Future Neutrino Physics Scenarios in Japan

Takashi Kobayashi

KEK
Quest for the Origin of Matter Dominated Universe

One of the Main Subject of the KEK Roadmap

T2K (2009~) → Discovery of the $v_e$ Appearance →

Neutrino Intensity Improvement → Huge Detector R&D →

Establish Huge Detector Technology → Huge Detector Technology

Construction of Huge Detector

Discovery of Lepton CP Violation
Proton Decay

Water Cherenkov → Liquid Ar TPC
Power upgrade plan of MR

For 8 bunches, 30 GeV at MR: $P_{MR} = 1.6 \times (P_{RCS} / T_{MR})$

Collimator shields, RF (1st HH), FX kicker
Collimator shields, RF (6th F, 2nd HH), Inj. Sep 1
ACS Installation in JFY2012
400 MeV injection in the RCS
RF (3rd HH), Inj. Sep 2, FX Septa, ..

Need to secure appropriate budget to realize this
1~2MWx10^7s will be critical milestone for determining future direction.

Solid: 3s discovery
Dashed: 90% CL sensitivity

\[
\sin^2 2\theta_{12} = 0.87 \\
\sin^2 2\theta_{23} = 1.0 \\
\Delta m^2_{12} = 7.6 \times 10^{-5} \text{eV}^2 \\
\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2 \\
\delta = 0
\]

3.75MWx10^7s (Proposal)
## Technically Feasible MR Power Improvement Scenario — KEK Roadmap —

<table>
<thead>
<tr>
<th></th>
<th>Day1 (up to Jul.2010)</th>
<th>Next Step</th>
<th>KEK Roadmap</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>0.1</td>
<td>0.45</td>
<td>1.66</td>
<td>?</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Rep Cycle (sec)</td>
<td>3.5</td>
<td>3-2</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>No. of Bunch</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Particle/Bunch</td>
<td>$1.2 \times 10^{13}$</td>
<td>&lt;$4.1 \times 10^{13}$</td>
<td>$8.3 \times 10^{13}$</td>
<td></td>
</tr>
<tr>
<td>Particle/Ring</td>
<td>$7.2 \times 10^{13}$</td>
<td>&lt;$3.3 \times 10^{14}$</td>
<td>$6.7 \times 10^{14}$</td>
<td></td>
</tr>
<tr>
<td>LINAC (MeV)</td>
<td>181</td>
<td>181</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>RCS</td>
<td>h=2</td>
<td>h=2 or 1</td>
<td>h=1</td>
<td></td>
</tr>
</tbody>
</table>

After 2010, plan depends on financial situation
Item to be Modified from DAY1 toward High Intensity

- **No. of Bunch in MR (6→8)**
  - Fast Rise Time Extraction Kicker Magnet

- **Increase Repetition Rate (3.5Sec→1.92Sec)**
  - RF and Magnet Power Supply Improvement

- **RCS h=1 Operation** (longer beam bunch to decrease space charge effect)
  - RF Improvement

- **LINAC 400MeV Operation** (avoid severe space charge effect at RCS injection)
  - $h=2$: 2 bunches $\times$ 4cycle injection to MR
  - $h=1$: Single bunch with doubled no. of proton $\times$ 8cycle injection
Lepton Sector CP Violation

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\
    -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\
    -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23}
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

Effect of CP Phase \(\delta\) appear as

- \(\nu_e\) Appearance Energy Spectrum Shape
  * Peak position and height for 1\(^{st}\), 2\(^{nd}\) maximum and minimum
  * Sensitive to all the non-vanishing \(\delta\) including 180°
  * Could investigate CP phase with \(\nu\) run only

- Difference between \(\nu_e\) and \(\bar{\nu}_e\) Behavior
Angle and Baseline

- Off-axis angle
  - On-Axis: Wide Energy Coverage,
    ○ Energy Spectrum Measurement
    × Control of $\pi^0$ Background
  - Off-Axis: Narrow Energy Coverage,
    ○ Control of $\pi^0$ Background
    × Energy Spectrum Measurement
    → Counting Experiment

- Baseline
  - Long:
    ○ 2\textsuperscript{nd} Osc. Max. at Measurable Energy
    × Less Statistics
    ? Large Matter Effect
  - Short:
    ○ High Statistics
    × 2\textsuperscript{nd} Osc. Max. Too Low Energy to Measure
    ? Less Matter Effect

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{13} = 0.1 \]
No matter effects
Three Possible Scenario Studied at NP08 Workshop

NP08 is The 4th International Workshop on Nuclear and Particle Physics at J-PARC

http://j-parc.jp/NP08
Scenario 1

- Cover 1st and 2nd Maximum
- Neutrino Run Only 5 Years × 1.66MW
- 100kt Liq. Ar TPC - Good Energy Resolution - Good e/π⁰ discrimination
- Keeping Reasonable Statistics

\[ \sin^2 2\theta_{13} = 0.03, \text{Normal Hierarchy} \]

\[ \delta = 0^\circ \quad \delta = 90^\circ \quad \delta = 180^\circ \quad \delta = 270^\circ \]

