1 K2K Experiment

K2K (KEK PS-E362) is the first accelerator-based long-baseline neutrino oscillation experiment from KEK to Kamioka. The main physics goal of K2K is to confirm $\nu_\mu \rightarrow \nu_\tau$ oscillation discovered in atmospheric neutrinos. In addition, K2K has rich physics to study the other oscillation channel, such as $\nu_\mu \rightarrow \nu_e$ appearance, and neutrino-nucleus interactions in the few GeV region. In 2004, the evidence of neutrino oscillation: the energy-dependent disappearance of muon neutrinos is published. The result is one of the most important physics goals in K2K, and is described in in this report.

An intense muon neutrino beam is produced at KEK-PS, and the beam is detected at Super-Kamiokande (SK) after traveling 250 km. K2K started data taking in June 1999 and finished in November 2004 with 9.1×10^{19} protons on target (POT) accumulated for analysis. The record of delivered POT to K2K is summarized in Figure 1.

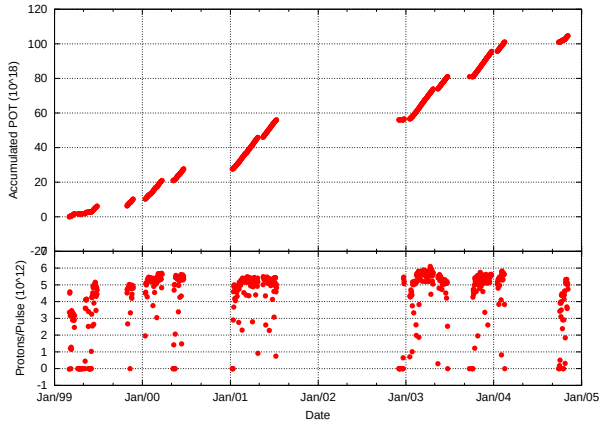

Figure 1: Delivered POT and beam intensity per pulse to the K2K experiment from June 1999 to November 2004.

In the analysis, we use a part of data before February 2004, corresponding to 8.9×10^{19} POT. The neutrino flux and spectrum at KEK are measured by near neutrino detectors: a one kiloton Water Cherenkov detector (1KT), a scintillating-fiber/water-target tracker (SciFi), a full-active fine-segmented scintillator tracker (SciBar), and a muon range detector (MRD). The number of interacted neutrinos corresponding to the flux is measured by 1KT with the similarly high efficiency as SK. The number of neutrino events in SK without neutrino oscillation is estimated to be 151^{+12}_{-10} based on the measured neutrino events by 1KT. The number of observed neutrino events in SK is 107 events summarized in Table 1. Thus, we observe a significant deficit of neutrino events in SK, as one of the evidences of neutrino oscillation.

Table 1: The SK event summary. MC is a prediction by the MC simulation without neutrino oscillation.

	Data	MC
1-ring μ-like	57	85.5
1-ring e-like	10	8.7
multi-ring	40	56.7
total	107	150.9^{+12}_{-10}

The neutrino energy spectrum at KEK is measured by 1KT, SciFi and SciBar complementarily. The measured neutrino spectrum, which is a product of flux times cross section, is shown in Figure 2. The measured spectrum agrees with the prediction of the beam Monte Carlo simulation. The neutrino spectrum at SK is estimated based on the measurement at KEK. In SK, neutrino energy is reconstructed with an assumption of the charged-current quasi elastic (CCQE) interaction. In order to enhance the fraction of CCQE events, the single-ring μ-like events are selected in SK. Fifty-seven events are selected to measured neutrino energy. The distribution of the reconstructed neutrino energy in SK is shown in Fig-

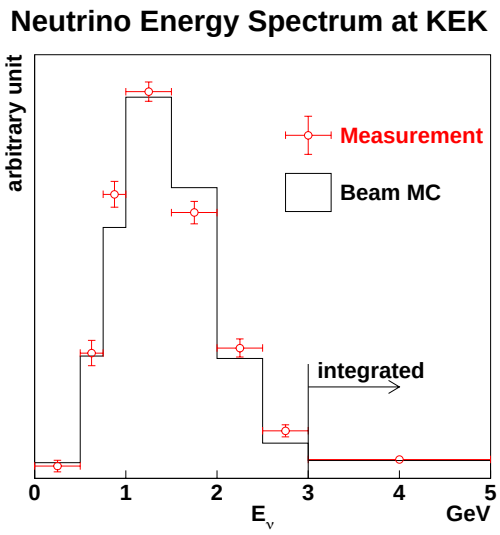

Figure 2: The neutrino energy spectrum measured at KEK. The spectrum is a product of flux times cross section.

