Long-Baseline Neutrino Oscillation Experiments in Japan

Taku Ishida (IPNS, KEK)
For the K2K collaboration, the T2K collaboration, and the J-PARC neutrino beam-line construction group

• Final Results from K2K
• T2K Phase-I Physics Goals
• Construction Status of the Neutrino Facility at J-PARC towards Commissioning in April, 2009
Introduction

K2K: the 1st accelerator-based long base-line experiment
KEK 12GeV PS(5kW) \( \Rightarrow \) Super-Kamiokande

- Working accelerator / adequate base-line length and beam energy, good \( E_\nu \) determination / good \( \mu\text{-}e \) separation / large volume
- Evidence for the muon neutrino oscillation
- Search for \( \nu_\mu \to \nu_e \) oscillation
  - Good BG rejection / systematic error / how to improve
- Cross section measurements / MC tuning at 1 GeV region
  - Fine-grain / water Cherenkov near detectors: CCQE / NC\( \pi^0 \)

T2K: the 1st super-beam long base-line experiment

JPARC MR (750kW) at Tokai \( \Rightarrow \) Super-Kamiokande

- Discovery of the 1st \( \nu_\mu \to \nu_e \) appearance signal
  - \( \Theta_{13} \): last unknown mixing angle in 3 neutrino scheme
  - Small, but non-zero, \( \theta_{13} \) is the key for the future CPV measurement.
- Precision measurement of \( \theta_{23} \) and \( \Delta m_{23}^2 \) in \( \nu_\mu \) disappearance mode
  - Are 2nd and 3rd generations symmetric?
- Search for the sterile components by detecting neutral current
  - If it does: modification of lepton physics to accommodate extra members of lepton(s)

Valuable outcomes for the next step!
The K2K Experiment

Wide-band, sub-GeV neutrino (on-axis) beam
- $<E_{\nu}> \approx 1.3\text{GeV}$
- $\nu_e/\nu_\mu \approx 1\%$
- 1.1$\mu$s spill width in 2.2s cycle
- $\approx 5.4 \times 10^{12}$ protons per pulse

Total Delivered [SK-live] Protons-On-Target:
$10.49 [9.22] \times 10^{19}$
For A Stroll...

- Al target
- Double HORNs
- $\pi$-monitor($p\pi, \theta\pi$)

Target Station

Decay Section (200m)

Muon Pit

Primary Beam-line

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

Front Detectors

$\nu_\mu$

Direction($\mu$)

Direction($\nu$)

$\nu$ Spectrum/Rate

TRISTAN RING (B-factory)

East Counter Hall

12GeV PS

1.1 $\mu$s pulse/2.2s

6~7×10$^{12}$ ppp

You are here

Photograph by T.K.Ohska
Event Selection

-500μs  TDIFF  500μs

|ΔT|<500μsec, no pre-activity (Decay-e cut)  578k
≥20MeV Deposit Energy  53k
FC, Evis>30MeV, Fiducial Volume(Dwall>2m)  115
|ΔT|=-0.2 - +1.3μsec  112

[Expected w.o. oscillation: 158.1 +9.2 / -8.6]

KEKTC07: KEK Topical Conference, February 2007

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νμ disappearance results

Reconstructed $E_\nu$ spectrum for 58 single ring, μ-like events

PRD 74, 072003 (2006)

Null oscillation probability

- Norm.: 0.06% (3.4σ)
- Shape: 0.42% (2.9σ)
- Shape+Norm.: 0.0015% (4.3σ)

(1.0, 2.75x10^{-3})

