1. Physics goal
2. Experimental principle
3. Status
4. Run plan for fiscal 2004
5. Activities before T2K

Koichiro Nishikawa
for K2K collaboration
Japan
KEK, ICRR, Kobe U, Kyoto U, Niigata U, Okayama U,
Tokyo U of Science, Tohoku U
Korea
Chonnam National U, Dongshin U, Korea U, Seoul National U
U.S.A.
Boston U, U of California (Irvine), U of Hawaii (Manoa), M. I.T.
S UNY at Stony Brook, U of Washington
Poland
Warsaw U, Solton Institute for Nuclear Study
New members since 2002
Hiroshima U., Osaka U.
Canada
TRIUMF, U. of British Columbia
Europe
Institute of Nuclear Study-Moscow
Brief history of K2K

• 1995
  – Proposed to study neutrino oscillation for atmospheric neutrino anomaly.

• 1999
  – Started taking data.

• 2000
  – Detected the less number of neutrinos than the expectation at a distance of 250 km. Disfavored null oscillation at the 2σ level.

• 2002
  – Observed indications of neutrino oscillation. The probability of null oscillation is less than 1%.

• 2003
  – installed new detector (SciBar)

• 2004
  – Confirmed neutrino oscillation with both number of events and spectrum distortion
  – Detail will be presented at KEK seminar (June 9) and will be presented
Principle of K2K

Fixed distance, direction
\(E_\nu \sim 1.3 \text{ GeV}, L=250\text{km}\)
\(99\% \, \nu_\mu, \, \sigma_\tau \ll \sigma_\mu\)

\[
\text{prob.} = \sin^2 2\theta \cdot \sin^2 \left(\frac{1.27 \Delta m^2 \cdot L}{E_\nu}\right)
\]

Observations
- Reduction of events
- Spectrum distortion

Goal
- Does \(\nu_\mu\) decrease?
- Does it depend on \(E_\nu\)?
- What is \(\Delta m^2\)?
- (Is it consistent to \(\sin^2(1/E_\nu)\)?)
Setup and Neutrino beam monitoring
μ-monitor
Front (Near) Detector
direction (π → µ) p_µ > 5 GeV
direction (ν) low E neutrinos
spectrum, rate

12 GeV PS
>5x10^{13} ppp
2.2 sec/pulse

Target/Double Horn
~ 20 x flux

North Counter Hall

Primary beam line
100 m

Front detector
ν_µ

Decay section
(π → µν_µ)
200 m
Total Delivered POT
Jun 1999 - Feb. 15, 2004
101.12x10^{18} \text{ POT}

POT/spill = \sim 5.4 \times 10^{12} \text{ Protons}

K2K thanks to the PS division for great accomplishments
Requirement from MC and muon monitor results (segmented ionization ch. + Si pads)

Neutrino (pion) direction has been controlled within 1 mrad
Near Detectors at KEK

At 300 m from target
1. neutrino beam profile
   • massive MRD
2. $\nu_\text{e}$ contamination
3. rate in KT
   • same response as SK for each interaction
4. spectrum
   • selection of CCQE
5. CCQE nonQE NC
   • PID ($p \rightarrow \pi, \mu$)
   • Low energy particles
6. neutron backgrounds
   • good timing
MRD (419 ton fid.)
Fe & drift tubes

- Profile width beam stability during spill
- Center of beam within 1 mrad
- Stability of $E_\mu$, $\theta_\mu$ weekly/monthly basis
Number of events
Super-Kamiokande

(April 1996 commissioned)

50,000 ton water Cherenkov detector  (22.5 kton  fiducial volume)

Optically separated INNER and OUTER detector
Selection of SK events: $T_{SK}^{GPS} - T_{acc}^{GPS} - TOF$

