Recent Results from K2K

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SUNY at Stony Brook

LP01 at Rome
July, 2001
K2K (KEK to Kamioka)
Long baseline Neutrino Oscillation Experiment

250km
The K2K Collaboration
(18 institutions from Japan, Korea and U.S. ~100 physicists)

Chonnam National University
Dongshin University
Seoul National University

ICRR, University of Tokyo
KEK
Kobe University
Kyoto University
Niigata University
Okayama University
Osaka University

Science University of Tokyo
Tohoku University

Boston University
University of California, Irvine
University of Hawaii
SUNY at Stony Brook
University of Washington

Warsaw University
K2K Physics Programs

• Neutrino Oscillations
  – confirm SuperK atm neutrino oscillation results
  – muon neutrino disappearance (99% pure $\nu_\mu$ beam)
    1) simple counting: observed/expected # of events
    2) distortion in observed energy spectrum
       ==> direct observation of energy dependent neutrino oscillation

• Neutrino Cross-section Measurements
  – NC $\pi^0$ production cross-section
     ==> application to $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_s$ discrimination in SuperK atmospheric neutrino analysis

• Study of Neutrino Background to Proton Decay Searches
K2K Neutrino Beamline

Muon Profile Monitors
 Beam Monitors: pion, proton
K2K Near Detector Complex

- **1kt (mini-SuperK)**: similar systematics as SuperK
- **Scifi (scintillating fiber tracker)**: 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking
- **LG (Lead Glass calorimeter)**: Measure $\nu_e$ contamination
- **MRD (muon range detector)**: 12 layers of iron plates w/ D.C.s

![Diagram of K2K Near Detector Complex]

*10 m Neutrino beam*
KEK 12 GeV PS - Neutrino Beam

- Beam intensity: $\sim 5.5 \times 10^{12}$ protons/pulse
- Repetition rate: 1 pulse/2.2 s
- Pulse width: 1.1 $\mu$s (9 bunches)
- Integrated POT delivered: $4.6 \times 10^{19}$ POT (Apr 01)
- Average $\nu$ beam energy: 1.3 GeV

![Graph showing integrated POT delivered and beam intensity over time]
1. Monitor the Beam Direction
   - muon monitor: spill by spill ($E_\mu > 5\text{GeV}$)
   - MRD: day by day ($E_\mu > 1\text{GeV}$)
   - 1 kton: day by day ($E_\mu > 0.2\text{GeV}$)

2. Measure neutrino beam flux and energy spectrum by utilizing
   CC QE events ($\nu_\mu + n \rightarrow \mu^- + p$) at near detectors

Recoil proton
   --> not seen in 1kt: below Cherenkov threshold
   --> can be seen in Scifi
3. Extrapolate the measured flux and the energy spectrum at the near detector to the far detector
   - pion monitor
   - beam MC

4. Compare the observed number of events with the predicted and Look for distortion in the measured $E_\nu$ at SuperK

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<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>#Observed</td>
<td>1</td>
<td>3</td>
<td>17</td>
<td>28 (27)</td>
<td>???</td>
</tr>
<tr>
<td>#Expected</td>
<td>~5*</td>
<td>12*</td>
<td>29*</td>
<td>38 (40*)</td>
<td>64</td>
</tr>
</tbody>
</table>

hep-ex/0103001
(accepted for publication in PLB)
- Survey Accuracy using GPS ~0.01 mrad
- Civil Construction Accuracy ~0.1 mrad
- Beam Aiming Requirement < 3-5 mrad
- Monitored Accuracy < 1 mrad
Beam Direction Monitoring: High Energy Muon

Muon monitor

Monitor the profile center of muons spill by spill. (at 200 m from the target)

±1 mrad

Jun99

±1 mrad

Apr01

LP01@Rome

Chang Kee Jung
Beam Direction Monitoring: Neutrino

Neutrino beam profile center in MRD at 300 m from the target

±1 mrad

profile x (0.5 GeV < E_μ < 1.0 GeV)

profile center x (cm)

profile y (cm)

Arbitrary Unit

profile x (1.0 GeV < E_μ < 2.5 GeV)

Arbitrary Unit

cm
Muon-like Event in 1kt
Charateristics of 1kton Events

FC Events

25 ton Fiducial volume (4mφ×2m)

1000 P.E.  
FADC threshold

ε~74%

#Photo-electrons (P.E.)

