Highlights in the T2KK Workshops in 2005 and 2006

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Abstract

Topics discussed at the first and second International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam are summarized. The Korea detector together with the detector at Kamioka will serve as the far detector for the next generation long baseline experiment with the upgraded J-PARC neutrino beam after the present T2K phase I. Through the workshops, it was recognized that this setup will be a powerful experiment to explore the yet-unknown neutrino parameters.

1. Introduction

This paper describes the highlights of topics discussed at the first and the second International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam.* The first workshops was held in KIAS, Seoul, Korea on Nov. 18 and 19, 2005. About a year later, on July 13 and 14, 2006, the second workshop was held in Seoul National University, Seoul, Korea.

The objective of the workshops was to explore various aspects of possible physics with the future long baseline experiment with Kamioka-Korea two detector complex. In this paper we refer this setup as T2KK in short.† T2KK is a candidate for the upgraded next project to T2K phase I for exploring the whole structure of the neutrino mass pattern and lepton flavor mixing We try to give an overview of the idea as it stands which may be more informative rather than restricting ourselves to a literal summary of each talk.

We point out that some of the results described here have been updated at the 3rd workshop. Therefore, this report is NOT the most updated status report of the T2KK studies. For the most updated individual studies, readers are asked to refer papers in these proceedings.

2. Physics Motivation

After the exciting discovery era of neutrino physics in the last several years, we now know that neutrinos have masses and their flavors mix. Overview of the current status of neutrino physics including discussions of future prospects were presented by Kim at the first and second workshops [1, 2]. Various theoretical

*It was agreed at the end of the second workshop that it is useful to produce a report by summarizing the works presented and discussions at the workshop. Accordingly the first draft of the report was prepared mostly by one of the authors of this paper. At the 3rd workshop, the other author of this paper summarized highlights of the 1st and 2nd workshops partly referring the draft report. After the 3rd workshop, the two authors worked together to write this paper.

†We note, however, that it is a temporary name to be used until the name of the experiment is decided.

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implications of the uncovered structure of neutrino masses and mixings were discussed by Kang [3, 4].

The next important step in neutrino physics is to complete our understanding of the structure of neutrino mass spectrum and the three-flavor mixing. To achieve this goal we have to make the following several steps:

- First, we must know how large θ_{13} is. Its measurement may be carried out by the next-generation accelerator experiments such as T2K [4] or NOνA [11], or by reactor experiments [7, 8, 1] .
- Assuming that θ_{13} is in a region accessible to these next-generation experiments, we may be able to proceed to the next step for uncovering leptonic CP violation and determining neutrino mass hierarchy.
- If nature requires, or if we seek precision measurement of the flavor mixing parameters, we may need to resolve so called the "parameter degeneracy".

T2KK is an idea to serve for the second and the third steps in the above list.

3. Basic Idea of T2KK

Let us start by describing the general feature of the Kamioka-Korea two detector setup. We intend to make generic points which are valid without recourse to any specific setup.

- The neutrino beam from J-PARC, according to the current design, automatically reappears in the Korean peninsula. See Fig. 1 which is taken from [7]. Therefore, it is a cost effective way to build a new experiment by having a far detector at an appropriate site in Korea.
- By placing a detector somewhere in Korea and by comparing its yield with that of a detector in Kamioka, the experiment can become sensitive to the interference between the vacuum and the matter effects in neutrino oscillation. It will give the experiment the ability of resolving the neutrino mass hierarchy.
- Discovery of leptonic CP violation can be made much more robust by comparing the two detectors, assuming that both detectors in Kamioka and in Korea are constructed in such a way that many of the systematic errors can cancel or can be correlated with each other.

However, if one wants to understand the sensitivity of the experiment quantitatively, there exists a variety of questions we have to address. In order to answer them, we must specify the experimental setup of T2KK.

