

Future possibilities with the J-PARC neutrino beam

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Abstract.

The J-PARC neutrino beam line is under construction. The next generation neutrino oscillation experiments, including the T2K experiment, will observe evidence for a finite θ_{13} , if $\sin^2 2\theta_{13} > 0.01$. In this case, it is likely that future long baseline experiments with the conventional but strong neutrino beam can measure important neutrino parameters such as the CP violation phase and the mass hierarchy. In this paper, possible future neutrino oscillation experiments to be carried out using the J-PARC neutrino beam are discussed.

1. Introduction

After the exciting discoveries [1, 2, 3, 4, 5, 6, 7] in neutrino physics in the last decade, we now know that neutrinos have masses and their flavors mix. Two of the three neutrino mixing angles, θ_{12} and θ_{23} have been measured and are known to be large. Only the upper limit [8] is known on the third mixing angle, $\sin^2 2\theta_{13} < 0.15$.

Since the measurement of θ_{13} implies the basic understanding of the neutrino mixing matrix, there are many activities to measure θ_{13} . Accelerator based long baseline experiments [9, 10], reactor experiments [11, 12], and atmospheric neutrino experiments [13, 14] are trying to observe evidence for non-zero θ_{13} . Especially, the next generation long baseline experiments and reactor experiments have high sensitivities. If the true value of $\sin^2 2\theta_{13}$ is larger than $\sim(0.01\sim0.02)$, it is likely that these experiments will observe evidence for non-zero θ_{13} . If this is the case, future neutrino experiments must be very exciting, since it must be possible to measure the CP violation and the mass hierarchy (sign of Δm_{23}^2) using conventional, high intensity neutrino beam and large neutrino detector(s).

2. J-PARC neutrino beam line

The J-PARC accelerator complex is under construction. The construction is expected to complete by the end of 2008. In the initial phase, the beam power of the main ring is designed to be 0.75 MW. The T2K experiment will use the proton beam produced by this machine. J-PARC has a plan to upgrade the beam power to 1.66 MW [15]. Therefore, in this paper we assume that the beam power available for future neutrino experiments at J-PARC is 1.66 MW unless otherwise mentioned.

Neutrinos produced by the J-PARC neutrino beamline will be observed at Kamioka. T2K uses 2.5 degree off-axis beam. Therefore the center of the beam is approximately 2.5 degree below the Super-Kamiokande detector at the Kamioka site. This implies that the center of the beam re-appears in the Japan Sea. It turned out that various off-axis beams with the off-axis

angles larger than 1.0 degree are available in Korea. The baseline length can be as long as 1250 km if the detector is located in Korea. We also notice that a rather small island (Okinoshima Island) is located along the beam at the distance of 660 km. In this paper, we assume three detector locations; Kamioka (295 km), Okinoshima Island (660 km), and Korea (1050 km). The detectors are assumed to be either large water Cherenkov detectors (0.27 Mton fiducial mass at Kamioka and Korea) or a large liquid Argon detector (0.1 Mton fiducial mass). We will not discuss any local issues related to the site selection.

3. Physics and oscillation probabilities

The main goals of the future neutrino oscillation experiments should be the discovery of the CP violation and the determination of mass hierarchy. If CP is violated, there must be difference in the oscillation probabilities between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. If the mass hierarchy is normal (inverted), the matter effect should enhance the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) probability.

Figure 1 shows $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 295, 660 and 1050 km. As seen from Fig. 1, the earth matter effect is proportional to the neutrino energies (as long as the neutrino energies are in the 1 GeV region). This suggests that it is better to carry out a higher energy, longer baseline neutrino oscillation experiment to determine the mass hierarchy. Clearly, a detector in Korea exposed to a high energy beam should have the highest sensitivity to the mass hierarchy among the three locations. On the contrary, at the Kamioka site, where the baseline length is only 295 km, the CP violation effect (for a typical CP phase δ) is larger than the matter effect. Therefore, Kamioka might be a good location for a detector to measure the CP violation. The 660 km location could have features of both 295 and 1050 km, and therefore it is interesting to know the potential physics to be achieved at this location. We also note that the 2nd oscillation maximum should appear around 700 MeV at 1050 km. This energy is high enough to observe CC interactions. Therefore, in a detector in Korea, it could be possible to use the events at the 2nd oscillation maximum to get information on the CP violation and mass hierarchy.

