K2K Neutrino Oscillation

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for the K2K Collaboration

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NuFact 05
Frascati (Rome)
Laboratori Nazionali di Frascati
The K2K Collaboration

JAPAN: KEK, ICRR, University of Tokyo, Hiroshima University, Kobe University, Kyoto University, Niigata University, Okayama University, Osaka University, Tokyo University of Science, Tohoku University

KOREA: Chonnam National University, Dongshin University, Korea University, Seoul National University

USA: Boston University, Duke University, University of California Irvine, University of Hawaii, Massachusetts Institute of Technology, State University of New York, University of Washington

POLAND: Warsaw University, Solton Institute

CANADA: TRIUMF, University of British Columbia

ITALY: Rome University and INFN

FRANCE: Dapnia Saclay

SPAIN: University of Barcelona, University of Valencia

SWITZERLAND: Geneva University

RUSSIA: INR-Moscow

Since 2002 for K2K-II
K2K Conceptual Layout

12GeV protons

Al Target + Horn

π monitor

π^+ decay pipe

μ^+ μ monitor

SK

ND

～1 event/2days

～10^{11}\nu_\mu/2.2\text{sec}

(/10m\times10m)

ν_\mu

～10^6\nu_\mu/2.2\text{sec}

(/40m\times40m)

ν_\tau

K2K signature of neutrino oscillation

➲ Reduction of ν_\mu events

➲ Distortion of ν_\mu energy spectrum
**Far/Near Ratio**

- **Source:** $L_{\text{far}} = 250 \text{ km}$

- Equation for $R = f(E_{\nu}) \neq (L_{\text{near}}/L_{\text{far}})^2 \sim 10^{-6}$

- $
u_\mu$ spectrum at K2K-ND

- Beam MC and Pion monitor data
Neutrino Beam

12 GeV protons
1.1μs spill/2.2s
6x10^{12} p/spill
Al target
Two horns focussing
**Near Detector Layout**

- **1KT Water Cherenkov (1KT)**
- **Scintillating-fiber/Water sandwich (SciFi)**
- **Lead Glass calorimeter (LG) before 2002**
- **Scintillator Bar Detector (SciBar) after 2003**
- **Muon Range Detector (MRD)**

**Measure neutrino flux**

- **Far/Near: detector systematics, C vs O**
- **Study \( \nu \) properties**
- **Monitor \( \nu \) beam stability**
SuperKamiokande

Inner detector
11146 20° PMTs

Outer detector
1885 8° PMTs
Protons on Target

This analysis: K2K-I+K2K-IIa&b
10.1 $10^{19}$ PoT delivered
8.9 $10^{19}$ PoT for physics analysis
SuperKamiokande

Events

K2K-I + K2K-IIa + K2K-IIb

- Decay electron cut.
- \( \geq 20 \text{MeV Deposed Energy} \)
- No Activity in Outer Detector
- Event Vertex in Fiducial Volume
- More than 30MeV Deposited Energy

-0.2 < \( T_{SK} - T_{spill} - \text{ToF} \) < 1.3 \( \mu \text{sec} \)

107 events

(BG: 1.6 events within \( \pm 500 \mu \text{sec} \)
2.4 \times 10^{-3} \text{ events in } 1.5 \mu \text{sec} )
Analysis Strategy

Near Detector
Measure $\#\nu$, $P_{\mu}, \theta_{\mu},...$

Experimental Data

Far Detector
Measure $\#\nu$, $E_{\nu}^{\text{rec}}$

Oscillation Fit
$\sin^2 2\theta$, $\Delta m^2$

$v$ interaction MC near detector simulation

Far/Near Ratio
Beam MC + $\pi$ monitor, $v$ interact. properties

$\Phi_{\text{ND}}(E\nu)$, $v$ interact. properties

Expected $\#\nu$, $E_{\nu}^{\text{rec}}$
w/o oscillation
Neutrino Interaction MC
(NEUT)