3.1. Baseline setup; Kamioka-Korea two identical detectors

We start from a "baseline setup", which utilizes two half a megaton water Cherenkov detectors (with 0.27 Mton fiducial volume), one in Kamioka (295 km) and the other in somewhere in Korea (we take 1050 km in the baseline setup), which receive ν_μ and $\bar{\nu}_\mu$ superbeam of 4 MW from the upgraded J-PARC facility. We do so not because the "baseline setup" is the best choice *apriori*, but because it can serve as a "standard" setting on which one can discuss varying other options to improve performance over it.

In this idealized setting of identical two detectors one can assume that some of the systematic errors cancel between them. An exception may be the one due to slightly different beam energy spectrum viewed by the two detectors because of the non-cylindrical shape of the decay volume in the neutrino beam line [11]. The

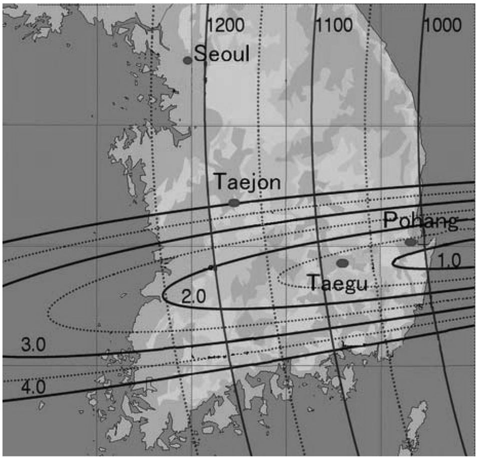

Fig. 1 Neutrino beam from J-PARC reappears in the Korean peninsula [7]. The solid lines with the numbers n imply locations at which neutrino beam of n degree off axis intersect with the earth surface (sea level). The three red lines with the numbers denote the equi-distance curves from J-PARC in units of km.

cancellation of errors will lead to a high sensitivity to the mass hierarchy resolution and in particular identifying CP violation. They are exhibited in the left and the right panels, respectively, in Fig. 2 [5, 13]. 4 years running with neutrino beam and another 4 years running with anti-neutrino beam are assumed. The sensitivity to the mass hierarchy greatly improves the one possessed by the original T2K Phase II setup (we call T2K II in this paper) and is competitive to other similar projects. The sensitivity for CP violation is similar to that of the T2K II setting except for at large θ_{13} region where the T2KK sensitivity surpasses that of the T2K II. In fact, it may be the highest among the similar proposals. We emphasize that it is due to the fact that T2KK solves the intrinsic and the sign-Δm^2 degeneracies.

3.2. θ_{23} octant degeneracy

In Fig. 3, the sensitivity to the θ_{23} octant degeneracy is presented [6, 15]. It is known that the θ_{23} degeneracy is the difficult one to solve only by accelerator long-baseline experiments. Nonetheless, T2KK circumvents the argument because it has sensitivity to the solar term. Again T2KK's sensitivity is competitive to those of the other methods. Resolution of the θ_{23} degeneracy by using an alternative method of combining reactor and accelerator experiments [12], in the present context T2KK, is also discussed in the workshop [17].

We emphasize that the estimates of sensitivities for the mass hierarchy resolution, CP violation, and the θ_{23} octant degeneracy are based on the known technology for rejecting NC induced background in water Cherenkov detectors. Therefore, the results presented in Fig. 2 and Fig. 3 can be regarded as robust bottom-line sensitivities achievable by conventional superbeam experiments. Of course, there may be ways to improve the sensitivities over the current one obtained by T2KK with identical two detector setting.

