Status of K2K experiment

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Abstract

The K2K, KEK to Kamioka, long baseline neutrino oscillation experiment started in the beginning of 1999. In the fiscal year of 1999, we have accumulated $\sim 2 \times 10^{19}$ protons on target (POT). So far, data corresponding to 7.2×10^{18} POT has been analyzed. We found 6 fully contained events in Super Kamiokande (SK). Three out of those fall in fiducial volume. Beam monitor data and front detector data are analyzed to estimate expected number of events in SK and it is found to be $12.3^{+1.7}_{-1.9}$ in the case of no oscillation for the observed 3 in-fiducial events.

1 Introduction

Neutrino masses have long been one of the most important issue in the particle physics. The standard model of electroweak interactions is generally presented with the neutrino masses being identically zero. Experimentally, direct measurements of neutrino mass only give upper limits. The limits are 15 eV, 170 keV and 18.2 MeV for ν_e, ν_μ and ν_τ, respectively [2]. Discovery of finite neutrino mass could be a breakthrough in searching for new physics beyond the standard model.

In 1998, Super Kamiokande collaboration reported that they found an evidence of neutrino oscillation between ν_μ and ν_τ (or sterile neutrino ν_s) in the zenith angle distribution of atmospheric neutrino [3]. Neutrino oscillation is a phenomena that a neutrino changes its flavor during propagation [4]. It occurs only when mass eigenstates with different masses mix with each other. In the case of two flavor oscillation, the oscillation probability is given by

$$P(\nu_\mu \to \nu_a) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\mathrm{eV}^2] L[\mathrm{km}]}{E_\nu [\mathrm{GeV}]} \right), \tag{1}$$

where θ and Δm^2 are the mixing angle and the difference of mass squared, respectively, between the two mass eigenstates, L is the flight length and E_ν is the energy of the neutrino. The SK results is the first indication of finite neutrino mass. It suggest $\Delta m^2 = 2 \sim 5 \times 10^{-3}$ eV^2 and mixing angle $\sin^2 2\theta > 0.8$. Confirmation of the results is therefore urgent and important task. Recent analysis of atmospheric neutrino by SK excluded the possibility of oscillation from ν_μ to ν_s at 99 % CL [5]. Reactor-neutrino long baseline experiments, CHOOZ and Palo Verde reported that oscillation probability between ν_μ and ν_e is small [6, 7].

The K2K experiment is the first accelerator-based long baseline neutrino oscillation experiment [8]. The ν_μ beam with $< E_\nu > \sim 1.4$ GeV is generated at High Energy Accelerator Research Organization (KEK) and detected by SK at 250 km from KEK. We look for oscillation modes $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_x$ disappearance. The sensitive region of the oscillation parameters is $\Delta m^2 \gtrsim 3 \times 10^{-3}$ eV^2. It covers most of the allowed region by SK. The K2K experiment started January 1999 as scheduled. After engineering run, we started physics run from April 1999. Here we report results obtained in 1999.

2 Experimental setup

2.1 Neutrino Beam

A wide-band ν_μ beam is generated at KEK by using the 13 GeV/c proton synchrotron (PS) [9]. The proton beam is extracted from the PS in single turn with 2.2 sec cycle. The number of bunches in one spill is 9 and the spill width is 1.1 μsec. The design intensity of the proton beam at the production target is 6×10^{12} protons/spill.

The extracted proton beam is transported about 360 m and bent 1.05° downward in order to aim SK, then hit a production target. The target is 66 cm long Al rod. The diameter of the target is 2 cm for runs until June 1999, and 3 cm for runs since November 1999. Positive secondary particles are focused by two electromagnetic horns [10]. Both horns are operated by pulsed current of 1 msec width and 250 kA peak. The target is embedded in the first horn and plays also a role as an inner conductor. The length of the decay tunnel is 200 m. At the end of the tunnel, there is a beam dump of 3-m thick iron followed by 2 m thick concrete. Most particles except muons above 5 GeV stop in the dump.

