

K2K EXPERIMENT

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Evidence of muon neutrino oscillation with an accelerator-based experiment is reported. Data corresponding to 8.91×10^{19} *p.o.t.* were used for the analysis. There were 108 events fully contained in the Super-Kamiokande inner detector fiducial area, which were synchronized to the beam-spill timing. In the case of no oscillations, the expected number of events was $150.9^{+11.6}_{-10.0}$. Out of the 108 events, we obtained 56 events of single ring μ -like events. The neutrino energy spectrum, reconstructed by assuming two-body kinematics of quasi-elastic interactions, shows a clear oscillation pattern compared with the spectrum at the production observed by the near detectors. These two facts strongly indicate neutrino oscillation with common oscillation parameter regions. A combined oscillation analysis gives $\Delta m^2 = 1.7 \sim 3.5 \times 10^{-3} \text{eV}^2$ at $\sin^2 2\theta = 1.0$ at the 90% confidence level, and the null oscillation probability is found to be less than 0.01%.

1 Motivation

The atmospheric neutrino anomaly observed by Super-Kamiokande and other experiments strongly suggests the $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillation with a mass-squared difference (Δm^2) of around $2.5 \times 10^{-3} \text{eV}^2$ and a mixing angle parameter ($\sin^2 2\theta$) close to unity.¹ The principal goal of the K2K (*KEK-to-Kamioka*) experiment² is to confirm the phenomenon with a man-made neutrino beam and to measure the oscillation parameters. The 12-GeV PS at KEK produces a wide-band neutrino beam with an average energy of 1.3 GeV. The far detector, Super-Kamiokande (SK), a 50 kt water Cherenkov detector, is located $L = 250 \text{ km}$ East from KEK. The E_ν/L value is just in a similar range to that of atmospheric neutrinos. We compare the number of ν_μ events and the spectrum observed by SK to those expected from measurements by a near detector system at KEK. A deficit of ν_μ events and a distortion of the spectrum are evidence of neutrino oscillation.

2 The Experimental Setup

The 12-GeV PS provides $\sim 6 \times 10^{12}$ protons per spill every 2.2 sec in a 1.1 μsec spill width. Protons are bent in the direction of Kamioka

in the primary beam line, and are injected on an aluminium target of $3\text{cm}\phi \times 66\text{cm}$ length, embedded in the 1st horn magnet. Two horn magnets focus the produced positively charged pions effectively towards the direction of Kamioka. The produced pions decay into μ and ν_μ within 200 *m* of a decay pipe filled with helium gas, and the produced ν_μ beam flies underground to the SK direction with a tilting angle of -1° . We measure the profile of muons from pion decays by ionization chambers and silicon pad detectors located behind the beam dump, which indirectly guarantees that the center of the neutrino beam profile is stable *spill-by-spill* within $\leq \pm 1\text{mrad}$. A pion monitoring gas Cherenkov counter is occasionally placed in the beam axis downstream of the 2nd horn. This enables us to extrapolate the neutrino flux from the near site to the far site in the $E_\nu \geq 1\text{GeV}$ region within an accuracy of $\sim \pm 10\%$.^a We employ a near-detector system located 300 *m* downstream from the primary target, which is composed of two independent detectors: a 1 kiloton SK-like water Cherenkov detector (*1kt*) and a fine-grained

^aFor an energy lower than 1 GeV, we employ an empirical pion production model,³ which reproduces the pion monitor measurements very well.

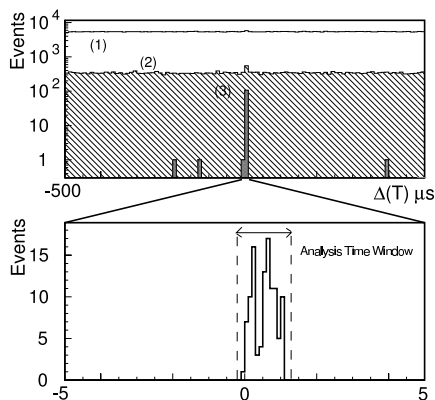


Figure 1. $\Delta T \equiv T_{SK} - T_{KEK} - T_{T.O.F.}$ distributions at each reduction stage at SK in a ± 500 μsec time window (upper); (1) decay electron cut; (2) ≥ 20 MeV deposit energy; (3) no activity in the outer detector (fully-contained, FC) and the vertex in the fiducial volume (FV). $\pm 5\mu\text{sec}$ time window for FCFV events (lower).

detector (FGD). *1kt* is a miniature of SK with a fiducial mass of $25t$, whose data can be directly compared with the SK ones. FGD aims to measure neutrino interactions precisely by using a tracking-type device. It consists of a scintillating fiber tracker/water target (SciFi⁴), plastic scintillator veto/trigger counters surrounding the SciFi, an electromagnetic calorimeter of 600 lead glass blocks (LG) measuring the ν_e component in the beam, and a muon range detector (MRD⁵) that can measure the momentum of the primary muon track with an accuracy of 2.7%. During the summer PS shutdown in 2001, the LG was removed to enlarge the sensitivity of FGD to a lower energy, and a full active scintillator detector (SciBar⁶) was installed in the space during the summer of 2003 for further study on neutrino interactions.