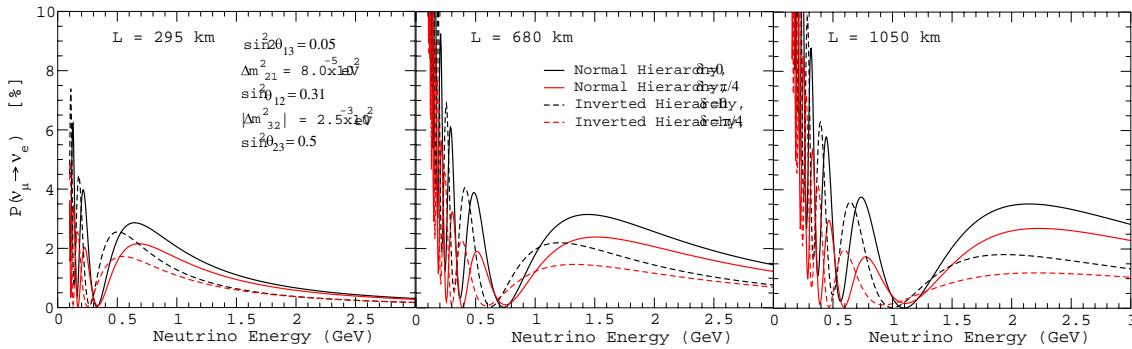


Figure 1. $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 295, 660 and 1050 km.

4. Sensitivity Studies

4.1. Some early results

Initially, the sensitivity to the CP violation was studied assuming the upgraded J-PARC and a megaton water Cherenkov detector at Kamioka [16]. Then, the sensitivities of an experiment with detectors both in Korea and Kamioka were studied [17]. It was assumed that both detectors are exposed to the 2.5 degree off-axis beam. In order to estimate the sensitivities for the experiment, a χ^2 analysis was carried out, taking into account various detector effects, such as background contamination, detection efficiency, and their systematic errors.

Figure 2 (left) shows the contours for the sensitivity to the mass hierarchy at 2 and 3 standard deviations on the δ - $\sin^2 2\theta_{13}$ plane. The 2 and 3 standard deviations for the mass hierarchy

are defined to be $\chi^2_{min}(\text{wrong hierarchy}) - \chi^2_{min}(\text{true hierarchy}) > 4$ and 9, respectively. The sensitivity for the CP violation is defined similarly. As expected, better sensitivity to the mass hierarchy is obtained in Kamioka-Korea two-detector setup. Also shown in Fig. 2 is the sensitivity to the leptonic CP violation, i.e., the lines indicate the parameter region where $\sin \delta = 0$ can be rejected at 2 and 3 standard deviations. For small $\sin^2 2\theta_{13}$, Kamioka-only set-up has a slightly better sensitivity to the CP violation. Whereas for large $\sin^2 2\theta_{13}$, Kamioka-Korea setup gives the better sensitivity. It is due to the fact that in the two-detector setup, the mass hierarchy can be resolved for large $\sin^2 2\theta_{13}$, and therefore the value of δ is uniquely measured in the case of the two-detector setup. More details have been discussed elsewhere [17]. These studies triggered various further studies as discussed in this article.

