Recent K2K Results *†

Takanobu ISHII

(for the K2K Collaboration)

KEK/IPNS, 1-1 Oho, Tsukuba, Ibaraki, JAPAN

E-mail: takanobu.ishii@kek.jp ‡

The disappearance of $\nu_\mu$ was studied using the K2K-I dataset, which was taken before July, 2001. We observed indications of neutrino oscillation. The resultant oscillation-parameter region was consistent with the atmospheric neutrino result. The appearance of $\nu_e$ was searched for in the same dataset. No excess was found over the expected background.

1 Introduction

K2K[1] (KEK to Kamioka long-baseline neutrino experiment) is the first accelerator-based long-baseline neutrino experiment to investigate the neutrino oscillation observed in atmospheric neutrinos.[2] K2K intends to confirm the $\nu_\mu$ disappearance by observing a reduction of $\nu_\mu$ events and a distortion of the $E_\nu$ spectrum, and to search for the appearance of $\nu_e$.

2 Beam and Detectors

For neutrino-beam production, 12-GeV protons from the KEK proton synchrotron (PS) are extracted in a 1.1$\mu$s spill every 2.2 seconds. The proton beam is bent to the Kamioka direction, and hits an aluminum target embedded in the first horn. A pair of horn magnets focuses positively charged particles, mainly positive pions produced in the proton-aluminum interaction. A pion monitor[3] is occasionally put downstream of the 2nd horn in order to measure the direction and momentum of the pions. The positive pions decay into $\mu^+$ and $\nu_\mu$ during their flight in a 200-m decay pipe. The $\nu_\mu$ is used for the experiment. The beam is monitored by a muon monitor pulse-by-pulse by measuring the muons from $\pi$ decay. The neutrino beam, itself, is monitored by a near detector system located 300 m from the target.

The near detector system consists of a 1-kiloton water cherenkov detector (1KT), a scintillation fiber detector (SCIFI),[4] a muon range detector (MRD)[5] and originally a

*KEK Preprint 2004-22
†Talk presented at the 5th Workshop on Neutrino Oscillations and their Origin (NOON2004), Tokyo, Japan, February 11-15, 2004
‡Partially supported by the Grants for Scientific Research of Monkasho.
lead-glass detector, which was replaced with a new scintillator-bar detector (SCIBAR) last summer.

K2K uses Super-Kamiokande (SK) as the far detector, which is located at 250 km away.

As for the data-taking period, before the SK restoration we call it K2K-I and after SK restoration it is called K2K-II. K2K-II started in December, 2002. SCIBAR was installed after half-year running of K2K-II.

3 Data accumulation and data quality

Even during the K2K-II period, we have been accumulating data smoothly. The delivered protons on target (POT) reached $9.5 \times 10^{19}$ at the end of the year 2003.

![Figure 1: (left): Stability of the muon-energy distribution plotted every month. (right): Stability of the muon-angle distribution plotted every month.](image)

Figure 2: (top): $\Delta T$ distribution after each cut. (bottom): Expanded $\Delta T$ distribution for the final sample.

The neutrino direction is stable within 1 mrad for the entire experimental period, which has been monitored by MRD. According a beam Monte Carlo simulation, the neutrino flux at SK does not change by more than 1%, even in a beam direction shifted by 3 mrad. The
neutrino spectrum was measured by the pion monitor at the beginning. The spectrum stability has been confirmed by measurements of the energy and angle of muons produced by the charged-current interactions in the MRD. Fig. 1 shows the stability of the muon energy spectrum and the muon angle plotted monthly.

SK events generated by the K2K neutrinos are selected in the same way as in the atmospheric neutrino analysis. Fig. 2 shows the remaining events after each cut as a function of $\Delta T$. $\Delta T$ is the difference of the GPS time stamps between the SK event and the beam spill time. In this figure, the data sample of June’99 to April’03 is plotted, namely K2K-I plus part of K2K-II. We observe 72 events in the 1.5 $\mu$s time window. The expected atmospheric neutrino background in this time window is about $2 \times 10^{-3}$ events. The selected 72 events are plotted as a function of POT in Fig. 3 (left). During the K2K-II period, the event rate seems to be the same as that of K2K-I. Fig. 3 (right) shows the event-gap distribution of each consecutive event. It fits to an exponential shape quite well, as expected. This means that the fluctuation of the event rate is statistical.

\section{Oscillation analysis}

For an oscillation analysis of $\nu_\mu$ disappearance,[6] we use both the number of events and the spectrum shape distortion in the K2K-I dataset. For the spectrum analysis, first we deduced the spectrum at the near site using the 1KT and SCIFI data. The pion monitor data was used to constrain the fit and also to extrapolate the near spectrum to the far spectrum.

For 1KT, single-ring $\mu$-like events are used to enrich charged current quasi-elastic (QE) events. Since SCIFI has a good tracking ability, we use both 1-track and 2-track events. The momentum distributions of the 1KT single-ring $\mu$-like events and the SCIFI 1-track events are plotted in Fig. 4. For the SCIFI 2-track events, as is shown in Fig. 5, we can enrich the QE or non-QE by looking at the $\Delta \theta_p$ distribution, where $\Delta \theta_p$ is the difference of the 2nd-track angle measured and the angle calculated from the 1st track assuming QE kinematics. The
Figure 4: (left): Momentum distribution of the 1-ring $\mu$-like events in 1KT. (right): Momentum distribution of the 1-track events in SCIFI which has a corresponding track in MRD. The crosses are data and the boxes are MC with the best-fit parameters.

