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STATUS OF THE K2K EXPERIMENT

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ABSTRACT

Current status of the K2K (KEK to Kamioka) long-baseline neutrino-oscillation experiment is presented.

1 Introduction

The K2K experiment [1, 2, 3, 4] is the first long-baseline neutrino-oscillation experiment with hundreds of km distance using an accelerator-based neutrino beam. The nominal sensitive region in the neutrino-oscillation parameters is $\Delta m^2 > 3 \times 10^{-3}\mathrm{eV}^2$. This covers the parameter region suggested by the atmospheric neutrino anomaly observed by several underground experiments, [5, 6, 7] and confirmed by Super-Kamiokande(SK). [8]

An overview of the K2K experiment is as follows. Almost a pure wide-band ν_μ beam from π^+ decays is generated in the KEK 12-GeV/c Proton

Synchrotron and a neutrino beam-line, and is detected in SK at a distance of 250km. Various beam monitors along the beam line and two different types of front detectors (FDs) are also constructed at the KEK site. The FDs are a 1kt water Cherenkov detector (1KT), which is a miniature of the SK detector, and a so-called fine-grained detector (FGD), which is composed of a scintillating fiber tracker (SFT) [9], trigger counters (TRG), lead glass counters (LG) and a muon range detector (MRD). Since the design and performance of these components as well as the properties of the neutrino beam were already described precisely in previous articles [3, 4], they are not discussed here.

The K2K experiment was successfully started in early 1999, and data were recorded in January to March, and May to June in 2000. The total data-taking period in 1999 and 2000 was 112.2 days. The accumulated beam intensity was 22.9×10^{18} protons on target (p.o.t.), which is about 20% of the goal of the experiment, 10^{20} p.o.t.

2 Study of Neutrino beam properties in KEK site

The characteristics of the neutrino beam in the KEK site were examined using FDs and beam monitors. In this section, the present status of analyses on (1)the neutrino beam direction, (2)the neutrino beam intensity and its stability, (3)the ν_e/ν_μ ratio, and (4)the neutrino energy spectrum are presented.

2.1 Neutrino beam direction

The neutrino beam-line was constructed with a GPS position survey [10], and the alignment of the beam-line, FDs and SK is better than 0.1 mrad. The neutrino beam direction relative to the beam-line was measured with the muon monitors and MRD independently.

The muon monitor consists of a segmented ionization chamber and an array of silicon pad detectors, which are located downstream of the beam dump. Their position resolution is about 2cm, corresponding to an angular resolution of 0.1mrad. Because ν_μ and muons originate in the same pion decay in the decay volume, the ν_μ beam direction can be examined from the profile center of the muon beam. The time variation of the profile center is plotted in Figure 1(a). The direction of the muon beam agrees with the beam-line within 1 mrad.

The neutrino beam direction is also measured using neutrino interactions in MRD. The distribution of the vertex position is plotted in Figure 1(b). The center of the beam profile agrees with the SK direction within 1 mrad. The time variation of the beam center, also plotted in Figure 1(c), shows that the steering of the beam direction is stable, and is consistent with the results from the muon monitors.

The energy spectrum of the neutrino beam is expected to be uniform within 3 mrad from the center of the beam axis. On the other hand, the angular acceptance of the SK detector from the KEK site is about 0.2 mrad. Therefore, the adjustment of the neutrino beam direction, (< 1 mrad), is sufficient.

