Physics potential of future long baseline neutrino oscillation experiments with KEK-JAERI HIPA

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We study physics potential of Very Long Base-Line (VLBL) Neutrino-Oscillation Experiments with the High Intensity Proton Accelerator, which will be completed by the year 2007 in Tokai-village, Japan. As a target, a 100 kton-level water-Cherenkov detector is considered at 2,100 km away. Assuming the pulsed narrow-band $\nu_\mu$ beams, we study sensitivity of such experiments to the neutrino mass hierarchy, the mass-squared differences, one CP phase and three angles of the lepton-flavor-mixing matrix. We find that experiments at a distance 2,100 km can determine the neutrino mass hierarchy if the mixing matrix element $|U_{e3}|$ is not too small. The CP phase and $|U_{e3}|$ can be constrained if the large-mixing-angle solution of the solar-neutrino deficit is realized.

1. Introduction

In order to measure the neutrino oscillation parameters, such as the neutrino mass-squared differences and the elements of the $3 \times 3$ Maki-Nakagawa-Sakata (MNS) lepton flavor-mixing matrix elements $U$, various long base-line (LBL) neutrino oscillation experiments are proposed. In Japan, as a sequel to the K2K experiment, a new LBL neutrino oscillation experiment between the High Intensity Proton Accelerator (HIPA) and the Super-Kamiokande (SK) with the base-line length of $L=295$ km has been proposed. The HIPA has a 50 GeV proton accelerator, which will be completed by the year 2007 in the site of Japan Atomic Energy Research Institute (JAERI) as the joint project of KEK and JAERI. It is expected to deliver $10^{21}$ protons on target (POT) in one year. The intensity of the neutrino beam in the $\sim 1$ GeV range is two orders of magnitude higher than that of the KEK beam for the K2K experiment. The HIPA-to-SK experiment with $\langle E_\nu \rangle = 1.3$ GeV will measure the larger mass-squared difference with 3 % accuracy and the mixing angle at about 1 % accuracy.

In this report we examine physics potential of Very Long Base-Line (VLBL) neutrino oscillation experiments with HIPA and a huge neutrino detector in Beijing, at about $L=2,100$ km away. As a beam option, the pulsed narrow-band $\nu_\mu$ beam (NBB) is assumed. For a target at $L=2,100$ km, we consider a 100 kton water-Cherenkov detector which is capable of measuring the $\nu_\mu \rightarrow \nu_e$ transition probability, $P_{\nu_\mu \rightarrow \nu_e}$, and the $\nu_\mu$ survival probability, $P_{\nu_\mu \rightarrow \nu_\mu}$. We study the sensitivity of such experiments to the neutrino mass hierarchy, the mass-squared differences, the three angles and one CP phase of the MNS matrix.

2. Neutrino oscillation in the three-neutrino model

The MNS matrix has three mixing angles and three phases in general. We adopt the following parameterization

$$V = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\varphi_2} & 0 \\
0 & 0 & e^{i\varphi_3}
\end{pmatrix}. $$

Two Majorana phases in the latter matrix, $\varphi_2$ and $\varphi_3$, do not contribute to the neutrino oscillation. The former matrix can be parameterized by three mixing angles and one phase just the same as the CKM matrix. Because the present neutrino oscillation experiments constrain directly the elements, $U_{e2}$, $U_{e3}$, and $U_{\mu3}$, these three matrix elements are taken as the independent param-
meters. Without losing generality, we can take $U_{e2}$ and $U_{\mu 3}$ to be real and non-negative. By allowing $U_{e3}$ to have the complex phase $U_{e3} = |U_{e3}|e^{-i\delta_{\text{MNS}}} \ (0 \leq \delta_{\text{MNS}} < 2\pi)$, the four independent parameters are $U_{e2}, U_{\mu 3}, |U_{e3}|$ and $\delta_{\text{MNS}}$. All the other matrix elements are then determined by the unitary conditions.