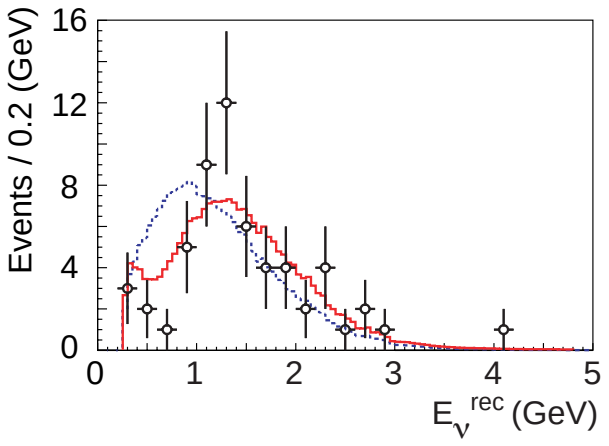

Figure 3: The reconstructed neutrino energy distribution of single-ring μ-like events. Points with error bars are data, the solid line is the best fit spectrum with neutrino oscillation, and the dashed line is the expected spectrum without oscillation. These histograms are normalized by the number of observed events (57).

ure 3. The observed spectrum is not matched with the expectation without neutrino oscillation, but one with neutrino oscillation.

A two flavor neutrino oscillation analysis is performed by the maximum-likelihood method. In the analysis, both the number of neutrino events and the energy spectrum shape are used. The best fit point in the physical region is found at ($\sin^2 2\theta$, Δm^2)=$(1.0, 2.8 \times 10^{-3}\ \mathrm{eV}^2)$. Allowed regions of oscillation parameters are shown in Figure 4, where the likelihood ratio of each point to the best fit point is evaluated. With neutrino oscillation of the best fit parameters, the expected number of events is 103.8, which agrees with the observation of 107 events. The neutrino energy distribution with the expected distributions of the best fit parameters is also shown in Figure 3. The no-oscillation probability is calculated to be 0.0050% (4.0σ). When only normalization (spectrum) information is used, the probability

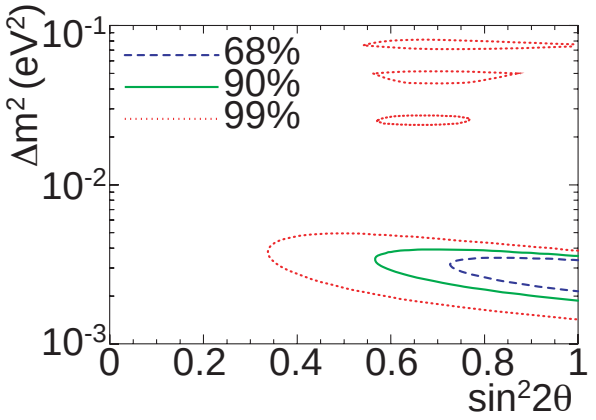

Figure 4: Allowed regions of oscillation parameters. Dashed, solid and dot-dashed lines are 68.4%, 90% and 99% C.L. contours, respectively.

is 0.26% (0.74%). The 90% C.L. contour crosses the $\sin^2 2\theta = 1$ axis at $\Delta m^2 = 1.9$ and 3.6×10^{-3} eV^2, which is consistent with the results from atmospheric neutrinos.

In 2004, K2K achieved the original goal and confirms neutrino oscillation. For the oscillation analysis, knowledge of neutrino-nucleus cross section is improved by near neutrino detectors: 1KT, SciFi and SciBar. As an improvement, the analysis of SciBar data gives the much smaller cross section of charged-current coherent pion production than the prediction by several models, which resolves the long-standing problem of the forward muon deficit in K2K. More results are expected to come in year 2005.