RESULTS FROM K2K

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for

THE K2K COLLABORATION[1)]

ABSTRACT

The K2K Experiment (KEK to Kamioka, KEK E362) has successfully demonstrated the effectiveness of the long-baseline technique for the study of neutrino oscillations. A neutrino beam generated by the KEK 12 GeV proton synchrotron is directed through a near detector suite, 300m from the proton beam target, toward the Super–Kamiokande detector, 250 km distant. The investigation of neutrino oscillations suggested by atmospheric neutrino observations is now well under way. In the data available at time of writing, 28 neutrino events have been detected in coincidence with the expected arrival time of the beam in the 22.5 kt fiducial volume of Super–Kamiokande. The expected number of events, in the absence of neutrino oscillations, is $37.8^{+3.5}_{-3.8}$, derived using measurements of neutrino interactions in a near detector and extrapolation using a beam simulation validated by a measurement of pion kinematics after production and focusing. The background is of order 10^{-3} events.

1. Introduction

Studies of atmospheric neutrinos[2,3,4)] find a significant path-length dependence in the observed flux of atmospheric ν_μ. The interpretation of these results provides not only strong evidence of $\nu_\mu \rightarrow \nu_\tau$ (or $\nu_\mu \rightarrow \nu_{sterile}$) oscillations[5,6)] but also evidence for different mixing properties in the lepton and quark sectors. The probability of flavor oscillation can be written in terms of the mixing angle θ and the difference of the squared masses Δm^2 (eV^2) in the two–flavor approximation as $P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$. where E_ν(GeV) is the neutrino energy, and L(km) is the distance from its point of production in the upper atmosphere. K2K, the KEK to Kamioka long-baseline neutrino experiment (KEK experiment E362) is the first accelerator-based experiment with hundreds of km neutrino path length. The KEK 12 GeV proton synchrotron generates an intense, nearly pure muon neutrino beam (98.2% ν_μ, 1.3% ν_e, and 0.5% $\overline{\nu}_\mu$) has an average $L/E_\nu \approx 200 (L = 250\text{km}, \langle E_\nu \rangle \approx 1.3\text{GeV})$. Properties of the neutrino beam are sampled just after production, and the kinematics of parent pions are also measured *in situ* to extrapolate the measurements at the near detector to the expectation at the far detector.

K2K focuses on the study of neutrino oscillations in ν_μ disappearance, as observed in atmospheric neutrinos, and on the search for $\nu_\mu \rightarrow \nu_e$ oscillation with well under-

stood flux and neutrino composition in the $\Delta m^2 \geq 2 \times 10^{-3}\mathrm{eV}^2$ region. This paper describes the design and performance of various components of the long-baseline neutrino experiment (Fig 1). It also reports results on event rates, using approximately 100 days of data taken from June 1999 to June 2000, corresponding to a beam exposure equivalent to 2.29×10^{19} protons on target (*pot*).

2. Beam

The K2K neutrino beam[7,8] is a double-horn wide band ν_μ beam. The primary beam for K2K is 12 GeV (kinetic energy) protons from the KEK proton-synchrotron (KEK-PS)[9]. Every 2.2 s, approximately 6×10^{12} protons in nine bunches are fast-extracted in a single turn, making a 1.1 μs beam spill. The proton beam is focused onto a 30 mm diameter, 66 cm long aluminum target embedded in the first horn. Both horn magnets are operated at 250 kA[10]. The horn system was designed to maximize the efficiency for focussing positive pions produced in proton-aluminum interactions, while sweeping out negative secondary particles.

Between the horn system and the 200 m long decay volume where the pions decay to ν_μ and muons, the pion monitor (PIMON)[11], a gas-Cherenkov detector of novel design, can be temporarily inserted in the beam to measure the kinematics of the pions after their production and subsequent focusing. Once the kinematic distribution of pions after production and focusing is known, it is possible to predict the ν_μ spectrum at any distance from the source.

PIMON measurements are made at seven different indices of refraction, controlled by gas pressure, to give additional information on the velocity distribution of the particles. The indices of refraction are chosen so that the corresponding pion momentum interval is 400 MeV/c. The two-dimensional distribution of pion momentum versus angle is derived by unfolding the photon distribution data with various indices of refraction. To avoid background from 12 GeV primary protons, the index of refraction is adjusted below the Cherenkov threshold of 12 GeV protons. As a consequence, results are available only for $\mathrm{P}_\pi \geq 2\mathrm{GeV/c}$, giving the ν_μ energy spectral shape above 1 GeV. These data are used to validate the beam simulation, as described below.

Following the decay volume, an iron and concrete beam dump stops essentially all charged particles except muons with an energy greater than 5.5 GeV. Downstream of the dump there is a muon monitor system (MUMON)[11] consisting of a segmented ionization chamber and an array of silicon pad detectors. This monitors the residual muons spill-by-spill to check beam centering and muon yield. The ionization chamber consists of 5 cm wide strips covering roughly $2 \times 2\mathrm{m}^2$ area with separate planes for horizontal and vertical read-out. The 26 silicon pads, each of $\sim 10\mathrm{cm}^2$ transverse area, are distributed through a $3 \times 3\mathrm{m}^2$ area.

