New Results from K2K

March 2002, La Thuile
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1. Introduction

K2K is the first long baseline (250km) neutrino experiment to investigate the neutrino oscillation observed in atmospheric neutrinos by the Super-K

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

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

$E_{\nu} \sim 1.3$GeV

250km
Motivation

Atmospheric $\nu$ anomaly by Kamiokande

Evidence for oscillation of atm. $\nu$ by SK

$\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$

$\sin^2 2\theta \gg 0.88$

almost $\nu_\mu \rightarrow \nu_\tau$

Neutrino Oscillation (in 2-flavor approximation)

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)
\]

K2K aims to establish the neutrino oscillation in $\nu_\mu$ disappearance and $\nu_e$ appearance

well defined flight length (=250 km)

well understood flux of pure (98%) $\nu_\mu$ beam with $<E\nu> \sim 1.3\text{ GeV}$
Super-Kamiokande (SK) as Far Detector

Water Cherenkov detector
- $39.3\text{m} \times 41.4\text{m} \cdots 50\text{kton water}$
- Inner detector 11146 PMTs($20''$)
- Outer detector 1885 PMTs($8''$)

- 1000m underground
- Atmospheric $\nu$ B.G. $\sim 8\text{events/day}$ reduced by $10^{-6}$ by timing window (GPS)
The Accident on Nov.12

Many PMTs were broken within a few seconds

60% of the inner PMTs, half of the outer PMTs were broken. Small water leak found.

Most possible cause is one PMT broken and chain reaction occurred by a shock wave.
We will rebuild the detector. There is no question. The strategy may be the following two steps, which will be proposed and discussed among my colleagues.

1. Quick restart of the K2K experiment.
   (1) We will clear the safety measures which may be suggested by the committees, (2) reduce the number density of the photomultiplier tubes by about a half, (3) use the existing resources, (4) resume the K2K experiment as soon as possible; the goal may be within one year.

To achieve our objective is formidable but we are determined to do so. We certainly need your encouragement, advice and help. I should appreciate it very much if you could support our effort as you have kindly done so before.
Neutrino Beam Production

\[ p + Al \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ e^+ + \nu_e + \nu_\mu (1\%) \]

Pion Monitor

T-Station (×5)

Near Detectors

Muon Pit (×10)

Muon Monitor

200m

PS: 12GeV proton

1.1 \( \mu \) sec spill/2.2 sec

6 \times 10^{12} \text{protons/spill}
Pion Monitor

Measure Momentum / Angle Dist. of π’s Just after Horn/Target

- Well known π Decay Kinematics
- Well Defined Decay Volume Geometry

Predict

νμ Energy Spectrum at Near Site Far Site.

νμ Flux Ratio (Far/Near) as a Function of Neutrino Energy

Ring Image Gas Cherenkov Detector (Index of Refraction is Changeable)

To Avoid Severe Proton Beam Background, νμ Energy Information above 1GeV is Available (β of 12GeV Proton ~ β of 2GeV π)
Muon Monitor

Behind beam dump
→ sensitive to initially high energy $\mu$ (>5.5GeV)
Provide fast (spill-by-spill) monitoring of
   Intensity $\rightarrow$ targeting/horn stability
   Profile $\rightarrow$ beam direction
Near Site Neutrino Detectors

1kt: Same Type Detector as SK  Neutrino Flux Measurement at Near Site
MRD: Massive Large Area Coverage  Neutrino Beam Monitor
SciFi+MRD: Fine Grained  Precise Neutrino Interaction Study
1kt as a Near Site Neutrino Detector

Same Type Detector as SK

Total Photo Electron Distribution

Analysis Threshold
(100MeV Deposited Energy)

Data
M.C.