**K2K-1 Jun 1999 - Jul 2001**

- FC 22.5kt
- 56 events

**K2K-2 Jan 2003 - Feb 2004**

- HE trig.
- FC 22.5kt
- 52 events

No activity in outer SK
Number of Events vs POT
FC 22.5kt

KS probability = 77.7%
### K2K-SK events

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<thead>
<tr>
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<tbody>
<tr>
<td>FC 22.5kt</td>
<td>108</td>
<td>150.9 (79.1, 71.8)</td>
</tr>
<tr>
<td>1ring for $E_{\nu \text{rec}}$</td>
<td>66</td>
<td>93.7 (48.6, 45.1)</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>57</td>
<td>84.8 (44.3, 40.5)</td>
</tr>
<tr>
<td>e-like</td>
<td>9</td>
<td>8.8 (4.3, 4.5)</td>
</tr>
<tr>
<td>Multi Ring</td>
<td>42</td>
<td>57.2 (30.5, 26.7)</td>
</tr>
</tbody>
</table>

Ref: K2K-I($47.9 \times 10^{18}$POT), K2K-II($41.2 \times 10^{18}$POT)
Neutrino spectrum and the far/near ratio

ν beam

ν energy spectrum

@ K2K near detector

Far/Near Ratio

beam MC w/ PION Monitor $10^{-6}$
1KT Flux measurement

- The same detector technology as Super-K. (same response for each interaction)
- Sensitive to low energy neutrinos.

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

\[\equiv \text{Far/Near Ratio (by MC)} \approx 1 \times 10^{-6}\]

**\(M\):** Fiducial mass \(M_{SK}=22,500\text{ton}, M_{KT}=25\text{ton}\)

**\(\varepsilon\):** efficiency \(\varepsilon_{SK-I(II)}=77.0(78.2)\%, \varepsilon_{KT}=74.5\%\)

\[N_{SK}^{\text{expect}}=150.9^{+10.3}_{-9.1} \quad \leftrightarrow \quad N_{SK}^{\text{obs}}=108\]
Spectrum measurement
NEUT: K2K Neutrino interaction MC

• CC quasi elastic (CCQE)
  – Llewellyn Smith’s with $M_A = 1.1\text{GeV}$
• CC (resonance) single $\pi$ (CC-1$\pi$)
  – Rein and Sehgal’s with $M_A = 1.1\text{GeV}$
• DIS
  – GRV94 + JETSET with Bodek and Yang correction.
• CC coherent $\pi$
  – Rein&Sehgal with the cross section rescale by J. Marteau
• NC
  with Nuclear Effect

\[ \frac{\sigma}{E} \left( 10^{-38}\text{cm}^2/\text{GeV} \right) \]

\[ E_\nu \text{ (GeV)} \]
$E_\nu$ reconstruction

$$P = \sin^2 2\theta \cdot \sin \left( \frac{1.27\Delta m^2 \cdot L}{E_\nu} \right)$$

$p,n$ no signal in W-C $E_{\text{had}}$ measurement!

✧ CC QE (1R$_\mu$ in W-Cherenkov)
✧ can reconstruct $E_\nu \leftarrow (\theta_\mu, p_\mu)$

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

✧ CC nQE
✧ Bkg. for $E_\nu$ measurement

✧ NC
Oscillation analysis

1. Obtain \( E_\nu \) flux and spectrum shape just after production \( \phi_{KEK}(E_\nu) \)

\[
\text{Events} = \sum_{i=\text{QE, nonQE, NC}} \sigma_i \times F(E_\nu) \times \varepsilon_i(E_\nu)
\]

\( \sigma(\text{CCQE}), \sigma(1\pi), \text{NC} \) ratios known to \( \sim 30\% \) 1KT to predict \( N_{SK} \)

2. Extrapolate from near to far without oscillation \( \phi_{SK}(E_\nu) \)

3. \( \phi_{SK}(E_\nu) \otimes \text{Oscillation} (\sin^2 2\theta, \Delta m^2) \otimes \text{Int. Model} \)

*Prediction*

\( N_{SK}(\text{exp’t}) : \text{Expected no. of SK events} \)

