Sensitivity Study for T2KK with Reactor θ_{13} Experiments

Chizue Ishihara
Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

Abstract

T2KK experiment has potential of resolving the θ_{23} octant degeneracy by observing difference of the solar oscillation term between two identical water Cherenkov detectors, one in Kamioka and the other in Korea, which receive the neutrino beam from J-PARC facility. And it has shown in a previous study that T2KK can resolve all the 8-fold parameter degeneracy under the assumption that θ_{13} is within reach by the next generation accelerator experiments and θ_{23} is not too close to $\pi/4$. While, the next generation reactor θ_{13} experiments are expected to be able to determine parameter θ_{13} accurately. We discuss the sensitivity for resolving the parameter degeneracies with the combination of T2KK experiment and reactor neutrino experiments.

1. Introduction

Neutrino experiments have been raveling the structure of lepton mixing described by the Maki-Nakagawa-Sakata(MNS) matrix. One of the mixing parameters θ_{13} limited by CHOOZ is known to be small. T2K experiment, which is in preparation and will start in 2009 [1], is expected to provide new results of neutrino mixing parameter θ_{13}.

While the atmospheric neutrino observation by the Super-Kamiokande experiment established that the mixing angle θ_{23} is nearly 45° [2], θ_{23} could be any from 45° by ±8° at 90% C.L. If θ_{23} is not maximal 45°, $\sin^2\theta_{23}$ should have 2 degeneracy solutions. These degenerate solutions would cause ambiguity in the θ_{13} measurements in accelerator experiments because the dominant ν_e appearance term is proportional to $(\sin^2 2\theta_{13} \cdot \sin^2\theta_{23})$. The measurement of the other remaining unknowns in neutrino masses and the flavor mixing, the neutrino mass hierarchy and CP violation would be disturbed by the octant ambiguity. It is known that there could be 8-fold parameter degeneracy in the measurement of the oscillation parameters. These parameter degeneracy problems are important topics for the next generation neutrino experiment.

In the previous analysis [3], it is demonstrated that Kamioka-Korea two-detector setting, which receives the neutrino beam from J-PARC,(T2KK experiment) could solve total 8-fold parameter degeneracy in some cases. In this paper, we suppose the high presicion reactor θ_{13} experiments, and we demonstrate that the reactor experiments could contribute resolving parameter degeneracy combined with the long baseline experiments, especially T2KK.

pp. 143–149

2. Analysis Method

The basic strategy for resolving parameter degeneracy in T2KK experiment is driven by the solar Δm^2_{21} oscillation term, the first term in Eq. (1).

$$\begin{aligned}
P[\nu_\mu(\bar{\nu}_\mu) &\rightarrow \nu_{\rm e}(\bar{\nu}_e)] = c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta m^2_{21}L}{4E}\right)^2 \\
&+ \sin^2 2\theta_{13}s^2_{23}\left[\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \frac{1}{2}s^2_{12}\left(\frac{\Delta m^2_{21}L}{2E}\right)\sin\left(\frac{\Delta m^2_{31}L}{2E}\right)\right. \\
&\qquad \left. \pm\left(\frac{4Ea}{\Delta m^2_{31}}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \mp \frac{aL}{2}\sin\left(\frac{\Delta m^2_{31}L}{2E}\right)\right] \\
&+ 2J_r\left(\frac{\Delta m^2_{21}L}{2E}\right)\left[\cos\delta\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \mp 2\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\right] \qquad (1)
\end{aligned}$$

Eq. (1) show $P[\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_{\rm e}(\bar{\nu}_e)]$ appearance oscillation probability valid to first order in matter effect. $a \equiv \sqrt{2}G_F N_e$ [4] where G_F is the Fermi constant, N_e denotes the averaged electron number density along the neutrino trajectory in the earth, J_r ($\equiv c_{12}s_{12}c^2_{13}s_{13}c_{23}s_{23}$) denotes the reduced Jarlskog factor. The solar Δm^2_{21} is essentially negligible in the intermediate detector in Kamioka but not negligible at the far detector in Korea because of the very long baseline, we take the baseline length to the Korea detector to be 1050km. So a very far detector and a high intensity neutrino beam are needed for this strategy.

