Indications of Neutrino Oscillation in a 250 km Long-baseline Experiment

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Summary. The K2K experiment observed indications of neutrino oscillation after 250 km flight of ν_μ. The observed number of events in the data corresponding to 4.8×10^{19} protons on target is 56, while $80.1^{+6.2}_{-5.4}$ is expected. Both the decrease of the events and observed spectrum shape distortion are consistent with neutrino oscillation. The probability that the observations are statistical fluctuation of non oscillation is less than 1%. The allowed region of oscillation parameters is consistent with the one obtained from the atmospheric neutrino observation. After the accident of Super-Kamiokande (SK) detector, the reconstruction of SK has finished in 2002 and the K2K experiment resumed in December 2002.

1 Introduction

The KEK to Kamioka (K2K) experiment is the first accelerator-based long baseline neutrino experiment[1] to probe the same Δm^2 region as that explored with atmospheric neutrinos[2, 3]. The ν_μ 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 ν_μ 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 December 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[4]. Also current status, latest results from the new data and future prospect are described.

2 Experiment

The 12 GeV proton beam from the KEK proton synchrotron (KEK-PS) hits an aluminum target and the produced positively charged particles, mainly pions, are focused by a pair of electromagnetic horns [5]. Most of the focused pions enter and decay in flight in subsequent decay pipe of 200-m long. The neutrinos produced from the decays of these particles are 98% pure muon neutrinos with a mean energy of 1.3 GeV.

High energy muons of $\gtrsim 5$ GeV from pion decay pass through a beam dump at the end of the decay pipe. The intensity and profile of the muons are measured by a MUMON, a segmented ionization chamber and silicon pad detectors placed behind the beam dump. They provide spill-by-spill monitoring of the beam direction and intensity.

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) [6], a lead-glass calorimeter (LG), and a muon range detector (MRD) [7]. 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 measured one at 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[8].

The neutrino energy is reconstructed from muon momentum and angle with respect to the neutrino direction, assuming quasi-elastic (QE) interactions $\nu_\mu + n \rightarrow \mu^- + p$, and neglecting Fermi momentum:

$$E_\nu^{\mathrm{rec}} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_\mu}, \tag{1}$$

where m_N, E_μ, m_μ, P_μ and θ_μ are the nucleon mass, muon energy, the muon mass, the muon momentum and the scattering angle relative to the neutrino beam direction, respectively. Inelastic interactions with additional pion(s) associated (non-QE interaction) are possible background for the energy reconstruction when the pions are not detected due to, eg., Cherenkov threshold.

In Fig. 1, accumulated number of protons on target (POT) and number of protons per spill are plotted since the beginning of the experiment in 1999. The analysis is based on data taken from June 1999 to July 2001, corresponding to 4.8×10^{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.

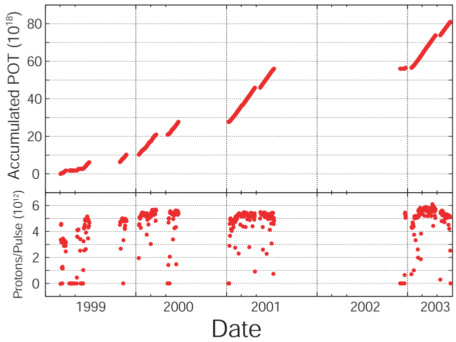

Fig. 1. History of the beam since the beginning of K2K. (top) Accumulated protons on target (POT) and (bottom) number of protons on target/pulse averaged over 1 day.

Event selection criteria for the flux normalization are the same as those in reference[1]. The measurement has a 5% systematic uncertainty, of which the largest contribution comes from the vertex reconstruction[1].

The energy spectrum is measured by analyzing the muon momentum and angular distributions in both detector systems. In 1KT, event sample of single-ring μ-like ($1R\mu$) 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 the 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}).

