Physics Potentials of T2KK and T2KK

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Based on the works

Workshop on the 2nd HK detector in Korea
KNRC & SNU, Sep 2 (2016)
Neutrino Physics

- Many important questions unanswered yet
- Masses (and their origin) ? (NH or IH ?) CP phase(s) ?
- Dirac or Majorana ?
- Sterile neutrinos ?
- Neutrino DM connection ?
- Need new experimental data to answer them
Contents

• Physics potential of the T2KK experiment (Many thanks to Yoshitaro Takaesu and Naotoshi Okamura for their help for preparation of this talk)

• New Physics sensitivity of T2K and T2KK
Physics Potential of the T2KK Experiment

For the probe for new physics in the neutrino sector at T2KK, Cipriano Ribeiro, Kajita, Ko, Minakata, Nakayama, Nunokawa, hep-ph:0712.4314, PRD
Our knowledge of neutrino oscillation

Three light flavor mixing

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
\sin^2 2\theta_{23} \sim 1
\]

\[
\theta_{13} \sim 9^\circ
\]

\[
\theta_{12} \sim 35^\circ
\]

\[
\delta_{CP} : \text{unknown}
\]

Mass differences

\[
m_2^2 - m_1^2 = 7.5 \times 10^{-5} [\text{eV}^2]
\]

\[
|m_3^2 - m_1^2| = 2.32 \times 10^{-3} [\text{eV}^2]
\]

Next targets

Mass hierarchy: NH or IH

Oscillation probability

\[ P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - \sin^2 2\theta_{\text{atm}} \sin^2 (\Delta_{31} + \Delta_{21} \cos^2 \theta_{12}) \]

\[ P_{\nu_\mu \rightarrow \nu_e} \simeq 4 \sin^2 \theta_{13} \sin^2 \theta_{23} (1 + A^e) \sin^2 (\Delta_{31} + B^e) \]

\[ \sin \theta_{\text{atm}} = \sin \theta_{23} \cos \theta_{13}, \quad \Delta_{ij} = \frac{\delta m_{ij}^2 L}{4E} \]

\[ a = 2\sqrt{2} G_F E n_e \approx 7.56 \times 10^{-5} [\text{eV}^2] \left( \frac{\rho(x)}{\text{g/cm}^3} \right) \left( \frac{E}{\text{GeV}} \right) \]

\[ A^e \simeq \frac{aL}{2\Delta_{31} E} - \Delta_{21} \frac{\sin 2\theta_{12}}{\tan \theta_{23} \sin \theta_{13}} \sin \delta_{\text{CP}} \]

\[ B^e \simeq -\frac{aL}{4E} + \frac{\Delta_{21}}{2} \frac{\sin 2\theta_{12}}{\tan \theta_{23} \sin \theta_{13}} \left( \cos \delta_{\text{CP}} - 2 \sin^2 \theta_{12} \right) \]

(Up to linear terms of \( \Delta_{21}, \sin^2 \theta_{13}, \frac{aL}{4E} \) are retained in A and B)

Matter effect terms enhances sign difference of \( \Delta_{31} \).

\[ \rightarrow \text{ Longer baseline } L \text{ has better sensitivity to the mass hierarchy.} \]

\[ \sin \delta_{\text{CP}} \text{ term typically has larger coefficient than } \cos \delta_{\text{CP}} \text{ term.} \]

\[ \rightarrow \text{ More sensitive to } \sin \delta_{\text{CP}} \text{ than } \cos \delta_{\text{CP}}. \]
T2KK and T2KO proposals

- Longer baseline than T2K to enhance sensitivity to the MH
- Wide band beam for sensitivity to $\cos \delta_{CP}$ (phase) as well as $\sin \delta_{CP}$ (amplitude).

**T2KK**: 100 kton in Korea and SK [hep-ph/0410229, 0504026, 0901.1517, 1001.5165]

**T2KO**: 100 kton in Oki island and SK [0804.2111, 1209.2763]

* SK (22.5kton) is also used as a second detector
Neutrino beam is produced by colliding protons on target. The total neutrino flux is expressed by POT (Protons On Target). (like Luminosity @ collider)

We assume $10^{21}$ POT/year ($10^7$ sec) with 40 GeV proton beam.