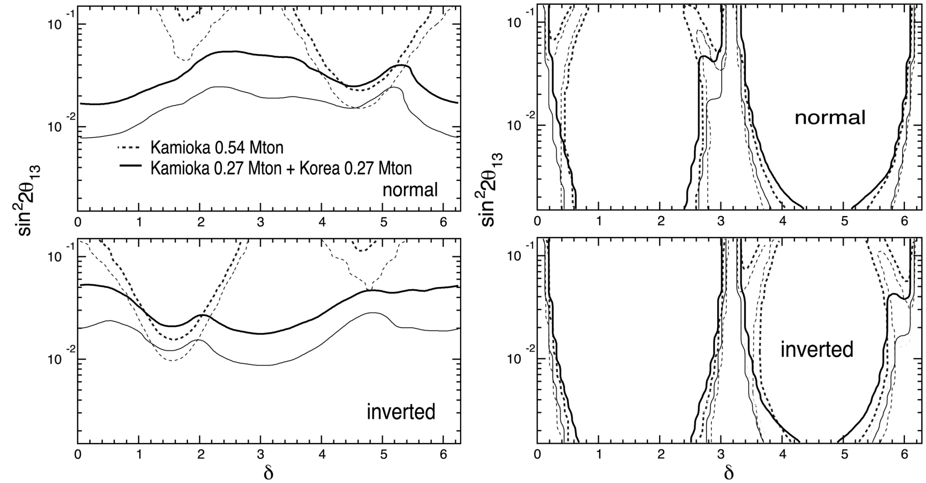

Fig. 2 2σ(thin lines) and 3σ (thick lines) sensitivities to the mass hierarchy (left panels) and CP violation (right panels). The solid (black) lines are for the T2KK setting while the dotted (blue) lines are for the T2K II setting. θ_{23} is taken to be maximal. The top and bottom panels correspond to the cases for the normal and the inverted mass hierarchies as nature's choice, respectively.

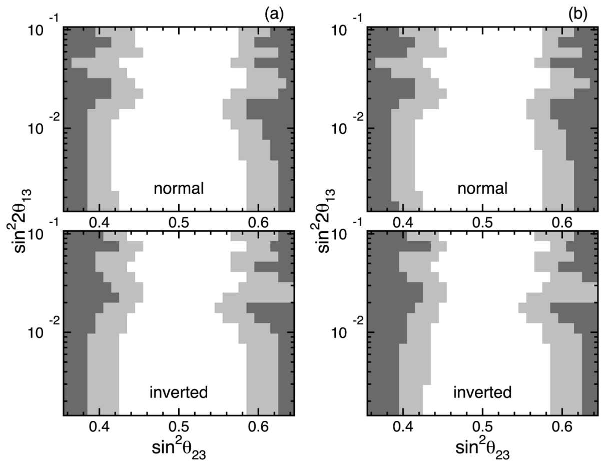

Fig. 3 2σ (light gray area) and 3σ (dark gray area) sensitivities to the θ_{23} octant degeneracy for T2KK. In (a), the sensitivity is defined so that the experiment is able to identify the octant of θ_{23} for any values of the CP phase δ. In (b), it is defined so that the experiment is able to identify the octant of θ_{23} for half of the CP δ phase space. The upper and lower panels assume that the true mass hierarchy is normal and inverted, respectively.

4. Possible Improved Setup

4.1. Near on-axis Korean detector

There are various possibilities of optimization of detector setting which include off-axis angle from the beam direction and baseline distance from the beam source. The later aspect will be discussed in the next section.

It was noticed that if one can observe multiple oscillation maxima of neutrino oscillation, $\Delta m^2_{31} L/2E = (2n+1)\pi$ (n=0, 1, 2, ...), such measurement will have sensitivities to the mass hierarchy as well as CP violation phase in a single experiment. This strategy has been formulated and implemented into the concrete proposal [18, 10].

In the context of T2KK, there is a possibility for this strategy to be adopted by placing the detector in Korea in near on-axis along the beam direction. As indicated in Fig. 1 the J-PARC neutrino beam, to which the Kamioka detector is placed at 2.5 degrees off-axis, reappears in Korean peninsula as a beam with off-axis angle larger than 1 degree. Then, depending upon the off-axis angle chosen, a wide range of neutrino energy spectra becomes available, as exhibited in Fig. 4.