Let us look at to the second term in Eq. (1). $\nu_{\rm e}$ appearance probability is proportional to $(\sin^2 2\theta_{13} \cdot \sin^2\theta_{23})$. $\sin^2 2\theta_{23}$ is mesured accurately ($\sin^2 2\theta_{23} \geq 0.92$ at 90% C.L. [2]). If $\sin^2 2\theta_{23} = 0.96$, $\sin^2\theta_{23}$ is either 0.40 or 0.60. θ_{23} octant degeneracy could make two degenerate solutions obeying an approximate relationship $(\sin^2 2\theta_{13}s^2_{23})^{1st} = (\sin^2 2\theta_{13}s^2_{23})^{2nd}$.

Now, we describe reactor θ_{13} experiments. The disapearance probability of $\bar{\nu_{\rm e}}$, neglecting the solar terms and the matter effect, is

$$P[\bar{\nu}_e \rightarrow \bar{\nu}_e] = 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right). \qquad (2)$$

The disapearance probability is independent of θ_{23}. This suggests that the θ_{23} octant ambiguity can be resolved, if data from reactor θ_{13} experiments and long baseline experiments such as T2KK are combined. In this paper, we use the expected sensitivity of the RENO experiment [1] as an example of the reactor θ_{13} experiment.

Here, we describe our analysis for resolving θ_{23} octant degeneracy. In order to understand the sensitivity of the experiment with the two detector system at 295 km (Kamioka) and 1050 km (Korea), we carry out a detailed χ^2 analysis. This sensitivity study is based on the previous analysis [3].

The assumption on the experimental setting is 0.27 Mton fiducial masses for the intermediate site Kamioka and the far site Korea. The neutrino beam is assumed to be the 2.5 degree off-axis beam produced by the upgraded J-PARC 4 MW proton beam. It is assumed that the experiment will continue for 8 years with 4 years of neutrino and 4 years of anti-neutrino runs.

We use the reconstructed neutrino energy for single-Cherenkov-ring electron and muon events. The resolution in the reconstructed neutrino energy is 80 MeV for quasi-elastic events. We assume that $|\Delta m^2_{31}|$ should be known precisely by the time when the experiment will be carried out. Hence, we assume that the energy spectrum of the beam is the one expected by the 2.5 degree off-axis-beam in T2K. The shape of the energy spectrum for the anti-neutrino beam is assumed to be identical to that of the neutrino beam. The event rate for the anti-neutrino beam in the absence of neutrino oscillations is smaller by a factor of 3.4 due mostly to the lower neutrino interaction cross sections and partly to the slightly lower flux. The signal to noise ratio is worse for the anti-neutrino beam than that for the neutrino beam by a factor of about 2.

We assume that the experiment is equipped with a near detector which measures the rate and the energy dependence of the background for electron events, unoscillated muon spectrum, and the signal detection efficiency. These measurements are assumed to be carried out within the uncertainty of 5%. The possible difference between fluxes in the intermediate and the far detectors is taken into account as a systematic error in this analysis.

In this χ^2 analysis, we fix the value$|\Delta m^2_{31}|$ to be $\pm 2.5 \times 10^{-3} eV^2$. and solar parameters as $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12}$=0.31.

The statistical significance of the measurement considered in this analysis was estimated by using the following definition of χ^2:

$$\begin{aligned}\chi^2 &= \sum_{k=1}^{4}\left(\sum_{i=1}^{5}\frac{\left(N(e)_i^{\rm obs}-N(e)_i^{\rm exp}\right)^2}{\sigma_i^2}+\sum_{i=1}^{20}\frac{\left(N(\mu)_i^{\rm obs}-N(\mu)_i^{\rm exp}\right)^2}{\sigma_i^2}\right)\\ &+ \sum_{j=1}^{7}\left(\frac{\epsilon_j}{\tilde{\sigma}_j}\right)^2+\frac{(\sin^2 2\theta_{13}^{\rm obs}-\sin^2 2\theta_{13}^{\rm exp})^2}{(\delta\sin^2 2\theta_{13})^2},\end{aligned} \tag{3}$$

where

$$N(e)_i^{\rm exp} = N_i^{\rm BG}\cdot(1+\sum_{j=1,2,7} f(e)_j^i\cdot\epsilon_j) + N_i^{\rm signal}\cdot(1+\sum_{j=3,7} f(e)_j^i\cdot\epsilon_j)\ , \tag{4}$$

$$N(\mu)_i^{\rm exp} = N_i^{\rm non-QE}\cdot(1+\sum_{j=4,6,7} f(\mu)_j^i\cdot\epsilon_j) + N_i^{\rm QE}\cdot(1+\sum_{j=4,5,7} f(\mu)_j^i\cdot\epsilon_j)\ . \tag{5}$$