$\nu_{\mu}(\bar{\nu}_{\mu})$ focusing beam

0.64 MW

Current: 0.32 MW
Plan: 0.75 MW in 5 years (Talk by T.Nakaya @Flavor of New Physics (2015.3.9))
Off-axis beam

- Neutrino beam spreads.
- A detector receives spreaded beam (off-axis beam: OAB)

(The direction of neutrino beam is specified by OA at SK in this talk.)

Neutrino beam energy distribution depends on OA.
Off-axis angle @ SK, Oki, Korea

OAB set up 2.5° OAB @SK $\rightarrow$ 0.9° @Oki and 1° @Korea
in our study 3.0° OAB @SK $\rightarrow$ 1.4° @Oki and 0.5° @Korea

Korea and Oki detectors cover wider energy range than SK.

敏感 to $\cos \delta_{CP}$ term (phase) as well as $\sin \delta_{CP}$ term (Amp.).

But more NC $\pi0$ BG from the high energy tail
Electrons and π0 can be very similar in a water Cherenkov detector.

- e: one fuzzy ring
- π0 → γγ: two fuzzy rings

If π0 is highly boosted or one of the photons is missed, π0 looks like an electron.

→ NC π0 events can be major backgrounds for the ve appearance signal.
NC $\pi^0$ background

Smaller OA angle gives more NC $\pi^0$ events.

We use POLfit $\pi^0$ ID algorithm developed by T2K collaboration. [T. Barszczak, Ph.D. thesis (2005)]

NC $\pi^0$ BG can be reduced significantly. helpful especially for smaller OA beam
Aim of Current study

Analysis details between previous and current studies for the same two detector setups (T2KK and T2KO).

<table>
<thead>
<tr>
<th></th>
<th>T2KK (0901.1517)</th>
<th>T2KK,T2KO (1001.5165, 1209.2763)</th>
<th>T2KK, T2KO (current study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino beam</td>
<td>$\nu$ beam</td>
<td>$\nu$ and anti-$\nu$ beam</td>
<td>$\nu$ and anti-$\nu$ beam</td>
</tr>
<tr>
<td>Signal events</td>
<td>All CC events</td>
<td>CCQE events</td>
<td>All CC events</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>NC $\pi^0$/miss-ID mu(e) /secondary $\nu$</td>
<td>Secondary $\nu$</td>
<td>NC $\pi^0$/miss-ID mu(e) /secondary $\nu$</td>
</tr>
<tr>
<td>Detector smearing</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Efficiency (e)</td>
<td>90% ±5%</td>
<td>100%</td>
<td>90% ±5%</td>
</tr>
<tr>
<td>Efficiency (mu)</td>
<td>100% -1%</td>
<td>100%</td>
<td>100% -1%</td>
</tr>
<tr>
<td>Bin size</td>
<td>200 MeV</td>
<td>200 MeV</td>
<td>50 MeV</td>
</tr>
</tbody>
</table>

We study effects of anti-$\nu$ beam on sensitivities to MH and CP phase with NC $\pi^0$ BG by updating previous studies.
Points of this study, comparing to previous works

- We study $\text{SK (22.5 kton)} + 100 \text{ kton}$ detector at Korea/Oki as in Hagiwara, Okamura et.al. [hep-ph/0410229, 0504061, 0607255, 0901.1517, 1107.5857, 1209.2763] as **economical setup** for MH & CP phase.

  - Minakata, Kajita et. al. considered $270 \text{ kton (Kamioka)} + 270 \text{ kton (Korea)}$ detectors as an optional configuration of Hyper-K (540 kton at Kamioka). [hep-ph/0504026, 0609286, 1001.5165]

  - T2KK, but different philosophy

- We study effects of **anti-$\nu$ beam** systematically in addition to $\nu$ beam with **NC $\pi$0 BG**.