Oiloshima

658km 0.8deg. Off-axis

NP08, arXiv:0804.2111
Scenario 2

- Cover 1st Maximum Only
- 2.2 Years Neutrino + 7.8 Years anti-Neutrino Run 1.66 MW
- 540 kt Water Cherenkov Detector

Kamioka to Tokai

\[ \delta = 0 \quad \sin^2 2\theta_{13} = 0.03, \text{Normal Hierarchy} \]
\[ \delta = \frac{\pi}{2} \]

\[ \nu_\mu \rightarrow \nu_\mu + \nu_e + \bar{\nu}_e + \text{BG} \]

CP sensitivity

\[ \sin^2 2\theta_{13} \]

K. Kaneyuki @NP08
Scenario 3

- Cover 2nd Maximum @ Korea
- Cover 1st Maximum @ Kamioka
- 5 Years $\nu + 5$ Years $\bar{\nu}$ Run 1.66MW
- 270kt Water Cherenkov Detector each @ Korea, Kamioka

---

**Mass hierarchy**

**Scenario B**

**CP violation**

---

$\sin^2(2\theta_{13}) = 0.04$, neutrino, normal hierarchy, Scenario B

F.Dufour@NP08

(study is initiated by M.Ishitsuka et. al. hep-ph/0504026)
Comparison of Each Scenario

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1 Okinoshima</th>
<th>Scenario 2 Kamioka</th>
<th>Scenario 3 Kamioka Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (km)</td>
<td>660</td>
<td>295</td>
<td>295 &amp; 1000</td>
</tr>
<tr>
<td>Off-Axis Angle (°)</td>
<td>0.8(almost on-axis)</td>
<td>2.5</td>
<td>2.5 1</td>
</tr>
<tr>
<td>Method</td>
<td>νe Spectrum Shape</td>
<td>Ratio between νe ¯νe</td>
<td>Ratio between 1st 2nd Max</td>
</tr>
<tr>
<td>Beam</td>
<td>5 Years νμ, then Decide Next</td>
<td>2.2 Years νμ, 7.8 Years ¯νμ,</td>
<td>5 Years νμ, 5 Years ¯νμ,</td>
</tr>
<tr>
<td>Detector Tech.</td>
<td>Liq. Ar TPC</td>
<td>Water Cherenkov</td>
<td>Water Cherenkov</td>
</tr>
<tr>
<td>Detector Mass (kt)</td>
<td>100</td>
<td>2 × 270</td>
<td>270+270</td>
</tr>
</tbody>
</table>

Study is continuing to seek for optimum choice
Additional requirement for far detector optimization

• Proton Decay Discovery Performance

• Realization of the huge detector
  – Test of the key components
  – Experimentally prove the detector performance
    • if necessary, good prototyping
      (able to predict Huge Detector Performance well)
      is important
    • Test with the beam is important

KEK started R&D for Huge Liq. Ar TPC with ETH Zurich

⇒ See Maruyama’s talk
Accelerator Based Neutrino Project in Japan

<table>
<thead>
<tr>
<th></th>
<th>K2K</th>
<th>T2K</th>
<th>3rd Generation Exp. (KEK Roadmap)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Power Proton Synchrotron</strong></td>
<td>KEK PS 12GeV 0.005MW Existing</td>
<td>J-PARC MR 30GeV up to 0.75MW Brand New</td>
<td>J-PARC MR 30GeV 1.66MW Technically Feasible Upgrade</td>
</tr>
<tr>
<td><strong>Neutrino Beamline</strong></td>
<td>K2K Neutrino Beamline Brand New</td>
<td>J-PARC Neutrino Beamline Brand New</td>
<td>J-PARC Neutrino Beamline Existing</td>
</tr>
</tbody>
</table>
| **Far Detector**    | Super Kamiokande Existing at KAMIOKA | Super Kamiokande Existing at KAMIOKA | Brand New
- Detector Technology ?
- Place ?
(Angle and BaseLine) |
| **1st Priority Physics Case** | Neutrino Oscillation \(\nu_\mu\) Disappearance | Neutrino Oscillation \(\nu_\mu \rightarrow \nu_e\) | Lepton Sector CP Violation + Proton Decay Search |

Able to concentrate on Far Detector issue toward the 3rd Generation Experiment after T2K startup.
Summary

• Aim to realize an experiment to discover CPV in neutrino and Proton decay with
  – Upgraded J-PARC 0.75MW ➔ 1.66MW (➔ ??MW)
  – Huge, high sensitivity detector

• Studies are continuing
  – Optimization of physics potential
    • Distance and off-axis angle of detector
      – Okinoshima (658km), Kamioka (295km), Korea (1000km)
    • Detector technology: ~100kt Liq. Ar TPC/~1Mt Water Cherenkov
  – Detector R&D. KEK started R&D of Liq Ar TPC w/ ETHZ

• To realize the experiment, it is essential to
  – Commission and improve intensity of J-PARC accelerator
  – Discover $\nu_e$ appearance in T2K
    • First beam on Apr. 23, 2009
      • First T2K physics result in 2010 w/ 100kWx10^7s equivalent data
      • 1~2MW.10^7s data in few years
  – Acquire experience of high intensity beam operation