Recent results from Atmospheric $\nu$ and K2K

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ICRR, Univ. of Tokyo
Super-Kamiokande and K2K experiment

World Largest Water Cherenkov detector

- 1996.4  Start data taking
- 1999.3  K2K start
- 2001.7  Detector upgrade
- 2001.11 Accident
- 2002.10 resume data taking
- 2002.12 resume K2K beam

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

K2K-I
39m

K2K-II
42m
SK is back!

Full water on 10-Dec.-2002

Jan.-2003, fully contained event

Sep.-2002, before water filling

Acrylic + FRP vessel

Super-Kamiokande
Run 21588 Event 5348354
103-01-20:14:53:35
Inner: 1906 hits, 8472 pE
Outer: 1 hits, 0 pE (in-time)
Trigger ID: 0x03
D wall: 1690.0 cm
Fully-Contained
Outline of this talk

- Atmospheric results from SK-I
  - Entire re-analysis with new $\nu$-flux, $\nu$-int model.
- K2K-I results
  - $\nu_\mu$ disappearance
  - $\nu_e$ appearance search
  - Study $\nu$ interaction
- Status of SK-II / K2K-II
Neutrino oscillation

Two neutrino case

\[
\begin{pmatrix}
\nu_{\alpha} \\
\nu_{\beta}
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

\[
P(\nu_{\alpha} \rightarrow \nu_{\beta}) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)
\]

\(\Delta m^2 = m_2^2 - m_1^2 \text{ (eV}^2\text{)}\)

L (km): Distance from source to detector

E (GeV): Neutrino energy
Atmospheric neutrinos

- $\pi^\pm$, $K^\pm$ → $e^\pm$, $\nu_e$, $\nu_{\mu}$
- $\nu_{\mu}$
- $p$, He

Primary cosmic ray

$L = 10-20 \text{ km}$

$L = 10-30 \text{ km}$

$L = 13000 \text{ km}$
Atmospheric $\nu$ categories at SK

Energy spectrum of $\nu$ for each event category

- FC $\nu\mu$
- PC $\nu_e$
- Stopping $\mu$
- Through going $\mu$

Atmospheric $\nu\nu$ categories at SK

![Energy spectrum graph]
Summary of SK-I contained events

**Sub-GeV (Fully Contained)**

- \( E_{\text{vis}} < 1.33 \) GeV,
- \( P_e > 100 \) MeV, \( P_{\mu} > 200 \) MeV

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC(Honda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ring</td>
<td>e-like</td>
<td>3353</td>
</tr>
<tr>
<td></td>
<td>( \mu )-like</td>
<td>3227</td>
</tr>
<tr>
<td>Multi ring</td>
<td>(( \mu )-like)</td>
<td>2361</td>
</tr>
<tr>
<td></td>
<td>(( \mu )-like)</td>
<td>(208)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>8941</td>
</tr>
</tbody>
</table>

\[
\frac{(\mu/e)_{\text{data}}}{(\mu/e)_{\text{MC}}} = 0.649^{+0.016}_{-0.016} \pm 0.051
\]

**Multi-GeV**

- Fully Contained (\( E_{\text{vis}} > 1.3 \) GeV)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC(Honda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ring</td>
<td>e-like</td>
<td>746</td>
</tr>
<tr>
<td></td>
<td>( \mu )-like</td>
<td>651</td>
</tr>
<tr>
<td>Multi ring</td>
<td>(( \mu )-like)</td>
<td>1504</td>
</tr>
<tr>
<td></td>
<td>(( \mu )-like)</td>
<td>(439)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2901</td>
</tr>
</tbody>
</table>

**Partially Contained (assigned as \( \mu \)-like)**

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC(Honda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td>913</td>
</tr>
</tbody>
</table>

\[
\frac{(\mu/e)_{\text{data}}}{(\mu/e)_{\text{MC}}} = 0.700^{+0.032}_{-0.030} \pm 0.083
\]
Atmospheric $\nu$ zenith angle distribution

--- Honda

Best fit ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{eV}^2$)

- Sub GeV 1ring $e$-like
- Sub GeV 1ring $\mu$-like
- Sub GeV Multi ring ($\mu$)
- Upward stopping $\mu$

- Multi GeV 1ring $e$-like
- Multi-GeV 1ring $\mu$-like + Partially Contained
- Multi GeV Multi ring ($\mu$)
- Upward through going $\mu$
Allowed region of the oscillation parameters
(subGeV+multiGeV+PC+MultiRing+Upμ)
(complete SK-I data set)

Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit

$\chi^2_{\text{min}} = 170.8/170$ d.o.f.