  - Hagiwara, Okamura et.al. [hep-ph/0901.1517(T2KK)] **only** used $\nu$ beam.  → Rooms to be improved with anti-$\nu$ beam

  - Hagiwara, Okamura et. al. [hep-ph/1107.5857(T2KK), 1209.2763(T2KK & T2KO)] used anti-$\nu$ beam ($\nu : \text{anti-}$-$\nu = 1:1$ only) but did not considered NC $\pi$0 BG. → **Optimistic results.**
Analysis method $\chi^2$ analysis

- **Signal:** $\nu_\mu \rightarrow \nu_e, \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e, \bar{\nu}_\mu$  
  *Improvements from 0901.1517 1209.2763*

- **Backgrounds**
  - Secondary beam: $\nu_e, \bar{\nu}_e, \bar{\nu}_\mu (\nu_\mu)$
  - miss-ID muon/electron
  - $\pi^0$ BG with improved ID algorithm (POLfit)

- **Oscillation parameters** (updated)
  \[
  \delta m^2_{12} = (7.5 \pm 0.2) \times 10^{-5} \text{eV}^2 \\
  \delta m^2_{13} = \pm 2.35 \times 10^{-3} \text{eV}^2 \\
  \sin^2 2\theta_{12} = 0.857 \pm 0.024 \\
  \sin^2 2\theta_{13} = 0.095 \pm 0.005 \\
  \sin^2 \theta_{23} = 0.5 \pm 0.1 \quad \delta_{\text{CP}}
  \]

- **Systematics**
  - matter density: 6%
  - Cross section, normalization: 3% - 20%
  - fiducial volume: 3%
  - NC $\pi^0$ BG modeling ($\pi^0$ ID, axial masses)
chi^2 function and sensitivity measures

$$\chi^2 \equiv \chi^2_{SK} + \chi^2_{Oki/Kr} + \chi^2_{sys} + \chi^2_{para}$$

$$\chi^2_D = \sum_i \left\{ \left( \frac{\left( N_{i_\mu,D} \right)_{\text{fit}} - \left( N_{i_\mu,D} \right)_{\text{input}}}{\sqrt{\left( N_{i_\mu,D} \right)_{\text{input}}}} \right)^2 + \left( \frac{\left( \overline{N}_{i_\mu,D} \right)_{\text{fit}} - \left( \overline{N}_{i_\mu,D} \right)_{\text{input}}}{\sqrt{\left( \overline{N}_{i_\mu,D} \right)_{\text{input}}}} \right)^2 \right\}$$

MH sensitivity measure:
$$\Delta \chi^2_{min} = \chi^2_{min}(\text{wrong MH}) - \chi^2_{min}(\text{true MH})$$

CP phase sensitivity measure:
$$\Delta \chi^2_{min} = \chi^2_{min}(\text{test } \delta_{CP}) - \chi^2_{min}(\text{true } \delta_{CP})$$

Difference between Data and prediction

Systematic uncertainty

External constraints on oscillation parameters

$$\chi^2_{sys} = \sum_{D=SK,Oki,Kr} \left\{ \left( \frac{f_D^N - 1}{0.03} \right)^2 + \left( \frac{f_D^P - 1}{0.06} \right)^2 + \sum_{\nu_\alpha=\nu_\mu,\nu_\tau,\nu_e,\nu_\tau} \left( \frac{f_D^{\nu_\alpha} - 1}{0.03} \right)^2 \right\}$$

$$+ \left( \frac{\varepsilon^D_e - 0.9}{0.05} \right)^2 + \left( \frac{\varepsilon^D_\mu - 0.1}{0.01} \right)^2 + \left( \frac{P^D_{e/\mu} - 0.01}{0.01} \right)^2 + \left( \frac{P^D_{e/\mu} - 0.01}{0.01} \right)^2$$

$$+ \sum_{\nu_\beta=\nu_\mu,\nu_\tau,\nu_e,\nu_\tau} \left\{ \left( \frac{f^{CCQE}_{\nu_3} - 1}{0.03} \right)^2 + \left( \frac{f^{\text{non-CCQE}}_{\nu_3} - 1}{0.20} \right)^2 \right\}$$

$$+ \left( \frac{f^{NC}_{\pi^0} - 1}{0.11} \right)^2 + \left( \frac{f^{NCRes}_{\pi^0} - 1}{0.13} \right)^2 + \left( \frac{f^{NCCoh}_{\pi^0} - 1}{0.15} \right)^2 \right\}$$

$$\chi^2_{para} = \left( \frac{\sin^2 2\theta_{12}^{\text{fit}} - 0.875}{0.024} \right)^2 + \left( \frac{\sin^2 2\theta_{13}^{\text{fit}} - 0.095}{0.005} \right)^2 + \left( \frac{\sin^2 \theta_{23}^{\text{fit}} - 0.5}{0.1} \right)^2$$

$$+ \left( \frac{\left( \delta m_{21}^2 \right)_{\text{fit}} - 7.5 \times 10^{-5}[eV^2]}{0.20 \times 10^{-5}[eV^2]} \right)^2 + \left( \frac{\left( \delta m_{31}^2 \right)_{\text{fit}} - 2.32 \times 10^{-3}[eV^2]}{0.10 \times 10^{-3}[eV^2]} \right)^2$$
### Parameters in chi^2 analysis (summary)