The beam-line was aligned by an engineering survey using the Global Positioning System (GPS)[7]. The precision of this survey defines the line from the target to

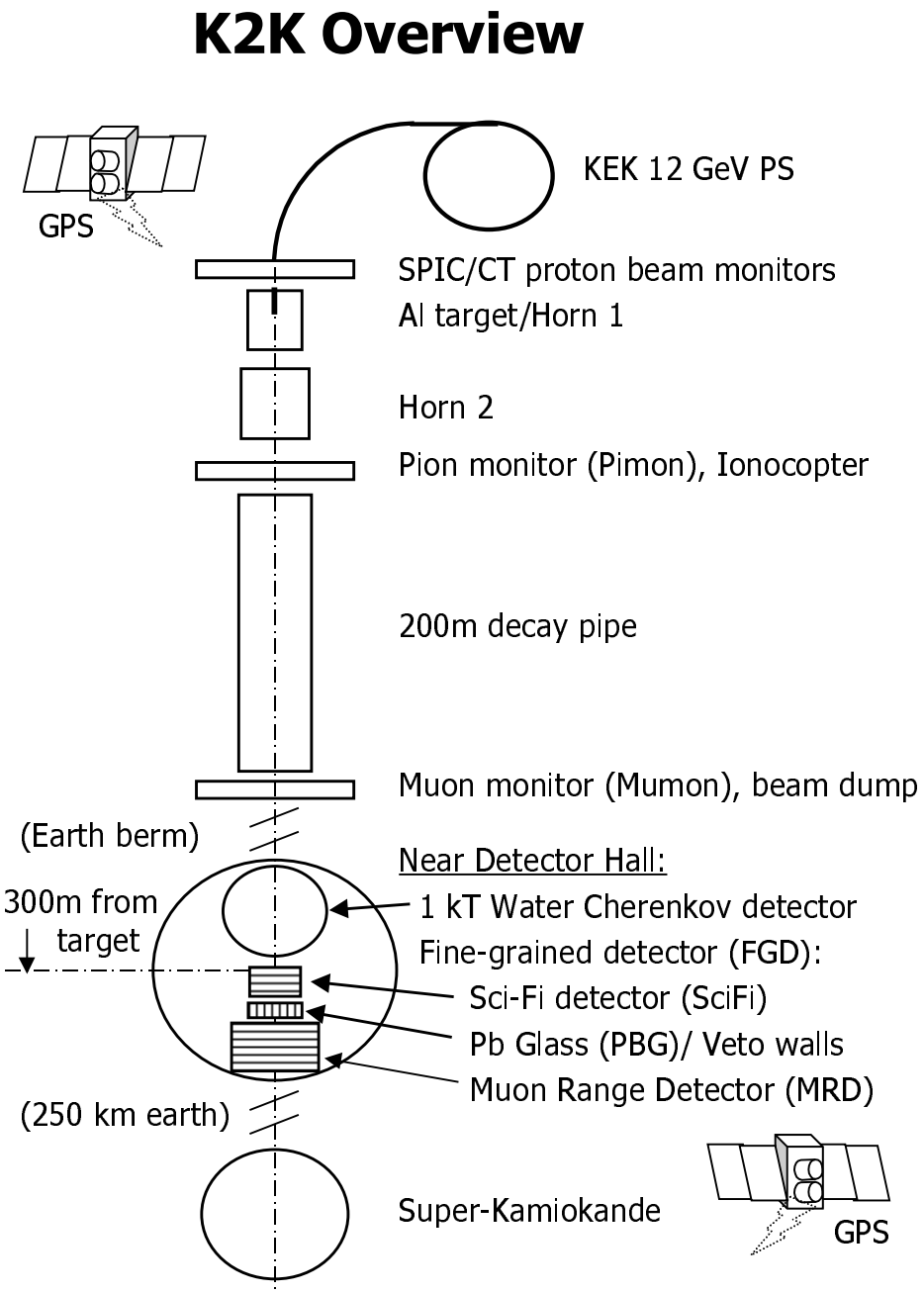

Figure 1: Overview of the K2K Experiment (not to scale).

the far detector to better than 0.01 mr, and the construction precision for the near site alignment is better than 0.1 mr. The predicted neutrino spectrum at 250 km is approximately constant over nearly 1 km, giving a required accuracy of 3mr for the pointing of the beam.