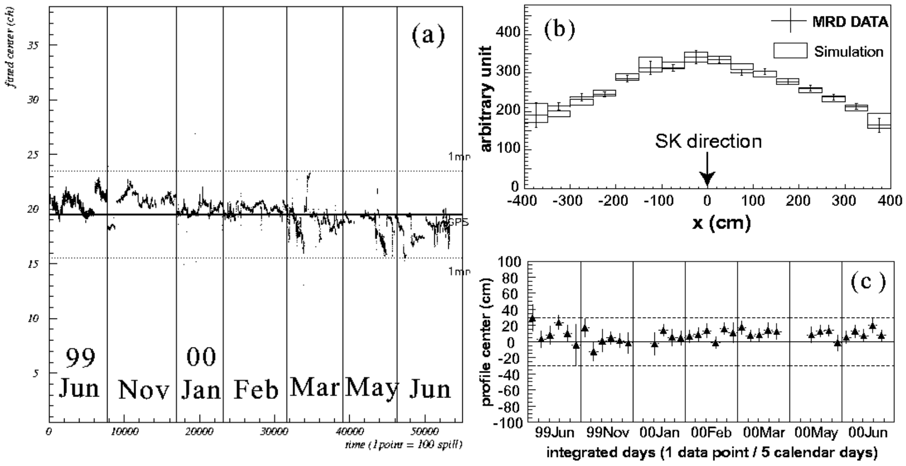

Figure 1: *Examination of the neutrino beam direction. They are (a) time variation of the beam direction from the muon monitors, (b) vertex distribution of neutrino interactions in MRD, and (c) time variation of the profile center. In (a) and (c), the SK direction and 1 mrad off axis are shown by the solid and dashed lines, respectively.*

2.2 Neutrino beam intensity and its stability

The neutrino beam intensity can be estimated from absolute numbers of the neutrino interactions in 1KT, SFT and MRD, and a comparison with Monte-Carlo expectations.

The Monte-Carlo simulation is based on GEANT [11] with a detailed description of the materials and magnetic fields in the target region and the decay volume. It uses as input a measurement of the primary-beam intensity and profile at the target. Primary proton interactions on aluminum are modeled with a parameterization of hadron production data [12]. Other hadronic interactions are treated by GEANT-CALOR [13].

The number of neutrino interactions in 1KT, SFT and MRD are consistent with each other, and agree with the Monte-Carlo expectations within the systematic errors.

The stability of the beam intensity is contaneously measured from the neutrino event rate in MRD because of its large statistics. The time variation of the neutrino interactions in MRD is shown in Figure 2. The neutrino beam

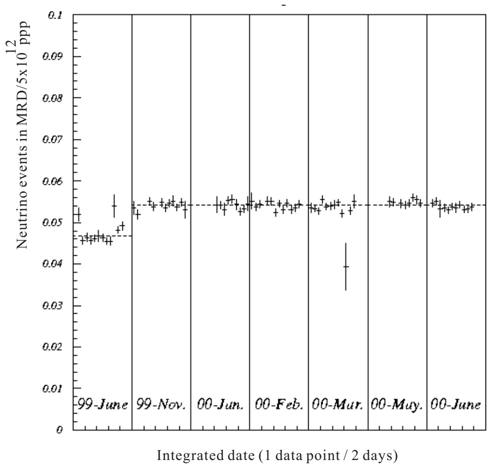

Figure 2: *Time variation of the neutrino event numbers in MRD. The denominator of the vertical axis,* 5×10^{12}*ppp (protons per pulse) is a nominal beam intensity in one spill. The June 99 data is smaller than the other periods because the current of the magnetic horn was different. The neutrino beam intensity is stable within the statistical errors.*

intensity is stable within a few %. Although the statistics is poor, the neutrino event rates in SFT and 1KT are also stable.

2.3 ν_e/ν_μ ratio

The ν_e/ν_μ ratio of the neutrino beam at the KEK site was measured by 1KT and FGD. The idea of the measurements is given in Ref.4. An analysis with 1KT is still under way, and no numerical result has been obtained yet. On the other hand, a very preliminary result with FGD is reported to be $(1.8 \pm 0.6^{+0.8}_{-1.0})\%$, [14] where the expectation based on a Monte-Carlo simulation is 1.3%. The original neutrino beam has been proved to be almost a pure ν_μ beam.

2.4 Neutrino energy spectrum

The neutrino energy spectrum was studied with FGD and the pion monitor, and compared with the Monte Carlo expectation.