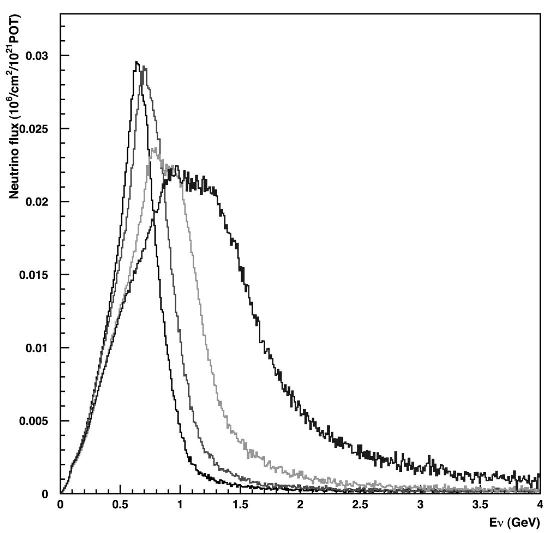

Fig. 4 Neutrino energy spectra received by detectors placed at various off-axis angles. The lines from the higher to lower energy spectrum (blue, green, red, and black lines) are, respectively, for 1, 1.5, 2, and 2.5 degree off-axis from the beam direction.

It was argued that using a higher energy beam is better for the mass hierarchy determination due to the larger matter effect [13, 14]. However, experimentally, one expects higher background rate in the sub-GeV energy range for the higher energy beam due to the larger amount of neutral current contamination. Therefore one has to estimate the expected background carefully in order to compare the sensitivities of the low and high energy beam options. Furthermore, it was discussed, at the first workshop, that the signal to noise separation gets worse for higher energies [22].

The possibility of using wide-band beam for the detector in Korea with the background estimation was discussed [15, 16]. In Fig. 5 the understanding of the signal and background events in a water Cherenkov detector for various off-axis angle is presented [15]. One can recognize that there is an accumulation of background events at low energies which comes from high energy tail of the neutrino energy spectrum. This feature makes it highly nontrivial to reject background in an unambiguous way in water Cherenkov detectors.

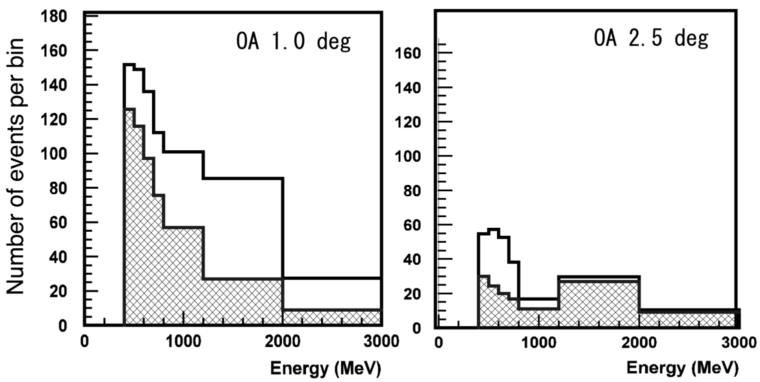

Fig. 5 Expected background (hatched regions) for the electron appearance search for the Korean detectors with off-axis angles 1.0(left) and 2.5(right) degrees. Also shown are the expected signal (solid histograms) over the background for $\sin^2 2\theta_{13} = 0.1$ and $\delta = \pi/2$.

With the current understanding of the background one can examine if the near on-axis detector in Korea improves the sensitivities to the mass hierarchy and CP violation. In Fig. 6, off-axis angle dependence of the sensitivity to the mass hierarchy is shown [15].[‡]

The sensitivity to the mass hierarchy resolution improves with the decreasing off-axis angles (namely with the increasing beam energy). The sensitivity to the CP violation is not shown but it essentially remains intact. This is the most attractive feature of the near-on-axis option of the Korean detector. The improved sensitivity to the mass hierarchy is indeed expected. The near on-axis Korean detector can cover the neutrino energy spectrum including the first and the second oscillation maxima with much higher event rate in the former region, i.e., at higher energies. The matter effect is stronger in this region and hence the higher resolving power for the mass hierarchy.