The steering and the monitoring of the ν_μ beam are carried out based on data from the muon monitor following the beam decay volume. The ν_μ and muons in the decay volume originate from the same pion decays, so the measured center position of the muon profile is correlated with the ν_μ beam direction. The r.m.s. muon profile width is $\sim$ 90cm for both the horizontal and vertical directions. These measurements are used in tuning the beam direction at the start of every beam period, usually once per month. Since there is a magnetic field in and around the target, the direction of the secondary pions, which determines the direction of decay ν_μ and muons, is highly sensitive to the position of the primary proton beam at the target. A 1 mm displacement of protons at the target face causes roughly 0.5 mr deflection in the opposite direction for muons observed by the muon monitor at the beam dump[12]. During beam tuning, the primary proton position at the target is adjusted so that the muon profile is centered on the SK direction within 0.1 mr. The center of the muon profile is observed to be stable spill-by-spill within $\pm$1mr in each dimension throughout the whole experimental period. The muon yield, normalized to proton intensity measured by a current transformer, is stable spill-by-spill within a measurement uncertainty of 2%. This measurement is directly correlated with the stability of the horn-focused ν_μ beam.

3. Near Detector

The near detector suite is located in an underground experimental hall approximately 300 m from the pion production target, with approximately 70 m of earth eliminating virtually all prompt beam products reaching the beam stop other than neutrinos.

A one kiloton water Cherenkov detector (1kt) uses the same technology and analysis algorithms as the far detector, Super-Kamiokande. It has 680 20" photomultiplier tubes (PMTs) on a 70 cm grid lining a 8.6m diameter, 8.6m high cylinder. The PMTs are of the same type, and their geometrical arrangement is the same as in Super–Kamiokande, giving identical fractional-area photo-cathode coverage (40%). Because the 1kt detector has the same target material, PMTs, and basic geometry as the Super-Kamiokande detector, and uses the same event identification and analysis methods, many potential biases and systematic error sources cancel between the two detectors. For this reason, the 1kt detector is used as the primary source of data on event rates at the near site. Other components of the near detector suite are used to provide independent checks on the event rates, in addition to supplementary data on interaction characteristics and rates.

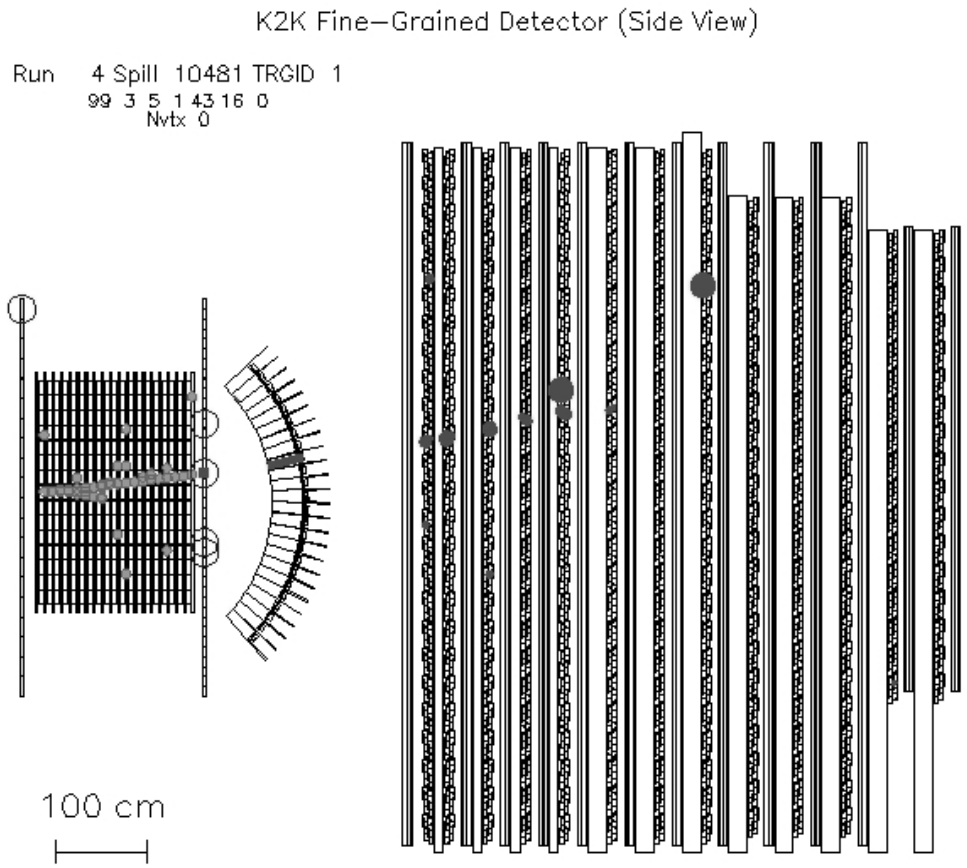

Figure 2: The K2K Fine-Grained Detector system: from left, veto wall, SciFi detector, veto wall, Pb–glass detector, Muon Range Detector.