\( S_{SK}(E_{\text{rec}}) : 1R_\mu \text{ Erecdistribution(shape)} \)

*SK observation*

\( N_{SK}(\text{obs}) \)

1R_\mu E_{\text{rec}} distribution

Maximum Likelihood Fit in \( (\sin^2 2\theta, \Delta m^2) \)
QE and nQE separation in SciFi

SciFi 2 track $\cos(\Delta \Theta_p)$ distribution

- Data
- MC
- (CCQE)

$>30^\circ$  $<25^\circ$

nQElike  QElike
SciBar Detector

start taking data Oct. 7, 2003

- Extruded scintillator with WLS fiber readout
- No dead material
- 2.5 x 1.3 x 300 cm$^3$ cell
- ~15000 channels
- Light yield
  \[ 7\text{~to}20\text{p.e./MIP/cm (2 MeV)} \]
- Detect 10 cm track
- Proton ID by using dE/dx
  - High CC-QE efficiency
  - Low non-QE backgrounds

\[ \pi^0, E_e \text{ measurement} \]
SciBar neutrino interaction study.

- Full Active Fine-Grained detector.
  - Sensitive to a low momentum track.
  - Identify CCQE events and other interactions (non-QE) separately.
Used data for $\phi_{\text{near}}(E\nu)$

**KT**

Fully Contained Fiducial Volume (FCFV) events
- No. of events
  (Evis>100MeV)

(1) Single $\mu$–like events

**SciFi**

(2) 1-track $\mu$ events
(3) 2-track QE-like events
(4) 2-track nonQE-like events

**SciBar**

(5) 1-track $m$ events
(6) 2-track QE-like events
(7) 2-track nonQE-like events

- $\nu$ flux $\phi_{\text{near}}(E\nu)$ (8 bins)
- $\nu$ interaction model ($n\text{QE}/\text{QE}$ ratio as parameter)

norm. ($N_{SK}$) from KT & 7 sets of ($p_\mu$, $\theta_\mu$) distributions
Actual Procedure

\[(p_\mu, \theta_\mu) \rightarrow \phi(E_\nu), \ nQE/QE\]

\[\chi^2 = 638.1 \text{ for 609 d.o.f.}\]

\[\begin{align*}
\text{0-0.5 GeV} & \quad \text{QE (MC)} \\
\text{0.5-0.75 GeV} & \\
\text{0.75-1.0 GeV} & \\
\text{1.0-1.5 GeV} & \\
\end{align*}\]

E_\nu \quad \text{MC templates}

DATA

eight 2-dimensional hist’s
Flux measurements

\( \chi^2 = 638.1 \) for 609 d.o.f

- \( \Phi_1 (E_\nu < 500) = 0.78 \pm 0.36 \)
- \( \Phi_2 (500 \leq E_\nu < 750) = 1.01 \pm 0.09 \)
- \( \Phi_3 (750 \leq E_\nu < 1000) = 1.12 \pm 0.07 \)
- \( \Phi_4 (1500 \leq E_\nu < 2000) = 0.90 \pm 0.04 \)
- \( \Phi_5 (2000 \leq E_\nu < 2500) = 1.07 \pm 0.06 \)
- \( \Phi_5 (2500 \leq E_\nu < 3000) = 1.33 \pm 0.17 \)
- \( \Phi_6 (3000 \leq E_\nu ) = 1.04 \pm 0.18 \)
- \( nQE/QE = 1.02 \pm 0.10 \)

The \( nQE/QE \) error is assigned based on the variation by the fit condition.

