J-PARC Neutrino Beam and Detectors

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T2K collaboration

- Formed in May 2003
- 12 countries, 53 institutions
  ~150 collaborators
- Spokesperson: K. Nishikawa

France: CEA Saclay
Japan: ICRR, U. Tokyo, KEK, Tohoku U., Hiroshima U., Kyoto U., Kobe U., Osaka City U., U. Tokyo, Miyagi U. of Education
Poland: Warsaw U.
Russia: INR
Spain: U. Barcelona, U. Valencia
Switzerland: U. Geneva
UK: RAL, Imperial College London, Queen Mary Westfield College London, U. Liverpool
Three Flavor Mixing in Lepton Sector

Weak eigenstates

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{MNS}} \cdot V_{\text{MNS}}^{\text{CP}} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

mass eigenstates

\[ m_1 \]
\[ m_2 \]
\[ m_3 \]

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

\[ c_{ij} = \cos(\theta_{ij}), \quad s_{ij} = \sin(\theta_{ij}) \]

\[ \theta_{12}, \theta_{23}, \theta_{13} \]
\[ + \delta \quad (+2 \text{ Majorana phase}) \]
\[ \Delta m_{12}, \Delta m_{23}, \Delta m_{13} \]
Current Knowledge

$\theta_{13}$

$m^2$

Atmospheric $\nu$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

$m_3^2$

$\sim 3 \times 10^{-3} \text{eV}^2$

$\sim 5 \times 10^{-5} \text{eV}^2$

Solar $\nu$

$m_1^2$

$m_2^2$

$m_1^2$

$\sim 5 \times 10^{-5} \text{eV}^2$

$\sim 3 \times 10^{-3} \text{eV}^2$

Next step

sterile, $\theta_{13}$, sign of $\Delta m^2$, CP violation.....
Neutrino Oscillation
as a unique way to access neutrino (very small) mass and mixing

Oscillation Probabilities when $\Delta m_{12}^2 \ll \Delta m_{23}^2 \approx \Delta m_{13}^2$

$\nu_e$ appearance
$$P_{\mu \rightarrow e} \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \left(1.27 \frac{\Delta m_{23}^2 L}{E_\nu}\right)$$

$\nu_\mu$ disappearance
$$P_{\mu \rightarrow \nu_x} = 1 - (P_{\mu \rightarrow e} + P_{\mu \rightarrow \tau}) \approx 1 - P_{\mu \rightarrow \tau}$$

$\nu_\tau$ appearance
$$P_{\mu \rightarrow \tau} \approx \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2 \left(1.27 \frac{\Delta m_{23}^2 L}{E_\nu}\right)$$

CPV
$$A = \frac{P_{\mu \rightarrow e} - P_{\mu \rightarrow \bar{e}}}{P_{\mu \rightarrow e} + P_{\mu \rightarrow \bar{e}}} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

$L$ : flight length(km), $E_\nu$ : neutrino energy(GeV), $\Delta m_{ij}^2 = m_i^2 - m_j^2$, $m_i$ : mass eigenvalues(eV)
Overview of experiment

- Super-K: 50 kton Water Cherenkov
- ~Mton “Hyper Kamiokande”
- Kamioka
- JAEIRI (Tokai-mura)

νµ beam of ~1GeV

1st Phase
- νµ → νx disappearance
- νµ → ve appearance
- NC measurement

2nd Phase
- CPV
- Proton decay
Principle

– Neutrino energy reconstruction by using Quasi-Elastic (QE) interaction.
  • Oscillation pattern measurement
  • BG due to miss-reconstruction of inelastic interaction
    – Greatly improved by using narrow spectrum

– Narrow spectrum tuned by the Off-Axis method at the oscillation maximum.
  • High sensitivity
  • Less background

– Gigantic water Cherenkov detector
  • High statistics
  • High efficiency for low energy
  • Good PID (e/µ) capability

$\Delta m^2 = 2.2 \sim 3.2 \times 10^{-3} \text{eV}^2$

$E_\nu = 0.5 \sim 0.8 \text{GeV}$
Neutrino Energy $E_\nu$ reconstruction

CC quasi elastic reaction

$\nu_\mu + n \rightarrow \mu + p$  \hspace{2cm} $\nu_\mu + n \rightarrow (\mu^- + p + \pi^-)$

$\theta_\mu = (E_\mu, p_\mu)$

$E_\nu = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos \theta_\mu}$

CC cross sections

Inelastic (BG)

$\nu_\mu$ CC cross sections

True $E_\nu$ (GeV) vs. Reconstructed $E_\nu$ (GeV)
Off Axis Beam

(ref.: BNL-E889 Proposal)

- Quasi Monochromatic Beam
- x 2~3 intense than NBB

Tuned at oscillation maximum

Statistics at SK

(OAB 2.5 deg, 1 yr, 22.5 kt)

~ 2200 $\nu_\mu$ tot
~ 1600 $\nu_\mu$ CC
$\nu_e \sim 0.4\%$ at $\nu_\mu$ peak

Neutrino energy spectrum $\sigma \times \Phi$
(Note $\sigma \propto E$)
Flux

OAB2.5deg, $E_p=40$GeV
SuperKamiokande@Kamioka, Japan

Water Cherenkov detector

- 1000 m underground
- 50,000 ton
  (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

Since 1996.
Accident on 2001.
Partial recovery on 2002.
(Full recovery on 2006)
$\nu_\mu$ disappearance

1ring FC $\mu$-like

Oscillation with
$\Delta m^2 = 3 \times 10^{-3}$
$\sin^2 2\theta = 1.0$

No oscillation

Reconstructed $E_\nu$ (MeV)

