The K2K experiments had accumulated $4.8 \times 10^{19}$ protons on target, about half of the proposed amount, by July 2001. After the reconstruction of the Super-Kamiokande has finished, the K2K experiment resumed in December 2002. These proceedings describe the latest results based on the data by July 2001, report the current status and future prospects.

1. Introduction

The KEK to Kamioka (K2K) experiment is the first accelerator-based long baseline neutrino experiment to probe the same $\Delta m^2$ region as that explored with atmospheric neutrinos. The $\nu_\mu$ beam is produced at KEK and detected by the Super-Kamiokande (SK) at a distance of 250 km. Primary purpose is a search for the $\nu_\mu$ disappearance. Number of events and energy spectrum are measured at SK and compared with expectation with or without oscillation to test the oscillation scenario. The experiment started in June 1999 and has been accumulating data for typically about 6 month in a year until July 2001. After the SK accident in Nov. 2001, the reconstruction work was done in 2002. In Dec. 2002, the work finished and the K2K experiment resumed with about half density of PMT's. In this paper, latest results based on the data collected before SK accident are presented. Also current status and future prospect are briefly mentioned.

2. Experiment

The 12 GeV proton beam from the KEK proton synchrotron hits an aluminum target and the produced positively charged particles, mainly pions, are focused by a pair of pulsed electromagnetic horns. The neutrinos...
produced from the decays of these particles are 98% pure muon neutrinos with a mean energy of 1.3 GeV. The direction of the beam is monitored on a spill-by-spill basis by observing the profile of the muons from the pion decays with a set of ionization chambers and silicon pad detectors located just after the beam dump. Properties of the neutrino beam just after the production are measured by a set of near neutrino detectors (ND) located 300 m from the proton target. The ND consists of two detector systems: a 1 kiloton water Cherenkov detector (1KT) and a fine-grained detector (FGD) system. The FGD is comprised of a scintillating fiber and water detector (SciFi), a lead-glass calorimeter (LG), and a muon range detector (MRD). The measurements made at the ND are used to verify the stability and the direction of the beam, and to determine the flux normalization and the energy spectrum before the neutrinos travel the 250 km to SK. The flux at SK is estimated from the flux of the ND by multiplying the Far/Near (F/N) ratio, the ratio of fluxes between the far detector (SK) to that of the ND. The ratio is estimated by the beam Monte Carlo (MC) simulation which is validated by measurements of a pion monitor (PIMON) placed just downstream of the second horn. The neutrino energy is reconstructed from muon momentum and angle with respect to the neutrino beam direction, assuming quasi-elastic (QE) interactions, and neglecting Fermi momentum:

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

where $m_N$, $E_\mu$, $m_\mu$, $P_\mu$ and $\theta_\mu$ are the nucleon mass, muon energy, the muon mass, the muon momentum and the scattering angle relative to the neutrino beam direction, respectively. The analysis is based on data taken from June 1999 to July 2001, corresponding to $4.8 \times 10^{19}$ protons on target (POT).

3. Neutrino Flux and Spectrum at the near site

The flux normalization is measured by the 1KT to estimate the expected number of events at SK. Since the 1KT has the same detector technology as SK, most of systematic uncertainties on the measurement are canceled. Event selection criteria for the flux normalization are the same as those in reference. The measurement has a 5% systematic uncertainty, of which the largest contribution comes from the vertex reconstruction.

The energy spectrum is measured by analyzing the muon momentum and angular distributions in both detector systems. In 1KT, event sam-
ple of single-ring μ-like (1Rµ) events which stop in the detector is used for the spectrum measurement. In the FGD, events containing one or two tracks with vertex within the 5.9 ton fiducial volume of the SciFi are used.

The SciFi events are divided into three categories: 1-track, 2-track QE enhanced, and 2-track non-QE enhanced samples. The 2-track QE (non-QE) enhanced sample is selected by requiring the angle between the direction of the observed second track and a calculated direction of a proton assuming QE interaction to be \(\leq 25\) (\(\geq 30\)) degrees. The 2-dimensional distributions of the muon momentum versus angle with respect to the beam direction of four event categories (the 1KT event sample and the three SciFi event samples) are used to constrain the neutrino spectrum. The MC expected distributions are fitted to the observed ones by adjusting the weighting factor on each energy bin in the neutrino spectrum and on non-QE/QE ratio (\(R_{nqe}\)).

Table 1. The central values of the flux weighting factors for the spectrum fit at ND (\(\Phi_{ND}\)) and the percentage size of the energy dependent systematic errors on \(\Phi_{ND}\), F/N ratio, and \(\epsilon_{SK}\).