Figure 5: (left): Cosine of $\Delta \theta_p$. (top right): SCIFI $p_\mu$ distribution for the QE enriched sample. (bottom right): SCIFI $p_\mu$ distribution for the non-QE enriched sample. The crosses are data and the boxes are MC with the best-fit parameters. The hatched histogram shows the QE events estimated by MC.

Events with $\Delta \theta_p < 25$ deg are used as the QE enriched sample and those with $\Delta \theta_p > 30$ deg are used as the non-QE enriched sample. These 4 event categories are fit simultaneously. The fitting parameters are 8 $E_\nu$ bins and non-QE/QE ratio. After the fit, the agreement between data and MC looks good for all the categories.

The result for the $E_\nu$ spectrum at the near site is given in Fig. 6 compared with the beam MC.

We observed 56 events at SK in the K2K-I dataset, while the expectation from the near site measurement is $80.1^{+6.2}_{-5.4}$. Figure 7 (left) is the reconstructed $E_\nu$ distribution of the single ring $\mu$-like events at SK compared with the expectation from the near site measurement. From an analysis using both the number of events and the spectrum shape, the null oscillation probability is less than 1%. Fig. 7 (right) shows the resultant allowed parameter region.
5 Search for $\nu_e$ appearance

Appearance of $\nu_e$ is searched for[7] in the K2K-I dataset. We selected fully contained single ring, e-like events using the ring pattern and the opening angle. Then, the visible-energy cut and the decay-electron cut were placed. Fig. 8 (left) shows the PID likelihood distributions.

Table 1 gives a reduction summary. We have obtained 56 fully contained events at SK. After the selections, only 1 event remains. The main background comes from the $\nu_\mu$ interactions, of which the neutral-current $\pi^0$ production is dominant. We have encountered about 1% $\nu_e$ contamination in the $\nu_\mu$ beam, which also becomes the background. The observed 1 event is consistent with the expected background. The result of $\nu_e$ appearance is drawn in Fig. 8 (right). The excluded region is given by the K2K. The dotted line is the CHOOZ excluded region, which measured the $\bar{\nu}_e$ disappearance. The CHOOZ result was converted into $\sin^22\theta_{\mu e}$, assuming full mixing in the 2-3 sector.
Figure 8: (left): PID likelihood distributions. The top figure is based on the ring pattern and the bottom figure is based on the opening angle. The solid histogram is $\nu_\mu$ MC and the shaded area is the neutral-current component of the $\nu_\mu$ MC. The dotted histogram is the signal $\nu_e$ MC, assuming $\sin^2 2\theta_{\mu e} = 1$ and $\Delta m^2 = 2.8 \times 10^{-3} eV^2$. (right): Excluded $\nu_\mu \rightarrow \nu_e$ oscillation parameter regions.

Figure 9: Example of a SCIBAR event. The size of each point shows the pulse height of each scintillator bar. The left figure is a top view and the right one is a side view.

6 New near detector SCIBAR

In order to explore the low-energy region, a new near detector, SCIBAR, was installed during the summer of 2003. SCIBAR consists of 15,000 scintillator bars read out by the WLS fibers. Fig. 9 shows an example of a SCIBAR event.

7 Summary

The K2K-I data set has been analyzed. The reduction of the $\nu_\mu$ flux together with a distortion of the energy spectrum was observed. The probability that the measurements at SK can be explained by statistical fluctuation is less than 1%. The fitted oscillation parameters are consistent with those suggested by atmospheric neutrinos. The appearance of $\nu_e$ has been
searched for. One candidate event has been found, which is consistent with the background. An excluded region is set for the $\nu_\mu \to \nu_e$ oscillation. K2K-II data taking is going on smoothly. The event rate is consistent with K2K-I. The new near detector SCIBAR is working well. Low-energy neutrino data is coming.

References

[1] K2K Collaboration, S.H.Ahn et al., Phys. Lett. B 511, 178 (2001); T.Ishii, in the Proc. of the 16th Les Rencontres de Physique de la Vallee d’Aoste La Thuile, Aosta Valley, Italy, March 3-9 (2002).

[2] Super-Kamiokande Collaboration, Y.Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998).

[3] T.Maruyama, Ph.D. Thesis, Tohoku University (2000).

[4] K2K Collaboration, A.Suzuki et al., Nucl. Instr. and Meth. A 453, 165 (2000).

[5] K2K MRD Group, T.Ishii et al., Nucl. Instr. and Meth. A 482, 244 (2002).

[6] K2K Collaboration, M.H.Ahn et al., Phys. Rev. Lett. 90, 041801 (2003).

[7] K2K Collaboration, M.H.Ahn et al., hep-ex/0402017.
Table 1: Reduction summary of the $\nu_e$ appearance search. $\nu_\mu$ MC shows the background from misidentified $\nu_\mu$ interactions, assuming that no oscillation exists. The last column is the expected signal, assuming $sin^22\theta_{\mu e} = 1$, and $\Delta m^2 = 2.8 \times 10^{-3}eV^2$.

| Data          | $\nu_\mu$ MC | Beam $\nu_e$ MC | Signal $\nu_e$ MC(CC) |
|---------------|--------------|-----------------|-----------------------|
| FCFV          | 56           | 80              | 0.82                  | 28                     |
| Single ring   | 32           | 50              | 0.48                  | 20                     |
| PID(e-like)   | 1            | 2.9             | 0.42                  | 18                     |
| $E_{vis} 100MeV$ | 1        | 2.6             | 0.41                  | 18                     |
| w/o decay-e  | 1            | 2.0             | 0.35                  | 16                     |