However, we have to make a cautionary remark for the interpretation of the above results. The statistical procedure, in particular the definition of χ^2, used to produce Fig. 6 is identical with that used in the analysis of two identical detector case [5], which means that most of the systematic errors are assumed to be completely correlated between the two detectors. However, this could be a little too optimistic. Hence the sensitivities for off-axis angles other than 2.5 degrees are likely to be overestimated. Therefore, a careful reanalysis is called for including more realistic systematic errors. Nonetheless, improvement of potential for the mass hierarchy determination is likely to survive in a proper treatment because of the physics arguments presented above.

Another option one could take for the high energy beam is to use a much advanced detector technology to reduce the neutral current background as much as possible. One such example could be a very large Liquid Argon detector. In such detectors, the rejection of the neutral current background events will be achieved much more efficiently, reducing the background events in the higher energy beam [22]. Fig. 7 shows the expected sensitivity of the liquid argon detector located

[‡]At the 3rd workshop, an updated result based on an improved analysis was presented. The reported sensitivities showed significant improvements. See. Ref.[17].

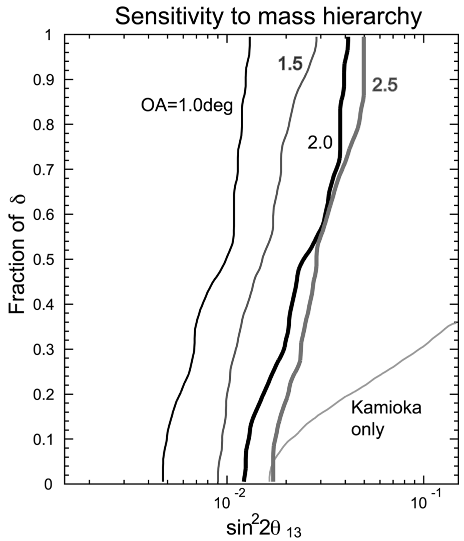

Fig. 6 The expected 3 σ sensitivities to the mass hierarchy are presented in a form of CP fraction; The ordinate is the fraction of region of δ in which the mass hierarchy can be identified. The thin-gray line is for Kamioka only setting with 0.54 Mton fiducial volume and is placed at 2.5 degree off-axis. The other four lines are for Kamioka-Korea two detector setting with each 0.27 Mton fiducial volume with Korean detector placed at various off-axis angles.

at the 1.0 degree off-axis in Korea [16]. It is clear that the sensitivity of the experiment will be very high even for very small $\sin^2 2\theta_{13}$ values.

4.2. Optimization of the baseline distance

In this section, the issue of baseline distance dependence of the sensitivities is discussed by keeping the Korean detector off-axis angle fixed to be the same, 2.5 degree from the beam direction. The result of the study on this issue was presented in the second workshop [27]. As indicated in Fig. 8 the sensitivities depend upon the baseline distance L only weakly. The feature is welcome because it means a rather large freedom in site selection for the Korean detector.

As a next step it is desirable that the optimization study of baseline distance will be extended to the one which combines optimization of off-axis angle of the Korean detector.

5. Possible T2KK Detector Sites

To realize T2KK, it is crucial that there exist candidate sites for these large detectors in both Kamioka and Korea. It was discussed that the requirement on depth should not be very tight if the solar neutrino measurement is not regarded as the physics goals by these detectors [28]. The rock overburden of 500 m is likely to be deep enough for most of the physics topics to be studied by these large detectors.

