Eur Phys J C **33**, s01, s829–s833 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2003-03-910-9

EPJ C direct
electronic only

Status of the Super-Kamiokande and the K2K experiment

Yoshinari Hayato for the SK and the K2K collaborations

High Energy Accelerator Research Organization, Oho 1-1, Tsukuba, Ibaraki, 305-0801, Japan

Received: 3 December 2003 / Accepted: 12 December 2003 /
Published Online: 18 December 2003 –

Abstract. In this paper, the recent results of atmospheric neutrino oscillation analysis and the current status of the Super-Kamiokande are presented. This time, entire SK-I data, which correspond to the 1489 days live days, were analyzed and the preliminary results of the oscillation analysis are reported. Also, the recent results and current status of the KEK to Kamioka long-baseline neutrino oscillation (K2K) experiment are presented.

PACS. 14.60.pq Neutrino oscillations

1 Results of the atmospheric neutrino oscillation analysis at SK-I

The atmospheric neutrinos are generated by the collision between the primary cosmic rays and the molecules in the atmosphere. The primary cosmic rays, most of which are protons, hit the particles in the atmosphere and produce hadronic showers. The mesons in the showers decay into neutrinos and leptons. Because the ν_e and $\bar{\nu}_e$ are generated mainly from the decay of muons, fraction of $(\nu_\mu + \bar{\nu_\mu})$ to $(\nu_e + \bar{\nu_e})$ is about 2 in the low energy region (less than a few GeV) and getting larger in the higher energy regions. The neutrinos are generated everywhere in the atmosphere. The down going neutrinos traveled of the order of 10's km to reach a detector. On the other hand, the upward going neutrinos traveled over 10000km through the earth. Therefore, there is a strong correlation between the zenith angle of the neutrinos and the path length. The zenith angle distribution of the atmospheric neutrino observed in the detector is expected to be symmetric except for the very low energy region, where the geomagnetic field cause some effects. However, the atmospheric neutrino observation experiments found that the $(\nu_\mu + \bar{\nu_\mu})$ to $(\nu_e + \bar{\nu_e})$ ratio is significantly less than 2 with energies around 1GeV [1]. Moreover, the observation at Super-Kamiokande shows the clear up-down asymmetry in the zenith angle distribution of ν_μ. This implies that there exists the strong correlation between the disappearance probability of ν_μ in the atmospheric neutrinos and its travel distance. These results are well described by the ν_μ to ν_τ oscillations.

The Super-Kamiokande detector [3] is the world's largest ring imaging water Cherenkov detector. It is located 1000m (2700m water equivalent) below the peak of Mt. Ikenoyama in the Mozumi zinc mine near Kamioka Japan. Fifty kilotons of ultra pure water are held within a stainless steel tank of height 41.4m and diameter 39.3m. The tank is optically separated into two regions, the inner and the outer detectors, by a PMT support structure covered with a white reflector sheet (Tybek), and a black sheet. The anti detector completely surrounds the inner detector and is used to identify incoming and outgoing particles. On the wall of the inner detector, there were 11,146 20inch inward-facing PMTs, which covered 40% of the surface. The anti detector was lined with 1,885 8inch PMTs equipped with 60x60cm wavelength-shifter plates to increased the collection efficiency for Cherenkov photons.

The atmospheric neutrino events at Super-Kamiokande are classified into 4 types. One is the fully-contained (FC) event which has no activity in the outer detector. This means that all the particles generated by the neutrino interaction stop in the inner detector.

If there is at least one particle,typically energetic muon, exiting from the inner detector in an event, it is classified as the partially contained (PC) event. As for the PC events, the energy of neutrinos is higher than those which produces the FC events, averaging ∼10GeV. This kind of events can be identified by using the activity in the outer detector. There are another two types of the event categories, one is the the upward through going muons and the other is the upward stopping muons. These upward going muons are generated by the interactions between the energetic atmospheric neutrinos and the rocks surrounding the detector. The parent neutrino of upward through going muon has a typical energy of 100GeV. As for the upward stopping muons, energy of parent neutrino has roughly same energy of the neutrinos which produce the PC events. By using these four types of events, it is possible to cover very wide energy range of neutrinos from ∼100MeV up to ∼1TeV.