at $(\sin^2 2\theta, \Delta m^2)$

$= (1.0, 2.0 \times 10^{-3} \text{ eV}^2)$

90% confidence level
allowed region

$\sin^2 2\theta > 0.9$

$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$

(eV$^2$)

Assuming null oscillation

$\chi^2 = 445.2/172$ d.o.f.
Comparison between old and new results

- Neutrino flux
  (Honda 1995 \(\Rightarrow\) Honda 2001)
- Neutrino interaction models
  (several improvements, agree with K2K near data)
- Improved detector simulation
- Improved event reconstruction tools

Each change slightly shifted the allowed region to lower \(\Delta m^2\)
Evidence for $\nu_\mu - \nu_\tau$

- Search for $\nu_\tau$-cc like events
  - Multi-GeV e-like multi ring events
  - $\tau$-likelihood

- Search for mixing supression by Matter effect

- Absolute NC rate by NC1$\pi^0$
  - Use $\pi^0$ rate measurement at K2K 1kt detector
zenith angle dist. of cc $\tau$-enhanced sample

$\tau$-like selection; eff$\tau$=44%, S/N=8%

cc-$\tau$ tagging

multi ring

decay-e

$\tau$ $\nu_{\tau}$ $\nu_{\mu}$

Consistent with $\nu_{\mu} \leftrightarrow \nu_{\tau}$

$$N_{\tau} = 145 \pm 44 \text{(stat)}^{+11}_{-16} \text{(sys)}$$

(86 expected)
limit on $\nu_\mu \leftrightarrow \nu_s$ admixture (4-flavor mixing)

(Following Fogli, Lisi, and Morrone, hep-ph/0002999)

$$\nu_\mu \rightarrow (\cos \xi \nu_\tau + \sin \xi \nu_s)$$

$\chi^2$ scan along $\Delta m^2 = 3.2 \times 10^{-3} \text{eV}^2$

Best Fit $\chi^2 = 172.6/190 \text{dof}$

at $(\sin^2 2\theta, \sin^2 \xi) = (1, 0)$

99% CL

90% CL

$\sin^2 \xi < 35\%$

$\sin^2 \xi < 25\%$

pure $\nu_\mu - \nu_\tau$    pure $\nu_\mu - \nu_s$

pure $\nu_\mu - \nu_s$ is excluded by $\Delta \chi^2 > 30$!
**π^0** in atm-ν sample at Super-K

Check
ν_μ → ν_τ and ν_μ → ν_s hypotheses
by a NC rate measurement

- SK Data set: 1489 days
- (*) normalized by livetime

<table>
<thead>
<tr>
<th>SK-atmν</th>
<th>Data</th>
<th>MC(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>π^0</td>
<td>475</td>
<td>483.8</td>
</tr>
<tr>
<td>1-R FC μ</td>
<td>3878</td>
<td>5415.1</td>
</tr>
<tr>
<td>π^0/μ</td>
<td>0.122±5%±7% (stat)</td>
<td>0.089±30% (sys)</td>
</tr>
</tbody>
</table>

Use K2K results

\[ \frac{π^0/μ}{MC} \]
- No osc
  - 0.087
- Pure ν_μ→ν_τ
  - 0.124
- Pure ν_μ→ν_s
  - 0.103

@ sin^22θ=1.0
Δm^2=2.0x10^{-3} eV^2

Detector systematics
- Particle ID
- Ring counting, etc.

K2K measurement (8%)
- SK- K2K ν-flux difference (4%), etc.
NC$\pi^0$ measurement at K2K

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>1kt</th>
<th>SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC frac.</td>
<td>86%</td>
<td>85%</td>
</tr>
<tr>
<td>Eff. for $\pi^0$</td>
<td>47%</td>
<td>46%</td>
</tr>
</tbody>
</table>

**Graph:**

- **Data:**
  - $\pi^0$: 2496
  - 1-R FC $\mu$: 22612
  - $\pi^0/\mu$: **0.110** ± 2% ± 8% (stat) ± 8% (sys)

- **MC(*)**:
  - $\pi^0$: 2582.3
  - 1-R FC $\mu$: 22545.2
  - $\pi^0/\mu$: **0.115** ± ~30% (sys)
Atm-$\nu \pi^0/\mu$ for data, $\nu_\mu-\nu_\tau$ and $\nu_\mu-\nu_s$ hypothesis @ $\sin^2 2\theta = 1.0$ $\Delta m^2 = 2.0 \times 10^{-3}$ eV$^2$