In Fig. 2.1, the expected neutrino spectra and the dependence of flux on distance from the beam axis are plotted for the front neutrino detector (FD) at 300 m from the target and for the SK. The average neutrino energy is 1.4 GeV and the contamination of ν_e is estimated to be about 1.3 %. As can be seen the figure, the neutrino flux is almost constant within 1 km at SK which corresponds to 4 mrad.

2.2 Beam Monitors

At just behind the beam dump, two types of muon monitors (MMs) are installed. One is a 2 m×2 m segmented ionization chamber. Horizontal and vertical strips are 5 cm width. The other MM is array of silicon pad detectors (SPDs). We use two types of SPDs; one is 10×10 mm^2 and the other is 34×30.5 mm^2. The smaller pads are aligned vertically and horizontally and the larger ones are aligned 45° direction as shown in Fig. 2. The MMs provide fast monitoring of the beam direction and efficiency of neutrino beam production.

The pion monitor (πM) is installed just downstream of the 2nd horn in the target station. Its purpose is to measure momentum and angular distribution of pions, $N(p_\pi, \theta_\pi)$. Once we know the distribution, we can predict neutrino spectra at any distance in principle just using decay kinematics. To avoid background from primary protons which are much more than pions, a gas Čerenkov detector is adopted. Schematic view of the πM is drawn in Fig. 2. The Čerenkov light from secondary particles is reflected by spherical mirror in the gas volume. The reflected light is detected by 1-dim PMT array placed at the focal plane of the mirror. In order not to expose the PMTs in severe radiation, the mirror is 30° tilted from normal to the beam axis and the PMTs are placed at about 3.5 m from the mirror. At the focal

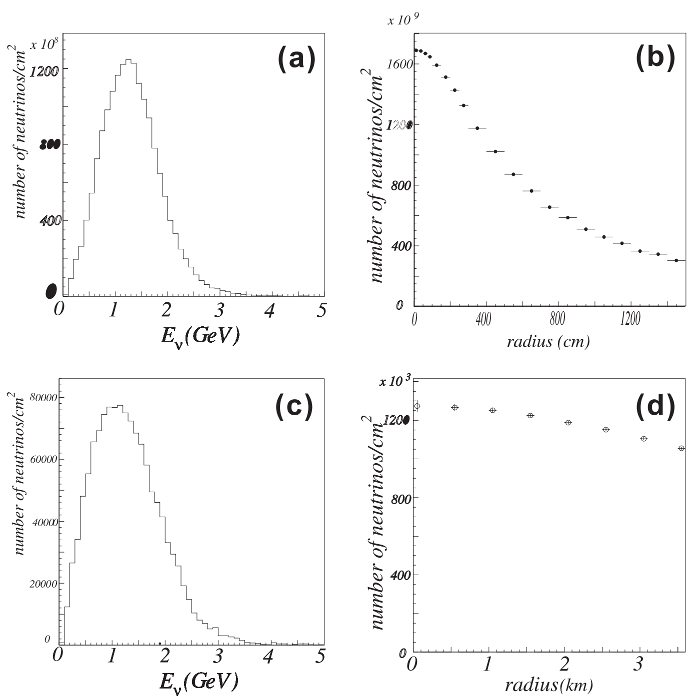

Figure 1: Expected ν_μ spectra and radial dependence of flux. Plots (a) and (b) are those at FD and (c) and (d) at SK. All plots are normalized to 10^{20} POT. The horizontal axes of (b) and (d) are the distance from the beam axis.