The constraints on the MNS matrix elements and the mass-squared differences are given by the atmospheric- and solar-neutrino and the CHOOZ reactor experiments. An analysis of the atmospheric-neutrino data from the SK experiment finds $\sin^2 2\theta_{\text{ATM}} \sim (0.88 - 1.0)$ and $\delta m^2_{\text{ATM}} \ (\text{eV}^2) \sim (1.6 - 4.0) \times 10^{-3}$. From the observations of the solar-neutrino deficit by the SK collaboration, the MSW large-mixing-angle solution (LMA) is preferred to MSW small-mixing-angle solution (SMA), MSW low-$\delta m^2$ solution (LOW) and Vacuum Oscillation solution (VO). The CHOOZ experiment gives the constraint $\sin^2 2\theta_{\text{CHOOZ}} < 0.1$ for $\delta m^2_{\text{CHOOZ}} > 1.0 \times 10^{-3} \text{eV}^2$. From the above experiments, the independent parameters in the MNS matrix are obtained as

$$U_{\mu 3} = \sqrt{1 - \sin^2 2\theta_{\text{ATM}}} \sqrt{\frac{\sqrt{2}}{\sin 2\theta_{\text{ATM}}}}$$

$$U_{e2} = \sqrt{1 - |U_{e3}|^2 - (1 - |U_{e3}|^2)^2 - \sin^2 2\theta_{\text{SOL}}} \sqrt{\frac{\sqrt{2}}{\sin 2\theta_{\text{SOL}}}}$$

$$|U_{e3}| = \sqrt{1 - \sin^2 2\theta_{\text{CHOOZ}}} \sqrt{\frac{\sqrt{2}}{\sin 2\theta_{\text{CHOOZ}}}} \times 0.16$$

Here, we have made the identification $\delta m^2_{\text{SOL}} = |\delta m^2_{\text{SOL}}| \leq |\delta m^2_{\text{ATM}}| = \delta m^2_{\text{ATM}}$, with $\delta m^2_{ij} = m^2_j - m^2_i$.

Since all the above constraints are obtained from the survival probabilities which are even-functions of $\delta m^2_{ij}$, there are four neutrino-mass hierarchy cases corresponding to the sign of the $\delta m^2_{ij}$ as shown in Fig. 1. If the MSW effect is relevant for the solar-neutrino oscillation, then the hierarchy cases II and IV are not favored. The hierarchy I (III) is called ‘normal’ (‘inverted’) hierarchy, which corresponds to $\delta m^2_{12} > 0$ and $\delta m^2_{13} > 0$ ($\delta m^2_{23} < 0$). From the Super-Nov 1987A observation, the hierarchy I is favored against the hierarchy III [6].

![Figure 1](image)

**Figure 1.** Schematical view of the four cases of neutrino-mass hierarchy.

### 3. VLBL neutrino oscillation experiment with $L=2,100$ km

We explore the capability of a VLBL experiment with $L=2,100$ km by using $\nu_\mu$ NBB. The parameterization of the NBB is made to study the effects of changing the peak energy, $E_p$, of the NBB. We find that the use of two different-energy NBB’s, NBB’s with $E_p = 4 \text{ GeV} \ (\text{NBB(4GeV)})$ and $E_p = 6 \text{ GeV} \ (\text{NBB(6GeV)})$, improves the physics resolving power of the experiment significantly. Fig. 2 shows our parameterizations of the main part of NBB(4GeV) and NBB(6GeV) fluxes ($\times$ neutrino-energy). Also overlayed in Fig. 2 are the oscillation probabilities, which are calculated for $\sin^2 2\theta_{\text{ATM}} = 1.0$, $\delta m^2_{\text{SOL}} = 3.5 \times 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{\text{SOL}} = 0.8$, $\delta m^2_{\text{SOL}} = 10 \times 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{\text{CHOOZ}} = 0.1$, $\delta_{\text{MNS}} = 270^\circ$ and the matter density, $\rho = 3 \text{ g/cm}^3$, with the hierarchy I. Note that the NBB(6GeV) makes the $e$-like event rates high while keeping $\mu$-like event rates low.

