Latest Results from K2K
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For K2K collaboration

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1. Introduction

K2K is the first long baseline (250 km) neutrino experiment to investigate the neutrino oscillation observed in atmospheric neutrinos by the Super-K [PRL81, 1562(1998)].

Search for $\nu_\mu$ disappearance and $\nu_e$ appearance

$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

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**Diagram:**
- Pure $\nu_\mu$ beam (99%)
- $<E_{\nu}> \sim 1.3 GeV$
- 50 kton Water Cherenkov detector
- 12GeV PS
  - $\nu_\mu$ beam
  - Beam monitor
  - Near detector
2. Neutrino Beam Line

\[ p + \text{Al} \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \ (\langle E_{\nu} \rangle = 1.3 \text{ GeV} \ll \tau \text{ threshold}) \]

- 1.1 \(\mu\)sec spill/2.2 sec
- \(6 \times 10^{12}\) protons on target (POT)/spill
- GPS alignment < 0.01 mrad.
- Civil construction < 0.1 mrad.
ν target (Al) and Two HORNS
Muon monitor

Behind beam dump

Monitor the profile center of muons spill by spill.

Silicon Pad Detector Array

Segmented Ionization chamber

μ-pit floor
Delivered Protons on Target (POT)

Accumulated POT ($10^{18}$)

Protons/Pulse ($10^{12}$)

Date

1999  2000  2001

5.6 x $10^{19}$ POT
(July 12, 2001)

4.8 x $10^{19}$ POT for Analysis
3. Near and Far Detectors

At KEK:

1kt: Same Type Detector as SK  Neutrino Flux Measurement at Near
MRD: Muon range detector     Neutrino Beam Monitor
SciFi+MRD: Fine Grained       Precise Neutrino Interaction Study
Neutrino Energy reconstruction
(assuming Quasi-Elastic (QE) interaction)

$\nu_\mu + n \rightarrow \mu + p$

$\nu_\mu$

$\theta$

$(E_\mu, p_\mu)$

$E_v = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu}$

Non Quasi-Elastic event gives lower $E_v$
1kt Water Cherenkov detector

Same Type Detector as SK Neutrino Flux Measurement at Near

# of photo-electrons

Analysis threshold

- data
- MC
$\mu$ momentum (MeV/c)

$\theta_\mu$ (degree)

Reconstructed $\nu$ Energy for 1-ring FC $\mu$

DATA
MC
non–QE (MC)

w/o acceptance correction

QE events
**SciFi events**
Fine Grained  Precise Neutrino Interaction Study

Water(+20%Al) target

Two track events to select QE events.
Can study non-QE background events.
**MRD (Muon Range Detector)**

Muon range detector  Neutrino Beam Monitor
Fe/drift-tube sandwitch

**Profile x (0.5GeV < \( E_\mu \) < 1.0GeV)**

**Profile x (1.0GeV < \( E_\mu \) < 2.5GeV)**
Far detector: Super-K

- Inner detector
- 11146 of 20” PMT
- 50kt water
- 41.4m
- 39.3m

Location:
- Ikeno-yama, Kamioka, Gifu
- Mozumi
- 1km (2700mwe)
- 3km
- 2km
- Atotsu

Dimensions:
- 3km
- 2km
- 1km (2700mwe)
K2K Events at Super-K
4. Extrapolation from Near to Far sites

How we extrapolate the measurement at the near site to that at the far site?
**Pion Monitor**

Gas Cherenkov detector: (insensitive to primary protons)
Measure momentum and angular distribution of pions, \( N(p_\pi, \theta_\pi) \) just after the horns.

\[
N_{\text{expected}} = N_{\text{measurement}} \times R(\text{Far} / \text{Near})
\]

\[
R = \frac{\int \Phi_{\text{SK}}(E_\nu) \sigma(E_\nu) dE_\nu}{\int \Phi_{\text{KEK}}(E_\nu) \sigma(E_\nu) dE_\nu} \cdot \frac{N^\text{Mass}_{\text{SK}}}{N^\text{Mass}_{\text{KEK}}}
\]

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**Graphs and Figures:**

- **Top view** of the Pion Monitor.
- **Beam view** showing the decay volume and detectors.
- Far/Near flux ratio plot with data points and fitted curve.
- Integrated flux above 2.5 GeV.