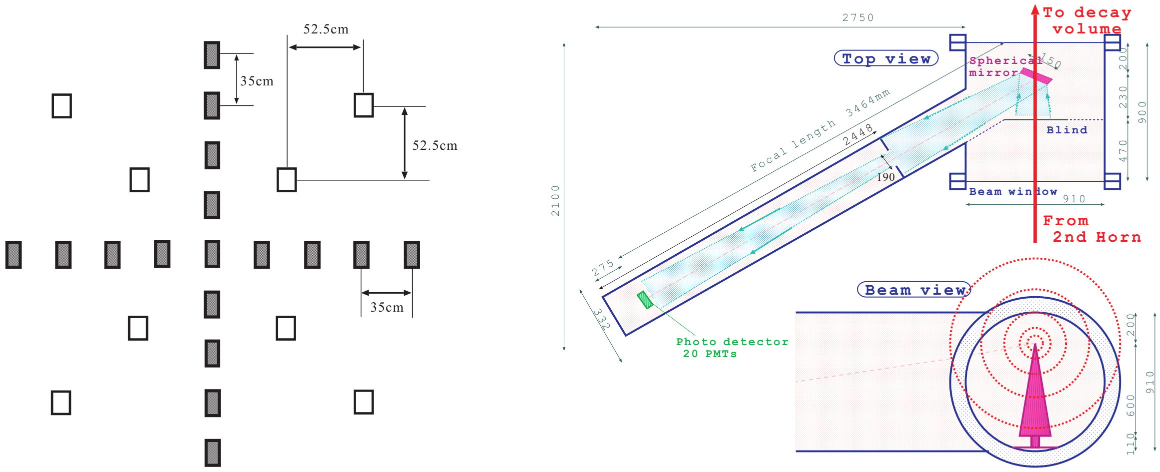

Figure 2: Front view of silicon pad detectors for muon monitoring (left). Hatched pads are 10×10 mm^2 and open boxes are 34×30.5 mm^2. Schematic view of pion monitor (right).

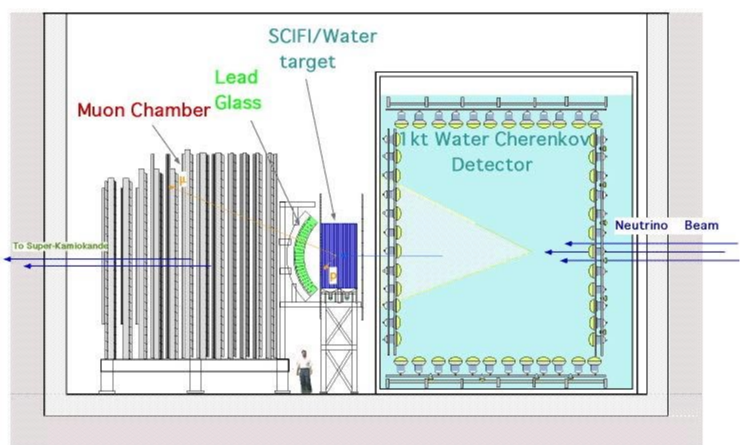

Figure 3: Front neutrino detector.

plane of a spherical mirror, position information of the original Čerenkov light is lost but only angular information is retained. And in order to be sensitive to various p_π region, measurements are performed at various refractive index. The refractive index is adjusted by changing the gas pressure. To eliminate the possible errors in the absolute measurement of the number of pions, we use the flux ratio at SK to FD, $R_\Phi(E_\nu) \equiv \Phi_{\rm SK}(E_\nu)/\Phi_{\rm FD}(E_\nu)$ as a result of the πM. Combining with the absolute $\Phi_{\rm FD}(E_\nu)$ measured at FD, we predict $\Phi_{\rm SK}(E_\nu)$.

2.3 Front Neutrino Detectors

The front neutrino detector (FD) is located at 300 m downstream from the target. The FD consists of a 1 kton water Čerenkov detector and a fine grained detector (FGD) as shown in Fig. 3. The main purpose of the FD is to measure absolute neutrino flux as a function of energy, i.e. $\Phi_{FD}(E_\nu)$. Measurement of beam center from the profile and ν_e contamination are also important purposes of the FD.

The 1 kton detector is a ring imaging Čerenkov detector which works with the same principle as SK. The detector volume of 8.6 m$^\phi \times$ 8.5 m is filled with pure water and is viewed by 860 20-inch PMT's. The fiducial mass is 50.3 ton. Since the MC simulation of 1kton is essentially same as the one used in SK, the 1kton detector has a role to test and tune MC simulation in SK.

