JHF-Kamioka

Neutrino Oscillation Experiment

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1. Introduction

- A next goal of the neutrino experiments is to explore the neutrino oscillation phenomena in detail beyond the discovery phase.
  - Three generation Matrix (NMS matrix)
  - CP Violation, matter effect, the sign of $\Delta m_{23}^2$
  - May be an unexpected physics behind the oscillation phenomena.

- More complete studies with high statistics by JHF-Kamioka:
  - more precision
    - $\theta_{23}$, $\Delta m_{23}^2$, oscillation curve, non-oscillation scenario
    - more sensitive to a rare process
    - $\theta_{13}$ ($\nu_\mu \rightarrow \nu_e$), CP Violation, unexpected phenomena.
JHF-Kamioka Neutrino Experiment

Plan to start in 2007

Kamioka
~1GeV ν beam

Super-K: 22.5 kt

Hyper-K: 1000 kt

JAERI (Tokai)

0.75MW 50 GeV PS

4MW 50 GeV PS

(conventional ν beam)

JHF 0.75MW + Super-Kamiokande

Future Super-JHF 4MW + Hyper-K ~ JHF+SK × 200
Strategy

- High statistics by high intensity $\nu$ beam
- Tune $E\nu$ at oscillation maximum
- Narrow band beam to reduce BG
- Sub-GeV $\nu$ beam for Water Cherenkov

0.75MW JHF 50GeV-PS
(4MW Super JHF)

Off-Axis $\nu$ beam
Super-Kamiokande
(Hyper-Kamiokande)
Organization

**Experiment working group**
- Dec.1999 : formed (ICRR/KEK/Kyoto/Kobe/Tohoku/TRIUMF)
- Mar.2002 : Meeting to discuss possibility to organize international collaboration

**Facility Construction Group**
- Officially formed in KEK on **April, 2001**
- The 3rd physics division, IPNS, Cryogenic facility group, Cryogenic Science Center, w/ strong support from KEK-PS beam channel group
In addition to the above user group, the neutrino facility construction group is OFFICIALLY formed at KEK.
JHF Facility

Construction 2001–2006 (approved)

ν beam-line under budget request

- 8 bunches/≈5μs
- 3.3x10^{14} proton/pulse
- 3.94 (3.64) sec cycle
- 1 yr ≈ 10^{21} POT (130 days)

- ν beam-line
- Transport line (Super-cond. Mag.)
- Target station
- Decay volume
- Near detectors (280m, 2km)
Off Axis Beam

WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics

\[ E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos \theta)} \]

\[ \nu(E) \]

\[ \mu(m_\mu, p_\mu) \]

\[ \pi(m_\pi, p_\pi) \]

\[ \theta = 0^\circ, 1.0^\circ, 2.0^\circ, 5.0^\circ \]

\[ \Delta m^2 = 3 \times 10^{-3} \text{eV}^2 \]

\[ L = 295 \text{km} \]

\[ \text{Osc. Prob.} = \sin^2(1.27 \Delta m^2 L/E_\nu) \]

\[ ~3000 \text{ CC int./22.5kt/yr} \]

\[ \nu_e: 1.0\% \ (0.2\% \ @ \ \text{peak}); \]
$\nu_\mu/\overline{\nu}_\mu$ flux for CP violation search.

Flux

-15% @ peak

Sign flip by change of horn polarity

$10^{21}$ POT/yr (1st phase)

CC interaction

cross section difference

Wrong sign BG
Assume CC Quasi Elastic (QE) reaction

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

\[ (E_\mu, p_\mu) \]

\[ \nu \rightarrow p \]

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

\[ \sigma = 80 \text{MeV} \]

1R-FC\(\mu\)

Ev reconstruction in Water Cherenkov

Soudan 2 Monte Carlo Cross Sections

- ccQE
- cc-inelastic

\[ \sigma_{cc}(\nu_\mu + N \rightarrow \mu \pm X) / E (10^{-38} \text{cm}^2 / \text{GeV}) \]

Ev(reconstruct) – Ev(True) (MeV)
Detectors

- **Muon monitors @ ~140m**
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- **First Front detector @ 280m**
  - Neutrino intensity/direction
- **Second Front Detector @ ~2km**
  - Almost same $E_{\nu}$ spectrum as for SK
  - Water Cherenkov can work
- **Far detector @ 295km**
  - **Super-Kamiokande (50kt)**

Neutrino spectra at diff. dist

- 1.5km
- 295km
- 0.28km
Far detector
Super-Kamiokande

50,000 ton water Cherenkov detector
(22.5 kton fiducial volume)
Rebuilding Super-K (2002 Aug.)
Hyper-Kamiokande
(Future Far Detector)

~1,000 kt

Good for atm. ν proton decay

Candidate site in Kamioka
Physics Goal at the first phase

- Precise measurement of neutrino mixing matrix

  Accuracy: \( \sin^2 2 \theta_{23} \cdots \cdot \cdot 1\% \)

  \( \Delta m^2_{23} \cdots \cdots \cdots \cdots \cdots \text{a few} \% \)

- Discovery and measurement of non-zero \( \theta_{13} \)

  \( \sin^2 2 \theta_{13} \cdots \cdots > 0.005 \)

  \( 1^{st} \) Evidence of 3-flavor mixing !