The first and second terms in Eq. (3) are for the number of observed single-ring electron and muon events, respectively. $N(e \text{ or } \mu)_i^{\rm obs}$ is the number of events to be observed for the given oscillation parameter set, and $N(e \text{ or } \mu)_i^{\rm exp}$ is the expected number of events for the assumed oscillation parameters in the χ^2 analysis. $k = 1, 2, 3$ and 4 correspond to the four combinations of the detectors in Kamioka and in Korea with the neutrino and anti-neutrino beams, respectively. The index i represents the reconstructed neutrino energy bin for both electrons and muons. For electron events, both $N(e)_i^{\rm obs}$ and $N(e)_i^{\rm exp}$ include background events. The energy ranges of the five energy bins for electron events are respectively 400-500 MeV, 500-600 MeV, 600-700 MeV, 700-800 MeV and 800-1200 MeV. The energy range for the muon events covers from 200 to 1200 MeV. Each energy bin has 50 MeV width. σ_i denotes the statistical uncertainties in the expected data. The third term in the χ^2 definition collects the contributions from variables which parameterize the systematic uncertainties in the expected number of signal and background events. The last term in Eq. (3) is the contribution from the reactor θ_{13} experiment.

$N_i^{\rm BG}$ is the number of background events for the $i^{\rm th}$ bin for electrons. $N_i^{\rm signal}$ is the number of electron appearance events that are observed, and depends on neutrino oscillation parameters. The uncertainties in $N_i^{\rm BG}$ and $N_i^{\rm signal}$ are represented by 4 parameters ϵ_j ($j = 1$ to 3 and 7). Similarly, $N_i^{\rm non-QE}$ are the number of non-quasi-elastic events for the $i^{\rm th}$ bin for muons. $N_i^{\rm QE}$ are the number of quasi-elastic muon events. The uncertainties in $N_i^{\rm non-QE}$ and $N_i^{\rm QE}$ are represented by 4 parameters ϵ_j ($j = 4$ to 7).

During the fit, the values of $N(e \text{ or } \mu)_i^{\rm exp}$ are recalculated for each choice of the oscillation parameters which are varied freely to minimize χ^2, and so are the systematic error parameters ϵ_j. The parameter $f(e \text{ or } \mu)_j^i$ represents the fractional change in the predicted event rate in the $i^{\rm th}$ bin due to a variation of the parameter ϵ_j. The overall background normalization for electron events is assumed to be uncertain by $\pm 5\%$ ($\tilde{\sigma}_1$=0.05). It is also assumed that the background events for electron events has an energy dependent uncertainty with the functional form of $f(e)_2^i = ((E_\nu(rec) - 800\ MeV)/800\ MeV)$. 5% is assumed to be the uncertainty in ϵ_2 ($\tilde{\sigma}_2$=0.05). The same functional form is used to define the uncertainty in the spectrum shape for muon events ($\tilde{\sigma}_4$=0.05). The uncertainties in the signal detection efficiency are assumed to be 5% for both electron and muon events ($\tilde{\sigma}_3 = \tilde{\sigma}_5$=0.05). The uncertainty in the separation of quasi-elastic and non-quasi-elastic interactions in the muon events is assumed to be 20% ($\tilde{\sigma}_6$=0.20). These systematic errors are assumed to be not correlated between the electron and muon events. In addition, for the number of events in Korea, the possible flux difference between Kamioka and Korea is taken into account in $f(e \text{ or } \mu)_7^i$. The predicted flux difference [11] is simply assumed to be the 1 σ uncertainty in the flux difference ($\tilde{\sigma}_7$).

