Reasons for & Results of the $K2K$ Long-Baseline Neutrino Oscillation Experiment

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Apr., 2002.
**Beta decay c.1930**

*Is it a 2-body process?*

Energy observed

Expected counts detected
Beta decay c.1930

Is it a 2–body process?
–but perhaps our resolution is really bad?
**Beta decay c.1930**

- Is it a 2–body process?
- But perhaps our resolution is really bad?

- Or a 3–body process with a 'hidden partner'?
If this is possible:
If this is possible:

This should also be possible:
Detection of the Neutrino: Experimental Evidence for its Existence

The mid-1950’s ‘discovery’ experiment:
Contrast the scale of the state of the art in 1996

Same photo as previous, approximately to scale
Through the decades...

- 1962: *There is a second type of neutrino!*
- 1977: *...and probably a third!*
- 1968: Neutrinos from the sun are detected.
- 1970’s: “Atmospheric neutrinos” from the sky are detected.
- 1985: *Atmospheric neutrinos are seeming to behave rather strangely...*
- 1987: *Neutrinos from a supernova are detected!*
- 1999: *The tau neutrino is finally detected!*
Two predictions for atmospheric neutrinos:

The ratio of mu-type to e-type is predictable and approximately 2

The flux on the earth is up/down symmetric
Atmospheric Neutrinos in the early 1990’s

- Water Čerenkov detectors measure an anomalous ratio of electron and muon neutrinos
- Their directional distributions show low-statistics hints of an up/down asymmetry
- Iron calorimeters have failed to see the effect, albeit with very poor statistics
- Super-Kamiokande, a truly huge new detector, is proposed to resolve the situation
- A beam test shows that water Čerenkov detectors can indeed do particle identification.
- Iron calorimeters continue operation to explore the apparent difference
‘...and by now we know all about neutrino oscillations...’

Recent Atmospheric evidence:

The ultimate goal:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
M_{1,e} & M_{2,e} & M_{3,e} \\
M_{1,\mu} & M_{2,\mu} & M_{3,\mu} \\
M_{1,\tau} & M_{2,\tau} & M_{3,\tau}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\]

Solar, reactor analyses Atm., K2K analyses terms probed by new experiments
The K2K Collaboration:

Approximately 100 physicists from Korea, Japan, the U.S., & Poland
(18 institutions)
The Conceptual Lay–out of the Experiment

Nearby neutrino detector

Far detector, Super–Kamiokande
The Far Detector, Super-Kamiokande
**K2K post-construction views**

12 GeV protons

Nearby neutrino detector

(T​hese & more available at https://neutrino.kek.jp/)
Check in the beamline. Do we really understand our beam?

Using gas–Cerenkov data:

**Light distribution in data and MC**

![Data vs. MC comparison graphs](image)

**Near/far ratios fit and MC**

![Near/far ratios graphs](image)

**Neutrino spectra fit and MC**

![Neutrino spectra graphs](image)
Now check that the beam is stable.

The MRD (Our Iron Range Stack)

Neutrino beam aiming

CC-Interaction Rate

Calendar time (1 data point / 5 days)

Calendar time (1 data point / 2 days)
**The Water Cherenkov Spectral Measurement**

Assuming quasi-elastic kinematics:

\[
P_{\nu} = \frac{m_n^2 + m_\mu^2 - m_p^2 - 2m_nE_\mu}{2(E_\mu - m_n - P_\mu \cos(\theta))}
\]

Reconstructed muon information:

- $P_\mu$ (GeV/c)
- $\theta_\mu$ (degrees)

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

- DATA
- MC
K2K Fine-Grained Detector

Run  2279 Spill  18568 TRGID   1
  100  1 24 14 21 23  0
Nvtx  0

Top View

Side View
Measuring the Backgrounds with 2–Track Events

Neutrino direction

Expected proton direction in Q.E.

Measured muon direction

\[ \Delta(\theta) \]

\[ \text{Meas. 2nd track} \]

\[ \text{Nv99–J101/N4.3 XFSI} \]

\[ \text{Entries} \quad 2218 \]

\[ \text{Mean} \quad 0.6676 \]

\[ \text{RMS} \quad 0.3590 \]
**Data Reduction for SK K2K Events**

\[
\Delta t \equiv T_{SK} - T_{KEK} - \text{time of flight}
\]

- Event is not a decay electron
- Total PMT charge cut
- Vertex in fid. volume & No OD activity

(90 total Contained events)

56 in fiducial 22.5ktons

Background \( \approx \mathcal{O}(10^{-3}) \)
<table>
<thead>
<tr>
<th>Event Class</th>
<th>Observed</th>
<th>Expected No osc.</th>
<th>Expected $\Delta(m^2)$[eV$^2$] =</th>
</tr>
</thead>
<tbody>
<tr>
<td>in FV</td>
<td>56</td>
<td>80.6±0.3$^{+7.3}_{-8.0}$</td>
<td>3 · 10$^{-3}$ 5 · 10$^{-3}$ 7 · 10$^{-3}$</td>
</tr>
<tr>
<td>1-ring</td>
<td>32</td>
<td>48.4±6.7</td>
<td>28 18 17</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>30</td>
<td>44.0±6.8</td>
<td>24 15 14</td>
</tr>
<tr>
<td>e-like</td>
<td>2</td>
<td>4.4±1.7</td>
<td>4 3 3</td>
</tr>
<tr>
<td>&gt;1-ring</td>
<td>24</td>
<td>32.2±5.3</td>
<td>24 17 13</td>
</tr>
</tbody>
</table>
Systematic Error Estimation

For the near detector (Water Cherenkov) overall flux estimation:
- Stat. error is very small
- Leading term is from **systematic vertex fit shifts**
  - Sum of known systematics  \( \pm 5\% \)