The FGD is composed of a scintillation fiber tracker (SFT), VETO/TRIG scintillater walls, a lead glass (LG) detector and a muon chamber (MUC). The SFT is a stack of the water containers and sheets

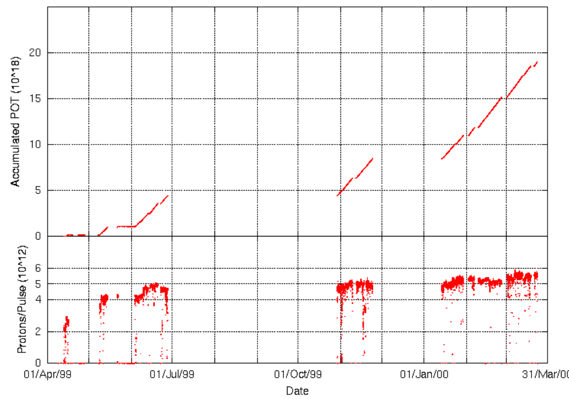

Figure 4: Delivered beam history in Japanese fiscal year 1999.

of staggered fibers [11]. The size of the SFT is $2.6 \times 2.6 \times 1.73$ m^3. The scintillating fiber is 0.7 mm$^\phi$ multi-cladding fiber (Kuraray SCSF-78M). The water acts as neutrino interaction targets. Between scifi sheets, 6-cm thick water containers are installed. Total water mass is 4 ton. The container is made from Al and the fraction of the Al mass is about 30 %. The scintillation light from the fibers is read out by image intensifier tube and CCD chain. Specialty of the SFT is good position resolution. It is measured to be 1.1 mm using cosmic-ray data taken after installation. The purpose of the LG detector is to identify electrons from ν_e interactions and to measure their energies. The energy resolution is $\sim$10 %/$\sqrt{E\ [\mathrm{GeV}]}$. The MUC is a stack of 10- or 20-cm thick 8×8 m^2 iron plates and drift chambers. The total mass of the iron plates is about 1 kton. Total thickness of the iron plates are 2 m which corresponds to about 3.5 GeV energy deposit by minimum ionizing particle.

In the FD, three types of events are analyzed, i.e. interactions in the 1kton water, in SFT water target and in MUC Fe plates.

2.4 Far detector (Super-Kamiokande)

SK is a ring imaging water Čerenkov detector located 1000 m underground (2700 m water equivalent) at 250 km away from KEK. The detector volume of 36 m in diameter and 34 m in height is viewed by 11146 20-inch PMT's. The fiducial mass is 22.5 kton. Detail description of the detector can be found elsewhere [3].

3 Results

3.1 Beam in JFY99

Beam history in JFY 1999 is plotted in Fig. 4. The first fast extraction succeeded on Feb. 3rd, 1999. After engineering runs, we started physics run since April, 1999. In April and May, we had some troubles in accelerator and horn system and could not accumulate protons on target (POT) as scheduled. Since June, 1999, all the system have been working stably. In the Japanese fiscal year 1999, about 2×10^{19} POT was delivered. At the end of March the beam intensity reached $\sim 5.5 \times 10^{12}$ protons/pulse (ppp).

So far, we have analyzed data corresponding to 7.2×10^{18} POT accumulated from April to November in 1999. The results presented here is based on the data in that period.

3.2 Observation at Super Kamiokande

In order to identify the events induced by neutrinos from KEK, time of every beam spill start(T_{spl}) and every SK event trigger (T_{SK}) are recorded by using global positioning system [12]. We expect

$$T_{Diff} \equiv T_{SK} - T_{spl} - TOF \tag{2}$$

to be between 0 and 1.1 μsec, where $TOF \simeq 830$ μsec is time of flight of neutrino from KEK to Kamioka. Figure 6 shows the T_{Diff} distribution of fully contained events. We observed 6 candidate events in the signal window. Three events out of them fall in the fiducial volume where distance from the wall is more

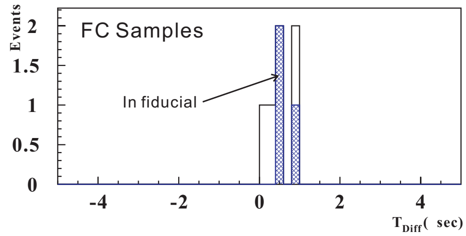

Figure 5: T_{Diff} distribution of fully contained events. Hatched region is events in fiducial volume.

than 2 m. Expected background from the atmospheric neutrino in the 1 μsec window is $\sim 1.4 \times 10^{-4}$ events. Event display of one of the candidates is shown in fig. 6. It is single ring μ-like event with the reconstructed muon momentum of 467 MeV/c.