1.9~3.5x10^{-3} eV^2
### Event selection for $\nu_e$ appearance search

#### T.Ishida

**IPNS, KEK**

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**Tight e-like cut**

<table>
<thead>
<tr>
<th>Event Selection</th>
<th>$\nu\mu$ MC</th>
<th>beam $\nu_e$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K2K-1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCFV</td>
<td>81.1</td>
<td>0.81</td>
<td>55</td>
</tr>
<tr>
<td>Single ring</td>
<td>50.92</td>
<td>0.47</td>
<td>33</td>
</tr>
<tr>
<td>Tight e-like cut</td>
<td>2.66</td>
<td>0.40</td>
<td>3</td>
</tr>
<tr>
<td>$E_{vis} &gt; 100$ MeV</td>
<td>2.47</td>
<td>0.40</td>
<td>2</td>
</tr>
<tr>
<td>No decay-e</td>
<td>1.90</td>
<td>0.35</td>
<td>1</td>
</tr>
<tr>
<td>Pi0 cut</td>
<td><strong>0.58</strong></td>
<td><strong>0.17</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>K2K-2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCFV</td>
<td>77.4</td>
<td>0.86</td>
<td>57</td>
</tr>
<tr>
<td>Single ring</td>
<td>49.41</td>
<td>0.52</td>
<td>34</td>
</tr>
<tr>
<td>Tight e-like cut</td>
<td>3.21</td>
<td>0.44</td>
<td>5</td>
</tr>
<tr>
<td>$E_{vis} &gt; 100$ MeV</td>
<td>2.93</td>
<td>0.44</td>
<td>5</td>
</tr>
<tr>
<td>No decay-e</td>
<td>2.17</td>
<td>0.39</td>
<td>4</td>
</tr>
<tr>
<td>Pi0 cut</td>
<td><strong>0.74</strong></td>
<td><strong>0.21</strong></td>
<td><strong>1</strong></td>
</tr>
</tbody>
</table>

In total:

<table>
<thead>
<tr>
<th>#BG</th>
<th>= 1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>#observed</td>
<td>= 1</td>
</tr>
</tbody>
</table>

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*Both opening angle and ring pattern are required to be e-like.*
Special 2$^{nd}$ ring search is applied to 1ring e-like candidates.

Invariant mass distribution for atmospheric $\nu$

Data
atmospheric $\nu$ MC
$\pi^0$ induced event

Efficiency for signal $\nu_e$ : 70% / $\pi^0$ BG : 30%
The only-one $\nu_e$ candidate

What is my nature?
Exclude region for $\nu_e$ appearance search

K2K-I+II (#obs.=1, #B.G.=1.70)

Comparison with the reactor experiment

$\sin^2 2\theta_{\mu e} \sim \frac{1}{\lambda} \sin^2 2\theta_{13}$

upper limit (90% CL) $\sin^2 2\theta_{\mu e} = 0.13 \pm 0.01 @ 2.8 \times 10^{-3} \text{ eV}^2$

PRL 96, 181801 (2006)
Neutrino-Nucleus Interactions

**Neutral Current $\pi^0$ production**  PLB619 (2005) 255
- $\sigma(\text{NC}1\pi^0)/\sigma(\text{CC Incl.}) = 0.064^{+0.001}_{-0.007}\text{ syst.}$

**CC Coherent pion production** PRL95 (2005) 252301
- $\sigma(\nu+C\rightarrow\mu+C+\pi^+)/\sigma(\text{CC Incl.}) < 0.60 \times 10^{-2}$

**CC Quasi-Elastic Interaction** PRD74 (2006) 052002
- “Axial Vector Mass” in the axial-vector dipole form factor by $q^2$ dist. fit = 1.20$^{+0.12}_{-0.12}$GeV
The T2K Experiment

A next-generation long-baseline neutrino oscillation experiment, designed to observe the first signal of $\nu_e$ appearance

- Pseudo-monochromatic, low-energy off-axis beam.
- Off-axis angle is tunable
- Quasi-Elastic interactions are dominant, suitable to minimize the electromagnetic shower background caused by the neutral current $\pi^0$ production
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam kinetic energy</td>
<td>50 GeV (30 GeV@T=0)</td>
</tr>
<tr>
<td># of protons / pulse</td>
<td>$3.3 \times 10^{14}$ ppp</td>
</tr>
<tr>
<td>Beam power</td>
<td>750 kW</td>
</tr>
<tr>
<td>Bunch structure</td>
<td>8 bunches</td>
</tr>
<tr>
<td>Bunch length / spacing</td>
<td>58 ns / 598 ns</td>
</tr>
<tr>
<td>Spill width</td>
<td>4.2 $\mu$s</td>
</tr>
<tr>
<td>Beam Emittance</td>
<td>$6_{\pi}$ mm.mr (10_{\pi}@30 GeV)</td>
</tr>
<tr>
<td>Cycle</td>
<td>3.64 sec (2.1 sec@30 GeV)</td>
</tr>
</tbody>
</table>