Data
MC

→#particles

ID 110
Entries 35238
Mean 5188.1
RMS 2835.

→#rings

PID probability (m = 251, FC, 1-ring)

→PID

e like (mainly come from π^0)

μ like

PID likelihood
Neutrino Energy Spectrum Reconstruction at 1kt

With single ringle mu-like events

==> assume QE interaction

not seen

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

w/o acceptance correction

CC QE $E_\nu$ spectrum [$\equiv \Phi(E_\nu) \cdot \sigma_{QE}(E_\nu)$]
Scifi two track events

==> measure non-QE background

QE

non-QE
Reconstructed Energy Spectrum at Scifi

CC QE $E_\nu$ spectrum after BG subtraction.

SciFi Data
PIMON
MC

$E_\nu$ (GeV)
Extrapolation to SuperK

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

\[ R = \frac{\int \Phi_{SK}(E_\nu) \sigma(E_\nu) dE_\nu}{\int \Phi_{KEK}(E_\nu) \sigma(E_\nu) dE_\nu} \]

\[ \frac{N_{SK}^{\text{Target mass}}}{N_{KEK}^{\text{Target mass}}} \]

PIMON sensitive region

PIMON

MC

Far/Ne flux ratio

1.0 \times 10^{-6}

0 0.5 1.0 1.5 2.0 2.5

E_\nu \text{ (GeV)}
**Expected # of Events (Null Oscillation) at SuperK**

<table>
<thead>
<tr>
<th></th>
<th>1kton (Near)</th>
<th>SuperK (Far)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume</td>
<td>25 tons</td>
<td>22,500 tons</td>
</tr>
<tr>
<td>Energy Threshold</td>
<td>&gt; 1000 p.e.</td>
<td>&gt; 300 p.e.</td>
</tr>
<tr>
<td>acc.*eff.</td>
<td>0.74</td>
<td>0.81</td>
</tr>
<tr>
<td># of Events</td>
<td>63,000</td>
<td>63.9</td>
</tr>
</tbody>
</table>

(no oscillation expected)

**Comparison of SuperK expected:**

- **1kton (water target):** \(63.9^{+6.1}_{-6.6}\)
- **Scifi (water target):** \(64.6^{+7.8}_{-8.8}\)
- **MRD (iron target):** \(69.8^{+10.2}_{-11.2}\)
Systematic Errors in SuperK Expected

- **Systematic Errors (1kton and SuperK)**
  - water target, similar detector ==> common sys. errors
    - some sys. errors such as x-section errors cancels out
  - Dominant sys. errors
    1) Far-near ratio: ~7%
    2) 1kton fiducial volume: ~4%
K2K Events Observed in SuperK

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

**Fully Contained Event Analysis**

- 44 FC events in FV
- Negligible background \(\sim 10^{-3}\) level

\(T_{Spill}\): Abs. time of spill start
\(T_{SK}\): Abs. time of SK event

**TOF:** 0.83 ms (KEK to Kamioka)
Vertex Distribution of the K2K Events in SuperK

(Solid dots are events with vertices in the fiducial volume; open are outside.)
Observed # of K2K Events vs. POT in SuperK

Events within FV

44 Events/3.85 x 10^{19} POT

KS probability: 32.3%

New data
(Jan-Apr 01)
16 Events

All Events

104 Events

KS probability: 20.5%
# of Observed Events vs. the Expected at SuperK

## June 1999 - April 2001

### FC Events in FV

<table>
<thead>
<tr>
<th>Type</th>
<th>Obs.</th>
<th>No</th>
<th>$\Delta m^2 (\times 10^{-3} eV^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC 22.5kt</td>
<td>44</td>
<td>63.9</td>
<td>41.5 27.4 23.1 (1kton)</td>
</tr>
<tr>
<td>1-ring</td>
<td>26</td>
<td>38.4</td>
<td>22.3 14.1 13.1 (sin^22\theta =1)</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>24</td>
<td>34.9</td>
<td>19.3 11.6 10.7</td>
</tr>
<tr>
<td>e-like</td>
<td>2</td>
<td>3.5</td>
<td>2.9   2.5     2.4</td>
</tr>
<tr>
<td>multi ring</td>
<td>18</td>
<td>25.5</td>
<td>19.3 13.3 10.0</td>
</tr>
</tbody>
</table>