3 Event Selection

Within a year from a severe accident during which about 60% of 11,140 PMTs were lost, the SK detector was repaired by rearranging the 5,182 remaining+spare PMTs at half density, and the K2K experiment was

resumed in December, 2002. Until February, 2004, 10.10×10^{19} protons on target were delivered to the experiment in 427 days of running since 1999. Among them, data corresponding to 8.91×10^{19} pot were used for the analysis. The GPS system was used to look for events at SK that synchronized to the KEK PS beam pulses. Fig. 1 shows the $\Delta T \equiv T_{SK} - T_{KEK} - T_{T.O.F.}$ distributions at each reduction stage. After the final requirements that the event be fully contained in the inner detector (FC) and the neutrino interaction vertex be inside of the 22.5kt fiducial volume (FV), we admitted a very clear peak, which coincided to a beam pulse of $1.1\mu\text{sec}$ width. Inside of an $1.5\mu\text{sec}$ analysis timing window, we observed 108 events in total. The statistics has been doubled to that accumulated before the SK accident (56). The atmospheric neutrino background expected for the timing window was estimated to be only 2.4×10^{-3} events. Among the FCFV events, 66 events were single-ring (1R) events, and 56 of the 1R events were identified as muon-like events by using Cherenkov ring image-pattern recognition.⁷ For 1R μ -like events, we could calculate E_{ν}^{rec} , which is the incoming neutrino energy deduced from the muon momentum and angle by assuming a charged-current quasi-elastic (CCQE) interaction, $\nu_{\mu} + n \rightarrow \mu + P$.^b

4 ν_{μ} Spectrum at Production

The 2-dimensional distributions of the muon momentum versus the angle with respect to the beam direction observed by near detectors are used to reconstruct the neutrino spectrum at the time of production. FCFV-1R μ -like samples are chosen for *1kt* by using the same analysis procedure as in SK. For FGD, the events whose vertex starts from

^bIn our relevant energy region a recoil proton track is usually not seen (Cherenkov threshold is $p_{thr.} \sim 1.1$ GeV/c), and the CCQE interaction is identified as a single ring μ -like event.

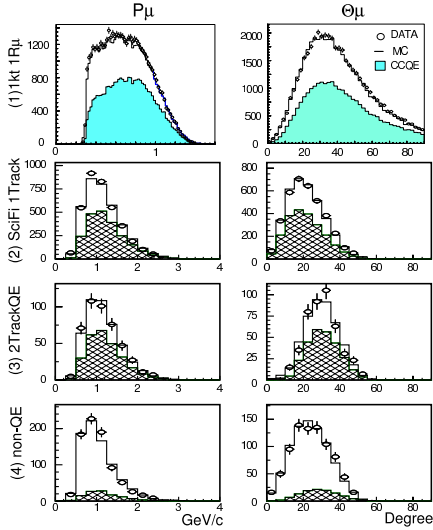


Figure 2. Muon momentum (left) and angle (right) distributions for (1) 1kt FCFV single-ring μ -like events, (2) SciFi single-track events, (3) 2-track QE enhanced events, and (4) 2-track non-QE enhanced events. The crosses are data and the lines are MC weighted by the best-fit parameters. The hatched histograms show the CCQE contributions.

SciFi (or SciBar) and a track matches that in MRD are chosen as candidates of CC interactions, which are further divided into three event categories, *i.e.*, 1-track, 2-track CCQE enhanced, and 2-track non-QE enhanced samples: By assuming a 2-body QE interaction, the direction of the scattered proton can be calculated from the muon momentum. For two-track events we define $\Delta\theta_P$ as the difference between the observed direction of the second track and the expectation. A CCQE-enhanced sample is selected by requiring $\Delta\theta_P$ to be within 25° , and non-QE enhanced samples by more than 30° (25° for SciBar), respectively. A χ^2 -fitting method is used to compare these data against the MC expectation. The neutrino spectrum is divided into 8 energy bins, and the flux in each energy bin is re-weighted relative to the values in the beam MC during the fit. In addition, a parameter, R_{nqe} , is used to re-weight the ratio between the QE and non-QE cross section relative to the MC simulation.