\( \forall \theta > 10^\circ \) cut: \( nQE/QE = 0.95 \pm 0.04 \)

- standard(CC-1\( \pi \) low \( q^2 \) corr.): \( nQE/QE = 1.02 \pm 0.03 \)
- No coherent: \( \pi = nQE/QE = 1.06 \pm 0.03 \)
SciBar (with measured flux) 
(also for KT, SciFi)
Observed spectrum shape and null oscillation prediction

Null oscillation normalized by observed number of events
Other Physics in K2K (based on K2K-I data)

\[ \nu_\mu + H_2O \rightarrow NC1\pi^0 \]

\[ \sigma(\nu_\mu \rightarrow NC1\pi^0) / \sigma(\nu_\mu \rightarrow CCall) = 0.065 \pm 0.001 \text{(stat.)} \pm 0.007 \text{(sys.)} = 0.064 \text{ (MC prediction)} \]

Preliminary

\[ \nu_\mu \rightarrow \nu_e \text{ search} \]

90\%CL limit

90\%CL sensitivity

PRL accepted
Near future
1. Systematic errors
   – Far Near ratio $+5.6 \pm 7.3\%$
     • $\pi$ production measurements should be available soon
   – $N_{SK}$ from 1kton detector 5% (fiducial)

Run plan for 2004
• More data in SciBar (Proton ID, low-E track)
  ~20,000 total events (1,500 CCQE <1 GeV ) ~4 months
  Determine neutrino interaction model
  – Can use 2 ring events in SK( in addition to 1R$\mu$ like events) almost double the statistics
  – SciBar can determine normalization with small fid. error, and spectrum
• Low energy neutrino interaction studies
  – determine background in low $E^{rec}$
  – ……….
• Anti neutrino (engineering run)
Status of proton ID in SciBar

Range vs Total deposit energy

DATA

Proton-like
(2track QE sample)

Mu-like
(MRD3D)

P/π identification is performed using dE/dx info.
Spectrum measurement at low energy w/ exclusive reconstruction

Currently total ~1250 CC-QE candidates with ~70% purity + short track (wo MRD) + proton ID

*Efficiency for low-energy events will be improved (x 2) x2 more data ~200 events <1GeV → ~1000 events
More data in SciBar

Level of nonQE background to low $E_{\nu}^{\text{rec}}$?
A hint of K2K forward $\mu$ deficit.

K2K observed forward $\mu$ deficit.

– A source is non-QE events.
– For CC-1$\pi$,
  • Suppression of $\sim q^2/0.1[\text{GeV}^2]$ at $q^2<0.1[\text{GeV}^2]$ may exist.
– For CC-coherent $\pi$,
  • The coherent $\pi$ may not exist.

We do not identify which process causes the effect. The MC CC-1$\pi$ (coherent $\pi$) model is corrected phenomelogically.

Oscillation analysis is insensitive to the choice.
Anti-neutrinos

- **On paper**, just flipping the polarity of horn.
  Need actual testing
- Geomagnetic effect to the beam
- Scibar
  - \(\sim 400 \text{ int} / 10\text{days} / 10\text{ton}\)
- MRD
  - \(\sim 15,000 \text{ int} / 10\text{days} / 419 \text{ ton}\)
  - Error in
  - Beam center: 7cm
  - width: 10cm
## Activities before T2K

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<th>Fiscal yr</th>
<th>2004</th>
<th>2005</th>
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<th>2007</th>
<th>2008</th>
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<td>K2K data taking</td>
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<td>Full paper on oscillation incl. ve</td>
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<td>Analysis of neutrino interactions</td>
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<td>SK full rebuild</td>
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<td>SK analysis tool</td>
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<td>T2K construction and commissioning</td>
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Summary

• K2K Oscillation analysis on June 99 ~Feb 04 data

1. Long baseline experimental method is working well
2. We observed $\nu_\mu$ deficiency and spectrum distortion over 250 km flight length
3. $\sin^2 2\theta$, $\Delta m^2$ are consistent with atmospheric neutrino results

For detail please attend the KEK seminar day after tomorrow

• In 2004, at least 6 months run can improve the quality of K2K
• More data in SciBar (at least four more months) can further improve statistical significance of K2K results
• More measurement of low energy neutrino interactions can be done