<table>
<thead>
<tr>
<th>(E_{\nu}) (GeV)</th>
<th>(\Phi_{ND})</th>
<th>(\Delta(\Phi_{ND}))</th>
<th>(\Delta(F/N))</th>
<th>(\Delta(\epsilon_{SK}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.5</td>
<td>1.31</td>
<td>49</td>
<td>2.6</td>
<td>8.7</td>
</tr>
<tr>
<td>0.5–0.75</td>
<td>1.02</td>
<td>12</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>0.75–1.0</td>
<td>1.01</td>
<td>9.1</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>1.0–1.5</td>
<td>(\equiv 1.00)</td>
<td>—</td>
<td>6.5</td>
<td>8.9</td>
</tr>
<tr>
<td>1.5–2.0</td>
<td>0.95</td>
<td>7.1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2.0–2.5</td>
<td>0.96</td>
<td>8.4</td>
<td>11</td>
<td>9.8</td>
</tr>
<tr>
<td>2.5–3.0</td>
<td>1.18</td>
<td>19</td>
<td>12</td>
<td>9.9</td>
</tr>
<tr>
<td>3.0–</td>
<td>1.07</td>
<td>20</td>
<td>12</td>
<td>9.9</td>
</tr>
</tbody>
</table>

The \(\chi^2\) at the best fit point is 227.2 with the degree of freedom 197. The best fit values of the flux weighting factors are shown in Table 1 and the best fit spectrum is plotted in Figure 1 together with the beam MC prediction. The muon momentum and angular distributions of 1Rµ events in the 1KT, and the muon momentum distributions of the 2-track QE enhanced and non-QE enhanced events in SciFi are overlaid with the re-weighted MC in Figure 2. The fit result agrees well with the data.

The F/N ratio from the beam simulation is used to extrapolate the measurements at the ND to those at SK. The errors including correlations above 1 GeV, where the PIMON is sensitive, are estimated based on the PIMON measurements. The errors on the ratio for \(E_{\nu}\) below 1 GeV are estimated based on the uncertainties in the hadron production models used in the K2K beam MC \(^1\). The diagonal elements in the error matrix for the
4. Observation at SK and Oscillation Analysis

The criteria to select neutrino beam events at SK are the same as those in the previous paper\(^1\): the event time within the time window of expected beam arrival, no activity in outer detector, energy deposit greater than 30 MeV, a reconstructed vertex within the 22.5 kiloton fiducial volume. This sample of events is referred to as the fully contained (FC) sample. The efficiency of this selection is 93% for CC interactions. Fifty-six events satisfy the criteria.

The expected number of FC events at SK without oscillation is estimated to be \(80.1^{+6.2}_{-5.4}\). The major contributions to the errors come from the uncertainties in the F/N ratio (\(\pm 4.9\%\)) and the normalization (5.0%), dominated by uncertainties of the fiducial volumes due to vertex reconstruction both at the 1KT and SK.

An oscillation scenario with \(\nu_\mu\) disappearance is tested by the maximum-likelihood method assuming two flavor oscillation. In the analysis, both the

---

Figure 1. Neutrino spectra measured by ND (points with error bars) and predicted by beam MC (solid histogram). They are normalized by area and the vertical axis is arbitrary.

F/N ratio are summarized in Table 1.
number of FC events and the energy spectrum shape for 1Rµ events are used. The likelihood is defined as \( L_{\text{total}} = L_{\text{norm}} \times L_{\text{shape}} \times L_{\text{syst}} \). The normalization term \( L_{\text{norm}}(N_{\text{obs}}, N_{\text{exp}}) \) is the Poisson probability to observe \( N_{\text{obs}} \) events when the expected number of events is \( N_{\text{exp}}(\Delta m^2, \sin^2 2\theta, f) \).

The shape term, \( L_{\text{shape}} = \prod_{i=1}^{N_{1R\mu}} P(E_i; \Delta m^2, \sin^2 2\theta, f) \), is the product of the probability for each 1Rµ event to be observed at \( E_{1R\mu} = E_i \), where \( P \) is the normalized \( E_{1R\mu} \) distribution estimated by MC simulation and \( N_{1R\mu} \) is the number of 1Rµ events. The term \( L_{\text{syst}} \) is a constraint term for a set of parameters \( f \) with systematic errors.

In the oscillation analysis, the whole data since June 1999 is used for \( L_{\text{norm}} \), i.e. \( N_{\text{obs}} = 56 \). The data taken in June 1999 are discarded for \( L_{\text{shape}} \). The spectrum shape in June 1999 was different from that for the rest of the running period because the target radius and horn current were different. The estimation of errors on the spectrum has not been completed for this period. The discarded data correspond to 6.5% of total POT and the number of 1Rµ events observed excluding the data of June 1999 is 29.