<table>
<thead>
<tr>
<th>Fitting parameters</th>
<th>Input Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sin^2 2\theta_{12} )</td>
<td>0.875</td>
<td>0.024 [28]</td>
</tr>
<tr>
<td>( \sin^2 2\theta_{13} )</td>
<td>0.095 [28]</td>
<td>0.005 [4]</td>
</tr>
<tr>
<td>( \sin^2 \theta_{23} )</td>
<td>0.5</td>
<td>0.1 [28]</td>
</tr>
<tr>
<td>( \delta m_{21}^2 ) [eV]^2</td>
<td>( 7.50 \times 10^{-5} )</td>
<td>( 0.20 \times 10^{-5} ) [28]</td>
</tr>
<tr>
<td>(</td>
<td>\delta m_{32}^2</td>
<td>) [eV]^2</td>
</tr>
<tr>
<td>( \delta_{CP} )</td>
<td>( 0^\circ )</td>
<td>-</td>
</tr>
<tr>
<td>( \bar{\rho}^{SK} ) [g/cm^3]</td>
<td>2.60</td>
<td>6% [21]</td>
</tr>
<tr>
<td>( \bar{\rho}^{Oki} ) [g/cm^3]</td>
<td>2.75</td>
<td>6% [21]</td>
</tr>
<tr>
<td>( \bar{\rho}^{Kr} ) [g/cm^3]</td>
<td>2.9</td>
<td>6% [21]</td>
</tr>
<tr>
<td>fiducial volume of detectors ( (f^D_V) )</td>
<td>1.00</td>
<td>0.03</td>
</tr>
<tr>
<td>neutrino flux at a detector ( (f^D_{\nu_o}) )</td>
<td>1.00</td>
<td>0.03</td>
</tr>
<tr>
<td>CCQE cross sections ( (f^{CCQE}<em>{\nu</em>\beta}) )</td>
<td>1.00</td>
<td>0.03</td>
</tr>
<tr>
<td>non-CCQE cross sections ( (f^{non-CCQE}<em>{\nu</em>\beta}) )</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>missidentified NC ( \pi^0 ) events ( (f^{NC}_{\pi^0}) )</td>
<td>1.00</td>
<td>0.11</td>
</tr>
<tr>
<td>missidentified NC resonant ( \pi^0 ) events ( (f^{NCRes}_{\pi^0}) )</td>
<td>1.00</td>
<td>0.13</td>
</tr>
<tr>
<td>missidentified NC coherent ( \pi^0 ) events ( (f^{NC Coh}_{\pi^0}) )</td>
<td>1.00</td>
<td>0.15</td>
</tr>
<tr>
<td>detection efficiency of ( e^\pm ) ( (\epsilon^D_e) )</td>
<td>0.90</td>
<td>0.05</td>
</tr>
<tr>
<td>detection efficiency of ( \mu^\pm ) ( (\epsilon^D_\mu) )</td>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>( \mu )-to-( e ) miss-ID probability ( (P^{D}_{e/\mu}) )</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>( e )-to-( \mu ) miss-ID probability ( (P^{D}_{\mu/e}) )</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Energy distributions: $\nu_e$ appearance mode (NH)

**Total events**
- CCQE signal
- non-CCQE signal
- NC $\pi^0$ BG
- miss-ID neutrino BG

**T2KK and T2KO**
can observe the $2^{nd}$ oscillation peak as well as the $1^{st}$ peak.
Energy distributions: ve appearance mode (IH)

Total events
CCQE signal
non-CCQE signal
NC π0 BG
miss-ID neutrino BG

T2KK and T2KO can observe the 2\textsuperscript{nd} oscillation peak as well as the 1\textsuperscript{st} peak.
Results
MH sensitivity with $\nu$ and $\bar{\nu}$ beam (T2KK)

The lowest sensitivity can be improved by including $\bar{\nu}_\mu$ beam.