The ν_μ interaction rate at the near site is measured in the 1kt detector via Cherenkov light emitted from produced charged particles. The vertices and directions of Cherenkov rings are reconstructed using the same methods as in Super-Kamiokande[3]. In the 1kt, however, an analog sum of signals from all PMTs is recorded by a flash–ADC (FADC) to select beam spills with only one event. The definition of events per spill is the number of peaks in the FADC signal with >1000 collected photo-electrons (p.e.) ($\approx$100MeV deposited energy). The average number of events observed in the full detector is about 0.2/spill including entering background events due to cosmic rays or ν_μ induced muons from upstream (about 1.5% of events in the fiducial volume defined below). Thus ≥ 2 events occur in about 10% of spills with ≥ 1 event. Neutrino interactions are selected by requiring: a) no detector activity in the 1.2μs preceding the beam spill; b) only a single event observed in the FADC peak search for that spill; c) reconstructed vertex within the 25–ton fiducial volume defined by a 2 m radius, 2 m long cylinder along the beam axis, in the upstream side of the detector. The efficiency of the 1kt detector for detecting CC interactions is 87% and for neutral current inelastic ($\mathrm{NC_{inel}}$) interactions it is 55%. The expected ratio of CC to $\mathrm{NC_{inel}}$ gives an overall efficiency of 72%. The main source of inefficiency is the 1000 p.e. threshold for the peak search in the FADC signal. The neutrino interaction simulator used for efficiency calculations is the same as that used in all SK analyses. The number of ν_μ events in the 1kt is corrected for spills with multiple events. The average ν_μ event rate per proton hitting the target is 3.2×10^{-15}. Correcting for efficiencies, relative target masses, and detector live times, the expected ν_μ signal at the far site is estimated by applying the extrapolation from the experimentally validated beam simulation.

Following the 1kt detector is a Fine-Grained Detector (FGD) consisting of a scintillating fiber tracking detector with water target layers, a set of veto counter layers, a Pb-glass detector, and an iron muon track detector (Fig. 2).

The scintillating fiber detector (SciFi)[13] has detailed tracking capability, and allows identification of different types of interactions such as quasi-elastic or inelastic. The SciFi detector consists of 19 planes of water target tanks, interleaved with scintillating fiber modules spaced 9cm apart. The track sensitive modules are made from 0.75mm scintillating fiber, with two layers each in the horizontal and vertical directions for each fiber module. Active area is 2.6m square. Fibers are bundled and read out by CCD cameras after optical amplification by image intensifiers. Each layer has a set of fiducial fibers which can be illuminated for calibration and efficiency checks. In addition, cosmic ray data are accumulated between beam exposures, providing additional alignment and calibration data. Thin-walled aluminum target tanks are used to ensure that most of the SciFi detector's mass is in the form of water, allowing direct comparison with results from the 1kt and Super-Kamiokande detectors.

Downstream of the SciFi there is a lead glass array for tagging electromagnetic showers. A muon range detector (MRD)[14], measures the energy, angle, and produc-

tion point of muons from charged current (CC) ν_μ interactions. It covers $7.6 \times 7.6\mathrm{m}^2$ transverse area with four 10-cm iron plates, followed by eight 20-cm iron plates, all interleaved with drift tubes. The total mass is 915 tons. The 6632 drift tubes each has $5\times7\mathrm{cm}^2$ cross section, and are arranged in horizontal and vertical read-out planes.

The characteristics and stability of the ν_μ beam are directly monitored at the near site by the MRD using ν_μ interactions in iron. The large transverse area of MRD makes it possible to measure the beam direction and intensity profile, and its large mass makes it possible to measure the time stability of the ν_μ event rate, profile and spectrum. The location of the center of the profile gives the beam direction. For the MRD beam profile measurement, the starting point of a reconstructed muon track is regarded as the vertex of a ν_μ-iron interaction. Only tracks correlated in time with a beam spill are accepted. Tracks with a common vertex are taken as a single event with the longest track assumed to be a muon. Tracks entering or exiting the detector are cut. Muons with reconstructed energy lower than 0.5 GeV or higher than 2.5 GeV are also cut, to avoid regions of small acceptance. The vertex distribution is corrected for geometrical acceptance to obtain the beam profile. As shown in Fig. 3(a), the horizontal profile is well centered on the SK direction. The vertical profile is also well centered on the SK direction, and both are stable in time. The profile width is well reproduced by the beam simulation which is described below. The profile center is plotted as a function of time in Fig. 3(b). The ν_μ direction has been stable within ±1 mr throughout all data-taking periods.

For the event rate and kinematic distribution analyses no energy cut is made, but only events with vertices inside a fiducial volume defined by a cylinder of 3m radius in the upstream 9 iron plates are accepted. The measured rate of ν_μ-iron events is typically 0.05 events/spill and can be monitored on a daily basis with good statistics. The event rate measured by the MRD, normalized to proton intensity, is stable within statistical error. The muon energy and angular distributions are also continuously monitored. They show no significant change as a function of time, indicating that the ν_μ energy spectrum is stable throughout this period.

