NEW RESULTS FROM K2K

T. Ishii (for the K2K Collaboration)
Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract
During the first half of the K2K run, data corresponding to $4.8 \times 10^{19}$ POT were accumulated. In this data set, 56 accelerator-produced neutrino events were observed in the far detector, while the expected number from the near site measurements is $80.6^{+7.3}_{-8.0}$. This means that the probability of the null-oscillation scenario is limited to less than 3%. A method for long-baseline neutrino experiments has been established.

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1 Introduction

K2K\(^\text{1}\) is the first accelerator-based long-baseline neutrino experiment, of which the baseline is 250 km between the KEK 12-GeV proton synchrotron (KEK-PS) and the Super-Kamiokande (SK) detector. The atmospheric neutrino anomaly found by the Kamiokande experiment\(^\text{2}\) triggered various studies of neutrino oscillation in the region \(\Delta m^2 \approx 10^{-2} - 10^{-3}\text{eV}^2\), where \(\Delta m^2\) is the difference of the squared masses. Among them, the SK experiment\(^\text{3}\) confirmed the deficit of the upward-going atmospheric \(\nu_\mu\)'s and announced evidence for oscillation of the atmospheric neutrino. For the neutrino energy \((E_\nu(\text{GeV}))\) and flight length \((L(\text{km}))\), the oscillation probability can be written in terms of the mixing angle \((\theta)\) and \(\Delta m^2\) in a two-flavor approximation as follows:

\[
P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta \cdot \sin^2 \frac{1.27\Delta m^2 \cdot L}{E_\nu}.
\]

K2K aims to firmly establish neutrino oscillation in the \(\nu_\mu\)-disappearance mode and in the \(\nu_e\)-appearance mode, with a well-defined flight length and a well-controlled and understood nearly pure \(\nu_\mu\) beam. The average neutrino energy is 1.3 GeV and the beam composition is 98.2\%\(\nu_\mu\), 1.3\%\(\nu_e\) and 0.5\%\(\bar{\nu}_\mu\).

2 Detectors

At the near site, 12-GeV protons are extracted from the KEK-PS in a 1.1-\(\mu\)sec spill every 2.2 seconds. The extracted protons are bent to the Kamioka direction and injected into an Al target of a 30 mm diameter and 66 cm length. A pair of horn magnets focuses produced positive pions, which subsequently decay into muons and \(\nu_\mu\)'s.

A pion monitor is occasionally put into the beam line just after the horn magnets. The pion monitor is a gas-Cherenkov detector, which measures the momentum and angular distributions of pions. From this measurement, it gives the far/near ratio of the neutrino flux as a function of the neutrino energy. A measurement is made when the beam parameters are changed.\(^\text{4}\)

A muon monitor is located after a 200 m decay pipe and a beam dump. The muon monitor consists of a segmented ionization chamber and a silicon pad detector array. It provides spill-by-spill monitoring of the intensity and direction of the beam.

A set of near neutrino detectors is located 300 m from the target. It consists of a 1kton-water-Cherenkov detector (1kt), a scintillating fiber tracker with a water target (SCIFI),\(^\text{5}\) lead-glass counters and a muon range detector (MRD).\(^\text{6}\) The
1kt is used to measure the neutrino flux at the near site to normalize the event rate at the far site while taking advantage of being the same type detector as the SK. Since the MRD is massive and has large-area coverage, it is used to monitor the neutrino beam. The SCIFI together with the MRD is used to study neutrino interactions.

K2K uses the SK as a far neutrino detector. It is a 50 kton water-Cherenkov detector comprising 11 thousand inner PMTs and 18 hundred outer PMTs.

3 New results

3.1 Delivered beam

Fig. 1 shows the delivered protons on the target (POT) as a function of time. The top plot shows the integrated POT and the bottom plot shows the instantaneous POT. The instantaneous POT has nearly reached its design value of $6 \times 10^{12}$ protons/pulse. Data corresponding to $4.8 \times 10^{19}$ POT are used for analyses, which were accumulated during the period between June 1999 and July 2001. The goal is to accumulate $10^{20}$ POT for analyses.

![Delivered Protons on Target (POT)](image)

Figure 1: (top) Integrated protons on the target; (bottom) Instantaneous protons on the target.
3.2 Beam stability

The neutrino beam direction has been monitored by the MRD by watching the neutrino profile center using $\nu_\mu$ interactions with iron. As shown in fig. 2, the neutrino beam has been directed to the SK detector within $\pm 1\text{mrad}$. It has also been confirmed pulse-by-pulse by the muon monitor by watching the muon profile center. This is sufficient direction stability for the experiment. The MRD has also monitored the neutrino event rate, and shows good stability. Fig. 3 shows the energy and angular distributions of muons produced by the charged-current $\nu_\mu$ interaction, which were measured by the MRD and plotted monthly. Both energy and angular distributions show good stability, which implies that the neutrino spectrum has been stable.