- CC quasi-elastic (CCQE)
  Smith and Moniz with $M_A = 1.1$GeV
- CC (resonance) single $\pi$ (CC1$\pi$)
  Rein and Seghal with $M_A = 1.1$GeV
- DIS
  GRV94+JETSET with Bodek and Yang corrections
- CC coherent
  Rein and Sehgal with Marteau's cross-section rescale
- Neutral Currents
- Nuclear effects
  Oxygen, Carbon

![Graph showing various neutrino interaction channels with their respective cross-sections and energy dependencies.]
MRD: Neutrino Beam Stability

Beam proved stable over more than 5 years
$1KT: \ \ N_{SK}$

Water Cherenkov replica of Super-K (scale 1/50, ~1/1000 fidicial)
Most of detector systematics cancel in the extrapolation

$$N_{SK}^{exp} = N_{SK}^{obs} \cdot \frac{\int \Phi_{SK} (E_{\nu}) \sigma (E_{\nu}) dE_{\nu}}{\int \Phi_{KT} (E_{\nu}) \sigma (E_{\nu}) dE_{\nu}} \cdot \frac{M_{SK}}{M_{KT}} \cdot \frac{\varepsilon_{SK}}{\varepsilon_{KT}}$$

≡Far/Near Ratio $\sim 1 \times 10^{-6}$ (from MC)

$M$: Fiducial mass $M_{SK} = 22,500$ton, $M_{KT} = 25$ton

$\varepsilon$: efficiency $\varepsilon_{SK-I(II)} = 77.1(78.2)\%$, $\varepsilon_{KT} = 74.5\%$

$N_{SK}^{exp} = 150.9^{+11.6}_{-10.0}$ $\rightarrow$ $N_{SK}^{obs} = 107$
Low $q^2$ Deficit

- A deficit at low $q^2$ for non-QE events is observed
- Two phenomenological models fit our data:
  - Suppression of CC1$\pi$ as $q^2/A$ for $<A=0.100.03(GeV/c^2)$
  - No coherent pion production

- The oscillation result is insensitive to the choice

“Search for coherent charged pion production in neutrino-carbon interactions”
hep-ex/0506008, Subm. to PRL

see F. Sanchez talk
Near Detector Spectrum measurement

- 1KT Water Cherenkov detector (H,O target)
  1. Fully contained one-ring muon-like sample
- SciFi fiber tracker (H,O target)
  2. Single-muon track sample
  3. Two-track QE sample ($\Delta \theta_p < 25^\circ$)
  4. Two-tracks nonQE sample ($\Delta \theta_p > 30^\circ$)
- SciBar fine-grained scintillator (H,C target)
  5. Single-muon track sample
  6. Two-track QE sample ($\Delta \theta_p < 25^\circ$)
  7. Two-tracks nonQE sample ($\Delta \theta_p > 25^\circ$)

For each event we measure $P_\mu, \Theta_\mu$

After the low $q^2$ correction, all data samples agree
Example: $1KT\ 1Ring\ \mu$-like

Effect of low $q^2$ correction (here CC$1\pi$ suppression)
Free parameters of the fit

- flux in 8 energy bins $\Phi(E\nu)$
- nonQE/QE
- detector uncertainties (energy scale, efficiencies,...)
- nuclear effect uncertainties (proton and pion rescattering)

Strategy

- fit $\Phi(E\nu)$ flux without low angle data
- apply either low $q^2$ CC1$_\pi$ or coherent pion suppression
- fit nonQE/QE for the entire angular range
- Use $\Phi(E\nu)$, nonQE/QE to calculate the spectrum at Super-K
Example of Spectrum fit