4. Extrapolation from Near to Far Detector

The far detector for K2K is the Super–Kamikande experiment, located at the Kamioka Observatory, Institute for Cosmic Ray Research (ICRR), University of Tokyo, which has been taking data since 1996. Its performance and results have been documented elsewhere[5]. Event selection for K2K in the far detector uses timing synchronization with the KEK-PS via the Global Positioning System (GPS)[18].

To predict the ν_μ beam characteristics at the far site, a normalization measurement at the near site and the extrapolation of the information from near to far are necessary. The MRD data described above are used only to provide beam stability data. For far/near rate normalization, only data from the 1kt detector are used. Due to the

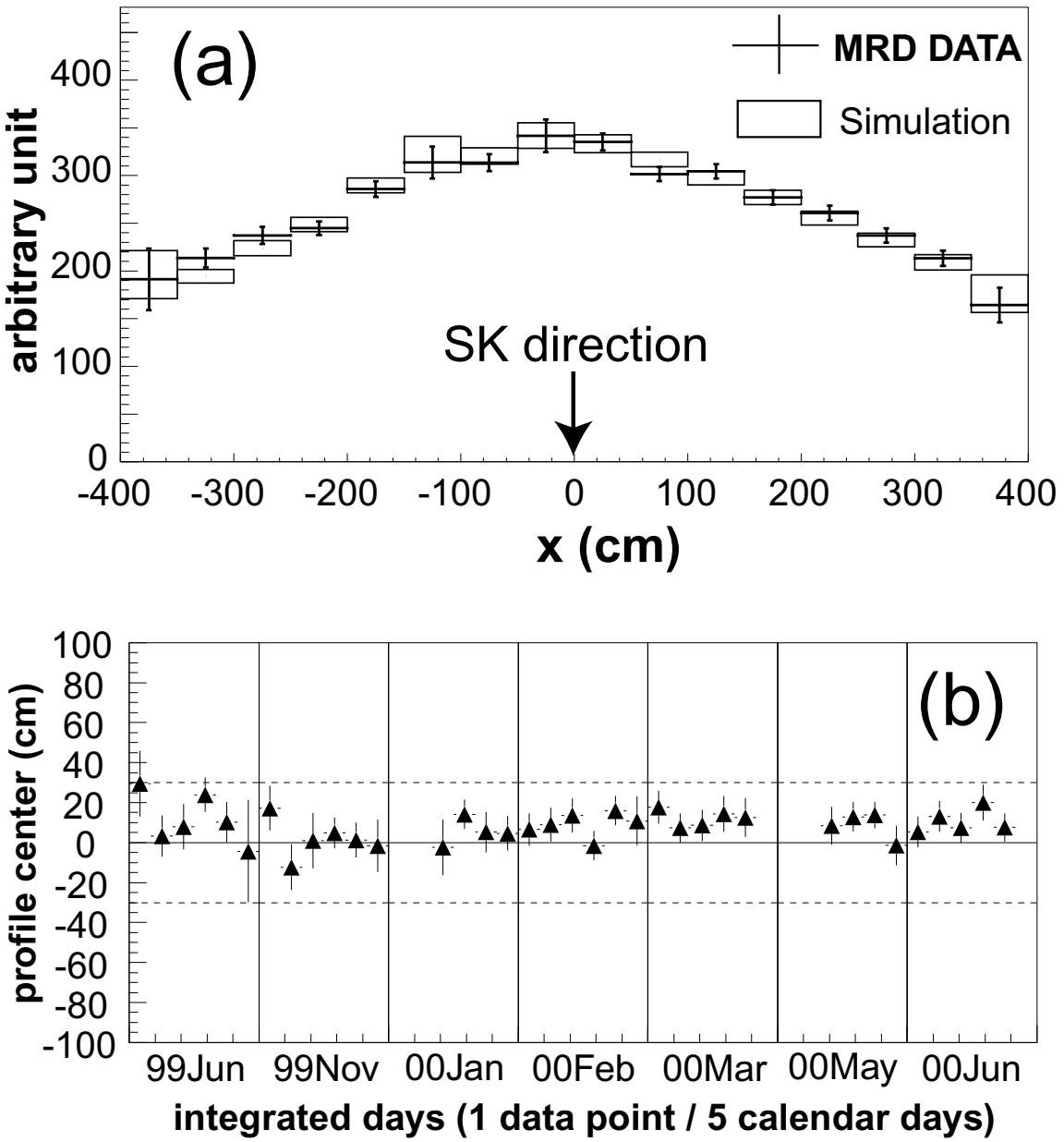

Figure 3: (a) Horizontal profile of the ν_μ beam measured by MRD in a one month period (points with error bars), and simulated (boxes; size corresponds to error). Errors include statistics and uncertainty of the acceptance correction. The normalization is by the area under the histograms. (b) Stability of the ν_μ beam direction. The fitted center of the horizontal profile is plotted for five day periods, with error bars from the fits. The dashed lines correspond to ± 1mr relative to the direction to SK.

similarities in design and data reduction between Super-Kamiokande and the 1kt detector, instrumental and analysis biases are suppressed.