- 1 x $10^{21}$ protons per year
  [130 days operation per year, 50 GeV]
Bird’s-Eye View (Feb. 2006)

- Neutrino Facility at J-PARC

- Hadron Experimental Hall
  - 50 GeV MR
    - A round=1,600m

- Materials & Life Experimental Hall
  - 3GeV RCS
    - A round=350m

- Linac (330m)

- MR tunnel became continuous in last June
- Commissioning Linac started last December
- Detailed report will come tomorrow
T2K Layout

- Quasi-monochromatic, sub-GeV Off-Axis Beam
- ∼ 2,200 (∼1,600) νμ (CC) interactions at Super-K  [OAB 2.5°, 22.5 kt-yr]
Measurement of $\theta_{23}$, $\Delta m_{23}^2$

- Use 1R $\mu$-like events
  - Large QE fraction
  - Beam with small high energy tail
  $\Leftrightarrow$ $\sin^2 2\theta$ less sensitive to systematics

- Clear deficit is expected in the reconstructed $\nu$ energy
  - $\delta E = \delta (E_{\nu \text{rec}} - E_{\nu \text{true}}) \sim 60\text{MeV}$
  $\Leftrightarrow$ $< 10\%$ measurement on $\Delta m^2$

\[
\nu_\mu + n \rightarrow \mu^- + p
\]

\[
E_{\nu \text{rec}} = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos \theta_\mu}
\]

\[
R(\text{measured} / \text{expected}) = \frac{\nu_\mu + n}{\mu^- + p}
\]

\[
\sin^2 2\theta \ \Delta E \sim 60\text{MeV}
\]

\[
\Delta m^2 = \delta (E_{\nu \text{rec}} - E_{\nu \text{true}}) \sim 60\text{MeV}
\]
Sensitivity for $\sin^2 2\theta_{23}$, $\Delta m_{23}^2$

**OA2.5°, 5×10^{21} \text{ POT}**

~ 5 years @ full Intensity

Assumed Systematic Errors

- Normalization: 5%
- non-QE/QE ratio: 5%
- Energy scale: 1%
- Spectrum Shape: 20%
- Beam Width: 5%

\[
\delta(\sin^2 2\theta) = 0.01
\]

\[
\delta(\Delta m^2) = 1 \times 10^{-4} \text{eV}^2
\]

Errors will be further reduced by near detector measurements and pion production measurements (CERN NA49)

KEKTC07: KEK Topical Conference, February 2007
Near Neutrino Detectors

- **Off-axis detector**
  - FGD, TPC, Ecal,.. In UA1 magnet
  - Spectrum / Cross section / νe contamination

- **On axis detector: NGRID**
  - 1mx1mx[0.1mx10lyr]
  - Monitor beam direction

- **Scintillator+WLS fiber with**
  - MRS APD (Russia)
  - MPPC (Hamamatsu)

```
~1.5 events /spill
1M / month
@center cell
```

A few cm beam center resolution

```
Near Detector at 2km
[ Working for approval ]
```
Sensitivity to $\theta_{13}$

T.Ishida
IPNS, KEK

- Expected signal + BG
- Total BG
- BG from $\nu_{\mu}$

5 x $10^{21}$ POT

(OA2.5°)

$\sin^2 2\theta_{13} = 0.1$
$[\sin^2 \theta_{23} = \frac{1}{2}]$
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$

$\Delta m_{13}^2 (eV^2)$

$0.008$ at $\delta_{CP} = 0/\pi$

BG subtraction: 10% error

$\sin^2 \theta_{13}$

# of events in $E_{rec} = 0.35$~$0.85$ [GeV]

<table>
<thead>
<tr>
<th>$\sin^2 2\theta_{13}$</th>
<th>Background in Super-K</th>
<th>Signal [~40% eff]</th>
<th>Signal + BG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_{\mu}$</td>
<td>$\nu_e$</td>
<td>total</td>
</tr>
<tr>
<td>0.1</td>
<td>10</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>0.01</td>
<td>10</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

KEKTC07: KEK Topical Conference, February 2007
Beam-line Construction Group

KEK

- Neutrino group, IPNS (Core)
  - Every beam line components (except S.C.magnets / cryo.)
  - DAQ control / ND
- Hadron group, IPNS
  - Monitor / N.C.magnets / Power supply
- Cryogenics group, IPNS
  - Cryogenics / Target Helium circulation system
- Cryogenics science center
  - Superconducting magnet / Cryogenics
- Mechanical Engineering Center
- Radiation Science Center