![Figure 2: Stability of the neutrino profile center. The dashed lines show $\pm 1\text{mrad}$ directions to SK. (top) Horizontal direction; (bottom) Vertical direction.](image-url)
3.3 SK events

Accelerator-produced neutrino events at the SK detector are selected essentially using the timing information of the global positioning system (GPS). Other selection cuts are the same as the atmospheric neutrino analysis. Fig. 4 shows the time-difference distribution between the beam spill start and the SK event occurrence after each selection cut. After all cuts we can see a bunch of events in the 1.1μsec range, which corresponds to the beam spill length. In the fiducial volume of 22.5 kton, 56 fully contained events were observed, which breaks down into 30 single-ring μ-like events, 2 single-ring e-like events and 24 multi-ring events. Fig. 5(left) shows the SK event number as a function of the accumulated POT. Fig. 5(right) shows the distribution of the interval between two consecutive events. It fits to an exponential shape quite well, as expected. This means that the fluctuation of the event rate is statistical.

3.4 Results from event numbers

A summary of the results is listed in table 1. We observed 56 SK events, while the expectation from the 1kt measurement extrapolated by the pion monitor measure-
Figure 4: (top) Time-difference distribution between the beam-spill start and the SK event occurrence after each selection cut: (unfilled histogram) no detector pre-activity, (hatched) more than 200 photoelectrons in 300nsec and (shaded) all cuts except timing; (bottom) Time-difference distribution after all cuts in a ±5μsec range.

Figure 5: (left) SK event number vs. POT; (right) Interval distribution between two consecutive events. The line shows the result of the exponential fit.
Table 1: Summary of the observed and expected numbers of events.

|                  | observed | expected w/o osci | $\Delta m^2 = 3 \times 10^{-3}$ |
|------------------|----------|------------------|---------------------------------|
| 1-ring $\mu$-like | 30       | 44.0 ± 6.8       | 24.4                            |
| 1-ring e-like    | 2        | 4.4 ± 1.7        | 3.7                             |
| multi-ring       | 24       | 32.2 ± 5.3       | 24.3                            |
| total            | 56       | 80.6^{+7.3}_{-8.0} | 52.4                           |

ment is $80.6^{+7.3}_{-8.0}$. This means that the probability of the null-oscillation scenario is less than 3%.

We observed 2 single-ring e-like events at SK. This is consistent with the Monte-Carlo expectation, suggesting that these events are from the neutral-current $\nu_\mu$ interaction with water.

3.5 Spectrum analysis

For a quasi-elastic event, $\nu_\mu + n \rightarrow \mu^- + p$, one can calculate the neutrino energy from the muon energy and angle by the following equation:

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu}.$$  \( (2) \)

For SK events, in order to enhance the quasi-elastic events, we select single-ring $\mu$-like events. Fig. 6 shows the muon momentum and angular distributions. Fig. 7 shows the reconstructed $E_\nu$ distribution calculated by equation 2. The histograms in the figures show the tentative Monte-Carlo calculation assuming no oscillation. A derivation of the spectrum expectation from the near-site measurements is under way while taking into account of the correct error correlation and the ambiguity of the neutrino interaction.

4 Near-detector upgrade

If $\Delta m^2 \approx 3 \times 10^{-3}$eV$^2$, as is indicated by atmospheric neutrino analyses, the first oscillation minimum appears at around $E_\nu \approx 0.6$GeV in the K2K experiment. It is desirable to monitor the neutrino energy spectrum down to this low-energy region at the near site. For this purpose, we are going to install a full-active scintillator-bar tracker (SCIBAR). SCIBAR will replace the lead-glass counters. As shown in fig. 8, the detector is made of fine segmented scintillator bars. It can detect a proton down to 350 MeV/c. Protons can be identified by a dE/dx measurement.
Figure 6: (left) Muon momentum of single-ring $\mu$-like events; (right) Muon angle with respect to the KEK direction of single-ring $\mu$-like events.

Figure 7: Reconstructed neutrino energy of single-ring $\mu$-like events.
Figure 8: Scintillator-bar detector (SCIBAR) to be installed.

5 Run plan

In order to firmly establish neutrino oscillation, K2K will accumulate $10^{20}$ POT, which corresponds to additional 18-month runs. In spite of the unfortunate accident of November 2001, the SK detector is being rebuilt while aiming at a restart within one year. The upgraded detector SCIBAR will be ready by the summer of 2003.

6 Conclusion

During the first half of the K2K run until summer 2001, data corresponding to $4.8 \times 10^{19}$ POT were accumulated for analyses. In this data set, 56 accelerator-produced neutrino events were observed in the far detector, while the expected number from the near site measurements is $80.6^{+7.3}_{-8.0}$. This means that the probability of the null-oscillation scenario is limited to less than 3%.

We can declare that a method for long-baseline neutrino experiments has been established. Namely, beam monitoring and handling towards the detector 250 km away, synchronization of the far detector with the accelerator by the GPS and spectrum and flux extrapolation from the near site to the far site.
An oscillation analysis by studying near and far spectra is under way.

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