$\nu_\mu-\nu_\tau$ is consistent

Data $\pi^0/\mu$

\[
\frac{(\pi^0/\mu)}{(\pi^0/\mu)_{\text{noosc}}}:
\]
- Data: 1.41
- Pure $\nu_\mu-\nu_\tau$: 1.42
- Pure $\nu_\mu-\nu_s$: 1.19
3 Flavor Mixing

If neutrinos are massive particles, then it is possible that the mass eigenstates and the weak eigenstates are not the same:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\theta_{12}, \theta_{23}, \theta_{13} + \delta \]

\[\Delta m^2_{12}, \Delta m^2_{23}\]

MNS (Maki-Nakagawa-Sakata) matrix
Allowed region for active 3-flavor oscillations

\[ \Delta m_{12}^2 \sim 10^{-5} \text{eV}^2 \]

Solar \( \nu \)

\[ \Delta m_{23}^2 = 3 \times 10^{-3} \text{eV}^2 \]

Atmospheric \( \nu \)

\( \nu_{\mu} \) \( \leftrightarrow \) \( \nu_{\tau} \)

\( \theta_{13} \)

consistent with CHOOZ’s excluded region
K2K experiment
KEK to Kamioka Neutrino Oscillation Experiment

Super-K (far detector)
50 kton Water
Cherenkov detector

12GeV PS@KEK
- $\nu$ beam line
- Beam monitor
- Near detectors

$\nu_\mu$

$E_{\nu} \sim 1.3 \text{ GeV}$

250 km
K2K collaboration

- University of Barcelona
- Boston University
- Chonnam National University
- Dongshin University
- University of Geneva
- Hiroshima University
- ICRR
- Inst. for Nuclear Research, Moscow
- KEK

- Kobe University
- Korea University
- Kyoto University
- Massachusetts Institute of Technology
- Niigata University
- Okayama University
- University of Rome
- "La Sapienza"Saclay (DSM-DAPNIA)
- Seoul National University
- SUNY at Stony Brook
- Tokyo University of Science
- Tohoku University
- University of California, Irvine
- University of Hawaii
- University of Tokyo
- University of Washington
- University of Valencia
- Warsaw University
SciBar has been installed in summer 2003
SciBar detector

**Full active**

**Large Volume:**

$$(300 \times 300 \times 166) \text{ cm}^3 \sim 15\text{tons}$$

**Fine segment:** $2.5 \times 1.3 \times 300 \text{ cm}^3$

**Large Light Yield:**

$7 \sim 20$ photo-electrons/cm for MIP

the factor 3 of 7~20 comes from the fiber attenuation.

**Particle ID:**

$p/\pi : dE/dx$

$\mu/\pi : \text{range}$

**Proton Momentum:**

by $dE/dx$ and the range

#channels : $\sim 15,000$
Cosmic Ray muon at SCIBAR
Results of K2K-I
Super-K Event selection

\[ -0.2 \leq \Delta T \equiv T_{SK} - T_{Spill} - \text{TOF} \leq 1.3 \mu\text{sec} \]

- \( T_{spill} \): Abs. time of spill start
- \( T_{SK} \): Abs. time of SK event
- TOF: 0.83ms (KEK to Kamioka)
- FC: fully contained (No activity in Outer Detector)
- FV: 22.5kt Fiducial Volume
- Expected Atm. \( \nu \) BG <10\(^{-3}\) within 1.5\( \mu\)s.

Number of total interactions
(Jun99-Jul01)

\[ N_{obs} = 56 \]
\[ N_{exp} = 80.1 \pm 5.4 \]

56 events!
**Ev spectrum analysis**

- Determination of expected $\Phi(E_{\nu})$ spectrum
  - Beam Monte Carlo
  - $\pi$-monitor
  - Measurement of CC spectrum by near detector

**CCQE interaction (2 body)**

$$\nu_l + n \rightarrow l + p$$

$$E_{\nu} = \frac{m_N E_l - m_l^2 / 2}{m_N - E_l + p_l \cos \theta_l}$$
Eν spectrum results in K2K-I

Reconstructed Eν shape of 1-RFCμ at SK
(29 1-R events in Nov99-Jul01)

Neutrino Spectrum at KEK

FD Measurements

Beam MC

Events

Normalized by area

no oscillation

w/ oscillations
(KS-test = 79%)
Allowed regions and Null osc. probability

Total no. of Events only

56FC events observed / 80.1 expected
(Jun99-Jul01 data)

Spectrum Shape only

29 1-R FC\(\mu\) events shape
(Nov99-Jul01 data)