For the oscillation analysis, the FC events were subdivided into two categories by the total energy deposit. One is the so-called sub-GeV sample, whose visible energy

(E_vis, electron equivalent energy) is less than 1.33GeV. The other is the multi-GeV sample, whose visible energy is larger than 1.33GeV. Then, we selected one ring events from the FC sample. After selecting the events, the particle identification were applied and separated into two categories, one is the e-like sample and the other is the μ-like sample. For the events which have more than one ring, the particle identification code was applied to the most energetic ring. If the most energetic ring was identified as μ-like and the E_vis of that ring was greater than 600MeV, that event was classified as the multi-ring μ-like sample. As for the PC samples, all the events were treated as μ-like. Because almost all the exiting particles were muons and muons were generated by the interaction of (anti-)muon neutrinos.

In order to simulate the atmospheric neutrino events for the oscillation analysis, the latest atmospheric neutrino flux by Honda *et al.* was used [4]. In the calculation, the recent measurements of primary cosmic rays were used as input and full 3D simulation has been performed. As the hadronic cascade simulation program to obtain the neutrino flux, DPMJET [5] was used.

The neutrino interaction simulation was updated. The electron scattering data have been used to check the momentum distributions of outgoing leptons of quasi-elastic scattering by changing the momentum distribution of nucleons in oxygen and the potential parameters. Also, the results from the K2K experiment have been used to check the various distributions and to determine the parameters. In order to reproduce the q^2 distributions of leptons, the axial vector mass was set to be 1.1GeV/c^2 for both (quasi-)elastic scattering and single pion productions. To improve the detector simulation program, the light scattering parameters have been adjusted to the measurements with the laser light source. The gain parameters of the outer detector PMT were also calibrated by the recent single photo-electron measurements. As for the analysis part, the improved ring counting method was applied. The fully automated vertex and direction fitting program for the PC events was also developed and applied.

We have analyzed the entire dataset of SK-I, which corresponds to 1489 days of exposure. The numbers of observed contained events and the expectations without oscillation are summarized in the Table 1.

The μ to e double ratio $\left(\frac{\mu-like}{e-like}_{data}/\frac{\mu-like}{e-like}_{MC}\right)$ of the FC sub-GeV events was obtained to be $0.649 \pm 0.016(stat.) \pm 0.051(syst.)$ and double ratio of the multi-GeV and PC samples was obtained to be $0.699 \pm^{0.032}_{0.030}$ $(stat.) \pm 0.083(syst.)$. The number of observed μ-like events was significantly smaller than expected whereas the number of observed e-like events was basically consistent with the expectation. The zenith angle distributions of the contained events are shown in Fig. 1. The μ-like samples show the clear up-down asymmetries. To the contrary, there is no such distortion observed in the zenith angle distributions of e-like event samples.

The obtained neutrino flux of the upward through going muons is $1.70 \pm 0.02(stat.) \pm 0.04(syst.) \times 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ and the flux of the upward stopping muons is $0.41 \pm 0.02(stat.) \pm 0.02(syst.) \times 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The expected values are $1.57 \pm 0.35(theo.) \times 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for the upward through going muons and $0.61 \pm 0.14(theo.) \times 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for the upward stopping muons. The zenith angle distributions of the upward going muon samples are also shown in the Fig. 1.

Table 1. The observed and expected numbers of events for each atmospheric neutrino contained event sample in 1489 days.

	Sub-GeV 1ring e-like	Sub-GeV 1ring μ-like	Sub-GeV multi ring(μ-like)
Data	3353	3227	208
Monte-Carlo	3013.9	4466.9	346.4
	Multi-GeV 1ring e-like	**Multi-GeV 1ring μ-like + PC**	**Multi-GeV multi ring(μ-like)**
Data	746	1562	439
Monte-Carlo	700.4	2098.0	739.4

By using all the samples, the neutrino oscillation parameters assuming 2 flavor oscillation (ν_μ to ν_τ oscillation), were fitted. The obtained allowed regions are shown in Fig. 2. As a result, the χ^2 value for the null oscillation was obtained to be 445.2 for 172 degrees of freedom. The region allowed in the $(\sin^2 2\theta, \Delta m^2)$ plane at 90% C.L. was obtained to be $\sin^2 2\theta > 0.9$ and $1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}(\mathrm{eV}^2)$. The zenith angle distributions with the best fit parameter set $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3}(\mathrm{eV}^2))$ are also shown in the Fig. 1.(preliminary)

2 The SK-II detector

After the accident of the Super-Kamiokande I, we have rebuild the detector successfully. In SuperK-II, all the 20 inch PMTs are equipped with the Acrylic front cover and the FRP vessel. About 5200 20 inch PMTs were used for the inner detector. For the outer detector, we have fully reconstructed and 1885 8inch PMTs with wavelength-shifter plates are placed as same as SK-I. The water filling was completed at the beginning of December 2002 and just after that, we resumed the experiment. Since then, the SK-II detector is running stably.