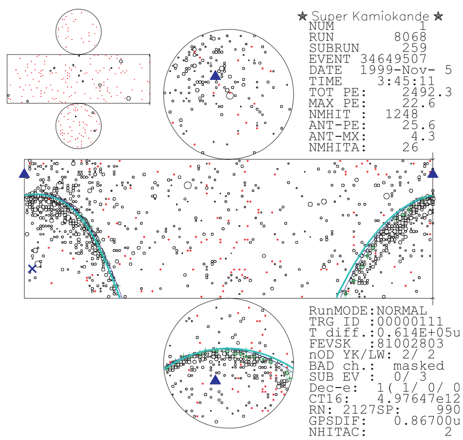

Figure 6: A candidate of fully contained single ring μ-like event in fiducial volume.

3.3 Beam Direction

Neutrino beam profile is measured by the FD. In Fig. 7 the profile measured by MUC Fe events is

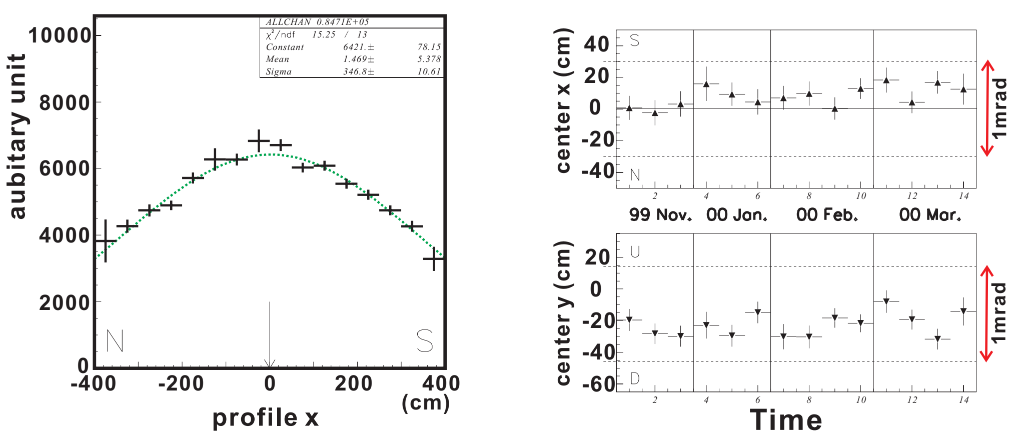

Figure 7: Beam profile measured by MUC Fe events (left), and stability of profile centroid during long period (right). New data up to March 2000 included.

plotted. Beam center is obtained by fitting Gaussian function to the data and is found to be 1 ± 5 cm and

-26 ± 4 cm in horizontal (x) and vertical (y) direction, respectively. Systematic uncertainty of centroid determination is estimated by MC simulation and is 20 cm. The beam center agrees well with the SK direction within systematic uncertainty. The error 20 cm at FD position corresponds to 0.7 mrad. In Fig. 7 also plotted is the stability of fitted center during long period. The center in both x and y directions are stable within statistical uncertainty.

It takes $\gtrsim$ day to accumulate enough statistics to discuss profile center with MUC Fe event. MMs provide fast monitoring of beam profile and center, although it is indirect. Figure 8 shows typical muon profile measured by MMs. They show that the beam is centered within 20 cm which corresponds to 1 mrad. The stability of the fitted center is shown in Fig. 9. We observed that the center stay well within