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**Notes:**

- PIMON data analysis.
- Simulation.

**Values:**

- Far/Near flux ratio: \( 1.0 \times 10^{-6} \)
Super-K Event selection

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

- No Decay-e HE Trig.
- FCFV

**FC: fully contained**
(No activity in Outer Detector)
(Both start & stop point in Inner Detector.)

**FV: 22.5kt Fiducial Volume**

\[0 \pm 5\mu\text{sec}\]

Expected Atm. ν BG <10^{-3}
within 1.5μs.

\[T_{spill}: \text{Abs. time of spill start}\]
\[T_{SK}: \text{Abs. time of SK event}\]
\[\text{TOF: 0.83ms (KEK to Kamioka)}\]
**Results**

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Observed</th>
<th>Expected</th>
<th>$\Delta m^2 = 3 \times 10^{-3}$ eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ring $\mu$-like</td>
<td>30</td>
<td>$44.0 \pm 6.8$</td>
<td>24.4</td>
</tr>
<tr>
<td>Single Ring $e$-like</td>
<td>2</td>
<td>$4.4 \pm 1.7$</td>
<td>3.7</td>
</tr>
<tr>
<td>Multi Ring</td>
<td>24</td>
<td>$32.2 \pm 5.3$</td>
<td>24.3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>56</td>
<td>$80.6 \pm 7.3$</td>
<td>52.4</td>
</tr>
</tbody>
</table>

$\sin^2 2\theta = 1.0$

Dominant Systematic Errors are an uncertainty of far-near ratio ($\sim 7\%$) and an uncertainty of 1kt fiducial volume ($\sim 4\%$).

The provability of null oscillation scenario is **only 3\%**. (It was 10\% in the last year.)
Gaussian tail hypothesis test

Contour definitions:
- 68%
- 90%
- 99%

Disfavored at 90% CL.

Reconstructed $E_\nu$

$E_\nu$ F.C. 22.5kt 1-ring $\mu$-like

Note:
$\Delta m^2 = 3 \times 10^{-3} \text{ eV}^2$

$\square$ 600 MeV $E_\nu$

Preliminary
**K2K Upgrade**

- K2K will install another brand new near detector in summer 2003.
  \[ L = 250 \text{ km}, \Delta m^2 = 3 \times 10^{-3} \quad E_{\nu} \sim 0.6 \text{GeV} \]

**Full Active (solid) Scintillator Tracker**

- High efficiency for a short (<4cm) track.
- Detect a proton down to 350 MeV/c.
- PID \((p/\pi)\) and the momentum measurement by \(dE/dx\).
- Fine segments \((1 \sim 2 \sim 300 \text{cm}^3)\).
7. Conclusion & Future Prospect

- K2K accumulate \(4.8 \times 10^{19}\) protons on target.
  Goal = \(1.0 \times 10^{20}\) protons.

- 56 Events are observed with an expectation of \(80^{+6.1}_{-6.6}\) events.
  - The probability of null oscillation is less than 3%.

- We have established the K2K experimental method.
  Spectrum and Flux Extrapolation from Near to Far.
  Synchronization of Far detector with an accelerator by GPS.
  Beam handling towards the detector 250km away

- Just starting the spectrum analysis.

- We hope, K2K will re-start run in 2003.

- New Full Active Scintillator Tracker will be installed in summer 2003 to study neutrino interactions in detail.
Supplement
Accident on Nov. 12

Broken PMTs

Inner : ~60%
Outer: ~50%

Most possible cause
One PMT broken
and chain reaction occurred
by shock waves.


We will rebuild the detector.