For a detector at $L=2,100$ km, we assume a 100 kton water-Čerenkov detector. It has a capability of distinguishing $e^\pm$ charged-current (CC) events from $\mu^\pm$ CC events, but does not distinguish their charges. The detection efficiencies of the $\mu$-like and $e$-like events are assumed to be 100% for simplicity. The statistical errors of each predictions are then simply square values of the observed numbers of events. We do not require capability of the detector to reconstruct the neutrino energy.
The signals of our analysis are then the numbers of $\nu_\mu$ CC events and those of $\nu_e$ CC events from the NBB. For NBB($E_p$), they are calculated as

$$N(\mu(e), E_p) = MN_A \int_0^{E_p} dE_\nu \Phi(E_\nu)\sigma^{CC}_{\mu(e)} P_{\nu_\mu \rightarrow \nu_{\mu(e)}},$$

where $M$ is the statistical significance (mass of the detector (= 100 kton) times the running years), $N_A = 6.017 \times 10^{23}$ is the Avogadro number, $\Phi(E_\nu)$ is the flux at $L = 2,100 \text{ km}$. The $\sigma^{CC}_{\mu(e)}$ is the $\nu_\mu(\nu_e)$ CC cross section per nucleon off water target.

Fig. 2 shows the numbers of signal events, $N(\mu, E_p)$ and $N(e, E_p)$, expected at the base-line length of $L = 2,100 \text{ km}$ for 500 kton-year with (a) the NBB(4GeV) and with (b) the NBB(6GeV). The predictions for the four cases of the neutrino-mass hierarchies, I, II, III and IV, are indicated explicitly. We take

$$\sin^2 2\theta_{\text{ATM}} = 1.0, \sin^2 2\theta_{\text{CHOOZ}} = 0.06, 0.1, \delta_{\text{MNS}} = 0^\circ - 360^\circ,$$

with $\rho = 3 \text{ g/cm}^3$. The remaining two parameters, $\sin^2 2\theta_{\text{SOL}}$ and $\delta_{\text{MNS}}$, are taken as the following sets for the three possible solutions to the solar-neutrino deficit anomaly:

$(\sin^2 2\theta_{\text{SOL}}, \delta_{\text{MNS}}) = (0.8, 15(3) \times 10^{-5}\text{eV}^2)$ for LMA, $(7 \times 10^{-3}, 5 \times 10^{-6}\text{eV}^2)$ for SMA, $(0.7, 7 \times 10^{-11}\text{eV}^2)$ for VO.

For the hierarchy I, the predictions reside in the corner at small $N(\mu, E_p)$ and large $N(e, E_p)$. For the LMA scenario, the predictions are shown by circles when $\delta_{\text{MNS}}$ is allowed to vary freely. We show the four representative phase values by solid-circle ($\delta_{\text{MNS}} = 0^\circ$), solid-square ($90^\circ$), open-circle ($180^\circ$), and open-square ($270^\circ$) in the largest circle. The two grand circles with smaller $N(\mu, E_p)$ give the predictions of the LMA solution for $\delta m^2_{\text{SOL}} = 15 \times 10^{-5}\text{eV}^2$, and those with larger $N(\mu, E_p)$ are for $\delta m^2_{\text{SOL}} = 3 \times 10^{-5}\text{eV}^2$. The $\nu_e$ CC event number $N(e, E_p)$ grows with increasing $\sin^2 2\theta_{\text{CHOOZ}}$. It is clearly seen that $\delta_{\text{MNS}}$ dependence is larger for larger $\delta m^2_{\text{SOL}}$ and for larger $\sin^2 2\theta_{\text{CHOOZ}}$.

Note that the $\delta_{\text{MNS}}$ dependence of $N(e, 4\text{GeV})$ is ‘orthogonal’ to that of $N(e, 6\text{GeV})$. The predictions of the SMA and the VO parameters appear just above the upper LMA circles, where the $\delta_{\text{MNS}}$ dependence diminishes to zero. We cannot distinguish the VO predictions between the neutrino-mass hierarchy I and II, nor between III and IV.