The χ^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 Fig. 2 together with the beam MC prediction. The muon momentum and angular distributions of $1R\mu$ 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 Fig. 3. 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[8]. The errors on the ratio for E_ν below 1 GeV are estimated

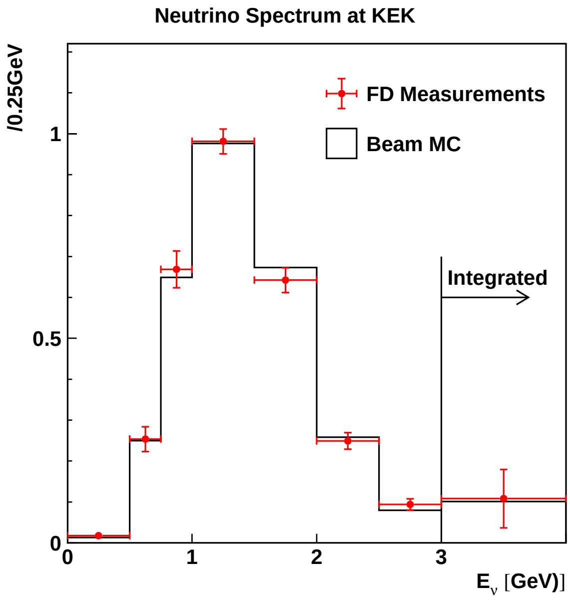

Fig. 2. Neutrino spectra measured by ND (points with error bars) and predicted by beam MC (solid histogram). They are normalized by area and the vertical axis is arbitrary.

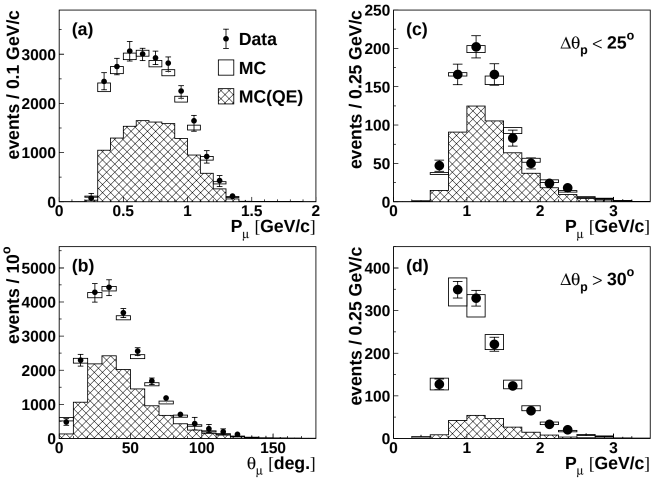

Fig. 3. (a) The muon momentum distribution of the 1KT $1R\mu$ sample, (b) the angular distribution of the 1KT $1R\mu$ sample, (c) the muon momentum distribution of the SciFi QE enhanced sample, and (d) that of the SciFi non-QE enhanced sample. The crosses are data and the boxes are MC simulation with the best fit parameters. The hatched histogram shows the QE events estimated by MC simulation.

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

E_ν (GeV)	$\Phi_{\rm ND}$	$\Delta(\Phi_{\rm ND})$	Δ(F/N)	$\Delta(\epsilon_{\rm SK})$
0−0.5	1.31	49	2.6	8.7
0.5−0.75	1.02	12	4.3	4.3
0.75−1.0	1.01	9.1	4.3	4.3
1.0−1.5	$\equiv$ 1.00	—	6.5	8.9
1.5−2.0	0.95	7.1	10	10
2.0−2.5	0.96	8.4	11	9.8
2.5−3.0	1.18	19	12	9.9
3.0−	1.07	20	12	9.9

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 F/N ratio are summarized in Table 1. The detail of the near to far extrapolation is described in ref. [9].

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 ($^{+4.9\%}_{-5.0\%}$) 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 ν_μ disappearance is tested by the maximum-likelihood method assuming two flavor oscillation. In the analysis, both the number of FC events and the energy spectrum shape for $1R\mu$ events are used. The likelihood is defined as $\mathcal{L}_{total} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$. The normalization term $\mathcal{L}_{norm}(N_{obs}, N_{exp})$ is the Poisson probability to observe N_{obs} events when the expected number of events is $N_{exp}(\Delta m^2, \sin^2 2\theta, f)$. The shape term, $\mathcal{L}_{shape} = \prod_{i=1}^{N_{1R\mu}} P(E_i; \Delta m^2, \sin^2 2\theta, f)$, is the product of the probability for each $1R\mu$ event to be observed at $E_\nu^{\rm rec} = E_i$, where P is the normalized $E_\nu^{\rm rec}$ distribution estimated by MC simulation and $N_{1R\mu}$ is the number of $1R\mu$ events. The term $\mathcal{L}_{syst}$ 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 $\mathcal{L}_{norm}$, i.e. $N_{obs} = 56$. The data taken in June 1999 are discarded for $\mathcal{L}_{shape}$.