To determine the neutrino energy spectrum from neutrino interactions in the FGD, quasi-elastic interactions of muon neutrinos, $\nu_\mu N \to \mu N'$, in SFT were employed. This is because most of the neutrino energy is transfered to

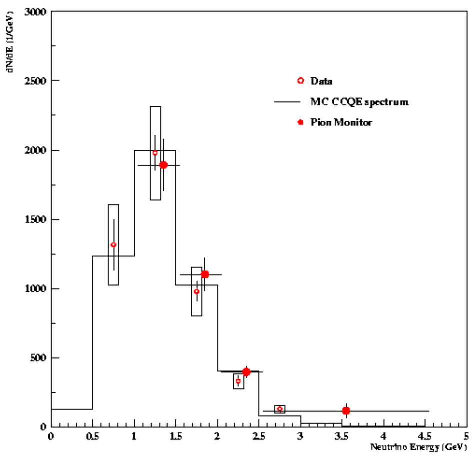

Figure 3: *Neutrino energy spectrum in FGD. They are (∘) measurement from the quasi-elastic interactions in SFT, (•) calculation based on a pion monitor measurement, (−) Monte-Carlo simulation.*

the muons in quasi-elastic interactions and the neutrino energy can be directly calculated from the energy and travel direction of the secondly muons. The muon energy distribution obtained from quasi-elastic interactions in SFT is shown in Figure 3

The pion monitor was a gas Cherenkov detector with a spherical mirror and R-C318 gas. The kinematic distribution of the pion beam was calculated from the intensity and shape of the Cherenkov light in the focus plane. The energy spectrum and profile of the neutrino beam can be calculated from a simple kinematics of the pion decay. The neutrino energy distribution in FGD calculated from the pion monitor data is shown in Figure 3.

The expected neutrino energy spectrum was also calculated by the Monte Carlo simulation described above. The result is also plotted in Figure 3. The agreement of 3 distributions is excellent.

Measurements of the various neutrino-beam characteristics at the KEK site agree with the Monte-Carlo expectations, which ensures that the comparison of neutrino events in SK with expectations based on the same Monte-Carlo simulation is relaiable.

3 Observation in Super-Kamiokande

To obtain beam-correlated fully contained neutrino interactions, an event selection similar to an atmospheric neutrino analysis [8] was applied; the time correlation with the neutrino beam was then examined. Figure 4 shows the

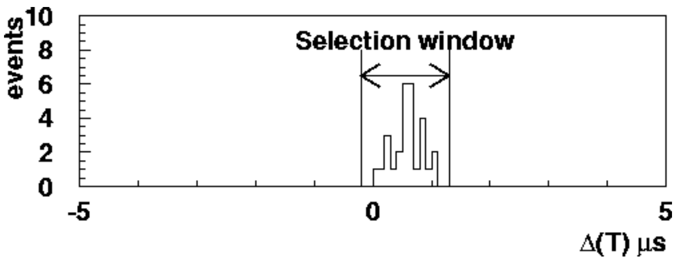

Figure 4: *Time correlation between the neutrino beam period and SK events which are selected by the standard atmospheric neutrino analysis. Events in the 1.5 μsec gate are finally selected.*

time difference between the neutrino beam and the events obtained from atmospheric neutrino selection.

Considering the neutrino beam duration (1.1μsec) and accuracy [16] of the absolute time determination ($< 0.2\mu$sec), events within a 1.5μsec time window covering the neutrino beam period were selected. A total of 28 fully-contained events were found in 22.5kt of the fiducial volume. Details of the neutrino events are summarized in Table.1. Because the expected atmospheric neutrino background in the fiducial volume within the neutrino beam period was calculated to be 6×10^{-4} events, the 28 events in the fiducial volume are a clear signal of neutrinos from KEK.

4 Oscillation analysis

Strategies concerning oscillation searches at K2K are summarized as follows. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation can be examined by a disappearance of neutrino events in SK, because the energy of the neutrino beam is smaller than the τ production threshold. In addition, the neutrino energy spectrum in SK should be distorted in the case of oscillation, because the oscillation probability is a function of the neutrino energy.