For the extrapolation, a beam simulation is used, validated by the PIMON measurements described above. This simulation is based on GEANT[15] with detailed description of materials and magnetic fields in the target region and decay volume. It uses as input a measurement of the primary beam profile at the target. Primary proton interactions on aluminum are modeled with a parameterization of hadron production data[16]. Other hadronic interactions are treated by GEANT-CALOR[17].

Figure 4 shows the inferred ν_μ energy spectral shape at the near site, and the far to near ν_μ flux ratio along with the beam simulation results. The beam simulation is well validated by the PIMON measurements, without any tuning.

Accelerator-produced neutrino interactions at Super–Kamiokande are selected by comparing two Universal Time Coordinated (UTC) time stamps from the GPS system, $T_{\rm KEK}$ for the KEK-PS beam spill start time and T_{SK} for the SK trigger time.

Duplicate GPS time clock systems[18] are used at the near and far detector sites to generate timestamps with 20 nsec precision. At each site, two independent GPS receivers are used, with a backup receiver used to monitor performance of the primary receiver, or replace it in case of failure. The primary and backup receivers are from different manufacturers and have independent internal hardware and software. Accuracy of timestamps with respect to absolute UTC should be better than 150 nsec, based on GPS system and receiver specifications. To check for possible systematic errors, a portable atomic clock was transported between sites. Results indicated that the near and far UTC systems are correlated well within the effective accuracy of the atomic clock used, approximately 200ns.

The time difference between the two UTC time stamps, $\Delta(T) \equiv T_{\rm SK} - T_{\rm KEK} - TOF$ where TOF is the time of flight at velocity c between the near and far detectors, should be distributed in the interval from 0 to $1.1\mu s$ to match the width of the beam spill of the KEK-PS. Using the conservative atomic clock estimate of the synchronization accuracy between the two sites, < 200ns, beam-induced events are selected in a time window of width 1.5μs. Data reduction similar to that used in atmospheric neutrino analyses at SK[3,4] is applied to select fully contained (FC) neutrino interactions. The criteria are: a) no detector activity within 30 μs prior to the event; b) total collected charge in a 300 ns time window is equivalent to > 200 photoelectrons (≈ 20MeV deposited energy); c) the number of PMTs in the largest hit cluster in the outer-detector is < 10 (to eliminate events with entering tracks); d) total deposited energy is > 30 MeV. Finally, a fiducial volume cut is applied, rejecting events with fitted vertices outside the same 22.5kt volume used for Super-Kamiokande atmospheric neutrino analysis. The detection efficiency of SK is 93% for CC interactions and 68% for $\rm NC_{inel}$ interactions, for a total of 79%. As in the 1kt detector, the inefficiency is mainly due to the energy cut. Figure 5 shows the $\Delta(T)$ distribution at various stages of the reduction. A clear peak in time with the neutrino beam from the KEK-PS