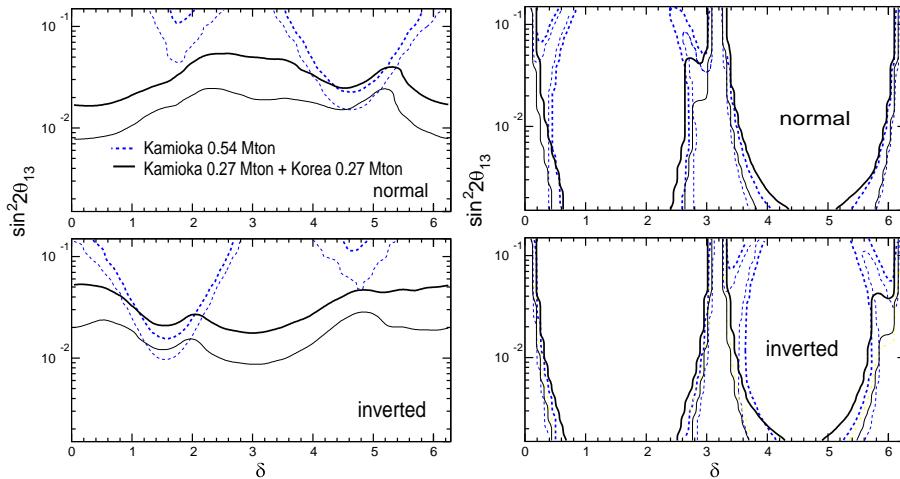


Figure 2. 2(thin lines) and 3(thick lines) σ sensitivities to the mass hierarchy (left) and the CP violation (right) for Kamioka only set-up and for Kamioka-Korea 2 detector set-up. 4 MW and 4 and 4 years of the neutrino and anti-neutrino runs were assumed.

4.2. Kamioka-Korea two detector setup with different off-axis beams

Since the matter effect is proportional to the neutrino energy, higher energy beam must be suited to determine the sign of Δm^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 neutral-current 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 [18]. Figure 3 shows the expected signal and background for the 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 powerful for the mass hierarchy determination. Figure 4 shows the sensitivities to the mass hierarchy and CP violation at 2 and 3 σ for 2 different off-axis beams. As expected, the sensitivity of the Kamioka-Korea setup 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 [18].

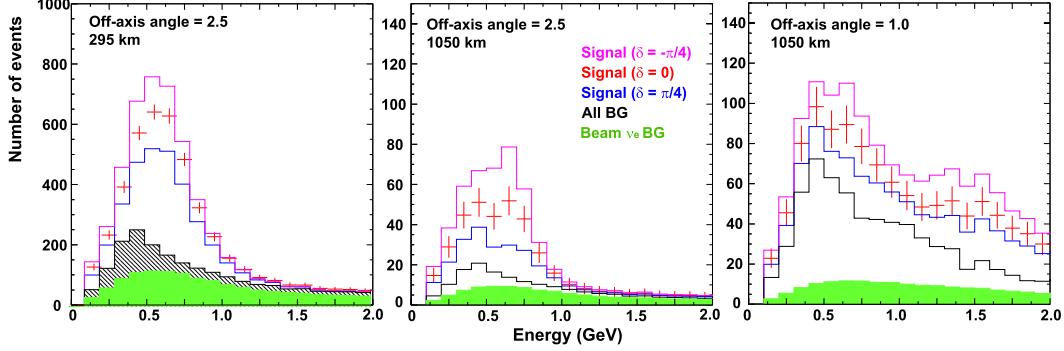


Figure 3. Expected background for the electron appearance search for the Kamioka detector and for the Korean detector with off-axis angles 1.0 and 2.5 degrees. Also shown are the expected signals for $\sin^2 2\theta_{13} = 0.04$ and normal hierarchy.

