Atmospheric neutrino experiments with Mega-ton water Cherenkov detector

Kimihiro Okumura (ICRR)
17-Oct-2004 @ UNO04-keystone meeting

Collaboration with M. Ishitsuka, T. Kajita, Y. Obayashi, M. Shiozawa
Outline

We discuss expected physics in neutrino oscillation measurements with Mega-ton water Cherenkov detector

- Present and future atmospheric neutrino observation
  - $(\sin^2 2\theta_{23}, \Delta m^2_{23})$ measurement
  - search for non-zero $\theta_{13}$
  - sign of $\Delta m^2$
  - effect of solar oscillation term ($\Delta m^2_{12}$)
Atmospheric neutrinos

Atmosphere

Cosmic Ray

$\pi, K$

$\nu_\mu, \nu_e$

$L \sim 15\text{km}$

$\nu_\mu$

$L \sim 13000\text{km}$

$\nu_e$

Neutrinos from the other side of the Earth.
Neutrino Mixing
\[ |\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \]

Mixing Matrix:
\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 & c_{13} & 0 & s_{13} & 1 & 0 & 0 \\
0 & c_{23} & s_{23} & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & -s_{23} & c_{23} & 0 & 0 & e^{i\delta} & -s_{13} & c_{13} & 0 \\
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

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

CP Violation

Normal mass hierarchy assumed

\[ \Delta m_{23} \]

Atmospheric \( \nu \)
Long baseline

(future) LBL Reactor

Solar Kamland
Current understanding of atmospheric neutrino oscillation

- Large $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - $\Delta m^2 = 1.9 \sim 3.0 \times 10^{-3}$ eV$^2$
  - $0.92 < \sin^2 2\theta_{23}$
  - consistent with full-mixing

- No evidence for non-zero $\theta_{13}$
  - reactor: $\nu_e \rightarrow \nu_x$
  - Super-K: $\nu_\mu \rightarrow \nu_e$
What can we expect in future atmospheric neutrino experiments?

- More precise measure of \((\sin^2 2\theta_{23}, \Delta m_{23}^2)\)
- Search for non-zero \(\theta_{13}\)
- Sign of \(\Delta m^2\)
- Effect of solar oscillation term \((\Delta m_{12}^2)\)
Measurement of \( \sin^2 2\theta_{23}, \Delta m_{23}^2 \)

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left( \frac{1.27\Delta m^2 L}{E} \right) \]

(0.5 for UP)

\[ \frac{\text{Up}}{\text{Down}} = 1 - \frac{\sin^2 2\theta_{23} + \varepsilon}{2} \]

\[ \Delta m_{23}^2 \] (L/E)

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left( \frac{1.27\Delta m^2 L}{E} \right) \]

\( \pi/2 \) @ dip

How accurate can we determine \( \sin^2 2\theta_{23}, \Delta m_{23}^2 \)?
### List of updated systematic errors

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
</table>
| **(A)** Neutrino flux ($N_{sys}=11$) | - flux absolute normalization  
  - flavor ratios ($E_V<1.33\text{GeV},E_V>1.33\text{GeV}$)  
  - anti-neutrino/neutrino ratio ($\bar{\nu},\nu_\mu$)  
  - Up/down ratio  
  - horizontal-vertical ratio  
  - Neutrino flight length  
  - Energy spectrum  
  - Sample-by-sample normalization ($\text{FC multi-GeV}, \text{PC+up stop } \mu$) |
| **(B)** Neutrino interaction(10) | - $M_\Lambda$ in quasi-elastic and single-pi  
  - Quasi elastic scattering (model dependence)  
  - Quasi elastic scattering (cross section)  
  - single-pion production (cross section)  
  - multi-pion production (cross section)  
  - multi-pion production (model dependence)  
  - coherent pion production (cross section)  
  - NC/CC ratio  
  - Nuclear effect in $^{16}\text{O}$  
  - Charged current nt interaction |
| **(C)** Event selection(8) | - FC reduction  
  - PC reduction  
  - Up-\(\mu\) detection efficiency (stop, thru)  
  - FC/PC relative normalization  
  - Hadron simulation  
  - Non-$\nu$ BG  
  - Through-going/stopping $\mu$ separation |
| **(D)** Event reconstruction(6) | - 1-ring/multi-ring separation  
  - Particle ID (single-ring, multi-ring)  
  - Energy calibration for FC  
  - Energy cut for upward stopping $\mu$  
  - Up-down asymmetry of energy calibration |

**Total number of errors:** 35

*We considered same systematic errors as current Super-K analysis*
Expected sensitivity in $(\sin^2 2\theta_{23}, \Delta m^2_{23})$

The allowed region will shrink as a function of $\sqrt{\text{exposure}}$.