In the last term of Eq. (3), $\sin^2 2\theta_{13}^{\rm obs}$ is the $\sin^2 2\theta_{13}$ value to be observed for the given oscillation parameter set, and $\sin^2 2\theta_{13}^{\rm exp}$ is the true value of $\sin^2 2\theta_{13}$ assumed in the χ^2 analysis. $\delta \sin^2 2\theta_{13}^2$ indicates the error of the observed $\sin^2 2\theta_{13}$ value. For this uncertainty, we use the estimate from RENO experiment which are described in detail in [1]. The estimated statistical and systematic errors are 0.35% and 1.2% respectively for 5 years run, 0.24% and 0.6% for 10 years run. The total uncertainty of $\sin^2 2\theta_{13}$ value is calculated to be $\delta \sin^2 2\theta_{13}$= 1.3% for 5 years run (conservative scenario) and $\delta \sin^2 2\theta_{13}$= 0.6% for 10 years run (aggresive scenario).

3. Analysis Results

Now we present the results of the sensitivity analysis for the θ_{23} octant degeneracy. The results for the mass hierarchy as well as CP violation sensitivities will be discussed later.

Fig. 1 shows the sensitivity to the θ_{23} octant determination as a function of $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$ for T2KK only[3] and T2KK + RENO with 5 and 10 years of the RENO data. The shaded areas in left (a) (right (b)) panels indicate the regions of parameters where the octant of θ_{23} can be determined at 3 (2) standard deviation confidence level, which is determined by the condition $\chi^2_{min}(wrong\ octant) - \chi^2_{min}(true\ octant) > 9$ (4) for any value of CP phase δ. The upper (lower) panels correspond to the case where the true hierarchy is normal (inverted). From these figures (Fig. 1), we conclude that RENO experiment is able to help solving the octant ambiguity, if $\sin^2 2\theta_{13} >$ (a few) $\times 10^{-2}$.

Let us show an example of the sensitivity to determine mass hierarchy adding the contribution from the reactor experiments. Fig. 2 show a comparison between the sensitivities by T2KK only and T2KK including RENO 10 years data with a particular set of true parameter values which are quoted in caption of Fig. 2. The upeer four panels of Fig 2 show the expected allowed regions of oscillation param-

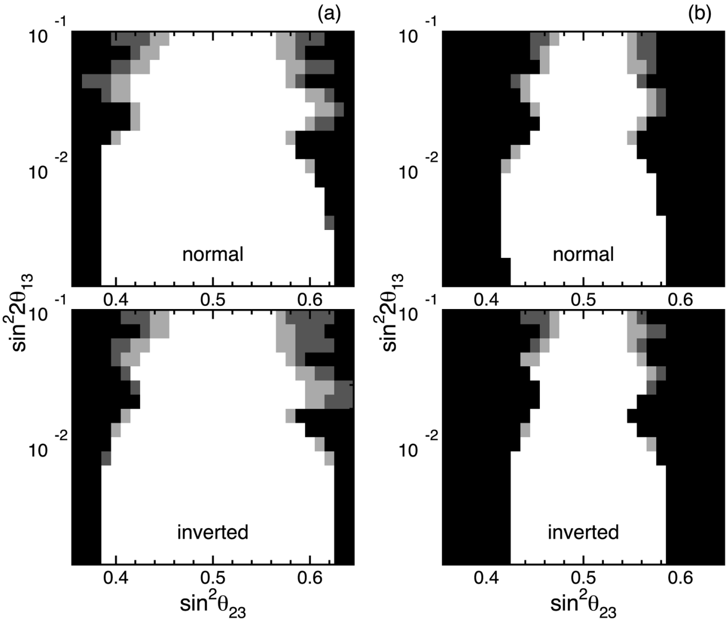

Fig. 1 The regions of parameters where the octant of θ_{23} can be determined at 3σ C.L. (a) and 2σ C.L. (b) for any values of the CP phase δ in case of T2KK only and the one including contribution from RENO experiment. Black region indicates in case of T2KK only and dark gray (light gray) region corresponds to T2KK + RENO 5 years (10 years) run.