1KT $P_\mu$ vs $\Theta_\mu$ distribution

- $P_\mu$ (MeV/c)
- $\Theta_\mu$ degrees

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>MC templates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\nu &lt; 0.5$ GeV</td>
<td>QE</td>
</tr>
<tr>
<td>0.5-0.75 GeV</td>
<td>nonQE</td>
</tr>
<tr>
<td>0.75-1.0 GeV</td>
<td></td>
</tr>
<tr>
<td>1.0-1.5 GeV</td>
<td></td>
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</tbody>
</table>

Free parameters of the fit:
- relative flux $\Phi(E_\nu)$ (8 bins)
- ratio nonQE/QE
The nonQE/QE error takes into account the variation with different fit criteria:
nonQE/QE = 0.95 ± 0.04 (standard angular cut)
nonQE/QE = 1.02 ± 0.03 (CC1π suppression)
nonQE/QE = 1.06 ± 0.03 (no coherent pion)
Example: SciBar Data with Measured Spectrum

flux measurement

\[ P_\mu \text{ 1trk} \]

\[ P_\mu \text{ 2trk QE} \]

\[ P_\mu \text{ 2trk nQE} \]

\[ \theta_\mu \text{ 1trk} \]

\[ \theta_\mu \text{ 2trk QE} \]

\[ \theta_\mu \text{ 2trk nQE} \]
# K2K/Super-K Data Sample

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FC 22.5kt</strong></td>
<td><strong>107</strong> (55, 52)</td>
<td><strong>150.9</strong> (79.1*, 71.8)</td>
</tr>
<tr>
<td>1-ring</td>
<td><strong>67</strong> (33, 34)</td>
<td><strong>93.7</strong> (48.6, 45.1 )</td>
</tr>
<tr>
<td>1-ring $\mu$-like</td>
<td><strong>57</strong> (30, 27)</td>
<td><strong>84.8</strong> (44.3, 40.5)</td>
</tr>
<tr>
<td>1-ring e-like</td>
<td><strong>10</strong> (3, 7)</td>
<td><strong>8.8</strong> (4.3, 4.5)</td>
</tr>
<tr>
<td>Multi Ring</td>
<td><strong>40</strong> (22, 18)</td>
<td><strong>57.2</strong> (30.5, 26.7)</td>
</tr>
</tbody>
</table>

K2K-I 47.9 $10^{18}$ PoT  
K2K-II 41.2 $10^{18}$ PoT
Oscillation Analysis

\[ L(\Delta m^2, \sin 2\theta, f^x) \]

\[ = L_{\text{norm}}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{\text{shape}}(\Delta m^2, \sin 2\theta, f^x) \cdot L_{\text{syst}}(f^x) \]

- Total Number of neutrino events
- Reconstructed \( E_{\nu}^{\text{rec}} \) spectrum shape for 1-ring \( \mu \)-like events
- Systematic error terms, \( f^x \)

Systematic error terms include: normalisation, flux, nonQE/QE ratio, pion monitor and beam MC constraints, Super-K systematic uncertainties.
Compare with Null Oscillation

\[ L_{\text{norm}}(f^x) \]

\[ L_{\text{shape}}(f^x) \]

#SK Events

Toy MC

KS probability = 0.08%

Expected shape (No Oscillation)

<table>
<thead>
<tr>
<th># of virtual experiments</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>107</td>
</tr>
<tr>
<td>1</td>
<td>150.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>events/0.2[GeV]</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>57</td>
</tr>
</tbody>
</table>
Best fit in the physical region:
\[ \sin^2(2\theta) = 1.0 \quad \Delta m^2 = 2.79 \times 10^{-3} \text{ eV}^2 \]

Highest likelihood for:
\[ \sin^2(2\theta) = 1.51 \quad \Delta m^2 = 2.19 \times 10^{-3} \text{ eV}^2 \]

The difference in these two fits is \( \Delta \log = 0.64 \)

A value \( \sin^2(2\theta) > 1.51 \) can occur, due to a statistical fluctuations, with a probability of 12.6\%.
\[ \Delta m^2 @ \sin^2 2\theta = 1: \]

\[ 2.14 < \Delta m^2 < 3.37 \text{ [eV]} \times 10^3 @68\% \]

\[ 1.87 < \Delta m^2 < 3.58 \text{ [eV]} \times 10^3 @90\% \]
Disappearance & Shape