(Large events)
# of Observed Events vs. the Expected at SuperK

<table>
<thead>
<tr>
<th>FC Events in FV</th>
<th>1999/06-2001/04</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta m^2 (\times 10^{-3} eV^2)$</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Obs.</td>
<td>No</td>
</tr>
<tr>
<td>FC 22.5kt</td>
<td>44</td>
</tr>
<tr>
<td>1-ring</td>
<td>26</td>
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<tr>
<td>ring</td>
<td></td>
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=> Null Oscillation probability: less than 3%
Neutrino Energy Spectrum at SuperK

\[ P_{\nu \rightarrow \nu} = 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]

with \( \sin^2 2\theta = 1.0 \), \( L = 250 \text{ km} \)

Reconstructed Neutrino Energy (MC)
Observed Energy Spectrum at SuperK

**Reconstructed Ev**

Note: $\Delta m^2 = 3 \times 10^{-3} \text{ eV}^2$ corresponds to 600 MeV eV

24 Events

Note no error bars for expected energy spectrum: Detailed evaluation of systematic errors underway, including bin-by-bin correlation.
K2K Upgrade

- Reduce systematic errors in below 1 GeV bins
  - Fall 2001: remove LG --> increase Scifi event statistics
  - Summer 2003: install a new detector in place of LG

Liquid Scintillator Tracker
- High efficiency for a short (~5cm) track
- Detect a proton down to 400 MeV/c.
- PID ($p/\pi$) by $dE/dx$.
- Fine segments ($2 \times 2 \times 300\,\text{cm}^3$).
- ~30,000 channels (segments).
**Relative X-section of NC $\pi^0$ Production**

**selection criteria for $\pi^0$**
- 50t fiducial
- Fully Contained
- 2 rings
- both e-like
- $85\text{MeV/c}^2 < M_{\gamma\gamma} < 215\text{MeV/c}^2$

**selection criteria for $\mu$**
- 25t fiducial
- Fully Contained
- $E_{vis} > 30\text{MeV}$
- 1 ring
- $\mu$-like

![Graph showing invariant mass cut](image)

- observed # of $\pi^0$: 4120
- observed # of $\mu$: 16487

\[
\frac{(\pi^0/\mu)_{DATA}}{(\pi^0/\mu)_{MC}} = 1.03 \pm 0.02 \pm 0.02 \pm 0.09
\]

data stat.  MC stat.  sys.
• K2K is running very well
  – Beam intensity at the design level
  – June 1999 - April 2001 data:
    3.85 (4.58) x 10^{19} POT SuperK live (delivered)

  ==> additional data (May - July 2001) being analyzed
  ==> Goal: accumulate 10^{20} POT (~until 2004)

  – 44 observed events compared to 63.9^{+6.1}_{-6.6} (sys) expected from null oscillation

  ==> null oscillation probability < 3%

  – Energy spectrum analysis is underway

  ==> qualitatively the observed energy spectrum consistent w/ the SuperK atm best fit parameters

  ==> quantitative results to come in spring 2002
Other cross-section measurements are underway

\[ \pi^0/\mu \] results to be published soon

Preliminary results on background study for proton decays

- First successful long-baseline neutrino oscillation experiment w/ a baseline O (100km)

- leads to rich neutrino physics programs of future long-baseline experiments: MINOS, CNGS, JHF--> SuperK, superbeams and neutrino factories...

- Neutrino Oscillation: only evidence for physics beyond SM

\[
(MNS) \leftrightarrow (CKM)
\]

- Leptogenesis?