eters in T2KK experiment, while the lower four panels show the allowed regions by the T2KK results with RENO experiment. In panels (aI) and (bI), the wrong mass hierarchy solutions are observed at 99% C.L. but they are eliminated in (cI) and (dI) which are T2KK + RENO results. As expected from Eq.(1), one finds that the fitted value of $\sin^2 2\theta_{13}$ is wrong in the wrong mass hierarchy solution. And in Figs. 3, the sensitivity regions to the mass hierarchy is presented in case of T2KK and T2KK + RENO (10 years). In both figures, the thin-lines and the thick-lines indicate the sensitivity region at 2 and 3 standard deviations, respectively. 2 (3) standard deviation sensitivity regions are defined by the conditions, $\chi^2_{min}(wrong\ hierarchy) - \chi^2_{min}(true\ hierarchy) > 4$ (9). Upper and lower figures show the cases for positive and negative mass hierarchies, respectively. The sensitivity to the mass hierarchy by T2KK + RENO is improved slightly compared with T2KK-only in case $\sin^2\theta_{23}$ being deviating from 0.5 and relatively large $\sin^2 2\theta_{13}$ (around 0.05). From Fig. 3, we conclude that reactor experiments also contribute resolving the mass hierarchy.

On the other hand, we found that there is no significant improvement in sensitivity to CP violation compared with [3] even if the reactor data are included.