The size of the underground cavity could be a cylindrical shape with approximately (50 m in diameter) $\times$ (250m in length). The candidate site in Kamioka exists at the Tochibora mine, which is located about 10 km south of the present Super-Kamiokande site. Detailed studies of the site are in progress. The status of the site studies at Kamioka was reported [29]. The studies with the currently

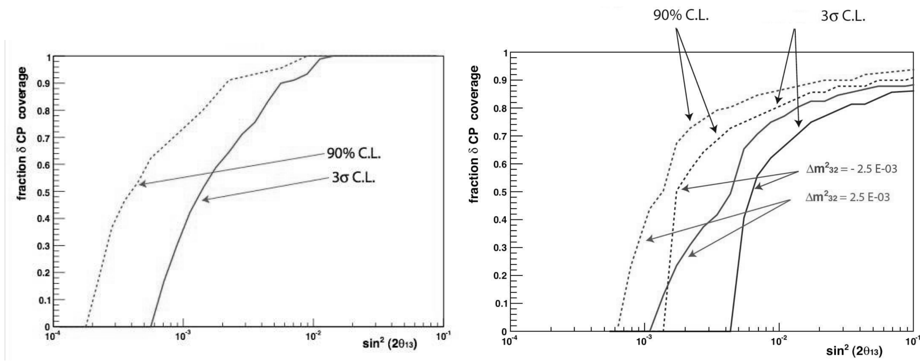

Fig. 7 The expected sensitivities to the mass hierarchy (left) and CP violation (right) are presented in the form of the CP fraction with a Liquid Argon detector in Korea. The sensitivity to mass hierarchy is based on the neutrino beam only. The dotted and solid lines are for sensitivities at 90% and 3σ CL, respectively.

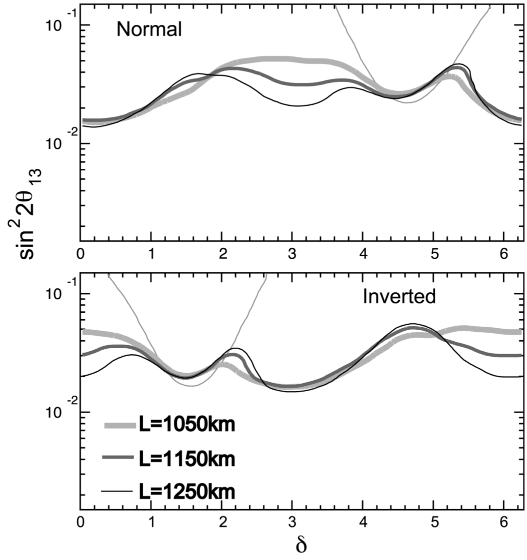

Fig. 8 3 σ sensitivities to the mass hierarchy for T2KK as a function of the baseline length to the Korean detector. Different lines indicate different baseline lengths. Also shown by the thin-gray line is the sensitivity for a 0.54 Mton detector at Kamioka. The upper and lower panels assume that the true mass hierarchy is normal and inverted, respectively.

available geological data at the Tochibora mine suggest that the construction of the large cavity for T2KK is possible.

One of the most important issue for the Korean detector is the site selection. This problem was discussed at the 2nd workshop [30]. Korea consists largely of the Precambrian rocks, such as granite gneisses and other metamorphic rocks. The Gyeongsang Supergroup is distributed across a wide area within the Gyeongsang-do province which is one of the area of our concerns. Throughout Korea, mountains are not high, rarely exceeding 1,200 meters, but they are found almost everywhere. The terrain is rugged and steep and only near the west, and southwest coasts are extensive flat

In order to satisfy the overburden of 500 m in depth, preferable site would be mountain area. If the site should be located within a 1.0 degree off-axis beam line, there seems no room for the candidate site except Tohamsan in Gyeongju and Guryongpo in Pohang area. If it may be located around 2.0 and 2.5 degree off-axis beam lines, there is much room for site selection.

It is suggested to investigate abandoned mines as well as running ones in more detail. There are several advantages of utilizing abandoned mine. One can reduce construction costs considerably, and minimize environmental impacts. Possibility of complaints from residents and environmentalist must be decreased. It is easy to get approval and to get support from local government, and also easy to get information on geological conditions

Overall, geological conditions in Korea seem to be quite favorable in general.

