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T. Hara (Kobe)
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A. Konaka (TRIUMF)

http://neutrino.kek.jp/jhfnu
Overview of JHF - SK

- $\nu_\mu \to \nu_x$ disappearance:
  - Precise measurement of oscillation parameters:
    $$\delta(\Delta m_{23}^2) \sim 2 \times 10^{-4} \text{eV}^2,$$
    $$\delta(\sin^2 2\theta_{\mu x}) \sim 1\%$$

- $\nu_\mu \to \nu_e$ appearance:
  - Explore down to
    $$\sin^2 2\theta_{\mu e} \sim 5 \times 10^{-3}$$

- Oscillation Max @ $E = 0.5\sim 1.2\text{GeV}$
  - $P = \sin^2 2\theta \cdot \sin^2 (1.27\Delta m_{23}^2 L/E)$
  - $\Delta m_{23}^2 = 2 \sim 5 \times 10^{-3} \text{eV}^2$, $L = 295\text{km}$
### JHF (Japan Hadrons Facility)

**JAERI @ Tokai-mura**  
Construction: 2001 ~ 2006

![Map of JHF facility with Neutrino Beam Line and Front Detector(s) leading to Super-Kamiokande](image)

<table>
<thead>
<tr>
<th></th>
<th>JHF</th>
<th>MINOS</th>
<th>K2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(GeV)</td>
<td>50</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>Int. ($10^{12}$ ppp)</td>
<td>330</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>Rate (Hz)</td>
<td>0.29</td>
<td>0.53</td>
<td>0.45</td>
</tr>
<tr>
<td>Power (MW)</td>
<td>0.77</td>
<td>0.41</td>
<td>0.0052</td>
</tr>
</tbody>
</table>

$10^{21}$ p.o.t./1 year (130 day)

Yoshihisa OBAYASHI, Honolulu - Oct. 6, 2000
Far Detector

Super-Kamiokande @ Kamioka
- Operation Start: 1996
- 295 km from JAERI
- 50.0kt Pure Water in the tank
- 22.5kt Fiducial Volume as a neutrino target
- Energy measurement by total amount of Cherenkov light
- e-μ separation is performed by ring pattern likelihood
Neutrino Beam at JHF

- **Three Possible options:**
  - **Wide Band Beam (WBB)**
    - 2 horns, almost same as K2K
  - **Narrow Band Beam (NBB)**
    - Horn(s) + Bending
  - **Off Axis Beam**
    - Another option of NBB

- **Present Strategy:**
  - **First 1(~2) year:**
    - High Statistics Run with WBB
    - Pin down $\Delta m^2$
  - **Next 5 years:**
    - Precise Analysis with (one of) NBB
    - Measurement of $\theta_{23}, \theta_{13}$
Wide Band Beam

- ☀ High Intensity
- ☀ Wide sensitivity in $\Delta m^2$
- ☀ Established technique
- ☹ Backgrounds from HE tail
- ☹ Spectra diff. btw near&far
  - Systematic error
- ☹ Needs Heavy shielding
  - decay pipe must be short
- $\sim 4200 \nu_\mu$ int./22.5kt/yr
  - ($\nu_e$: 0.8%)
Narrow Band Beam

- Less systematic error
- Less BG from HE tail
- Easy to tune $E_{\nu}$
- Less shielding
- Low intensity

- $\sim 830 \, \nu_\mu \, \text{int./22.5kt/yr}$
  
  (Ve: 0.3%@peak)
Off Axis Beam: Another option of NBB

WBB with intentionally misaligned from detector axis

Decay Kinematics

Quasi Monochromatic Beam
Off Axis Beam

- ☑ More intense than NBB
- ☹ More HE tail than NBB
- ☹ Hard to tune $E_{\nu}$
- ☹ Needs heavy shielding
- ☹ Not established technique
  - Beam monitor
  - Near/Far ratio, ...