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 $1R\mu$ 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 (Φ_{ND}), the F/N ratio, the reconstruction efficiency (ϵ_{SK}) of SK for $1R\mu$ events, R_{nqe}, the SK energy scale and the overall 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% [10].

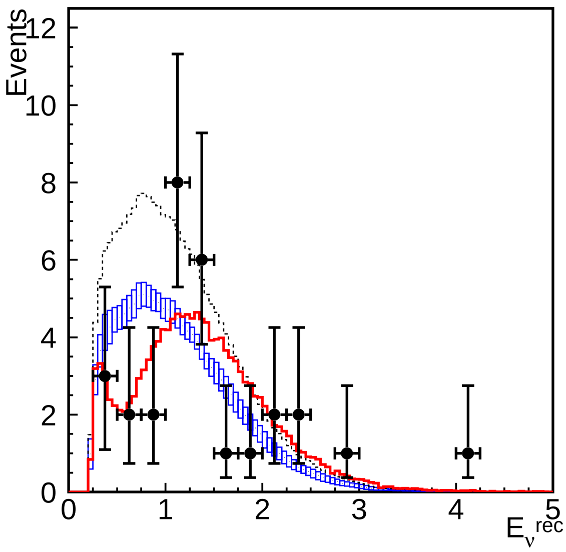

Fig. 4. The reconstructed E_ν distribution for $1R\mu$ sample (from method 1). Points with error bars are data. Box histogram is expected spectrum without oscillations, where the height of the box is the systematic error. The solid line is the best fit spectrum. These histograms are normalized by the number of events observed (29). In addition, the dashed line shows the expectation with no oscillations normalized to the expected number of events (44).

The best fit point in the physical region of oscillation parameter space is found to be at ($\sin^2 2\theta$, Δm^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 $E_\nu^{\rm rec}$ distribution of the

$1R\mu$ sample is shown in Fig 4 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 Fig. 5. The 90% C.L. contour crosses the $\sin^2 2\theta = 1$ axis at 1.5 and 3.9×10^{-3} eV^2 for Δm^2. Also drawn in the figure is the log likelihoods as a function of Δm^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 Δm^2 region.

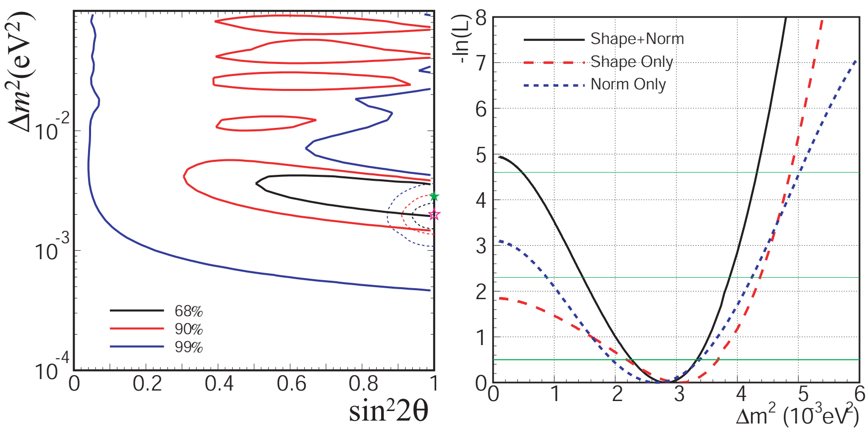

Fig. 5. (Left) Allowed regions of oscillation parameters. Dashed, solid and dot-dashed lines are 68.4%, 90% and 99% C.L. contours, respectively. Solid lines are K2K results and the dashed lines are results of Super-Kamiokande atmospheric neutrino observation. The best fit point is indicated by the stars. (Right) Log likelihood functions as a function of Δm^2 at $\sin^2 2\theta = 1$. Solid, dashed and dotted lines are $-\ln \mathcal{L}_{total}$, $-\ln \mathcal{L}_{shape}$ and $-\ln \mathcal{L}_{norm}$, respectively.