6. Miscellaneous Topics

Various miscellaneous topics were discussed in the workshops. Here, we try to summarize some of them. Both physics and detector issues were discussed.

In the physics side, they mainly concern with the problem of how to probe nonstandard properties of neutrinos and physics beyond the Standard Model. In the history of physics, experiments based on interference have played key roles in development of fundamental physics. Some prominent examples include the two-slit experiment using an electron beam, Michelson-Morley experiment, $K^0 - \overline{K^0}$ mixing, and neutrino oscillations, just to name a few.

Since T2KK can detect (anti)neutrinos of a given energy at two different length scales, it would provide another sensitive probe of new physics related with neutrino sector. At the workshops, a few topics were discussed in this category.

- Possible deviation of the MNS matrix (N) from unitarity: Neutrino masses and mixings indicate new physics (NP) beyond the SM at some scale $\Lambda > v$, and this new physics could induce deviations of the MNS matrix from unitarity. The present constraints on the MNS mixing matrix without assuming unitarity were discussed [31]. Long baseline neutrino experiment such as T2KK may be useful to disentangle $|N_{\mu 1}|^2$ from $|N_{\mu 2}|^2$, which is not currently possible if we analyze the atmospheric neutrino data without assuming that the MNS matrix N is unitary.

- Nonstandard neutrino interactions with matter: NP could affect neutrino interactions with matter (source, medium and detector), with nonuniversality in the charged and the neutral current interactions with matter, which could be studied in a model independent fashion using the effective lagrangian approach [32]. Constraints from charged leptons are not that strong, whereas those from neutrino experiments are quite strong. It was argued that T2KK ($\sim$ 1000 km) has more chance to see possible deviation from the universality compared to T2K (295 km) or MINOS (735 km).

- Probing quantum decoherence: On general grounds, it is expected that there could be quantum decoherence effects due to quantum gravity and spacetime foam, including its stringy realization. Such a quantum decoherence effect can be studied in the neutrino oscillation experiment. A possibility to constrain the quantum decoherence parameter at the T2KK experiment was discussed [33].

- Since the detectors in T2KK will be much larger than the present Super-Kamiokande detector, it must be possible to carry out various non-long-baseline physics. Especially, neutrino physics with atmospheric neutrinos and proton decay searches with water Cherenkov detectors [34] and liquid Argon detectors [22]were discussed.

In the detector side, the cost for the photo detectors is an important issue, since it will largely affect the total cost of the experiment. Related to this issue, there were several discussions.

- The coverage of the photon detectors is an important issue related to the total cost of the experiment. Many T2KK related work have assumed the performance of Super-Kamiokande for the water Cherenkov detector. It has the 40% coverage of the PMTs. It was discussed that the signal to background separation and the signal detection efficiency for the neutrino beam should be similar between 40% and 20% PMT coverage [35]. As far as the long baseline neutrino physics is concerned, this is good news.
- The PMTs used in the present-day large neutrino detectors are not satisfactory, because of the relatively high cost, and relatively poor timing and charge resolutions. One of the possible new photo-detector device is the hybrid photo-detector, which amplifies the photo-electrons from the photocathode using avalanche diode. The photo-electrons are accelerated to 15 to 20 keV and bombard the avalanche diode. The signal is amplified by the avalanche diode by about 10^5. This device has an excellent single photoelectron charge resolution as well as the high timing resolution. Details of the R&D for this device was discussed in the 1st and 2nd workshops [36, 37].

7. Conclusion

In conclusion, the participants of the workshop recognized the high physics potential of T2KK with the J-PARC beam. Among various physics capabilities in T2KK, the high sensitivities to the neutrino mass hierarchy and CP violation, and therefore the potential to resolve the neutrino parameter degeneracy, should be noticed. It was also recognized that detailed studies should be continued to fully utilize the advantages of a detector in Korea. We agreed to continue exploring the full physics potential of T2KK, and to continue the workshops. This is why we gathered again to hold the 3rd workshop of this series, the discussion of which is summarized in these proceedings.

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