$N_{SK}(\nu_\mu)$

$E_\nu$ shape

Allowed regions from $\nu_\mu$ disappearance and distortion of $E_\nu$ spectrum are consistents
Fit and Data are Consistent

Best likelihood for:
\[ \sin^2 2\theta = 1.51 \]
\[ \Delta m^2 [\text{eV}^2] = 2.19 \times 10^{-3} \]
Prob\{\sin^2 2\theta > 1.5\}\big|_{\text{Best Fit}} = 13\%

Best fit (physical region):
\[ \sin^2 2\theta = 1.00 \]
\[ \Delta m^2 [\text{eV}^2] = 2.79 \times 10^{-3} \]

Expected neutrino interactions at the best fit is 103.8, to be compared with 107 observed.

From LogL differences w.r.t. the best fit:
Prob\{No Oscill\} = 0.0050\% (4.0\sigma) (shape+norm.)
= 0.74\% (2.6\sigma) (shape only)
= 0.26\% (3.0\sigma) (norm. only)
Log Likelihood difference from the minimum

$\Delta \ln L$

$\Delta m^2 [\text{eV}^2]$

$\sin^2 2\theta = 1.00$
- 68%
- 90%
- 99%

$\Delta m^2 = 2.19 \times 10^{-3}$
- 68%
- 90%
- 99%

$\Delta m^2 < (1.87 \sim 3.58) \times 10^{-3} \text{ eV}^2$ at $\sin^2 2\theta = 1.0$ (90% C.L.)
Coherent $\pi$ vs Single $\pi$ Suppression

Color: Coherent-$\pi$ suppression $\rightarrow$ Null Osci. prob. = 0.0044\% (4.08$\sigma$)
Mono: CC-1$\pi$ suppression $\rightarrow$ 0.0050\% (4.06$\sigma$)
Summary

With $8.9 \times 10^{19}$ PoT, K2K confirms atmospheric neutrino oscillation at $4.0\sigma$ (PRL 94:081802, 2005).

- Disappearance of $\nu_\mu$ at $3.0\sigma$
- Distortion of $E_\nu$ spectrum at $2.6\sigma$
Extra Slides
## Syst. Error Contributions to Nsk

<table>
<thead>
<tr>
<th>Error</th>
<th>(relative error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far/Near</td>
<td>+7.7 (+5.1%)</td>
</tr>
<tr>
<td></td>
<td>-7.5 (-5.0%)</td>
</tr>
<tr>
<td>Normalization</td>
<td>+7.6 (+5.0%)</td>
</tr>
<tr>
<td></td>
<td>-7.7 (-5.1%)</td>
</tr>
<tr>
<td>NC/CC-QE, CC-nQE/QE</td>
<td>+0.7 (+0.5%)</td>
</tr>
<tr>
<td></td>
<td>-0.8 (-0.5%)</td>
</tr>
<tr>
<td>ND spectrum</td>
<td>+1.0 (+0.7%)</td>
</tr>
<tr>
<td></td>
<td>-0.9 (-0.6%)</td>
</tr>
</tbody>
</table>
Syst. Error Contributions to Spectrum
Pull of Syst. Parameters in the Fit

![Graph showing pull of systematic parameters for different systematic effects and nuisance parameters.](image-url)
Energy and QE/nonQE

**CC quasi-elastic (QE)**

\[ E_{v}^{\text{rec}} = \frac{(m_{N} - V)E_{\mu} - m_{\mu}^{2}/2 + m_{N}V - V^{2}/2}{(m_{N} - V) - E_{\mu} + p_{\mu} \cos \theta_{\mu}} \]

**non Quasi-Elastic**

\[ q \cos \theta_{\mu} \]