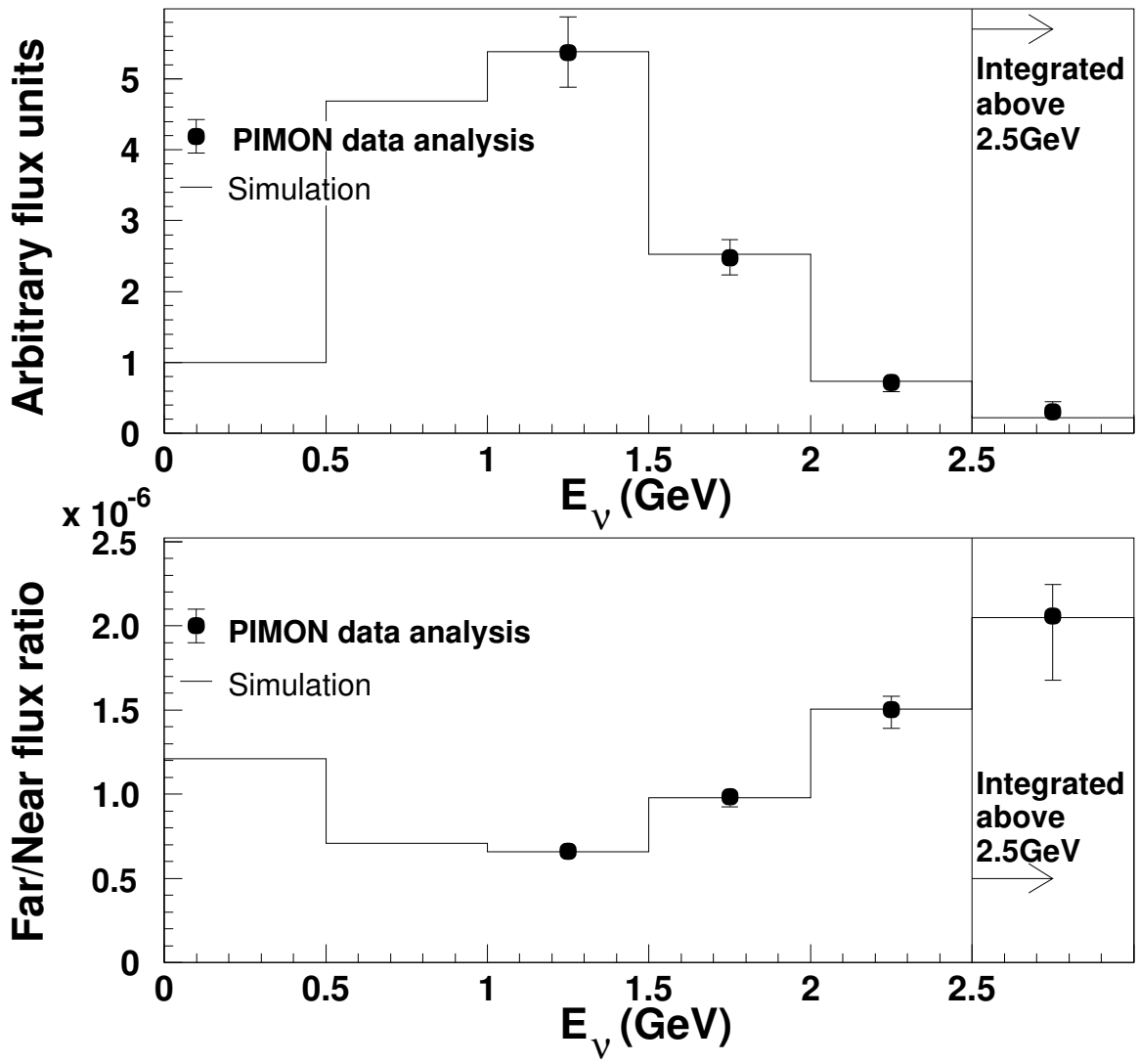

Figure 4: The top figure shows the ν_μ energy spectral shape at the near site and the bottom figure shows the far to near ν_μ flux ratio. The histograms are from the beam simulation results. The data points are derived from the PIMON measurement. For the top figure, normalization is done by area above 1 GeV. The vertical error bars for the data points reflect the total uncertainty.

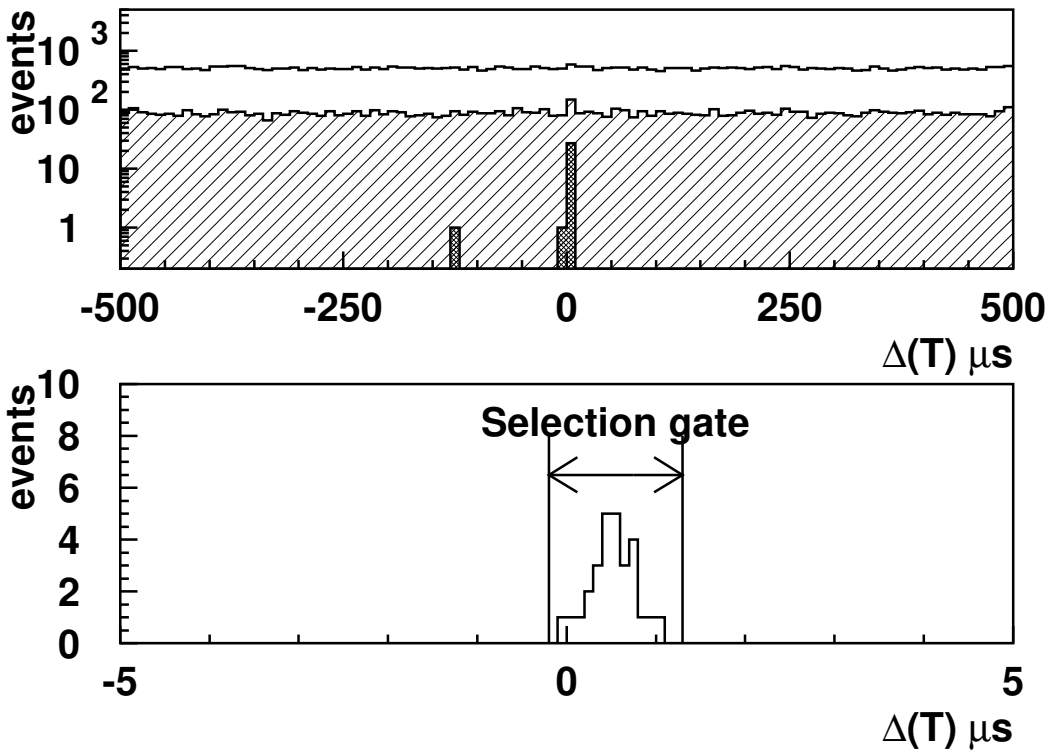

Figure 5: Far site timing analysis: (top) $\Delta(T)$ distribution over a $\pm 500\mu$s window for events remaining after cuts a) (unfilled histogram) and b) (hatched), and after all cuts except timing (shaded). The cuts are described in the text. (bottom) $\Delta(T)$ for a $\pm 5\mu$s window for FC events with vertices in the fiducial volume.

is observed in the coincidence time window. The 1.5μs selection window gives an expected background from atmospheric neutrino interactions of order 10^{-3} events for the total livetime considered.