Ratio after BG subtraction

Fit with $1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

$\sim 3\%$
**sin^22\theta_{13} from \nu_e appearance**

- **90\% C.L. sensitivities**
- **Expected Signal+BG**
  - \(\sin^22\theta_{13} = 0.10\)
  - \(\sin^22\theta_{23} = 1.0\)
  - \(\Delta m^2 = 0.003\text{eV}^2\)
- **Total BG**
- **BG from \nu_\mu + \text{anti}\nu_\mu**

### Background in Super-K (as of Oct 25, 2001)

<table>
<thead>
<tr>
<th>sin^22\theta_{13}</th>
<th>(\nu_\mu)</th>
<th>(\nu_e)</th>
<th>(\nu_\mu)</th>
<th>(\nu_e)</th>
<th>total</th>
<th>Signal</th>
<th>Signal + BG</th>
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<tbody>
<tr>
<td>0.1</td>
<td>12.0</td>
<td>10.7</td>
<td>1.7</td>
<td>0.5</td>
<td>24.9</td>
<td>114.6</td>
<td>139.5</td>
</tr>
<tr>
<td>0.01</td>
<td>12.0</td>
<td>10.7</td>
<td>1.7</td>
<td>0.5</td>
<td>24.9</td>
<td>11.5</td>
<td>36.4</td>
</tr>
</tbody>
</table>
Facilities
Neutrino facilities at Tokai

\[ p^+(\text{target}) \rightarrow \pi \rightarrow \nu_\mu + \mu \]

Components

- Proton beam transport
- Target/Horn system
- Decay pipe
- Beam dump
- Muon monitor
- First near detector (280m)

Kamioka direction
Primary beam line

Preparation section
Normal conducting 750W loss

Arc Section (R=105m)
Superconducting combined function magnets
- First application in the world
- Reduce cost (40→28 mags) comp. w/ sep. func.
- Larger acceptance
- 1W/m loss

Final Focusing Section
Normal conducting 250W loss

- Single turn fast extraction
- 8 bunches/≈5μs
- $3.3 \times 10^{14}$ proton/pulse
- 3.53 sec cycle
- $\varepsilon = 6\pi$ mm.mr, $\Delta p/p = 0.31\%$ @50GeV
- Total bending = 84.5°
Superconducting combined function magnet

- Dipole Field: 2.587 T
- Quad. Field: 18.62 T/m
- Precision: $10^{-3}$@r=5cm
- Magnetic Length: 3.3m
- Current: 7345A
- Inductance: 14mH
- Stored Energy: 0.38MJ

Two magnets in 1 vessel
Overview of target area

Beam window

Baffle

Target & 1st horn

2nd horn

3rd horn

Helium

collimator

Decay volume
Decay pipe common for SK/HK

Possible site for Hyper-K

Beam eye

Decay pipe have to cover $p/\pi$ beam axis -(3~4)deg corresponding to $\Delta m^2 = 2.2\sim 3.2 \times 10^{-3}$eV$^2$
Decay Volume

3NBT (BT bet. 3GeV&MLF) constructed in 2005

Construction Started in 2004

6m thick concrete structure

Cross section: 2.2m(W)x2.8m(H) 3.0m(W)x4.6m(H)

Target Station

Decay Volume ~110m

Dump

- Cover Off Axis angle: 2°~3°
- Square box shape made with water cooled iron plates (T<60°C at 4MW)
- Filled by 1atm Helium gas
Detectors

- **Muon monitors @ ~140m**
  - Behind the beam dump
  - Fast (spill-by-spill) monitoring of beam direction/intensity

- **First Near detector  “Neutrino monitor” @280m**
  - Neutrino direction/stability
  - Neutrino flux and spectrum

- **Second Near Detector @ ~2km**
  - Almost same $E_\nu$ spectrum as for SK
  - Absolute neutrino flux
  - Neutrino spectrum at near site
  - Precise estimation of background
    *Not approved yet*

- **Far detector @ 295km**
  - Super-Kamiokande (50kt)
  - Hyper-Kamiokande (~1Mt)
Concept of Near Neutrino Detector

- Off-axis (~2.5°)
  - $\nu_\mu$ and $\nu_e$ neutrino fluxes and the spectra.
  - $\nu$ interaction study (CC-QE, non-QE, $\pi^0$,)
  - Kaon Contributions

- On-axis (0°)
  - Beam direction
  - Beam stability
  - (Spectrum)?

The detectors are being designed
Off-Axis Detector
Magnetised ND280m Detector
Current design of the on-axis detector

N-Grid
One module consists of scintillator plates sandwiched with iron plates

- Purposes of the on-axis detector
  - Monitor the neutrino beam direction
  - Monitor the neutrino beam profile
Design of the Near Detector Hall

Due to the tight budget, the size of the experimental hall is reduced to its limit.
Construction schedule

- Five years construction in 2004~2008
- Half of decay volume is under construction
- Detailed design for construction in this fis year
Arial View as of Jan. 2005
Decay Volume Construction viewed from the downstream
50-m decay pipe has been installed
Welding is going on
One quarter of the 50-GeV tunnel is completed
The wood where the ND280 will be constructed
Summary

- The J-PARC neutrino project is making good progress
  - 5 years construction (JFY2004~JFY2008)
  - Start physics in 2009
  - Try to discover $\theta_{13}$ and precise measurement of $\theta_{23}$, $\Delta m_{23}$.

- International collaboration T2K was formed

- R&D in various components in the beam line and near detector is on-going

- Construction has started from Decay volume in May. 2004

- Civil engineering design will be completed soon
Appendix
(Not approved yet)