Our Acknowledges go to

Many Valuable Advices from Nu-TAC

Many supports from other experiments’ experiences through neutrino beam instrumentation (NBI) WS

In collaboration with

- U. Tokyo: Primary beam monitor
- Kyoto U: Primary beam monitor, Muon monitor
- UK: Target, Target remote handling, Beam window, Baffle, Dump
- Canada : Remote chamber for the most downstream monitors, OTR, Remote maintenance
- US: Horn, Beam monitor, S.C. corrector magnets, GPS, Monitor electronics
- France: Quench detection system
- Korea: Proton monitor electronics
Primary Beam-line

Completed in Last December!

Material Life & Science
Preparation Section
March, 2006

Primary Beam-line
Preparation Section
50GeV
July, 2006

Completed in Last December!
Superconducting Combined Function Magnet

- 28 SCFM in total, D: 2.6 T, Q: 18.6 T/m
- Length: 3.3m
- Current: 7,345A @ 50GeV

- Mass production started
  - 12 magnets / 6 doublets in hand (FY06)
  - 6D in FY07, 2 in FY08
- Refrigerator / Transport line construction: ’06 ~’08
- Installation/system testing in CY’08
**Beam Monitors**

- **Configuration**
  - Position: Electro-static monitor (ESM)
  - Profile: Segmented Secondary Emission Monitor (SSEM), OTR
  - Intensity: CT
  - Loss monitors (BLM): Ionization chamber
- **Readout by COPPER/KEK-DAQ**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Intensity (CT)</th>
<th>Center (ESM)</th>
<th>Profile (SSEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prep. Sect.</td>
<td>2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Arc sect.</td>
<td>0</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>FF sect.</td>
<td>2</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Beam loss monitor will be placed along the beam line.
Target Station

1/16, 2007

Final Focusing Section / ARC
Target Station

Ti-alloy Beam Window with pillow-seal

Helium-Cooled Graphite Target in the 1st Horn

Supported by CCLRC/RAL and BARTOSZEK ENGINEERING
Horn / Target R&D

Successful operation at 320kA / Long-term Test

Graphite tube (2mm-thick)
Decay Volume (Under 3NBT)

All cooling channels connected by 1,080 U-shape pipes.

Oct., 2005
Hadron Absorber (Beam Dump)

- Semiconductor detector array / Ionization chamber array

Target Station

Decay Volume

Hadron Absorber (Beam Dump)

Helium Vessel

Muon Monitors

OA 2°

2.5°

10m

4m

Graphite Blocks

Beam

Aluminum cast with inside water pipe
Summary

- **K2K** has confirmed muon neutrino oscillation at 4.3σ.
  - Allowed region for $\nu_\mu \rightarrow \nu_\tau$ oscillation for $\Delta m^2$ at $\sin^2 2\theta = 1$ is $1.9-3.5 \times 10^{-3} \text{eV}^2$ (90% C.L.).
  - No evidence for $\nu_e$ appearance. $\sin^2 2\theta_{\mu e} > 0.13$ at $2.8 \times 10^{-3} \text{eV}^2$ (90% C.L.).

- **T2K**, the 1st super-beam LBL experiment
  - Off-axis beam configuration, tunable between $2^\circ \sim 2.5^\circ$
    - $\Delta m^2_{\text{atm}} = 2.7 \sim 3.3 \times 10^{-3} \text{eV}^2$
  - 90% CL Sensitivities for the phase-I
    - $\Delta [\sin^2 2\theta_{23}] \sim 0.01 \Delta [\Delta m^2_{23}] \times 10^{-4} \text{eV}^2$
    - $\sin^2 2\theta_{13} > 0.008 \text{ (90%) X 20 improvements}$

- **J-PARC** neutrino facility: construction is under going:
  - Decay volume (50m finished), primary beam line, target station
  - Beam line equipment: shifting from R&D phase to actual production
  - International contributions for crucial parts of the beam line components.
  - Passing some of critical milestones: SCFM doublets, 1st Horn operation with 320 kA

**Much of struggle from now, towards beam commissioning in April, 2009**

**And towards new result in ~ 2010 !**