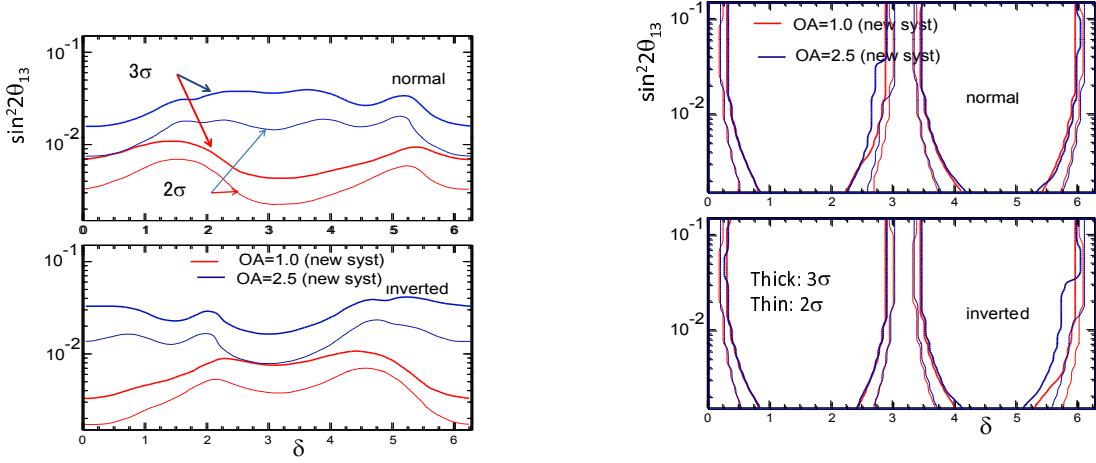


Figure 4. 2(thin lines) and 3(thick lines) σ sensitivities to the mass hierarchy (left) and the CP violation (right) with Kamioka-Korea setup and with 1.0 and 2.5 degree off-axis angles for the Korean detector. The off-axis angle for the Kamioka detector is always 2.5 degrees.

4.3. Intermediate baseline length with a Liquid Argon detector

There is an island, Okinoshima island, which is 660 km away from J-PARC. The off-axis angle is 0.8 degree. Therefore, a relatively high energy beam is available. A study was carried out to perform a long baseline experiment between J-PARC and a detector in this island. A 100 kton Liquid Argon detector was assumed [19]. Figure 5 shows the expected ν_e appearance signal with perfect, 100 MeV, and 200 MeV energy resolutions. It is clear that a very good energy resolution is important to see the 2nd oscillation maximum at this baseline length. Also shown in the same figure is the estimated sensitivity assuming 100 MeV neutrino energy resolution. (In Ref.[19], the sensitivities with the perfect and 200 MeV resolutions are also shown.) Even if $\sin^2 2\theta_{13} = 0.02$, the experiment will be able to determine the δ and $\sin^2 2\theta_{13}$ parameters accurately. The sensitivity depends on the energy resolution, and therefore it must be important to have a detector with a very good energy resolution, especially at the distance of 660 km.

4.4. Some remarks

We note a recent work on the importance of the systematic errors [20]. Various systematic errors were included in the oscillation analysis. It was concluded that the CP sensitivity for the Kamioka-only setup depends on the systematic errors rather strongly, while the sensitivity of the Kamioka-Korea 2 detector setup is rather insensitive to the systematic errors. A similar

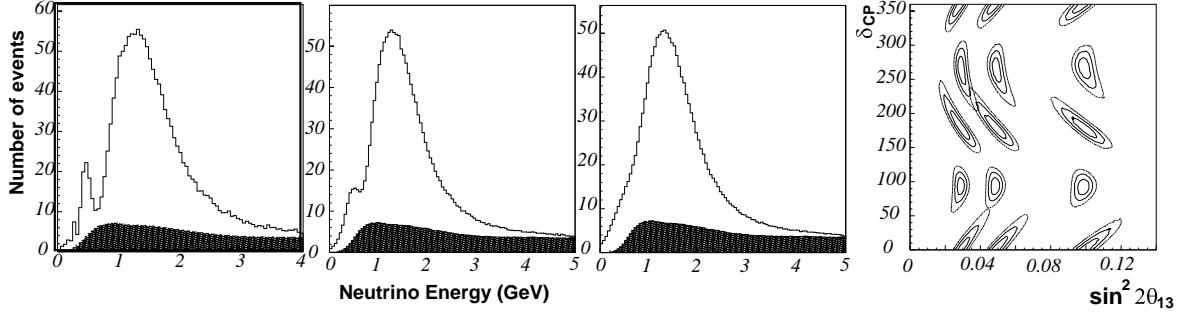


Figure 5. The left 3 panels show the expected signal (blank) and background (black) for the electron appearance search at 660 km with the perfect, the 100 and 200 MeV neutrino energy resolutions, respectively. These panels assume that $\sin^2 2\theta_{13} = 0.03$ and $\delta(\text{CP phase}) = (3/2)\pi$. The estimated allowed regions for the 100 MeV resolution detector is shown at the rightest panel assuming the normal hierarchy.

work was recently carried out using Monte Carlo generated water Cherenkov events [21]. Also, see Ref. [22].