Water Target,
Same Photo Coverage
with 680 20inc. PMT

Fiducial Mass: 25ton
for r<2m, -2 < z<0m
Event Rate : ~ 2/100pulses
Muon Range Detector (MRD) as a Neutrino Beam Monitor

Neutrino/Fe Charged Current (CC) Interaction

Fe/Drift tube Sandwich
(Fe: 10cm x 4.20cm x 8)
\( \Delta E_\mu = 150 \text{MeV} \)

Large area coverage
Vertex Distribution
Mom. and Angle of Inclusive\( \mu \)

High Mass
329ton for \( r < 3 \text{m} \)
High Statistics (~ 5/100 pulses)

Good Neutrino Beam Monitor
(Stability of Direction, Spectrum and Intensity)
2. New Results

Based on data accumulated between June 1999 and July 2001
Profile Center Stability (MRD)

Horizontal

Vertical

Beam is directed to SK within ±1 mrad
Event Rate (MRD) / Mumon

MRD

Stable
Muon Energy Angle Stability (MRD)

Implying neutrino spectrum is stable
Inferred Neutrino Energy Spectrum at Far/Near by Pion Monitor

Simulation is Validated by Pion Monitor Measurement
Evaluation of Far/Near Uncertainty is Based on this Measurement
SK Events

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

no pre.act

>200p.e

In 22.5kton
56 observed
1-ring \( \mu \) 30
1-ring e 2
multi ring 24
SK Events vs. POT

![Graphs showing SK Events vs. POT](image)

- **KS probability**: 43.6%
- **Fitted slope**: -1.21 ± 0.19/10^4 POT
- **Log likelihood**: mean slope = -1.17/10^4 POT
### History of K2K and the New Result

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<tr>
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<tbody>
<tr>
<td>#Observed</td>
<td>28</td>
<td>44</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>#Expected</td>
<td>38</td>
<td>64</td>
<td>80.6±0.3 (stat.) +7.3 -8.0</td>
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**The result:**

The probability of null oscillation scenario is **less than 3%**.

Method of a long-baseline $\nu$ experiment has been established.

- **Beam monitoring and handling** towards the detector 250km away.
- **Synchronization** of Far detector with an accelerator by GPS.
- Spectrum and Flux **Extrapolation** from Near to Far.
Near Site Neutrino Spectrum Measurement (SciFi+MRD)

Water Target (+20% Al)
Pos. Resolution ~1mm
Fiducial Mass: 5.9 ton
Event Rate ~ 1/1000 pulses

Suitable for Studying Neutrino Int., e.g. $\sigma_{QE}/\sigma_{\text{non-QE}}$

Reconstructed Neutrino Energy Distribution

Expected Angle (QE) Measured Angle

Select Here

Quasi-Elastic

Number of Events vs. $\cos(\Delta \theta)$

Number of Events vs. $E_{\nu}$ [GeV]
Angle and Momentum of Muon-like Events at SK

Histogram shows expectation from MC w/o oscillation

Sys. err. in expectation is under study using near detector information.
Observed Neutrino Spectrum at SK

Angular Distribution of Single-Ring $\mu$

- Statistical Uncertainty Only !!
- Evaluation of Systematic Uncertainty inc. Bin by Bin Correlation is Necessary !!
- Reconstructed Neutrino Energy Distribution
Reconstructed $E^\nu$ at SK

Histogram shows expectation from MC w/o oscillation

Full spectrum analysis is under way using all information.
3. Near Detector Upgrade

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

**Full active (solid) Scintillator tracker (SCIBAR)**

- 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 \((1 \times 2 \times 300\text{cm}^3)\).
CC-QE Event Display (SCIBAR)

Tracking Performance

\[ \sigma = 0.41 \text{ cm} \]

\[ \sigma = 0.41 \text{ cm} \]

\[ \sigma = 0.36 \text{ cm} \]
4. Run Plan

- Firmly to establish neutrino oscillation, K2K will accumulate $10^{20}$ POT (additional 18 month run).

- Super-K is being rebuilt with a reduced PMT density. Goal is within 1 year.

- After the Super-K rebuilt, we want to accumulate data as quick as possible. K2K can run for more than 7 month in a year.
  - The horns are sustained more than 8 M pulses.

- The upgrade detector, Full Active Scintillator Tracker (SCIBAR), will be installed and be ready by summer 2003.
5. Summary

The new result is:

#Events=56 for #expect=80.6±0.3(stat.)^{+7.3}_{-8.0}(sys.).
Probability of null-oscillation scenario is <3\%CL.

- We hope that Super-Kamiokande can be rebuilt within one year.
- K2K wants to achieve 10^{20} POT (additional 18 month run) to establish $\nu$ oscillation definitely.
- The new full active scintillator tracker will be installed in summer 2003 to measure $\nu$ spectrum precisely and to study $\nu$ interactions.