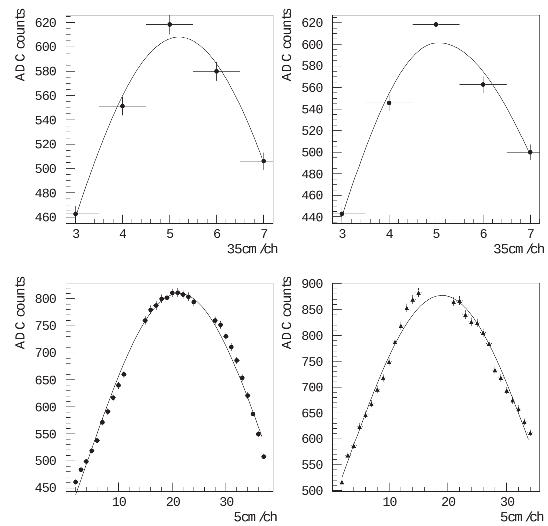

Figure 8: Muon profile measured by MMs. Points with error bars are data and solid lines are fitted curve. Upper figures are data of SPDs and lower are of ionization chamber. Left and right figures are horizontal and vertical profile.

1 mrad during full 1 month's operation.

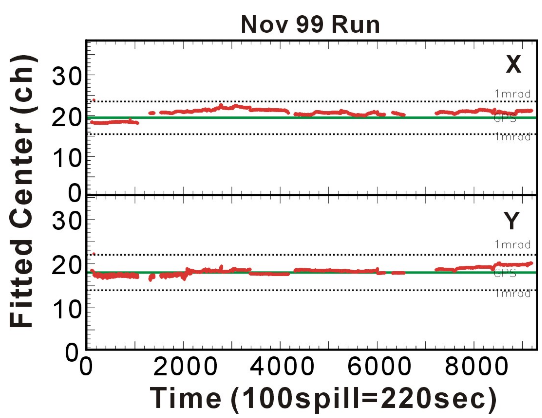

Figure 9: Stability of muon profile center. Dots are fitted center and solid line indicate SK direction and dotted lines indicate 1 mrad off axis. Upper and Lower figures are horizontal and vertical center, respectively. Each data dots represents 100 spill. Whole span of horizontal axis corresponds to about 23 days.

3.4 Observation at Front Detector

All FD components have been working well. Here some of the results obtained by FDs are presented.

The number of rings and total photoelectrons distribution in 1kton detector are plotted in Fig. 10. They agree well with MC simulation. Figures 11 are distributions of energy and angle of muons detected

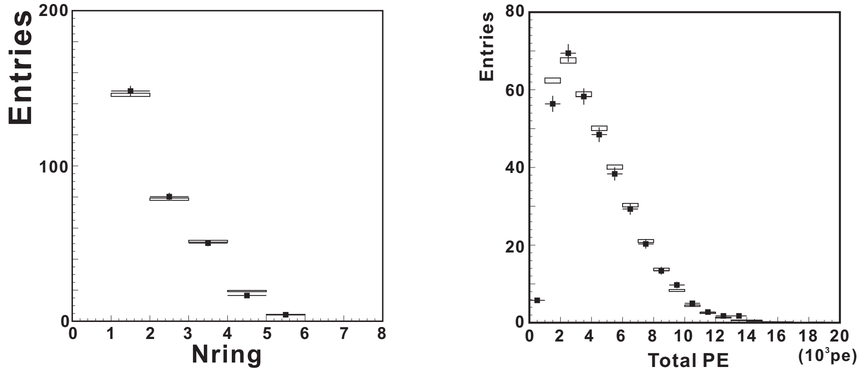

Figure 10: Number of rings and total photoelectrons distribution of the neutrino events in 1kton detector.

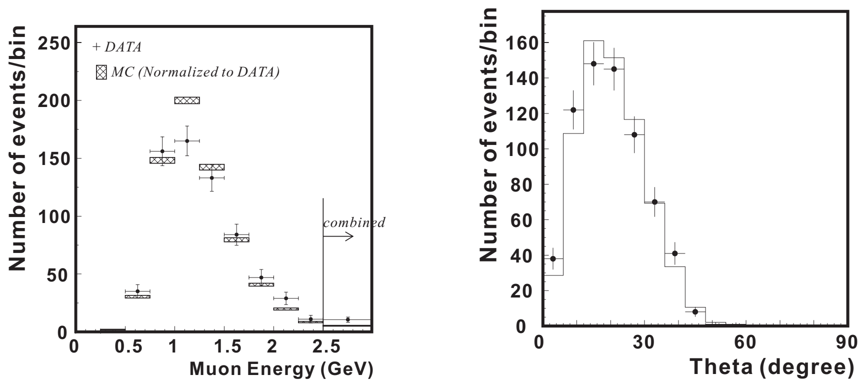

Figure 11: Energy (left) and angle (right) distribution of muons from neutrino interactions in SFT.