For the extrapolation from near measurement to far expectation:
- Error can be estimated two ways:
  - MC study only (with monitor inputs)  \( \pm 7\% \)
  - Monitor based study (with some MC input)
    - Leading terms come basically from **lack of knowledge of the pion kinematic distribution** after production.
    \( +6\% -7\% \)

For the event rate estimation at SK:
- Leading term is from **systematic vertex fit shifts**, but fractionally smaller due to large fiducial volume size.
  - Sum of known systematics  \( \pm 3\% \)

\( \Rightarrow \) Total estimated error on final prediction:

\[ \pm 9\% -10\% \]
Oscillation Analysis

- **Comparison to no oscillations hypothesis**

- **Overall rate analysis**

- **Spectral shape analysis**

- **Combined analysis of all information**
Probability for no-oscillations

A hypothesis that \(a \textit{ priori}\) predicts a central value expected to be higher than any competing scenarios is disfavored at a confidence level given by:

\[
C.L. \equiv 1 - \int_0^\infty \left( e^{-\lambda} \sum_{i=0}^{N_\Omega} \frac{\lambda^i}{i!} \right) \times \mathcal{P}(\lambda) d\lambda
\]

\textit{where}: \(N_\Omega\) is the number observed, and \(\mathcal{P}(\lambda) \approx \left(\sigma_L \sqrt{2\pi}\right)^{-1} e^{-\frac{1}{2} \left(\frac{\lambda - \mu}{\sigma_{\text{syst}}}\right)^2}\) for an expectation of \(\mu\) with a gaussian systematic error of \(\sigma_{\text{syst}}\).

This “one-tail integral” gives a probability of < 3%
Overall Rate Analysis

The two-tailed integral

\[ 1 - \text{erf} \left( \frac{|N_{\text{Obs}} - N_{\text{Exp}}|}{\sqrt{2} \sigma} \right) \]

This is more conservative than the "no-oscillations case" already cited.
$E_\nu$ F.C. 22.5kt 1-ring $\mu$-like

- no osci.
- $\Delta m^2 = 3 \times 10^{-3} \text{eV}^2$
(Preliminary)

work-in-progress
Spectra as probability density functions

(Sensitive region plot)
Non-oscillation parameters to be fit

→ **Regarding the beam:**
  - Parameters of pion production (“Sanford-Wang parameters”)
  - Beam aiming accuracy
  - K/π production ratio

→ **Regarding the neutrino interaction model and detectors:**
  - NC/CC ratio
  - “QE/non-QE ratio” (CC only)
  - Detector energy scales
Input information for fitting

- Near detector reconstructed $P_{\mu}, \theta_{\mu}$ distributions
- Near detector reconstructed “$\pi^0/\mu$ ratio” from the 1kt
- Near detector reconstructed “non-Q.E./Q.E. ratio” from the FGD
- (Fitted data from) Beamline pion kinematic measurement
- “Constraint terms” from previous knowledge of parameters

- ...and of course SK reconstructed $P_{\nu}$ spectrum (assuming q.e. kinematics)
Conclusions & Plans for the Near Future

- 1/2 of our anticipated $10^{20}$ protons on target have been collected and analysed.

- The probability that the no-oscillations scenario would give this result because of a statistical fluctuation is <3%.

- We are making significant progress on spectral analysis, so...
Conclusions & Plans for the Near Future

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Expect big things this summer!
The Longer Range Future:

- SK expects to finish rebuilding early next year.
- K2K will resume data taking at that time.
- Experiments at FNAL–Soudan (MINOS) and CERN–Gran Sasso will refine the measurements.
- Later plans at the Japan Hadron Facility will investigate other mixing matrix elements.
- ‘Neutrino factory’ to explore CP violation and refine measurements.
The first 6 FC SK-K2K events in the 2000 run
candidates found by the (almost) realtime monitor
Spatial uniformity of K2K’s far detector (SK) contained events

X–Y vertex position & track momentum

X–Z vertex position & track momentum

Muon momentum scale:

0 2 GeV

beam direction

beam direction
**Arrival Times of Events**

**Fine scale timing relative to beam:**

Relative timing distribution for events

- Data (box = stat. err.)
- Idealized model (normalized to data)

**Overall arrival time through all runs**

*Fully Contained, 22.5kt*

Data vs POT

KS probability = 43.1%
The Sanford-Wang Parameterization for Secondary Beam Kinematics:

\[
E \times \left( \frac{d^3 \sigma}{dp^3} \right) \text{(mbarns/GeV}^2) = \sigma_{total} \mathcal{W}_1 P_\pi^{\mathcal{W}_2} \left(1 - \frac{P_\pi}{P_p}\right) \\
\times e^{-\left(\mathcal{W}_3 P_\pi^{\mathcal{W}_4} / P_p^{\mathcal{W}_5}\right)} \\
\times e^{-\left(\mathcal{W}_6 \theta_\pi \left(P_\pi - \mathcal{W}_7 P_p \cos \theta_\pi \right)^{\mathcal{W}_8}\right)}
\]

for a proton beam of \( P_p \text{(GeV/c) to produce pions at } P_\pi, \theta_\pi \)

Note that \( \mathcal{W}_1 \) is just a normalization, and all the information of \( \mathcal{W}_3 \) is redundant with \( \mathcal{W}_5 \) for a beam of fixed momentum.
Detector Status in January, 2001
• On November 12, 2001 a PMT in Super–Kamiokande imploded.

• This set off a chain reaction destroying many other phototubes.

• 6777 inner- and 1160 outer-detector PMTs are destroyed.
Currently down but...

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- This set off a chain reaction destroying many other phototubes.

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**We plan to have the detector operational later this year.**

A complete rebuild will be done around 2005-2007.