If the Korean detector is exposed to the 2.5 degree off-axis beam, the L/E value at the energy of the peak flux is very large. In this case, it might be possible to see the effect of Δm_{12}^2 . 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 θ_{23} . The ν_e appearance probability driven by Δm_{23}^2 are proportional to $\sin^2 2\theta_{13} \cdot \sin^2 \theta_{23}$. This suggests that if $\sin^2 \theta_{23}^{1st}$ and $\sin^2 \theta_{13}^{1st}$ give a good fit to the data, $\sin^2(\pi/2 - \theta_{23}^{1st})$ and $\sin^2 2\theta_{13}^{2nd}$ also give a good fit. On the other hand, the appearance probability driven by the solar Δm_{21}^2 , is proportional to $\cos^2 \theta_{23}$. Therefore, the θ_{23} octant degeneracy can be resolved by measuring the solar- Δm^2 effect at the Korean detector, which is located at a very large L/E site. From the detailed χ^2 analysis, it was found that the Kamioka-Korea setup is able to solve the octant ambiguity at 2σ 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 [23].

It is usually assumed that there is no new physics in the neutrino propagation and interaction. However, this may not be the right assumption. For the purpose of illustration, we consider quantum decoherence as a nonstandard neutrino physics. In this case, the ν_μ survival probability (and the $\bar{\nu}_\mu$ survival probability) is given by;

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \frac{1}{2} \sin^2 2\theta \left[1 - e^{-\gamma(E)L} \cos\left(\frac{\Delta m^2 L}{2E}\right) \right], \quad (1)$$

where we assume $\gamma(E) = \gamma/E$. Then one can calculate the number of ν_μ and $\bar{\nu}_\mu$ events observed at two detectors placed at Kamioka and Korea, using the above survival probability and the neutrino beam profiles. In Fig. 6, we show the correlations between γ and $\sin^2 2\theta$ at three experimental setups. We immediately find that there are strong correlations between $\sin^2 2\theta$ and γ for the Kamioka-only and Korea-only setups. We also note that the slopes of the correlation for these two setups are different. Therefore the Kamioka-Korea setup can give a stronger bound on γ (and $\sin^2 2\theta$) than the one detector setups. From this example, it is clear that the two detector setup gives important information on the decoherence parameter. More generally, it is noted that two detector setup is powerful to check the overall consistency of the oscillation data. See Ref. [24] for more details.

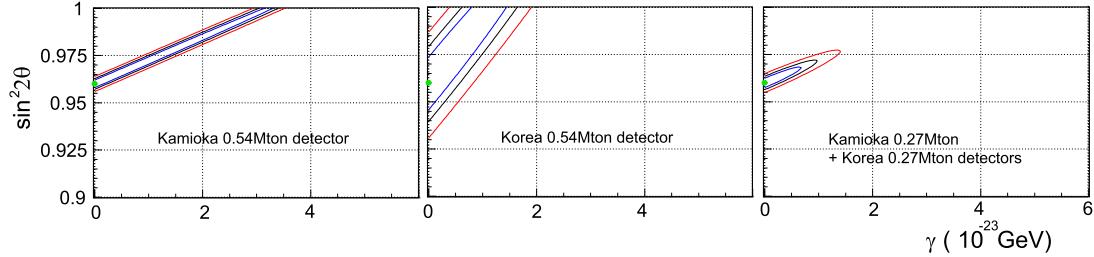


Figure 6. The correlations between γ and $\sin^2 2\theta$ for three experimental setups we consider: Kamioka-only, Korea-only and Kamioka-Korea. Blue, black and red curves represent the contours for 1σ , 2σ and 3σ standard deviations. Input values are $\gamma = 0$, $\Delta m^2 = 2.5 \times 10^{-3}$ eV 2 and $\sin^2 2\theta = 0.96$. 4 MW beam is assumed.

5. Summary

We discussed the results from various sensitivity studies that assumed the future J-PARC neutrino beam. They demonstrated that the experiment with the future J-PARC neutrino facility should have high sensitivities to the mass hierarchy and CP violation. These studies suggested that the J-PARC neutrino facility is very likely to continue to be an important one even after T2K phase-I. The details of the experiment, however, should be optimized knowing the value of θ_{13} .

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