by the SFT. They also agree with MC simulation. In Fig. 12, event rate of MUC Fe events normalized by

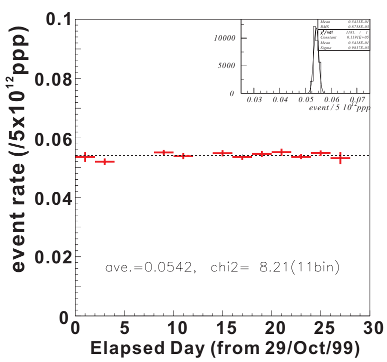

Figure 12: Event rate of MUC Fe event as a function of elapsed time. Points with error bars are data, solid horizontal line indicate mean. Histogram in upper right corner is projection of the stability plot on the vertical axis.

proton intensity is plotted. Event rate is stable within statistical error of 1.8 % during 1 month operation.

3.5 Flux ratio

Čerenkov light from pions was successfully observed by the πM as demonstrated in Fig. 13. Relative population in p_π–θ_π plane is determined by fitting expected light distribution to the data. The fit results are also shown in the same figure. It can be seen that the data is fitted well.

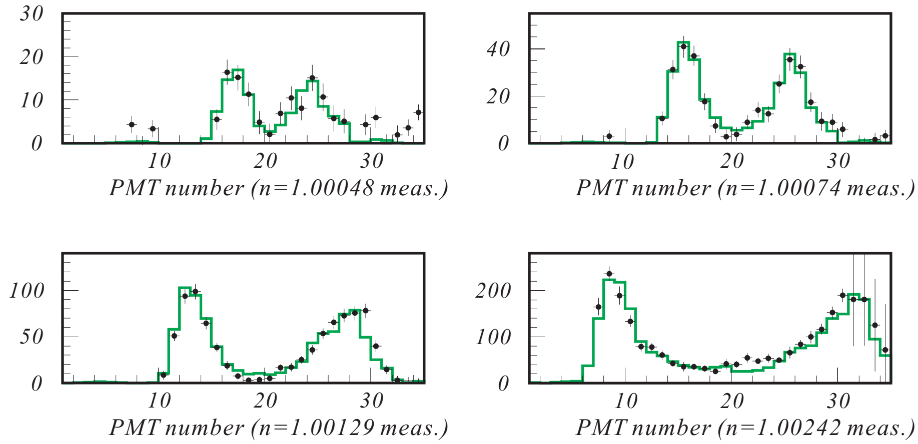

Figure 13: Čerenkov light distribution measured by the πM. The points with error bars are data and the solid lines are fitted results.

Using the pion distribution in p_π–θ_π plane obtained by the fitting, neutrino spectra at SK and FD are calculated. Fig. 14 shows the flux ratio at SK to FD thus obtained with MC prediction. We observed

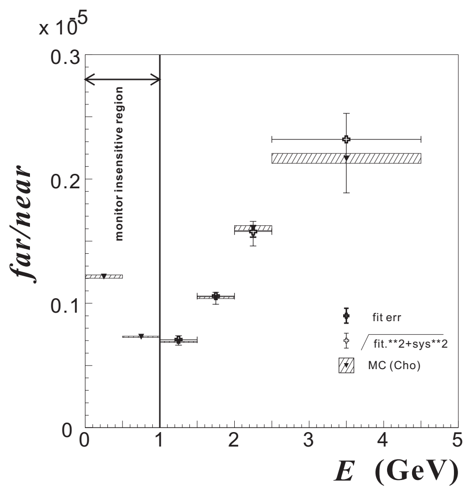

Figure 14: Near/far flux ratio obtained from πM data (points with error bars) and by MC simulation (shaded box)

very good agreement between πM measurement and MC prediction within uncertainty above $E_\nu \geq 1$ GeV. The πM has no sensitivity below 1 GeV due to Čerenkov threshold for pions.