In SK-II, about 900 channels of the 500MHz FADC boards were also installed to record the analog sum of the every 6 PMTs. In the SK-I era, it was difficult to measure the energy above ~10GeV because of the saturation of the electronics. With these FADCs, it is possible to extend the energy coverage of the detector by using the recorded time evolution of the charge from PMT. Also, the wave form information of charge are also useful to search for the decay electrons from muons and make it possible to improve the detection efficiency.

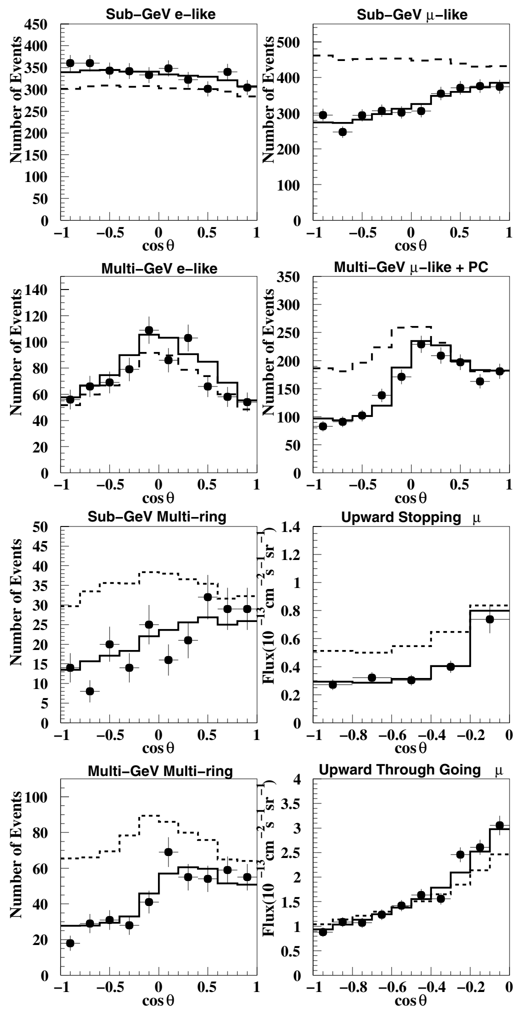

Fig. 1. The zenith angle distributions of atmospheric neutrino samples observed at Super-Kamiokande. The filled circles with the crosses show the data, the dashed lines show the Monte-Carlo predictions without oscillation and the solid lines show the Monte-Carlo predictions assuming ν_μ to ν_τ oscillation. The oscillation parameter set for the predictions with oscillation is $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3}(\mathrm{eV}^2))$

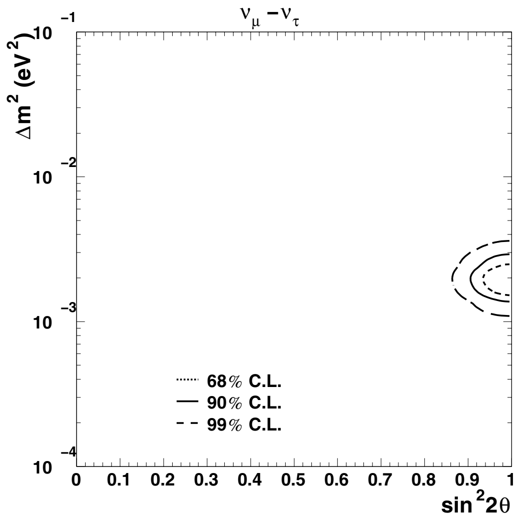

Fig. 2. Allowed regions of oscillation parameters obtained from the atmospheric neutrino observation at SK-I (preliminary). The short dashed line shows the 99% C.L. allowed region, the solid line shows the 90% C.L. allowed region, and the long dashed line shows the 68% C.L. allowed region, respectively (preliminary)

3 Results from the K2K-I experiment

The anomaly found in the atmospheric neutrino observations are well explained by neutrino oscillation. This implies that neutrinos should have non-zero masses. Therefore, the completely independent experiments, which use accelerators as the neutrino source, were proposed to investigate the oscillation and various characteristics of neutrinos.

Among of them, the K2K experiment became the first accelerator-based long baseline neutrino oscillation experiment which covers the parameter region suggested by the atmospheric neutrino experiments. The K2K experiment started in April 1999.