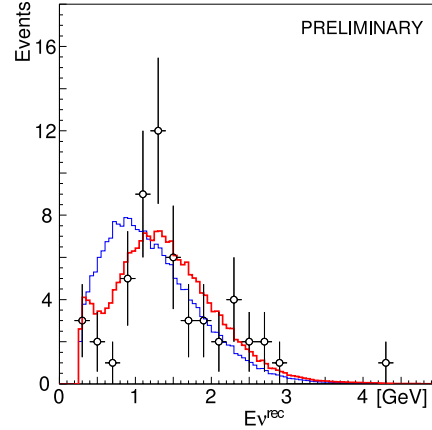


Figure 3. Reconstructed E_ν distribution for the 1R μ sample, overlaid with the distribution without oscillations (thin line) and the best-fit spectrum with oscillation (thick line). These histograms are normalized by the number of observed events, 56.

The systematic uncertainties of each detector, *i.e.* the energy scales, the track finding efficiencies, and the detector thresholds, are incorporated as fitting parameters. The best-fit results of the flux re-weighting factors, R_{nqe} , and all of the systematics parameters are found to lie within their expected errors. The χ^2 is 638.1/609 *d.o.f.*. The muon momentum and the angular distributions of each event category are overlaid with the re-weighted MC in Fig. 2. As can be seen, the fit result agrees well with the data. The errors of the fit are provided in the form of an error matrix to the following oscillation analysis.

5 Oscillation Analysis

A two-flavor neutrino oscillation analysis with ν_μ disappearance is performed by the maximum-likelihood method. In the analysis, both the number of FCFV events (108) and the energy spectrum shape for 1R μ events (56) are used. The likelihood is defined as $\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape}$, where 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 symbol f represents a set of parameters constrained by the systematic errors. They consist of the re-weighted neutrino spectrum measured at the near detectors, the F/N ratio, the reconstruction efficiency of SK for $1R\mu$ events, the re-weighting factor for the QE/non-QE ratio R_{nqe} , the SK energy scale (3%⁷) and the overall normalization. The errors on the first 3 items depend on the energy, and have correlations between each energy bin. The expected number of FCFV events, N_{exp} , at SK without oscillation with an overall normalization measured by the $1kt$ is estimated to be $150.9^{+11.6}_{-10.0}$, which is to be compared to $N_{obs} = 108$. The major contributions to the errors come from the uncertainties in the F/N ratio ($+5.6\%$ / -7.3%) and the normalization (4.7%). The latter is dominated by uncertainties of the fiducial volumes due to vertex reconstruction errors at both the $1kt$ and SK. On the other hand, the shape term,

$$\mathcal{L}_{shape} = \prod_{i=1}^{N_{1R\mu}} P(E_i; \Delta m^2, \sin^2 2\theta, f),$$

is a product of the probability for each $1R\mu$ event to be observed at $E_\nu^{rec} = E_i$, where P is the normalized E_ν^{rec} distribution, estimated by MC, and $N_{1R\mu}$ is the number of $1R\mu$ events. The likelihood is calculated at each point in the Δm^2 and $\sin^2 2\theta$ space to search for the point where the likelihood is maximized. The best-fit point in the physical region is found to be at $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.73 \times 10^{-3} \text{ eV}^2)$. At the best-fit point the predicted total number of FCFV events is 104.8, which agrees with the observation (108) within the statistical error. The observed E_ν^{rec} distribution of the $1R\mu$ sample is shown in Fig. 3 together with the expected distributions for the best-fit oscillation parameters, and the expectation without oscillations. Fig. 4 shows the allowed regions of oscillation parameters, evaluated by calculating the likelihood ratio of each point to the best-fit point. The 90% C.L. con-

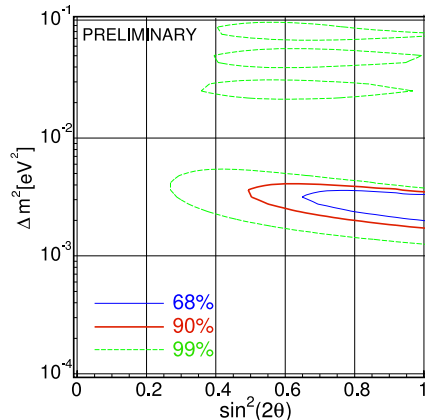


Figure 4. Allowed regions of oscillation parameters. The thin-solid, thick-solid and dashed lines are 68.4%, 90% and 99% C.L. contours, respectively.

tour crosses the $\sin^2 2\theta = 1$ axis at $\Delta m^2 = 1.7$ and $3.5 \times 10^{-3} \text{ eV}^2$. The probability that the observations are due to a statistical fluctuation instead of neutrino oscillation was calculated to be 0.01%. When only normalization (shape) information is used, the probabilities are estimated to be 0.33% (1.1%), respectively.

References

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