An examination of the $\nu_e \leftrightarrow \nu_\mu$ oscillation is an appearance search. A possible excess of ν_e events in SK is direct evidence of the $\nu_e \leftrightarrow \nu_\mu$ oscillation, because the original beam from KEK is almost pure ν_μ, and because the particle identification capability in SK is excellent. [8, 15] In addition, the total neutrino

Table 1: *Number of neutrino events in SK. Expectations based on the event rate at 1KT, SFT, and MRD are also shown*

Event Category	SK data	Expected		
		(1KT)	(SFT)	(MRD)
Single ring events	15	22.9		
(e-like)	14	20.9		
(μ-like)	1	2.0		
Multi ring events	13	14.9		
Total	28	$37.8^{+3.5}_{-3.8}$	$37.2^{+4.6}_{-5.0}$	$41.0^{+6.0}_{-6.6}$

interactions should be almost equal to the expectation with a null oscillation, because ν_e also interacts through charged-current interactions.

The following three subsections discuss the present status of the data analyses about three subjects, i.e. (1)absolute event number, (2)ν_e/ν_μ ratio, and (3)distortion of the neutrino energy spectrum.

4.1 Absolute event numbers

The expected event numbers in SK can be calculated from the neutrino event rate in FDs, and an extrapolation from the FDs to SK. The numbers obtained in 1KT, SFT, and MRD are used for the event rate in the FDs, as reported in *2.2*. The extrapolation is calculated from the neutrino beam intensity and its angular divergence obtained from the pion monitor. The expectations based on the data from the FDs are $37.8^{+3.5}_{-3.8}$(1KT), $37.2^{+4.6}_{-5.0}$(SFT), and $41.0^{+6.0}_{-6.6}$(MRD). These results are consistent with each other. We used the numbers from 1KT as an official number because of its small systematic errors.

The statistical probability that the observation is equal to, or smaller than, 28, where the expectation is $37.8^{+3.5}_{-3.8}$, is 9.6%. The observation is slightly smaller than the expectation, but it is not statistically significant.

4.2 ν_e/ν_μ ratio

The single ring events in SK are judged μ-like or e-like by the standard particle-identification program [15] developped for the SK atmospheric neutrino analysis. As shown in Table 1, the number of μ-like and e-like events are 14 and 1, respectively. Since the expected e-like events was calculated to be 2.0, there is no excess in the number of e-like events. The reduction of the total event numbers as well as the agreement of the ν_e events indicate that a pure $\nu_e \leftrightarrow \nu_\mu$ oscillation is not the solution. However, more statistics is needed to give a conclusion. The possibilities of the 3 flavor oscillation (ν_e, ν_μ and ν_τ) must also be studied. [14]

4.3 Distortion of neutrino energy spectrum

Neutrino energy spectrum calculated from 14 single ring μ-like events are shown in Figure 5 together with an expectation obtained from the pion monitor data and a Monte-Carlo simulation. At present, the statistics is too poor to examine the neutrino energy spectrum.

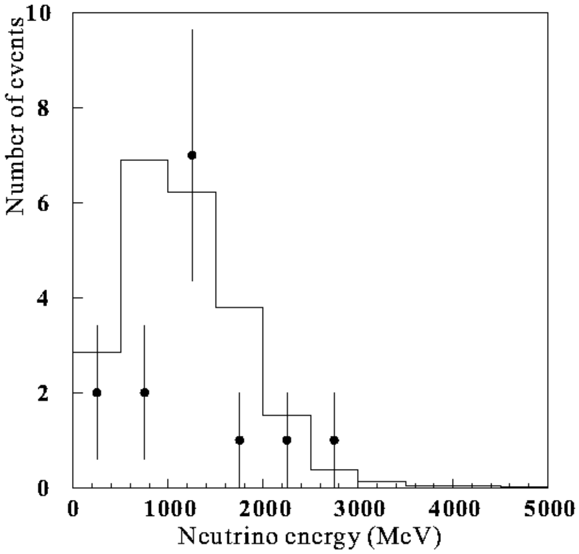

Figure 5: *Neutrino energy distribution for 14 single ring μ-like events in SK. Monte Carlo expectation for no oscillation is also shown.*