The neutrino beam is produced by a 12GeV proton beam from the KEK proton synchrotron [6,7]. The extracted protons hit the aluminum target and generate the particles. Among of the generated particles, positive charged ones, mainly π^+, are focused by a pair of pulsed magnetic horns [8]. The neutrino beam is produced by the decay of these particles and the generated beam is nearly pure ν_μ beam (98.2% ν_μ, 1.3% ν_e and 0.5% $\bar{\nu}_\mu$) The mean energy of the neutrino is about 1.3GeV.

For the oscillation analysis at K2K, it is essential to know the neutrino flux and energy spectrum. Therefore, the momentum and directional distributions of pions just after the horn have been measured with a gas-Cherenkov detector(PIMON) [9] and used to verify the neutrino beam Monte Carlo simulation. Also, the results from PIMON were used to estimate the errors on the flux predictions at SK. The direction of the neutrino beam should be stable and well under control. Therefore, we placed the muon monitor(MUMON) just after the beam dump and monitor the profile of the muons on a spill by spill basis [9].

To measure the neutrino flux and energy spectrum, There are two different types of the neutrino detectors, 1kt water Cherenkov detector(1KT) and fine grained detectors(FGD), located 300m from the target. The measurements made at these near neutrino detectors(ND) are used not only to determine the flux normalization and energy spectrum but to verify the stability and the direction of the neutrino beam. 1KT is the miniature of the SK detector. Since 1KT is the same type of the detector used in SK, most of the systematic uncertainties are canceled. FGD consists of a scintillating fiber tracking detector(SciFi) [10], a lead-grass calorimeter(LG) and a muon range detector(MRD) [11]. SciFi consists of the 20 layers of scintillating fiber tracking modules and 19 layers of 6cm thick water containers. This detector has very fine position resolution, less than 1mm. MRD consists of the drift chambers and 12 iron plates. In order to get better energy resolution, the upstream 4 iron plates are 10cm thick and the downstream 8 plates are 20cm thick. The total thickness of iron is 2.0m and it is possible to measure muons up to ∼3GeV/c. Because this detector has large coverage and volume, the stability of the neutrino beam direction has been confirmed on daily basis and the stability of the energy spectrum has been confirmed on monthly basis. 1KT has high efficiency for muons below 1GeV/c and full 4π coverage in solid angle. On the other hand, the FGD has high efficiency for measuring muons above 1GeV/c and these two complimentary detectors cover the relevant energy range.

The 1KT data were used to obtain the flux normalization factor. In order to measure the spectrum at the near detector, both of 1KT and FGD data were used. For the neutrino energy spectrum with 1KT, 1 ring μ-like events were selected to enhance the fraction of charged current quasi-elastic(CCQE) interactions($\nu_\mu + \mathrm{n} \rightarrow \mu^- + \mathrm{p}$). By selecting the CCQE events, it was possible to reconstruct the energy of parent neutrinos and to reduce the systematic errors. As for the FGD data, the events occurred in the fiducial volume of SCIFI (5.9 ton) were selected to study the neutrino energy spectrum. Because the target material of SCIFI is mainly water, which is same as the water Cherenkov detectors.

The flux and spectrum of neutrino at SK was obtained by multiplying the so-called Far to Near (F/N) ratio to the measured energy spectrum at the near detectors. This F/N ratio is an energy dependent function, which was derived from our neutrino beam Monte-Carlo simulation. The reliability of our beam simulation has been checked by using the results from the PIMON and the near neutrino detectors.

In order to identify the events which were generated by the neutrinos from KEK, the absolute timing information provided by GPS system were used. At the KEK site, the absolute timing information for each spill were recorded. Also at Super-Kamiokande, the absolute timing information of all the spills were recorded. With those information, the time differences between the beam spill and the trigger timing of the events in SK were calculated to select the events [12]. The detection efficiency of charged current interactions was estimated to be 93%. All of the beam induced events observed within the fiducial volume of SK were used to measure the overall suppression of the neutrino flux. In order to study the spectrum distortion, 1 ring μ-like events are selected. Then, assuming CCQE interaction and ignoring the Fermi momentum, the energy of the parent neutrino was calculated by using the observed momentum and direction of the muon as follows:

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

where m_N, E_μ, m_μ, P_μ and θ_μ are the nucleon mass, the muon energy, the muon mass, the muon momentum and the muon scattering angle relative to the neutrino beam direction, respectively. This reconstructed neutrino energy (E_ν^{rec}) was used to search for the distortion in the neutrino energy spectrum.