All the predictions of the hierarchy cases III and IV have very small $N(e, E_p)$, typically a factor of 5 or more smaller in magnitude than the corresponding number of events in case I. This striking sensitivity of $P_{\nu_\mu \rightarrow \nu_\mu}$ on the hierarchy cases is the bases of the capability of distinguishing the cases in the VLBL experiments. On the other hand, we find that the 5 % level differences in $N(\mu, E_p)$ between the hierarchy cases I and III are not useful for this purpose because $P_{\nu_\mu \rightarrow \nu_\mu}$ depends strongly on the atmospheric parameters $\delta m^2_{\text{ATM}}$ and $\sin^2 2\theta_{\text{ATM}}$, and also because $N(\mu, E_p)$ suffers from the neutrino-beam flux uncertainty.

We take into account for the background contributions to the $\mu$-like and the $e$-like events from the secondary-beams and the $\tau$ pure-leptonic decays. The $e$-like events also receive contributions from the neutral-current (NC) events where produced $\pi^0$’s mimic electron shower in the water-Čerenkov detector. The error in the $e$/NC misidentification probability, $F_{e/NC} = 0.0055 \pm 0.00055$, is accounted for as a systematic error.
Figure 3. The expected signal numbers, \( N(\mu, E_p) \) and \( N(e, E_p) \), at \( L=2,100 \) km for 500 kton-year with (a) NBB(4GeV) and (b) NBB(6GeV). The predictions for the four-cases of the neutrino-mass hierarchies are depicted as I, II, III and IV. The hierarchy cases II and IV are shown for completeness sake even though they do not lead to the MSW solution of the solar-neutrino deficit.

The \( \nu_\tau \) CC events with hadronic \( \tau \)-decays are counted as NC-like events with the same \( P_{e/NC} \) factor. The 10% errors in the branching fractions of the \( \tau \) decay are accounted for as systematic errors.

In addition, we account for the uncertainties in the total fluxes of the neutrino NBB’s and the matter density as the major part of the systematic uncertainty. We allocate common 3% uncertainty for all the NBB’s and 3.3% overall uncertainty in the matter density.

4. Results of the \( \chi^2 \) analysis

We examine the capability of the VLBL experiments with \( L = 2,100 \) km in determining the model parameters. The following questions are of our concern.

1. Can we distinguish the neutrino-mass hierarchy cases I (\( \delta m^2_{13} > 0 \)) and III (\( \delta m^2_{13} < 0 \))?
2. Can we measure \( \sin^2 2\theta_{\text{CHOOZ}} \) and \( \delta_{\text{MNS}} \)?
3. Can we distinguish the solar-neutrino oscillation scenarios?
4. How much can we improve the measurements of \( \sin^2 2\theta_{\text{ATM}} \) and \( \delta m_{\text{ATM}} \)?

We examine the questions by combining two experiments with different base-line length, \( L = 2,100 \) km (HIPA-to-Beijing) and \( L = 295 \) km (HIPA-to-SK). For a VLBL experiment at \( L = 2,100 \) km, we assume the statistical significance of 500 kton-year each with the NBB(4GeV)and NBB(6GeV). As for the LBL experiment at \( L = 295 \) km, we assume that 100 kton-year for the low-energy NBB with \( \langle p_\pi \rangle = 2 \) GeV (NBB(2\( \pi \))). The data obtained from the LBL experiment is what SK can gather in approximately 5 years with \( 10^{21} \) POT par year. (The latest design of the HIPA-to-SK project \( \square \) adopts off-axis beams in the first stage.)

The \( \chi^2 \) is a function of the three angles, the two mass-squared differences, the CP phase, the flux normalization factors and the matter density. For a given set of these parameters, we have defined predictions of the \( \mu \)-like and \( e \)-like event numbers including both the signal and the background.

4.1. I v.s. III

We show in Fig. \( \square \) the minimum \( \chi^2 \) as a function of \( \sin^2 2\theta_{\text{CHOOZ}} \) by assuming the hierarchy III
in the analysis, when the expected event numbers are generated for the following input (true) parameters with the hierarchy I in the LMA region.