The sensitivity does not depend strongly on the true oscillation parameter set.
Expected sensitivity in \((\sin^2 2\theta_{23}, \Delta m_{23}^2)\)

The allowed \(\Delta m^2\) region will shrink as a function of \(\sqrt{\text{exposure}}\).

The \(\Delta m^2\) sensitivity depends strongly on the true oscillation parameter set.
If $\Delta m^2 < \sim 2.0 \times 10^{-3} \text{eV}^2$, $(\sin^2 2\theta_{23}, \Delta m_{23}^2)$ sensitivity may compete with LBL
Search for non-zero $\theta_{13}$

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

0.45 Mtonyr
(Super-K 20yrs)

Electron appearance in the 5 – 10GeV upward going events.
(And stronger muon disappearance in the 5 – 10GeV upward going events.)
Expected allowed parameter regions

Example:
$\Delta m^2 = 0.0025\text{eV}^2$
$s^2 \theta_{23} = 0.50$
$s^2 \theta_{13} = 0.025$

0.45 Mton yr
(SK 20 years)

Example:
$\Delta m^2 = 0.0025\text{eV}^2$
$s^2 \theta_{23} = 0.65$
$s^2 \theta_{13} = 0.025$

$s^2 \theta_{23} = 0.91$
$s^2 \theta_{23} = 0.35$

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

$99\%\text{C.L.}$
$90\%\text{C.L.}$
Statistical significance for non-zero $\theta_{13}$

0.45 Mton yr (Super-K 20 yrs)

$\sin^2 \theta_{23} = 0.35$

$\Delta m^2 = 3.0 \times 10^{-3}$
$\Delta m^2 = 2.5 \times 10^{-3}$
$\Delta m^2 = 2.0 \times 10^{-1}$

$\sin^2 \theta_{23} = 0.50$

$\Delta m^2 = 3.0 \times 10^{-3}$
$\Delta m^2 = 2.5 \times 10^{-3}$
$\Delta m^2 = 2.0 \times 10^{-1}$

$\sin^2 \theta_{23} = 0.65$

$\Delta m^2 = 3.0 \times 10^{-3}$
$\Delta m^2 = 2.5 \times 10^{-3}$
$\Delta m^2 = 2.0 \times 10^{-1}$

($\Delta \chi^2 \propto \sim \text{exposure}$)

Importance of $s^2\theta_{23} > 0.5$
S. Pascoli et al., hep-ph/0305152
Sign of $\Delta m^2$?

Some long baseline experiments (JPARC-Kamioka 2nd phase) have the CP sensitivity, but do not have the sensitivity in the sign of $\Delta m^2$ (because the baseline is too short).

Will it be possible to determine the sign of $\Delta m^2$ using atmospheric neutrino events?

Assumptions: $|\Delta m^2|$ is known very well; $\delta$ (CP) is also known (set to be 0).
How can we discriminate positive and negative $\Delta m^2$?

Real $\Delta m^2 = \text{positive}$ assumed

$$P(\nu_\mu \rightarrow \nu_e)$$

$\Delta m^2 = 0.003\text{eV}^2$, $s\sin^2\theta_{23} = 0.5$, $s\sin^2\theta_{13} = 0.026$

$E_V (\text{GeV})$

(No resonance for anti-neutrinos)

Real $\Delta m^2 = \text{negative}$ assumed

$$P(\nu_\mu \rightarrow \nu_e)$$

$\Delta m^2 = 0.003\text{eV}^2$, $s\sin^2\theta_{23} = 0.5$, $s\sin^2\theta_{13} = 0.026$

$E_V (\text{GeV})$

(No resonance for neutrinos)
How can we discriminate neutrino and anti-neutrino interactions?

Simple answer: No. It is not possible to discriminate event by event in water Cherenkov experiments.

However, $\sigma$(total) and $d\sigma/dy$ are different.