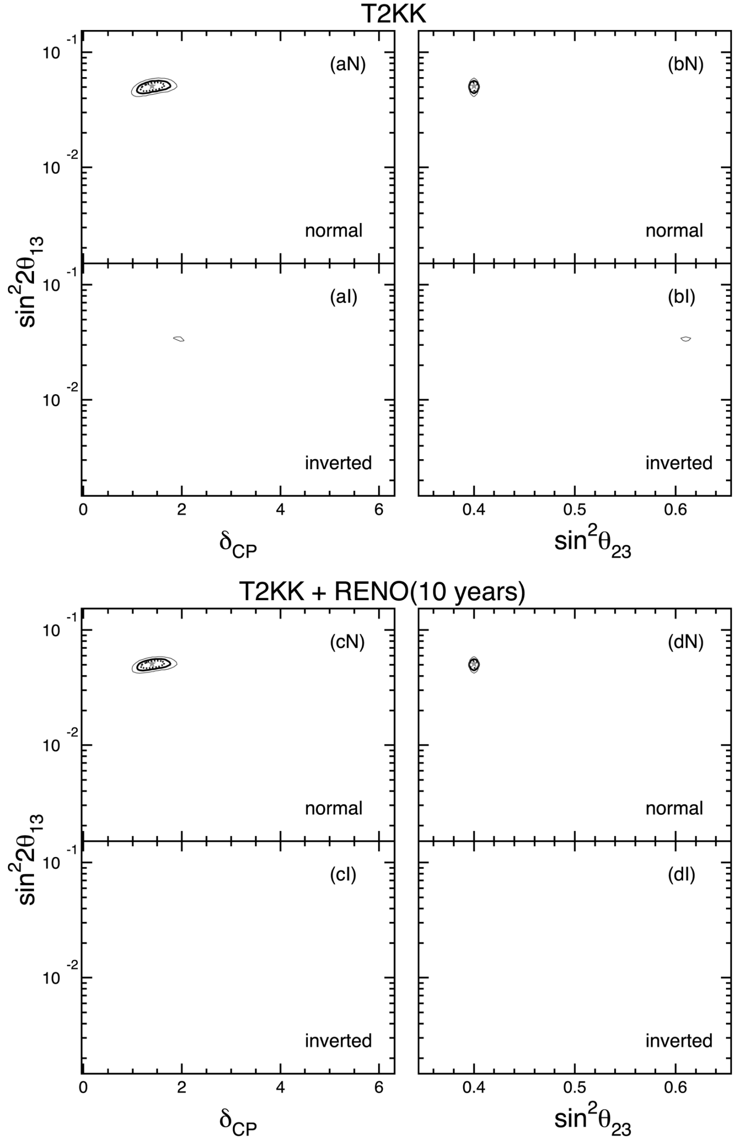

Fig. 2 The region allowed in $\delta - \sin^2 2\theta_{13}$ and $\sin^2\theta_{23} - \sin^2 2\theta_{13}$ spaces by T2KK only (upper four panels) and by the T2KK with RENO 10 years data (lower four panels). The panels with the description of normal (inverted) show the allowed region for the positive (negative) sign of Δm^2_{31}. The true solution is assumed to be located at $\sin^2 2\theta_{13}$=0.05, $\sin^2\theta_{23}$=0.40 and δ=1.4 with positive sign of $\Delta m^2_{31}(= +2.5 \times 10^{-3}\ \mathrm{eV}^2)$, which is indicated by the star. The solar mixing parameters are fixed as $\Delta m^2_{21} = 8 \times 10^{-5}\ \mathrm{eV}^2$ and $\sin^2\theta_{12}$=0.31. Three contours in each figure correspond to the 68%, 90% and 99% C.L. sensitivities, which are defined as the difference of the χ^2 being 2.30, 4.61 and 9.21, respectively.

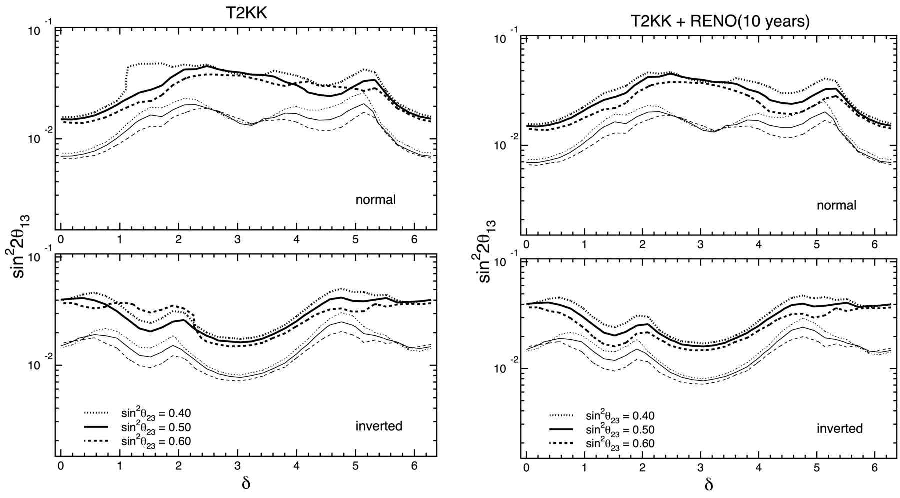

Fig. 3 2(thin lines) and 3(thick lines) standard deviation sensitivities to the mass hierarchy determination for several values of $\sin^2 2\theta_{23}$ (dotted, solid and dashed lines show the results for $\sin^2\theta_{23} = 0.40$, 0.50 and 0.60, respectively). The left and right panels are for T2KK-only and T2KK+RENO(10years), respectively. The sensitivity is defined in the plane of $\sin^2 2\theta_{13}$ versus CP phase δ. The top and bottom panels show the cases for positive and negative mass hierarchies, respectively.

4. Conclusion

We have carried out the sensitivity study with a setting with two identical water Cherenkov detectors of 0.27 Mton fiducial mass, one in Kamioka and the other in Korea, which receive almost the same neutrino beam from J-PARC, and reactor experiment RENO, which observe reactor neutrino. T2KK has capability of resolving the θ_{23} octant degeneracy by observing the solar oscillation term. Data from future reactor θ_{13} experiments such as RENO will enhance the θ_{13} octant sensitivity, if $\sin^2 2\theta_{13}$ is larger than (a few) $\times 10^{-2}$.

References

[1] T. Ishida in these Proceedings.
[2] Y. Ashie *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D **71**, 112005 (2005)
[3] T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, Phys. Rev. D **75**, 013006 (2007)
[4] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978). S. P. Mikheyev and A. Yu. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1985)]; Nuovo Cim. C **9**, 17 (1986).
[5] E. Jeon, Talk at the 3rd International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam, University of Tokyo, Hongo, Sep.30 - Oct.1, 2007; E. Jeon in these Proceedings.
[6] A. Rubbia and A. Meregaglia, Talk at the 2nd International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam, Seoul National University, Seoul, July 13-14, 2006. Web page: http://t2kk.snu.ac.kr/