Resolving mass hierarchy and CP degeneracy by two identical detectors in Kamioka and Korea

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Abstract. We explore the possibility of simultaneous determination of neutrino mass hierarchy and the CP violating phase by using two identical detectors placed in Kamioka and Korea for the J-PARC neutrino beam. We demonstrate, under reasonable assumptions of systematic uncertainties, that the two-detector complex with each fiducial volume of 0.27 Mton has potential of resolving neutrino mass hierarchy up to $\sin^2 2\theta_{13} > 0.03$ ($0.055$) at $2\sigma$ ($3\sigma$) CL for any values of $\delta$ and at the same time has the sensitivity to CP violation by 4 + 4 years running of $\nu_e$ and $\bar{\nu}_e$ appearance measurement. The significantly enhanced sensitivity is due to cancellation of systematic uncertainties between two identical detectors which receive the neutrino beam with the same energy spectrum in the absence of oscillations.

1. Introduction
In the neutrino sector, we still do not know the value of $\theta_{13}$, the sign of $\Delta m_{31}^2$, and the value of the CP violating phase $\delta$. It is well known that the determination of these parameters suffers from the ambiguities coming from the parameter degeneracy.

The T2K experiment will use an off-axis beam. The 2.5 degree (or more generally any angle between 2 and 3 degrees) off-axis beam in Kamioka (which is 295 km away from the target) and Korea is simultaneously available with the present T2K beam-line configuration. In this work, we discuss a possible way of determining the type of the neutrino mass hierarchy as well as the CP violating phase simultaneously by resolving the degeneracy using two identical detectors in Kamioka and Korea. Throughout this paper, mixing parameters other than $\theta_{13}$ and $\delta$ are fixed to be $\Delta m_{21}^2 = 7.9 \times 10^{-5}$ eV$^2$, $\sin^2 \theta_{12} = 0.29$, $\Delta m_{31}^2 = \pm 2.5 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{23} = 1$. We take the baseline distance of 1050 km as a typical distance to the Korean detector.

2. Sensitivities of resolving mass hierarchy and CP degeneracy
It is known that when we move from the first to the second oscillation maxima, the size of CP phase effects become larger by a factor of 3. To uncover possible advantages of the Korean detector we examine how the appearance probabilities depend upon the energy and baseline. Figure 1 represents how different are the energy dependence of the oscillation probabilities when

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they are seen by detectors in Kamioka and in Korea. In contrast to the quiet behavior in Kamioka, the ellipses are larger in size and are extremely dynamic in movement in Korea, when the energy is varied from 0.5 to 0.8 GeV. The strong energy dependence of the appearance oscillation probabilities in Korea, which are different for normal and inverted hierarchies, is the key to the high sensitivity of the two-detector complex as we will fully explore later.

![Figure 1](image.png)

**Figure 1.** Energy dependences of the oscillation probabilities for $\sin^2 2\theta_{13} = 0.05$ are represented by plotting ellipses (which results as $\delta$ is varied from 0 to $2\pi$) in bi-probability space for various neutrino energies from 0.5 to 0.8 GeV. Other mixing parameters are fixed as explained in the text. The left and the right panels are for detectors in Kamioka and in Korea, respectively.

There exists great merit of using two identical detectors together with the neutrino beam of identical spectrum shape (in the absence of oscillations) which makes demonstration of the CP violation and resolution of the mass hierarchy degeneracy much cleaner. In order to understand the advantage of the two detector system at 295 km (Kamioka) and 1050 km (Korea), we carry out a detailed $\chi^2$ analysis taking into account various detector effects, such as background contamination, detection efficiency, and their systematic errors. We use various numbers and distributions available from references related to T2K [1, 2].

We examine five different volume ratios of Kamioka to Korean detectors, keeping the total volume constant. We show in figure 2 the contours of sensitivity to the mass hierarchy at 2 and 3 standard deviations on $\delta-\sin^2 2\theta_{13}$ plane for these 5 detector configurations. Here, the 2 and 3 standard deviations are defined to be $\chi^2_{min}$(wrong hierarchy)$-\chi^2_{min}$(true hierarchy)$>4$ and $9$, respectively. As expected, better sensitivities are obtained for detector configurations with detectors both in Kamioka and in Korea. We find that the sensitivity on the mass hierarchy does not depend strongly on the mass ratio of the two detectors. Also shown in figure 2 is the sensitivity to leptonic CP violation by drawing the contours above which hypothesis of $\delta=0$ or $\pi$ can be rejected at 2 and 3 standard deviations. Notice that while the type of true hierarchy is assumed in each case, the fit is performed without assuming the mass hierarchy. For small $\sin^2 2\theta_{13}$ a single 0.54 Mton detector in Kamioka has the best sensitivity. Whereas for large $\sin^2 2\theta_{13}$, the two detector configuration gives the better sensitivity. It is due to the fact that in the two detector configurations, 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 the two detector configurations.

We also searched for the best option for dividing assumed whole period of 8 years into the neutrino and anti-neutrino running. Overall, two 0.27 Mt detectors in Kamioka and Korea, and 4 years of neutrino and 4 years of anti-neutrino beams are selected as the optimal choice.

In order to study the robustness of the results, we carry out several tests. As an example, we test the stability of the results by varying the systematic uncertainties in the background estimation and the signal detection efficiency. Because of the identical energy spectrum and
the detectors in Kamioka and in Korea, their background rates must be related simply by $(L_{Korea}/L_{Kamioka})^2$. Hence, the difference in the signal events in Kamioka and Korea cannot be explained by the uncertainty in the background, and therefore the measurement of the background rate by front detectors with a very high precision is not crucial in the identical two detector setup. See [3] for further discussions.

3. Summary

We have explored physics capabilities of the two identical megaton-class detector complex, one placed in Kamioka and the other in Korea under the assumption that they receive the same neutrino beam from J-PARC. We have shown that it can determine neutrino mass hierarchy and CP phase up to a level achievable by conventional superbeam experiments. The key to the enormous sensitivities is the use of two identical detectors that allows significant reduction of systematic errors by cancellation. We emphasize that, in our setting, the total volume of the two detectors is the same as the planned Hyper-Kamiokande with 1 Mton water in Kamioka, and the current design of the latter option already contains two tanks [4]. Hence, the cost of the present proposal should be roughly the same as that of the original design of T2K phase-II.

Acknowledgments

This work was supported in part by the Grant-in-Aid for Scientific Research, Japan Society for the Promotion of Science and by Conselho Nacional de Ciência e Tecnologia (CNPq).

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