Shape and \(N_{SK}\) +Shape indicate consistent parameter region
Combined Allowed region (Shape+Norm) for K2K-I

\[\Delta m^2 = 1.5\sim3.9\times10^{-3}\text{eV}^2\]

@ \sin^2 2\theta = 1

@ 90\% CL

null oscillation \(\Rightarrow\) \(< 1\%\)

\[\Delta m^2 = 1.5\sim3.9\times10^{-3}\text{eV}^2\]

\@ \sin^2 2\theta = 1

atm-\nu results Consistent!
## Search for $\nu_e$ appearance

### DATA SET
June’99 – July’01 (4.8 $\times$ 10$^{19}$ POT)

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>Background $\pi^0$ (missing 1 ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ generated</td>
<td>28 events</td>
<td>28 (98%)</td>
</tr>
<tr>
<td>FCFV</td>
<td>56</td>
<td>80 (78%)</td>
</tr>
<tr>
<td>Single ring</td>
<td>32</td>
<td>50 (48%)</td>
</tr>
<tr>
<td>PID (e-like)</td>
<td>1</td>
<td>2.9 (2.7%)</td>
</tr>
<tr>
<td>$E_{vis}&gt;100$ MeV</td>
<td>1</td>
<td>2.6 (2.4%)</td>
</tr>
<tr>
<td>w/o decay-e</td>
<td>1</td>
<td>2.0 (1.9%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\nu_e$ MC</th>
<th>$\nu_\mu$ MC</th>
<th>beam $\nu_e$ MC</th>
<th>signal $\nu_e$ MC (CC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{\mu e}=1$, $\Delta m^2=2.8\times10^{-3}$ eV$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.99 events</td>
<td>0.52 (83%)</td>
<td>28 events</td>
<td></td>
</tr>
<tr>
<td>0.41 (41%)</td>
<td>0.42 (42%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.82 (83%)</td>
<td>56</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Electron candidate:
1 event observed
2.4 events expected.

$\nu_e$, $\nu_\mu$, $\gamma$, $\pi^0$, $e^-$
Electron Candidate

Electron Candidate

- Reconst. momentum: 597 MeV/c
- Reconst. Event: 612 MeV

Assuming νe CCQE
Allowed region for $\sin^22\theta_{\mu e}$
Status of K2K-II

Delivered number of protons on target
(includes Beam studies and tunings)

from Dec. 21, 2002

<table>
<thead>
<tr>
<th>Date</th>
<th>Delivered P.O.T.</th>
<th>Usable P.O.T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>June ’99-July ’01</td>
<td>~5.6x10^{19}</td>
<td>4.8x10^{19}</td>
</tr>
<tr>
<td>Dec. ’02-Apr. ’03</td>
<td>~1.7x10^{19}</td>
<td>1.5x10^{19}</td>
</tr>
<tr>
<td>May ’03-Jun. ’03</td>
<td>~0.7x10^{19}</td>
<td>Analysis in progress</td>
</tr>
</tbody>
</table>

Very stable and no serious problems
### Status of K2K-II

#### K2K-II Preliminary

#### Status of K2K

- **T(SK)-T(spill)-TOF**
- **10^3**
- **10^2**
- **10**
- **10**
- **-500 -250 0 2 50 500**
- **FC**
- **∆(T) µs**
- **1.5 µs**
- **events**
- **0 5 10 15 20**

### POT vs events

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs.</th>
<th>Exp.</th>
<th>Obs/Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999-2001</td>
<td>56</td>
<td>80.1</td>
<td>0.7</td>
</tr>
<tr>
<td>(K2K-I)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003 Jan~Apr (K2K-II)</td>
<td>16</td>
<td>26</td>
<td>0.6</td>
</tr>
</tbody>
</table>

#### K2K-II events

- **2000**
- **2001**
- **2003**

#### K2K-I

- **KS probability = 64.3%**
- **~Apr 21, 2003**

#### K2K-II

- **FC 22.5kt**
- **2003 Jan~Apr**
- **K2K-II**
- **K2K-II experiment observed consistent reduction rate**
Summary

- Atmospheric $\nu$ results from SK-I
  - Finalization for SK-I data is going on
  - $\Delta m^2 = 1.3 \sim 3.0 \times 10^{-3}\text{eV}^2$, $\sin^2 2\theta > 0.92$ @ 90%CL

- K2K results
  - K2K-I results (Total events + $E\nu$ spectrum)
    - Null oscillation probability is less than 1%
    - $\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3}\text{eV}^2$ for $\sin^2 2\theta = 1$ @ 90%CL

- Sk-II / K2K-II successfully resumed
  - K2K-II observe consistent $\nu$ rate with K2K-I