1.0 and 2.5 degree off-axis beams. As expected there are much more background in the sub-GeV region for the 1.0 degree off-axis beam, while the background level from this analysis for the 2.5 degree off-axis beam is similar to the standard T2K analysis. We note that the background level for the 1.0 degree off-axis beam in the multi-GeV region, where the electron appearance signal from the first oscillation maximum is expected, is not very high compared with that of the 2.5 degree off-axis beam. This suggests that this configuration might be useful for the mass hierarchy determination. Figure 2 shows the sensitivities to mass hierarchy at 3 $\sigma$ for various off-axis
beams. As expected, the sensitivity of the T2KK experiment to the mass hierarchy improves with the higher energy neutrino beam. The sensitivity to the CP violation is almost independent of the off-axis angle for the Korean detector [4].

![Figure 2](image-url)  
**Figure 2.** (Left) Expected background for the electron appearance search for the Korean detector with off-axis angles 1.0 and 2.5 degrees. Also shown are the expected signals for $\sin^2 2\theta_{13} = 0.1$ and $\delta = \pi/2$. (Right) $3 \sigma$ sensitivities for the mass hierarchy determination in T2KK with off-axis angles for the Korean detector between 1.0 and 2.5 degrees (preliminary). The true mass hierarchy is assumed to be normal.

2.3. Resolving the octant ambiguity of $\theta_{23}$

So far, we assumed that $\sin^2 2\theta_{23}$ is maximal. However, if it is not the case, there is a parameter degeneracy due to the octant ambiguity of $\theta_{23}$. The $\nu_e$ appearance probability driven by $\Delta m_{23}^2$ are proportional to $\sin^2 2\theta_{13} \cdot \sin^2 \theta_{23}$. This suggests that if $\sin^2 \theta_{23}^{\text{1st}}$ and $\sin^2 2\theta_{13}^{\text{1st}}$ give a good fit to the data, $\sin^2(\pi/2 - \theta_{23}^{\text{1st}})$ and $\sin^2 2\theta_{13}^{\text{2nd}}$ also give a good fit, as far as $\sin^2 2\theta_{13}^{\text{1st}} \cdot \sin^2 \theta_{23}^{\text{1st}} = \sin^2 2\theta_{13}^{\text{2nd}}\cdot \sin^2(\pi/2 - \theta_{23}^{\text{2nd}})$. On the other hand, the appearance probability driven by the solar $\Delta m_{21}^2$, is proportional to $\cos^2 \theta_{23}$. Therefore, the $\theta_{23}$ octant degeneracy can be resolved by measuring the solar-$\Delta m^2$ effect at the Korean detector, which is located at a very large L/E site. From the detailed $\chi^2$ analysis, it was found that T2KK is able to solve the octant ambiguity at $2 \sigma$ CL, if $\sin^2 2\theta_{23} < 0.97$. This conclusion depends weakly on the value of $\sin^2 2\theta_{13}$, as well as the value of the CP phase and the mass hierarchy [5].

3. Summary

In this paper, we discussed the sensitivity of the oscillation experiment with the detectors at Kamioka and Korea (T2KK) to the yet unknown neutrino parameters. The possible measurements include the CP violation in the neutrino sector, the neutrino mass hierarchy and the octant of $\theta_{23}$. We have found that T2KK has high sensitivities to these measurements as far as $\sin^2 2\theta_{13}$ is not too small. Finally, we point out that there are possibilities to optimize the beam energy and the baseline length by selecting the proper location of the Korean detector.

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