~ 2200 $\nu_\mu$ int./22.5kt/yr
  - ($\nu_e$: 0.2%@peak)
Physics Sensitivity
$\nu_\mu$ Disappearance

**Ratio after BG subtraction:**

- Fit with
  $$1 - \sin^2 2\theta \cdot \sin^2 (1.27 \Delta m^2 L/E)$$
\textbf{V}_\mu \textbf{ Disappearance}

\begin{itemize}
    \item Possible systematic errors:
        \begin{itemize}
            \item inelastic cross section: 20\%
            \item Spectrum @FD: 4\% E
            \item Spectrum diff.(Near/ Far): 10\%
            \item Energy measurement: 3\%
        \end{itemize}
\end{itemize}

\[ \delta (\sin^2 2\theta) \sim 0.01 \text{ in 5 years} \]
Three flavor oscillation framework:

- $\Delta m_{12} << \Delta m_{23} \sim \Delta m_{13} \square \Delta m^2$
  - $\Delta m_{23} = \Delta m^2_{atm} > 10^{-3}\text{eV}^2$
  - $\Delta m_{12} = \Delta m^2_{sol} < 10^{-4}\text{eV}^2$

Oscillation Probability $P$:

- $m_3^2 \uparrow \Delta m^2_{atm}$
- $m_2^2 \downarrow \Delta m^2_{sol}$

$$
P(\nu_\mu \leftrightarrow \nu_e) = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 \left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E}\right)
$$

$$
P(\nu_\mu \leftrightarrow \nu_\tau) = \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} \cdot \sin^2 \left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E}\right)
$$

$$
P(\nu_e \leftrightarrow \nu_\tau) = \sin^2 2\theta_{13} \cdot \cos^2 \theta_{23} \cdot \sin^2 \left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E}\right)
$$

Present limit: $\sin^2 2\theta_{\mu e} > 5\times10^{-2}$

- $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23}$
  - $\sin^2 2\theta_{13} < 0.1$ (CHOOZ)
  - $\sin^2 \theta_{23} \sim 0.5$ (Atmospheric $\nu$)

Goal: $\sin^2 2\theta_{\mu e} \sim 5\times10^{-3}$
Signal & Backgrounds

Signal: $\nu_e$ C.C. interaction
- Single fuzzy ring
- Cherenkov angle $\sim 42$deg.

$\nu_e$ --- $e^{+/-}$ shower

BG 1: $\nu_\mu$ C.C. interaction
- Sharp ring edge
- Cherenkov angle $< 42$deg.

$\nu_\mu$ --- $\mu$

$\Rightarrow$ easy to reject
BG 2: N.C. $\pi^0$ production

$\nu \nu \pi^0 2\gamma$

2 showers

- 2 fuzzy rings hard to separate
- Not reproduce $E_{\nu}$

⇒ need effort to reject
**Ve Selection by SK Official Cuts**

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ (w/ $\pi^0$)</th>
<th>$\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fid. Vol.</td>
<td>3651</td>
<td>795</td>
</tr>
<tr>
<td>1Re-like</td>
<td>92</td>
<td>68</td>
</tr>
<tr>
<td>reduct rate</td>
<td>2.5%</td>
<td>8.6%</td>
</tr>
</tbody>
</table>

$\sin^2 2\theta_{\mu e} = 0.05, \Delta m^2 = 3 \times 10^{-3} \text{eV}^2$

- **S/N ~ 1/3 (@$\sin^2 2\theta_{\mu e} = 0.05$)**
- **Main Background come from $\pi^0$**

![Graph showing expected signal and background](image)
\( \pi^0 \) rejection

- **Force to find 2\(^{nd} \) \( \gamma \) ring
- **Cut with follow quantities:**
  - Shower direction w.r.t. \( \nu \) (\( \cos \theta_{\nu e} \))
  - Energy fraction of second \( \gamma \)
    \[ R(\gamma_2) = \frac{E(\gamma_2)}{E(\gamma_1) + E(\gamma_2)} \]
  - Pattern likelihood difference
  - Invariant mass of 2 \( \gamma \)
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π⁰ cut efficiency