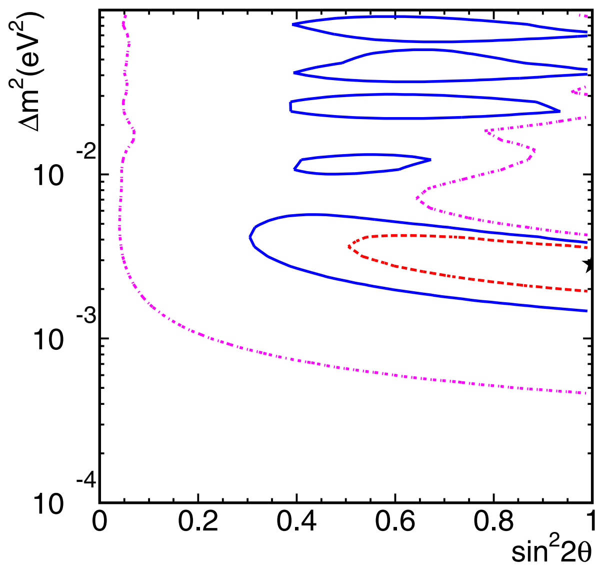

Fig. 3. Allowed regions of oscillation parameters from K2K-I. Dashed, solid and dot-cashed lines are 68.4%, 90% and 99% C.L. contours, respectively. The best fit point is indicated by the star

The K2K-I (with SK-I detector) oscillation analysis uses the data taken from June 1999 to July 2001, corresponding to 4.8×10^{19} protons on target(POT). After applying the cuts to the Super-Kamiokande data, 56 events passed the selection(N_{obs}) and the expected number of background is about 10^{-3} events. As described, only 1 ring μ-like events were used for the oscillation analysis, which utilize the energy spectrum, to increase the fraction of CCQE interactions. At the same time, the data taken in June 1999 were excluded. Because the diameter of the target and the horn current were different at that time and thus, the energy spectrum was also different. The data in June 1999 correspond to 3.1×10^{18} POT and the fraction to the total POT was 6.5%. The number of 1 ring μ-like events excluding the data taken in June 1999 was 29. The expected number of events at SK without oscillation was estimated to be $80.1^{+6.2}_{-5.4}$, which should be compared to the $N_{obs} = 56$. The major contributions to the errors on the expected number of events were the uncertainties of the F/N ratio($^{+4.9}_{-5.0}$%) and the normalization error(±5%) dominated by the uncertainties of the fiducial volumes at 1KT and SK. The search for the oscillation parameters were performed by the maximum-likelihood method [13]. The obtained allowed regions are shown in Fig. 3, and these regions are consistent with the results from the atmospheric neutrino measurements. The best fit points in the physical region were found to be at $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.8 \times 10^{-3}\mathrm{eV}^2)$. The E_ν^{rec} distribution is shown in Fig. 4 together with the expected distributions for the best fit oscillation parameters and the expectation without oscillations. The probability to observe only 56 events and the observed energy spectrum due to statistical fluctuation was less than 1%.

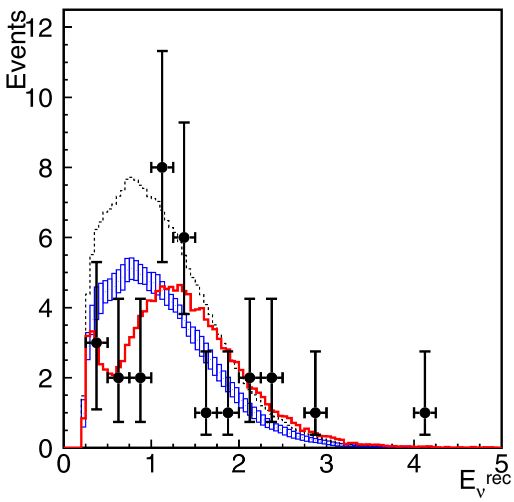

Fig. 4. The reconstructed neutrino energy(E_ν^{rec}) distribution for 1 ring μ-like sample. Points with error bars are data. Box histogram is expected spectrum without oscillation, where the height of the box is the systematic error. These histograms are normalized by the observed number of events(29). The solid line is the best fit spectrum. The dashed line shows the expectation with no oscillation normalized to the expected number of events(44)