5 Latest results and Status

In Dec. 2002, the K2K experiment is resumed after the shutdown during the SK reconstruction (K2K-II run). The first part of the 2003 run has finished at the end of June and 2.5×10^{19} POT has been delivered by the end of the run.

The data from January to April 3rd, 2003, corresponding to 1.5×10^{19} POT, has been analyzed. Observed number of fully contained events during that period is 16 and the expected number of events is estimated to be $26.4^{+2.3}_{-2.1}$. The ratio of observed to expected number of events is 0.61 ± 0.15

(stat. only) is consistent with the results from K2K-I, the first period of K2K run (June 1999 $\sim$ July 2001), 0.7 ± 0.09 (stat. only).

In order to maximize the sensitivity on neutrino oscillation, precise knowledge on the neutrino interactions at low energy of $\lesssim 1$ GeV is important. To improve ND sensitivity in low energy region, a full-active scintillator tracker, called SciBar detector, has been installed as a replacement of the LG detector. Detailed description of the SciBar is found elsewhere[11]. The fiducial mass will be about 11 tons. The detector construction has finished at the end of August 2003 and is now under commissioning in order to be in full operation from the next run starting at the end of September 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[12]. Analysis of the data is in progress.

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

6 Next generation experiment – J-PARC Kamioka neutrino project –

The J-PARC, Japan Proton Accelerator Research Complex, is a high intensity proton accelerator facility which is being constructed at Japan Atomic Energy Research Institute in Tokai-village, about 60 km N.E. of KEK. A 50-GeV proton synchrotron in J-PARC will provide 750 kW beam power, about 2 order of magnitude higher than KEK-PS.

New long baseline neutrino oscillation experiment is being planned in which the ν_μ beam is produced by the 50-GeV beam and detected by SK [13]. The neutrino flight distance is 295 km. The locations are depicted in Fig. 6. Main goals of the experiment are: (1) discovery of ν_e appearance, (2) precision measurement of oscillation parameters and eventually, (3) search for CP violation in lepton sector. As an example, the sensitivity to the ν_e appearance search is shown in Fig. 6. The J-PARC experiment will extend more than factor 20 compared to current upper bound from reactor neutrino experiments.

7 Summary

The K2K experiment observed the indication of neutrino oscillation. Observed number of events is 56 while expected one without oscillation is $80.1^{+6.2}_{-5.4}$. 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

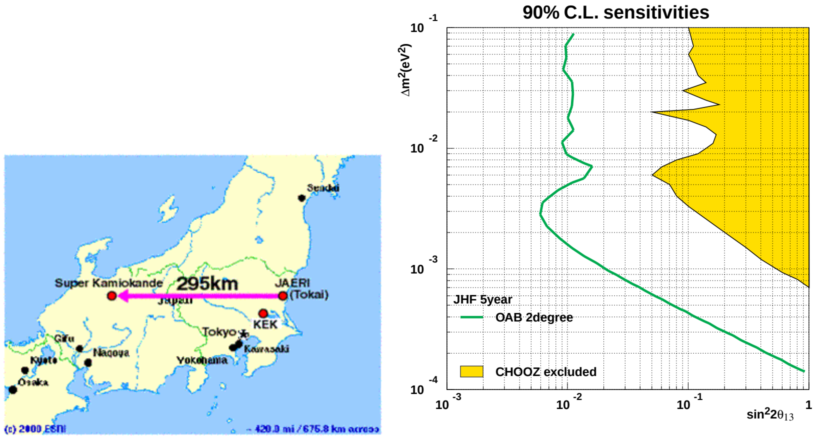

Fig. 6. Overview of the J-PARC Kamioka neutrino project (left) and sensitivity to ν_e appearance (right).

than 1%. The measured oscillation parameters are consistent with the ones suggested by atmospheric neutrinos. After long shutdown, K2K restarted on December 2002 and is accumulating data. New detector is installed in near site to improve the sensitivity of the experiment. The K2K experiment plans to accumulate 10^{20} POT at least.

Next generation high statistics and high sensitivity experiment is being planned.

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