5 Summary

The K2K long-baseline neutrino-oscillation experiment has been successfully operated since 1999. By the end of 2000, a total intensity of 22.9×10^{18} protons on target were accumulated, which is about 20% of the goal of the experiments. A total of 28 fully-contained neutrino interactions in the 22.5kt of the fiducial volume of the Super-Kamiokande detector were observed, where the expectation based on the data from the Front Detectors is $37.8^{+3.5}_{-3.8}$. The statistical probability that the observation is equal to or smaller than 28 for the expectation of $37.8^{+3.5}_{-3.8}$ is 9.6%. Although the observation is slightly smaller than the expectation and it is faint evidence of neutrino oscillations, the descrepancy is still within the statistical error, and is not significant. Oscillation analyses based on ν_e/ν_μ ratio and distortion of the neutrino energy spectrum are also in progress.

References

1. K.Nishikawa *et al.*, KEK-PS proposal, Nucl.Phys.B (Proc. Suppl.) 59,289

(1997).

2. S.H.Ahn *et al.* (K2K collaboration), submitted to Phys.Rev.Lett, hep-ex/0103001 (2001).

3. Y.Oyama, hep-ex/9803014 (1998).

4. Y.Oyama, hep-ex/0004015 (2000).

5. K.S.Hirata *et al.*, Phys.Lett.B205, 416 (1988);
K.S.Hirata *et al.*, Phys.Lett.B280, 146 (1992);
E.W.Beier *et al.*, Phys.Lett.B283, 446 (1992);
Y.Fukuda *et al.*, Phys.Lett.B335, 237 (1994);
S.Hatakeyama *et al.*, Phys.Rev.Lett 81,2016(1998).

6. D.Casper *et al.*, Phys.Rev.Lett. 66, 2561 (1991);
R.Becker-Szendy *et al.*, Phys.Rev. D46, 3720 (1992).

7. W.W.M.Allison *et al.*, Phys.Lett.B391, 491 (1997).

8. Y.Fukuda *et al.*, Phys.Lett.B 433,9 (1998);
Y.Fukuda *et al.*, Phys.Lett.B 436,33 (1998);
Y.Fukuda *et al.*, Phys.Rev.Lett. 81,1562 (1998);
Y.Fukuda *et al.*,Phys.Rev.Lett. 82,2644 (1999).

9. A.Suzuki *et al.*, Nucl.Instrm.Meth. A453, 165 (2000).

10. H.Noumi *et al.*, Nucl.Instrm.Meth. A398, 399 (1997).

11. R.Brun *et al.*, CERN DD/EE/84-1 (1987).

12. J.R.Sanford and C.L.Wang, BNL AGS internal reports No.BNL11299 and No.BNL11479 (1967);
C.L.Wang, Phys.Rev.Lett. 25, 1068 (1970);
Y.Cho *et al.*, Phys.Rev. D4, 1967 (1971);
J.G.Asbury *et al.*, Phys.Rev. 178, 2086 (1969);
G.J.Marmer *et al.*, Phys.Rev. 179, 1294 (1969);
G.J.Marmer and D.E.Lundquist, Phys.Rev. D3, 1089 (1971);
J.V.Allaby *et al.*, CERN-TH-70-12 (1970).

13. T.A.Gabriel *et al.*, ORNL/TM-11185;
C.Zeitnitz and T.A.Gabriel, Nucl.Instrm.Meth. A349, 106 (1994).

14. M.Yoshida, Ph.D thesis, University of Osaka (2001). Note that numbers in this article are very preliminary and are not official results of the collaboration.

15. S.Kasuga *et al.*, Phys.Lett. B374, 238 (1996).

16. H.G.Berns and R.J.Wilkes, IEEE Nucl.Sci. 47, 340 (2000).