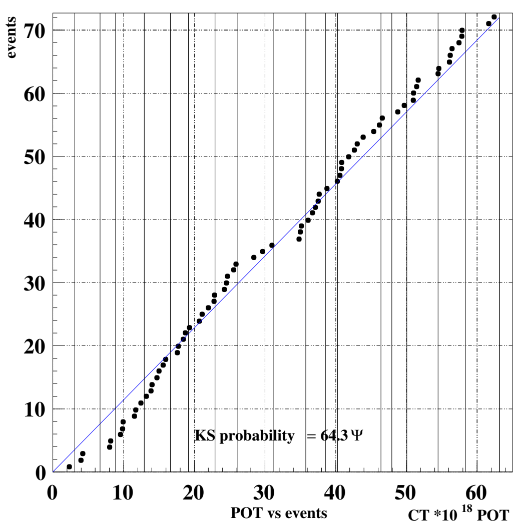

Fig. 5. The number of protons on target versus number of fully contained events observed at SK

4 The K2K-II experiment

The K2K-II experiment, which uses SK-II detector was started on December 2002. Since then, the data taking was very stable and no serious problems were found. The accumulated number of protons used for the analysis was 6.3×10^{19} at the end of April 2003. As shown in Fig. 5, the event rate ([Observed number of events]/[number of protons on target]) was obtained to be consistent.

This summer, we have replaced the lead-grass calorimeter with a new full active solid scintillator tracking detector (SciBar). This detector consists from about 15000 of the fine segmented extruded scintillator. The dimension of each scintillator is $2.5 \times 1.3 \times 300 cm^3$. These scintillators are read out by the wavelength shifting fiber equipped with 64ch multi anode PMTs. The SciBar detector can measure the momentum of the particles by range and energy deposit. The momentum threshold of the proton track is expected to be $\sim$ 350MeV/c and it makes us possible to detect the CCQE events with higher efficiency than before. The momentum resolution of the proton, whose momentum is from 500MeV/c to 1GeV/c, is expected to be $\sim$ 10%. By measuring the energy deposits in the detector, it is possible to identify the particle types (protons from π and μ). The p/π miss identification probability was estimated to be less than 20% at 1.2GeV from the prototype beam tests. The detector is running very stably since October 2003 and accumulating the events.

5 Summary

This time, the entire SK-I atmospheric neutrino data samples were analyzed. As a preliminary result, the region allowed in the $(\sin^2 2\theta, \Delta m^2)$ plane at 90% C.L. was obtained to be $\sin^2 2\theta > 0.9$ and $1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}(\mathrm{eV}^2)$. The rebuild of the Super-Kamiokande detector was successfully finished and running since December 2002. The K2K-II experiment also started from December 2002 and stably running. Also, the new detector called SciBar was installed at KEK and accumulating the data.

References

1. K.S. Hirata et al.: Phys. Lett. B **205**, 416 (1988); Y. Fukuda et al.: Phys. Lett. B **335**, 237 (1994); R. Becker-Szendy et al.: Phys. Rev. D **46**, 3720 (1992); W.W.M. Allison et al.: Phys. Lett. B **449**, 137 (1999)
2. Y. Fukuda et al.: Phys. Lett. B **433**, 9 (1998); Y. Fukuda et al.: Phys. Lett. B **436**, 33 (1998); Y. Fukuda et a.: Phys. Rev. Lett. **81**, 1562 (1998)
3. Y. Fukuda et al.: NIM A **501**, 418 (2003)
4. M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa: Phys. Rev. D **64**, 053011 (2001)
5. J. Ranft: arXiv:hep-ph/9911232
6. M. Ieiri et al.: Proc. 1st Asian Pacific Accelerator Conference, 579 (1998)
7. H. Sato: Proc. Particle Accelerator Conference (1999); K. Takayama: ICFA Beam Dynamics Newsletter No.20, (1999)
8. Y. Yamanoi et al.: Proc. 15th International Conference on Magnet Technology (1997); Y. Yamanoi et al.: IEEE Transactions on Applied Superconductivity **10**, 252 (2000); Y. Suzuki et al.: Proc. International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS) (1997); Y. Suzuki et al.: Proc. of ICALEPCS (1999)
9. T. Maruyama, P.D. Thesis: Tohoku University (2000)
10. A. Suzuki et al.: NIM A **453**, 165 (2000)
11. T. Ishii et al.: NIM A **482**, 244 (2002)
12. S.H. Ahn et al.: Phys. Lett. B **511**, 178 (2001)
13. S.H. Ahn et al.: Phys. Rev. Lett. **90**, 041801 (2003)