**Input (true) parameters:**

\[
\begin{align*}
\sin^2 2\theta_{\text{true}}^{\text{ATM}} & = 1.0, & \delta m_{\text{true}}^{\text{ATM}} & = 3.5 \times 10^{-3} \text{ eV}^2 \\
\sin^2 2\theta_{\text{true}}^{\text{SOL}} & = 0.8, & \delta m_{\text{true}}^{\text{SOL}} & = 10 \times 10^{-5} \text{ eV}^2 \\
\sin^2 2\theta_{\text{true}}^{\text{CHOOZ}} & = 0.02, 0.04, 0.1, & \delta_{\text{true}}^{\text{MNS}} & = 0^\circ, 90^\circ, 180^\circ, 270^\circ, \\
\delta m_{12} & = \delta m_{23} = \delta m_{13}^{\text{true}} \quad \text{(hierarchy I)}
\end{align*}
\]

In total 12 minimum \( \chi^2 \) lines are labeled by the input values of \( \sin^2 2\theta_{\text{true}}^{\text{CHOOZ}} = 0.02 \) (thin lines), 0.04 (medium-thick lines), 0.1 (thick lines) and \( \delta_{\text{true}}^{\text{MNS}} = 0^\circ \) (solid lines), 90\(^\circ\) (long-dashed lines), 180\(^\circ\) (short-dashed lines), 270\(^\circ\) (dot-dashed lines).

**Figure 4.** Minimum \( \chi^2 \) as a function of \( \sin^2 2\theta_{\text{CHOOZ}} \) when the hierarchy III is postulated in the analysis. The event numbers are calculated for the hierarchy I in the LMA region. The input (true) values of \( \sin^2 2\theta_{\text{CHOOZ}} \) and \( \delta_{\text{MNS}} \) are shown by the line thickness and the line type, respectively.

The \( \chi^2 \) fit has been performed by assuming the hierarchy III. The minimum of the \( \chi^2 \) function is found for a \( \sin^2 2\theta_{\text{CHOOZ}} \) value in the range below 0.12, by varying the parameters, \( \sin^2 2\theta_{\text{SOL}} \) and \( \delta m_{\text{SOL}}^{\text{true}} \), in the LMA region, and the remaining three parameters, \( \sin^2 2\theta_{\text{ATM}} \), \( \delta m_{\text{ATM}} \) and \( \delta_{\text{MNS}} \), freely.

**Fitting parameters:**

\[
\begin{align*}
\sin^2 2\theta_{\text{ATM}} & : \text{free}, & \delta m_{\text{ATM}} & : \text{free}, \\
\sin^2 2\theta_{\text{SOL}} & = 0.7 - 0.9, & \delta m_{\text{SOL}} & = (3 - 15) \times 10^{-5} \text{ eV}^2, \\
\sin^2 2\theta_{\text{CHOOZ}} & : \text{free}, & \delta_{\text{MNS}} & : \text{free}, \\
\delta m_{12} & = \delta m_{23}, & \delta m_{13} = -\delta m_{23} \quad \text{(hierarchy III)}
\end{align*}
\]

The uncertainties in the total fluxes of the NBB's and the matter density are taken into account.

The minimum \( \chi^2 \) for \( \sin^2 2\theta_{\text{CHOOZ}} = 0.1 \) is always larger than 50, which allows us to distinguish the hierarchy I from III at 7\( \sigma \) level. We also find that the hierarchy III can be rejected at 3\( \sigma \) level when \( \sin^2 2\theta_{\text{CHOOZ}} \gtrsim 0.04 \), and at 1\( \sigma \) level \( \sin^2 2\theta_{\text{CHOOZ}} \gtrsim 0.02 \). The capability of distinguishing the hierarchy cases I and III comes from the remarkable differences of the transition probability \( P_{\nu_e \rightarrow \nu_e} \) between them.