WBB 1year

<table>
<thead>
<tr>
<th></th>
<th>WIDE</th>
<th></th>
<th>Ve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fid. Vol.</td>
<td>3651</td>
<td>53.3</td>
<td></td>
</tr>
<tr>
<td>1Re-like</td>
<td>92(2.5%)</td>
<td>29.5(55.3%)</td>
<td></td>
</tr>
<tr>
<td>π⁰ cut</td>
<td>4.0(0.1%)</td>
<td>9.8(18.4%)</td>
<td></td>
</tr>
</tbody>
</table>

NBB 1year

<table>
<thead>
<tr>
<th></th>
<th>LE2π</th>
<th></th>
<th>Ve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fid. Vol.</td>
<td>740</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>1Re-like</td>
<td>13.2(1.8%)</td>
<td>16.2(70.4%)</td>
<td></td>
</tr>
<tr>
<td>π⁰ cut</td>
<td>1.8(0.2%)</td>
<td>11.6(50.4%)</td>
<td></td>
</tr>
</tbody>
</table>

Off Axis 1year

<table>
<thead>
<tr>
<th></th>
<th>2deg.</th>
<th></th>
<th>Ve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fid. Vol.</td>
<td>1801</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>1Re-like</td>
<td>37.4(2.1%)</td>
<td>32.1(70.5%)</td>
<td></td>
</tr>
<tr>
<td>π⁰ cut</td>
<td>3.8(0.2%)</td>
<td>24.3(53.4%)</td>
<td></td>
</tr>
</tbody>
</table>

sin²2θₑµ=0.05, Δm²=3x10⁻³eV²
V_{\mu} \to V_{e} Oscillation Sensitivity

\[ \sin^2 2\theta_{\mu e} \approx 5(3) \times 10^{-3} \] \text{ at 90\% C.L.} by 5-year run of NBB (off axis beam)

10\% systematic in BG rate is considered

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10% systematic in BG rate is considered
Comparison to MINOS

JHF neutrino is more sensitive especially in Atmospheric $\Delta m^2$ region
\[ \nu_\mu \oplus \nu_\tau? \nu_{\text{sterile}?} \]

- **NC \( \pi^0 \) production:**
  \[ \nu + N \leftrightarrow \nu + N + \pi^0 \]

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu )</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>( \nu_\tau )</td>
<td>Few</td>
<td>Yes</td>
</tr>
<tr>
<td>( \nu_{\text{sterile}} )</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

- **In the case of \( \nu_\mu \oplus \nu_{\text{sterile}} \) oscillation,**
  - Number of \( \pi^0 \) also decrease

- \( \nu_\tau \oplus \nu_{\text{sterile}} \) discrimination

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Summary

- **JHF neutrino experiment**
  - Expected to start in **2006**

- **Far Detector**: Super-K

- **By 5 years of run:**
  - $\nu_\mu$ disappearance search
    - $\delta(\Delta m^2) \sim 2 \times 10^{-4} \text{eV}^2$
    - $\delta(\sin^2 2\theta) \sim 1\%$

  - $\nu_e$ appearance search
    - $\sin^2 2\theta_{\mu e} \sim 5 \times 10^{-3}$ @90\%CL

- $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_{\text{sterile}}$
  - Can be tested
Test of CP Violation

If $\sin^2 2\theta_{13} \sim 0.01$:

**1MW (2deg. off axis) vs. SK:**
- $2\nu_\mu \rightarrow \nu_e / \text{year}$
  - Too few to see CP

**4MW vs. Mton:**
- $300\overline{\nu}_\mu \rightarrow \overline{\nu}_e / \text{year}$
- $100\nu_\mu \rightarrow \nu_e / \text{year}$

**1year $\nu + 3\text{year}\overline{\nu}$**
- 600 total events with asym: $150\times \sin\delta$
  - $\delta = 30\text{deg.}(3\sigma), 12\text{deg.}(90\% \text{ CL})$