  \( 1^{st} \) step to \( CP \) measurement
\( \nu_e \) appearance in JHF-Kamioka (phase 1)

**Background for \( \nu_e \) appearance search**
- Intrinsic \( \nu_e \) component in initial beam
- Merged \( \pi^0 \) ring from \( \nu_\mu \)

**Requirement**
- 10% uncertainty for BG estimation

The 1kt \( \pi^0 \) data will be studied for exercise
Tight e/$\pi^0$ separation

- Shower direction w.r.t. beam
  - $\cos\theta_{\nu e}$: $\gamma$ from $\pi^0$ tend to have a forward peak
- Force to find 2nd ring and...
  - $E(\gamma_2)/E(\gamma_1+\gamma_2)$: Large for BG
  - Likelihood diff. between 1-ring and 2-rings
  - Invariant mass: Small for $\nu_e$
$\sin^2 2\theta_{13}$ from $\nu_e$ appearance (5 years running)

\[ \sin^2 2\theta_{13} > 0.006 \]

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

<table>
<thead>
<tr>
<th>$\nu_\mu (\pi^0)$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\bar{\nu}_e$</th>
<th>total</th>
<th>Signal</th>
<th>Signal + BG</th>
</tr>
</thead>
<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>
</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>
</tr>
</tbody>
</table>

(*) still can be further improved

**Efficiency** = 42% (66% for QE)
$\nu_\mu$ disappearance

1 ring FC $\mu$-like

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

$\delta (\sin^2 2\theta)$

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

Reconstructed $E_\nu$ (MeV)

$\delta \sin^2 2\theta_{23} \sim 0.01$

$\delta \Delta m_{23}^2 < 1 \times 10^{-4}$ eV$^2$
$\nu_\mu \not\equiv \nu_\tau$ confirmation w/ NC interaction

- NC $\pi^0$ interaction ($\nu + N \not\equiv \nu + N + \pi^0$)
  - $\nu_\mu \rightarrow \nu_e$ CC + NC($\sim 0.5CC$) $\sim 0$ ($\sin^2 2\theta_{13} \sim 0$)
  - $\nu_\mu$ CC + NC($\sim 0.5CC$) $\sim 0$ (maximum oscillation)
  - $\nu_\tau$ NC

$\#\pi^0$ is sensitive to $\nu_\tau$ flux.

Limit on $\nu_s$ ($\delta f(\nu_s) \sim 0.1$)

$\nu_\mu \rightarrow \nu_\tau$

$\Delta = 390 \pm 44$

$3.5 \times 10^{-3}$

$\Delta m_{23}^2$
CP Violation Study w/ Hyper-K (Phase 2)

- Compare $\nu_\mu\rightarrow\nu_e$ (2 years) with $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$ (6 years)

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_v} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

$\Delta m_{12}^2 = 5 \times 10^{-5}eV^2$

$\Delta m_{23}^2 = 3 \times 10^{-3}eV^2$

$\sin^2 2\theta_{13} = 0.01$

$\theta_{23} = \pi/4$, $\theta_{12} = \pi/8$

NO CP violation w/o matter effect.

$|\delta| > 20^\circ (3\sigma ~ discovery)$
Sensitivity\(3\sigma\) to CP violation w/ sys. uncertainty

\begin{align*}
\text{Chooz excluded} & \quad \text{at } \Delta m_{31} \sim 3 \times 10^{-3}\text{eV}^2 \\
\sin^2 2\theta_{13} & \approx 0.12 \\
\sin\delta & > \sim 14\text{deg} \\
\sin\delta & > \sim 27\text{deg}
\end{align*}

4MW, 1Mt
2yr for \(\nu_\mu\)
6.8yr for \(\bar{\nu}_\mu\)

\(\delta > \sim 14\text{deg}\)

\(\delta > \sim 27\text{deg}\)
Global Schedule


- JHF-ν construction
- physics run (OAB)

SK rebuild  SK-half  SK-full

MINOS 2yr  OPERA 5yr
Summary

• Precision study of neutrino mixing matrix
  - Next step after the discovery
  - We may find a hint for next break-through

• JHF-Kamioka neutrino experiment (2007~)
  - JHF 50GeV-PS+Off Axis beam+Super-K
  - Narrow band beam at oscillation maximum (~ 1GeV)
  - \( \nu_e \) appearance, discovery of \( \theta_{13} \) (\( \sin \theta_{13} > 0.006, 90\% \text{CL} \))
  - Budget request, R&D started

• Possible upgrade in future
  - 4MW Super-J HF + Hyper-K (1Mt water Cherenkov)
  - CP violation in lepton sector (\( \delta \rightarrow 10\sim20^\circ \))
  - Bonus! (Proton Decay! )