3.6 Expected number of events

Expected number of events at SK N_{SK}^{expt} without neutrino oscillation is estimated as follows;

$$N_{SK}^{expt} = \frac{N_{FD}^{obs}}{\varepsilon_{FD}} \times R_{int} \times \varepsilon_{SK} \tag{3}$$

where N_{FD}^{obs} is number of selected ν_μ events in one of the front detectors, ε_{FD} is the detection efficiency of the detector, R_{int} is the ratio of number of interactions in SK to FD and ε_{SK} is the detection efficiency of SK events.

Observed number of events in each FD and its detection efficiencies are summarized in Table 1. For R_{int}, flux ratio estimated by MC is used as central value. For systematic error estimation, error from the πM measurement is taken at $E_\nu \geq 1$ GeV and uncertainty in MC prediction is used below 1 GeV. Calculated number of expected events for June and November runs are plotted in Fig. 15. All numbers

	1kton	Scifi	Fe(MUC)
M_{FD}	50.3 ton (H_2O)	6.25 ton (H_2O + Al)	450 ton (Fe)
N_{FD}	17672	662	56062
ε_{FD}	0.85	0.21	0.22

Table 1: Summary of number of events observed in FDs and detection efficiencies.

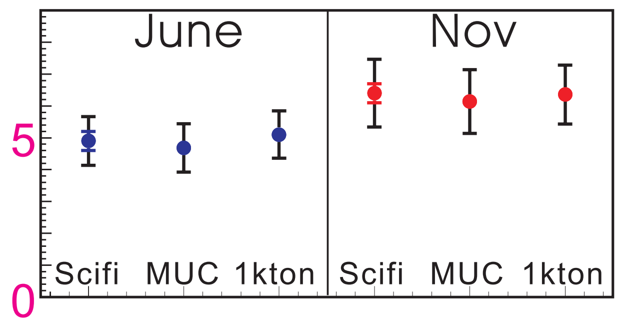

Figure 15: Expected numbers of SK event with no oscillation for June and November runs. The shorter error bars are statistical errors and long error bars are total errors including systematic errors.

from different FDs agree with each other very well within systematic error. In Table 2, total observed and expected number of events during the whole period from April to November are summarized. To

	Observed	No osc.	3×10^{-3}	5×10^{-3}	7×10^{-3}
In fiducial	3	$12.3^{+1.7}_{-1.9}$	8.0	5.4	4.6
Out of fid.	3	$5.5^{+1.1}_{-1.2}$	3.5	2.4	2.1

Table 2: Summary of observed and expected number of events at SK for data from April to November 1999 with some expected number of events when neutrino oscillation is assumed. Numbers in the first line are Δm^2 assumed in eV^2 unit.

calculate the total number, 1 kton value is adopted. Major sources of the systematic errors are flux extrapolation error, i.e. error in R_{int} ($^{+7.7}_{-10.4}$ %) and 1 kton fiducial volume error (±8.4 %). Studies to reduce the systematic errors are underway.

4 Summary

The K2K experiment have started Jan. '99 as scheduled. All detector components have been working well. In the Japanese fiscal year 1999, $\sim 2 \times 10^{19}$ POT is delivered during the 5 months physics run. The proton beam intensity reached about 5.5×10^{12} ppp. So far data corresponding to 7.2×10^{18} POT acquired from April to November 1999 have been analyzed. Six fully contained events are found in SK. Out of them, 3 events are in the fiducial volume of 22.5 ton. Expected number of events in the case of no oscillation is estimated by analyzing beam monitor data and front detector data and found to be $12.3^{+1.7}_{-1.9}$.

References

[1] K2K (KEK to Kamioka) experiment is a collaboration of Japan, Korea and the United States. The following institutions are members of the K2K experiment: ICRR, KEK, Kobe, Kyoto, Niigata, Okayama, Tohoku, Tokai, Chonnam, Dongshin, Korea Univ., Seoul Nat. Univ., Boston, Los Alamos, SUNY, Hawaii, UC Irvine, Univ. of Washington.

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