~20% improvement for 3.0° OAB@SK (4:1) in 5 years run.
~40% improvement for 2.5° OAB@SK (3:2 – 2.5:2.5) in 5 years run.
MH sensitivity with $\nu$ and $\bar{\nu}$ beam (T2KO)

The lowest sensitivity is not improved by including $\bar{\nu}_\mu$ beam. But over all sensitivity tends to be improved.

$\Delta \chi^2_{\min}$

3:2 – 2.5:2.5 beam ratio is preferred for T2KO.
The sensitivity to the mass hierarchy depends on $\theta_{23}$.

$\nu : \bar{\nu} = 2.5 : 2.5$

$\Delta \chi^2_{\text{min}}$ degrades 30% – 40% when $\sin^2 \theta_{23}$ decreases by 0.1.
Sensitivity to CP phase

We also consider T2K (22.5kton) +100kton experiment @ Kamioka (T2K122) as a reference for CP phase sensitivity.

**T2KK:** 100 kton in Korea [hep-ph/0410229, 0504026, 0901.1517, 1001.5165]

**T2KO:** 100 kton in Oki island [0804.2111, 1209.2763]

* SK (22.5kton) is also used as a second detector
$\delta_{CP}$ measurement around $0^\circ$, $180^\circ$ is improved.
around $\pm60^\circ$, $\pm120^\circ$ is degraded. $\Longleftarrow$ due to $\sin \delta_{CP}$ term

CP phase measurement is also affected by including $\bar{\nu}_\mu$ beam.
CP measurement with $\nu$ and $\bar{\nu}$ beam

Longer baseline helps to resolve $\delta_{CP}$ and $\pi - \delta_{CP}$ degeneracy in $\sin \delta_{CP}$.

T2KK & T2KO have better sensitivity than T2K122 around $\pm 60^\circ$, $\pm 120^\circ$. Poor accuracy due to the degeneracy due to $\cos \delta_{CP}$ term
Using around 2.5:2.5 beam ratio, CP phase can be measured with 20° - 50° (T2KK) and 20° - 45° (T2KO) accuracy.

**T2KK 3°OAB**

**T2KK 2.5°OAB**

**T2KO**

**T2K122**
Sensitivity to CP phases (global picture)

The sensitivity to the CP phase measurement is fully expressed in test $\delta_{CP}$ vs. true $\delta_{CP}$ plane.

Exclusion contours:
- $\Delta \chi^2_{\text{min}} = 1$
- 4
- 9

$\delta_{CP}$ and $\pi - \delta_{CP}$ degeneracy is clearly seen.

Corresponds to CP measurement accuracy in previous slides.
The region of the CP violation detection is also clearly seen.

Sensitivity to CPV in 5 years

\[ \Delta \chi_{\min}^2 > 9 \]

for 33\% of \( \delta_{CP} \) (T2K122)

\[ \Delta \chi_{\min}^2 > 4 \]

for 25\% of \( \delta_{CP} \) (T2KO)

\[ \Delta \chi_{\min}^2 > 9 \]

for 45\% of \( \delta_{CP} \) (T2KK)

CPV sensitivity:

T2K122 > T2KO > T2KK

Statistics matters
Summary of this study

We revisited the sensitivity of T2KK and T2KO proposals to neutrino mass hierarchy and leptonic CP phase with nu and anti-nu beam realistic pi0 background estimation

MH
The sensitivity is significantly improved by including anti-nu beam (nu : anti-nu = 4:1 – 2.5:2.5 (in $10^{21}$ POT)). Especially for CP phase of -90 deg. (NH) and 90 deg. (IH).

T2KK has sensitivity of $\Delta \chi^2_{\text{min}} = 10 - 30$ (3° OAB @ SK, th23 = 0.5).
T2KO has sensitivity of $\Delta \chi^2_{\text{min}} = 3 - 20$ (2.5° OAB @ SK, th23 = 0.5).

CP phase
The sensitivity is slightly improved.
If MH is determined,
T2KK measures $\delta_{\text{CP}}$ with $\pm 20^\circ$ - $\pm 50^\circ$ uncertainty.
T2KO measures $\delta_{\text{CP}}$ with $\pm 20^\circ$ - $\pm 45^\circ$ uncertainty.
New physics sensitivity of T2K and T2KK