The parameters \( f \) consist of the weighting factor on neutrino spectrum measured at the ND (\( \Phi_{\text{ND}} \)), the F/N ratio, the reconstruction efficiency (\( \epsilon_{\text{SK}} \)) of SK for 1Rµ events, \( R_{\text{qe}} \), the SK energy scale and the overall

---

Figure 2. (a) The muon momentum distribution of the 1KT 1Rµ sample, (b) the angular distribution of the 1KT 1Rµ sample, (c) the muon momentum distribution of the SciFi QE enhanced sample, and (d) that of the SciFi non-QE enhanced sample. The crosses are data and the boxes are MC simulation with the best fit parameters. The hatched histogram shows the QE events estimated by MC simulation.
normalization. The errors on the first 3 items depend on the energy and have correlations between each energy bin. The diagonal parts of their error matrices are summarized in Table 1 as described earlier. The error on the SK energy scale is 3\%

![Figure 3. The reconstructed $E_{\nu}$ distribution for 1$R_{\mu}$ sample (from method 1). Points with error bars are data. Box histogram is expected spectrum without oscillations, where the height of the box is the systematic error. The solid line is the best fit spectrum. These histograms are normalized by the number of events observed (29). In addition, the dashed line shows the expectation with no oscillations normalized to the expected number of events (44).](image)

The best fit point in the physical region of oscillation parameter space is found to be at ($\sin^2 2\theta$, $\Delta m^2$) = (1.0, 2.8$\times$10$^{-3}$ eV$^2$). At the best fit point the total number of predicted events is 54.2, which agrees with the observation of 56 within statistical error. The observed $E_{\nu}^{\text{rec}}$ distribution of the 1$R_{\mu}$ sample is shown in Figure 3 together with the expected distributions for the best fit oscillation parameters, and the expectation without oscillations. The no-oscillation probabilities are calculated to be 0.7\% from the likelihood ratio between the best fit point to no-oscillation case. Allowed regions of oscillation parameters are drawn in Figure 4. The 90\% C.L. contour crosses the $\sin^2 2\theta = 1$ axis at 1.5 and 3.9 $\times$ 10$^{-3}$ eV$^2$ for $\Delta m^2$. Also drawn in
the figure is the log likelihoods as a function of $\Delta m^2$ at maximum mixing $\sin^2 2\theta = 1$ for normalization and shape terms separately. Both suppression of number of events and distortion of the spectrum indicate the same $\Delta m^2$ region.

\[ \sin^2 2\theta = 1 \]

Figure 4. (Left) Allowed regions of oscillation parameters. Dashed, solid and dot-dashed lines are 68.4%, 90% and 99% C.L. contours, respectively. The best fit point is indicated by the star. (Right) Log likelihood functions as a function of $\Delta m^2$ at $\sin^2 2\theta = 1$. Solid, dashed and dotted lines are $-\ln L_{\text{total}}$, $-\ln L_{\text{shape}}$ and $-\ln L_{\text{norm}}$, respectively.

5. Status and future

In Dec. 2002, the K2K experiment resumed after the long shutdown during the SK reconstruction. By the end of May 2003, about $2.1 \times 10^{19}$ POT have been DELIVERED after the restarting.

In order to maximize the sensitivity on neutrino oscillation, precise knowledge on the neutrino interactions at low energy of $\lesssim 1$ GeV is necessary. For that purpose, full-active scintillator tracker, called SciBar detector, are being installed as a replacement of the LG detector. Detailed description of the SciBar is found elsewhere. The fiducial mass will be about 11 tons. The LG detector has been already removed and 4 layer modules out of 64 have been installed in Jan. 2003. Remaining part will be installed during the next Summer shutdown in 2003.

In the current analysis, one of the sources of the dominant systematic error is the F/N ratio. The uncertainty comes from the error of the PIMON
measurements. In order to improve the precision of the F/N ratio, hadron production from a replica of the K2K target was measured at the HARP experiment at CERN\textsuperscript{11}. Analysis of the data is in progress.

The K2K experiment will accumulate at least $10^{20}$ POT.

6. Summary
The K2K experiment observed the indication of neutrino oscillation. Observed number of events is 56 while expected one without oscillation is $80.1^{+6}_{-5.4}$. Both the number of observed neutrino events and the observed energy spectrum at SK are consistent with neutrino oscillation. The probability that the measurements at SK are explained by statistical fluctuation is less than 1%. The measured oscillation parameters are consistent with the ones suggested by atmospheric neutrinos.

After long shutdown, K2K restarted on Dec. 2001 and is accumulating data. New detector is being installed in near site to improve the sensitivity of the experiment. It is planned to accumulate $10^{20}$ POT at least.

References