5. Results

Twenty-eight fully-contained beam-induced events are observed within the 22.5 kt Super-Kamiokande fiducial volume, for the data set available prior to January, 2001. The observed neutrino event rate in the far detector versus beam livetime is consistent with being constant within statistical fluctuations.

The systematic uncertainty for the 1kt measurement is 5%, for which the leading terms are due to vertex fitting and its effect on the fiducial cut (4%), and the treatment of multiple events in a spill (3%). Other sources such as energy scale uncertainty are relatively small. The statistical uncertainty of the 1kt measurement is $< 1\%$. The systematic uncertainty of the extrapolation from the near site measurement is estimated to be $^{+6}_{-7}\%$ based on the PIMON measurement uncertainty and

beam simulation uncertainty for low energy neutrinos. The systematic uncertainty in the SK measurement is 3%, mainly due to the fiducial cut. The systematic error contribution from uncertainty in the neutrino energy spectrum and cross section is small due to cancellations. The quadrature sum of all known uncertainties for the far site event rate prediction is $^{+9}_{-10}$%. The resulting expected number of events, in the absence of neutrino oscillations, is $37.8^{+3.5}_{-3.8}$. The observed and expected numbers for various categories are summarized in Table . The number of Cherenkov rings and particle identification are reconstructed by the same algorithms as those used at SK[3], and the event category definitions are also the same.

The expected number of events extrapolated from analyses of CC interactions in the other near detectors are $41.0^{+6.0}_{-6.6}$ for MRD (iron target) and $37.2^{+4.6}_{-5.0}$ for SciFi (water target), both of which are thus consistent with the value based on 1kt analysis.

Table 1: Summary of the observed and expected numbers of fully contained events in the fiducial volume at the far site.

Event Category	Observed	Expected (no osc.)
Single Ring μ-like	14	20.9
Single Ring e-like	1	2.0
Multi Ring	13	14.9
TOTAL	28	$37.8^{+3.5}_{-3.8}$

6. Acknowledgements

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7. References

1) For a complete list of K2K Collaboration members, see KEK preprint 2000-149 (hep-ex/0103001), to be published in *Physics Letters B.*

2) K.S.Hirata *et al.*, Phys. Lett. **B205**, 416 (1988); K.S.Hirata *et al.*, Phys. Lett. **B280**, 146 (1992); Y.Fukuda *et al.*, Phys. Lett. **B335**, 237 (1994); S.Hatakeyama *et al.*, Phys. Rev. Lett. **81**, 2016 (1998); Y.Fukuda *et al.*, Phys. Rev. Lett. **82**, 2644 (1999); Y.Fukuda *et al.*, Phys. Lett. **B467**, 185 (1999); D.Casper *et al.*, Phys. Rev. Lett. **66**, 2561 (1991); R.Becker-Szendy *et al.*, Phys. Rev. **D46**, 3720 (1992); W.W.M.Allison *et al.*, Phys. Lett. **B449**, 137 (1999); M.Ambrosio *et al.*, Phys. Lett. **B434**, 451 (1998).
3) Y.Fukuda *et al.*, Phys. Lett. **B433**, 9 (1998).
4) Y.Fukuda *et al.*, Phys. Lett. **B436**, 33 (1998).
5) Y.Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
6) S.Fukuda *et al.*, Phys. Rev. Lett. **85**, 3999 (2000).
7) H.Noumi *et al.*, Nucl. Instr. and Meth. **A398**, 399 (1997).
8) M.Ieiri *et al.*, Proc. 1st Asian Particle Accelerator Conference (1998).
9) H. Sato, Proc. Particle Accelerator Conference (1999);
K. Takayama, ICFA Beam Dynamics Newsletter No.20, (1999).
10) 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); Proc. ICALEPCS (1999).
11) T.Maruyama, Ph.D. Thesis, Tohoku University (2000); K2K Beam Monitor Group, in preparation.
12) H.Noumi *et al.*, in preparation.
13) A.Suzuki *et al.*, Nucl. Instr. and Meth. **A453**, 165 (2000).
14) K2K MRD Group, submitted to Nucl. Instr. and Meth. **A**.
15) R. Brun *et al.*, CERN DD/EE/84-1 (1987).
16) 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).
17) T.A.Gabriel *et al.*, ORNL/TM-11185; C.Zeitnitz and T.A.Gabriel, Nucl. Instr. and Meth. **A349**, 106 (1994).
18) H.G.Berns and R.J.Wilkes, IEEE Trans. Nucl. Sci. **47**, 340 (2000).