### 4.2. \( \sin^2 2\theta_{\text{CHOOZ}} \) and \( \delta_{\text{MNS}} \)

Fig. 3 shows the minimum \( \chi^2 \) in the \( \sin^2 2\theta_{\text{CHOOZ}} \) v.s. \( \delta_{\text{MNS}} \) plane. The event numbers are calculated at \( \sin^2 2\theta_{\text{CHOOZ}}^{\text{true}} = 0.06 \) for \( \delta_{\text{true}}^{\text{MNS}} = 0^\circ, 90^\circ, 180^\circ, 270^\circ \) in each figure. The other parameters are taken as the same as in Fig. 4. We show the input parameter point by a solid-circle and the minimum \( \chi^2 \) value in each figure. The \( \chi^2 \) fit has been performed by assuming the LMA scenario with the hierarchy I, while the other parameters are freely varied.

When \( \delta_{\text{true}}^{\text{MNS}} \) is around 0\(^\circ\) or 180\(^\circ\), 0.04 < \( \sin^2 2\theta_{\text{CHOOZ}} \) < 0.1 is obtained and \( \delta_{\text{MNS}} \) can be constrained to local values at 1\( \sigma \) level. On the other hand, when \( \delta_{\text{true}}^{\text{MNS}} \) is around 90\(^\circ\) or 270\(^\circ\), 0.02 < \( \sin^2 2\theta_{\text{CHOOZ}} \) < 0.08 or 0.045 < \( \sin^2 2\theta_{\text{CHOOZ}} \) < 0.12 are obtained, respectively, but we cannot constrain \( \delta_{\text{MNS}} \). As shown in Fig. 3, the \( \delta_{\text{MNS}} = 90^\circ \) (270\(^\circ\)) point for the hierarchy I lies in the lower (higher) \( N(e, E_{\nu}) \) corner. The same values of \( N(e, 4\text{GeV}) \) and \( N(e, 0\text{GeV}) \) can be obtained for the other \( \delta_{\text{MNS}} \) by changing appropriately the \( \sin^2 2\theta_{\text{CHOOZ}} \) parameter. On the
other hand, in the case of $\delta_{\text{MNS}} = 0^\circ$ or $180^\circ$, it is difficult to reproduce both $N(e, 4\text{GeV})$ and $N(e, 6\text{GeV})$ simultaneously because of the orthogonal $\delta_{\text{MNS}}$-dependence between $N(e, 4\text{GeV})$ and $N(e, 6\text{GeV})$.

4.3. Solar- and atmospheric-neutrino parameters

We give only results for the remaining two questions. If the LMA scenario is realized in Nature and $\sin^2 2\theta_{\text{CHOOZ}} > 0.06$, the SMA/LOW/VO scenarios can be rejected at $1\sigma$ level when $\delta_{\text{MNS}}^{\text{true}}$ is around $0^\circ$ or $180^\circ$ but not at all when $\delta_{\text{MNS}}^{\text{true}}$ is around $90^\circ$ or $270^\circ$.

For the atmospheric-neutrino oscillation parameters, $\sin^2 2\theta_{\text{ATM}}$ is measured to 1% level and $\delta_{\text{ATM}}^2$ with the 3% accuracy when $\sin^2 2\theta_{\text{CHOOZ}}^{\text{true}} = 1.0$ and $\delta_{\text{ATM}}^2 = 3.5 \times 10^{-3}$ with the LMA scenario.

5. Summary

The HIPA will be completed by the year 2007 and deliver $10^{21}$ POT at 50 GeV for one year operation. Assuming the NBB’s from the HIPA and a 100 kton-level water-Cerenkov detector, we study the physics potential of the VLBL experiments with $L=2,100 \text{ km}$ as a sequel to the proposed HIPA-to-SK LBL experiment with $L=295 \text{ km}$. Thanks to the enhancement of matter effect, it is expected to distinguish the neutrino-mass hierarchy cases in such VLBL experiments. We find that a combination of LBL experiments at $L=295 \text{ km}$ and VLBL experiments at $L=2,100 \text{ km}$ can determine the neutrino mass hierarchy at $3\sigma$ level if $\sin^2 2\theta_{\text{CHOOZ}} > 0.04$. Also it is found that, if the LMA scenario is realized in Nature, $\sin^2 2\theta_{\text{CHOOZ}}$ and $\delta_{\text{MNS}}$ can be constrained at $1\sigma$ level in favorable cases.

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