$\Rightarrow$ Try to discriminate positive and negative $\Delta m^2$ using these events.
Electron appearance for positive and negative $\Delta m^2$

$\Delta m^2 = 0.002 \text{eV}^2$

$s^2\theta_{23} = 0.5$

$s^2\theta_{13} = 0.05$

0.45 Mtonyr

(Super-K 20yrs)
\( \chi^2 \) difference (inverted-normal)

True = normal mass hierarchy assumed.

\( \Delta m^2: \) fixed, \( \theta_{23}: \) free, \( \theta_{13}: \) free

Exposure: 1.8Mtonyr
(Super-K 80yr or Hyper-K \( \sim 3.3 \) yr)

\[
\sin^2 \theta_{23} = 0.35 \quad \sin^2 \theta_{23} = 0.50 \quad \sin^2 \theta_{23} = 0.65
\]
$\chi^2$ difference (normal – inverted)

True= inverted mass hierarchy assumed.

$\Delta m^2$: fixed, $\theta_{23}$: free, $\theta_{13}$: free

Exposure: 1.8Mtonyr
(Super-K 80yr or Hyper-K ~3.3 yr)

$\sin^2 \theta_{23} = 0.35$

$\sin^2 \theta_{23} = 0.50$

$\sin^2 \theta_{23} = 0.65$
Effect of solar oscillation term ($\Delta m_{12}^2$)

KamLand hep-ex/0406035

- LMA solution of solar neutrino oscillation was confirmed by KamLand
- Allowed parameter region:
  - $\Delta m_{12}^2 = 7.7 \sim 8.8 \times 10^{-5}$ eV$^2$
  - $\tan^2 \theta_{12} = 0.33 \sim 0.49$

How this term affects to atmospheric neutrino events?
How does solar term ($\Delta m_{12}^2$) effect looks like in atmospheric neutrino?

Sub-GeV e-like

sub-GeV e-like events are enhanced according to $r \cdot \cos^2 \theta_{23} - 1$

Possible to probe $\sin^2 \theta_{23} > 0.5$ or $< 0.5$

$$\Delta m_{23}^2 = 2.1 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{12} = 0.82$$

$$\sin^2 \theta_{13} = 0$$

$$\frac{F_e}{F_0^e} - 1 = P_2 (r \ c_{23}^2 - 1)$$

0th order

$$- r \ s_{13} c_{13} \sin 2\theta_{23} \ (\cos \delta_{\text{CP}} \ R_2 - \sin \delta_{\text{CP}} \ I_2)$$

1st order

$$- s_{13}^2 [2(1 - r \ s_{23}^2) + P_2 (r - 2)]$$

2nd order

$$+ s_{13}^4 (1 - r \ s_{23}^2) (2 - P_2)$$

Sub-Gev GeV event likelihood vs. $\cos(\theta_e)$

Peres & Smirnov hep-ph/0309312
More on effect of $\Delta m_{12}^2$ term

Global oscillation analysis of Super-K and CHOOZ data w/ and w/o $\Delta m_{12}^2$ term

If non-zero $\Delta m_{12}^2$ is included, best-fit point was deviated from $\sin^2 \theta_{23} = 0.5$ due to sub-GeV e-like excess

Sub-GeV e-like sample in atmospheric neutrino will provide unique information on sign of deviation from $\sin^2 \theta_{23} = 0.5$
Summary

• Atmospheric neutrino still have many physics with Mega-ton detector.
  – Determination of $\Delta m^2$ and $\sin^2 2\theta_{23}$ can be improved with more data: $\delta(\sin^2 2\theta_{23}) = \sqrt{\text{exposure}}$.
  – Positive signal for non-zero $\theta_{13}$ can be seen if the true $\theta_{13}$ value is near the present CHOOZ limit and if $\sin^2 \theta_{23} > \sim 0.5$.
  – It can be possible to discriminate positive and negative $\Delta m^2$ using matter effect. But it is only possible for sufficiently large $\theta_{13}$ and $\theta_{23}$.
  – Due to $\Delta m_{12}^2$ effect, it can be possible to probe $\sin^2 \theta_{23} > 0.5$ or $< 0.5$ by seeing sub-GeV e-like. but this effect is small (few %).

• Future atmospheric neutrino experiments can still contribute to the neutrino oscillation physics. But the expected signal is small. We need better understanding of the atmospheric neutrino flux and neutrino interactions.