Indications of Neutrino Oscillation in a 250 km Long-baseline Experiment

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The K2K experiment observes indications of neutrino oscillation: a reduction of $\nu_\mu$ flux together with a distortion of the energy spectrum. Fifty-six beam neutrino events are observed in Super-Kamiokande (SK), 250 km from the neutrino production point, with an expectation of $80.1^{+6.4}_{-5.4}$. Twenty-nine one ring $\mu$-like events are used to reconstruct the neutrino energy spectrum, which is better matched to the expected spectrum with neutrino oscillation than without. The probability that the observed flux at SK is explained by statistical fluctuation without neutrino oscillation is less than 1%.

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Recent atmospheric and solar neutrino data indicate the existence of neutrino oscillation and therefore the existence of neutrino mass $\nu\to\nu'$. The zenith angle distribution of atmospheric neutrinos observed by Super-Kamiokande (SK) shows a clear deficit of upward-going muon neutrinos, which is well explained by two-flavor $\nu_\mu-\nu_\tau$ oscillations with $\Delta m^2$ around $3 \times 10^{-3} \text{eV}^2$, and $\sin^2 2\theta$ close to or equal to unity.

The KEK to Kamioka long-baseline neutrino oscillation experiment (K2K) uses an accelerator-produced neutrino beam with a neutrino flight distance of 250 km to probe the same $\Delta m^2$ region as that explored with atmospheric neutrinos. The neutrino beam is produced by a 12 GeV proton beam from the KEK proton synchrotron. After the protons hitting an aluminum target, the produced positively charged particles, mainly pions, are focused by a pair of pulsed magnetic horns. The neutinos produced from the decays of these particles are 98% pure muon neutrinos with a mean energy of 1.3 GeV.

This analysis is based on data taken from June 1999 to July 2001, corresponding to $4.8 \times 10^{19}$ protons on target (POT). The pion moment and angular distributions
downstream of the second horn are occasionally measured with a gas-Cherenkov detector (PIMON) in order to verify the beam Monte Carlo (MC) simulation and to estimate the errors on the flux prediction at SK. The direction of the beam is monitored on a spill-by-spill basis by observing the profile of the muons from the pion decays with a set of ionization chambers and silicon pad detectors located just after the beam dump. The neutrino beam itself is measured in a set of near neutrino detectors (ND) located 300 m from the proton target. The measurements made at the ND are used to verify the stability and the direction of the beam, and to determine the flux normalization and the energy spectrum before the neutrinos travel the 250 km to SK. The flux at SK is estimated from the flux of the ND by multiplying the Far/Near (F/N) ratio, the ratio of fluxes between the far detector (SK) and ND, to that of the ND.

Since both a suppression in the number of events and a distortion of the spectrum are expected for neutrinos which travel a fixed path length in the presence of oscillations, both the number of observed events and the spectral shape information at SK are compared with expectations, both the number of observed events and the spectral shape information at SK are compared with expectations. The measurements made at the ND are used to verify the beam Monte Carlo (MC) simulation. In the non-QE enhanced sample, 82% of the events are estimated to be QE events from the QE enhanced sample. In the QE enhanced sample, 62% of the events are estimated to come from interactions other than QE, and the fraction of QE events in the sample. Assuming QE interactions (νμ + n → μ− + p), where the proton produced in the QE interaction has a momentum greater than 600 MeV/c, its track may also be reconstructed. In the case where a second track is visible, the kinematic information is used to enhance the fraction of QE events in the sample. Assuming QE interaction, the direction of the proton can be predicted from the muon momentum. The QE enhanced sample is selected by requiring that the direction of the second track agrees with the prediction to within 25 degrees. Events where the direction of the second track differs from the prediction by more than 30 degrees are put into a non-QE enhanced sample. In the QE enhanced sample, 62% of the events are estimated to be QE events from the MC simulation. In the non-QE enhanced sample, 82% of events are estimated to come from interactions other than QE. The SciFi events are divided into three event categories: 1-track, 2-track QE enhanced, and 2-track non-QE enhanced samples.

The 2-dimensional distributions of the muon momentum versus angle with respect to the beam direction of four event categories (the 1KT event sample and the two complementary detectors are thus able to completely cover the relevant energy range.

In the 1KT analysis, a cylindrical fiducial volume of 25 tons oriented along the beam direction is used. Event selection criteria for the flux normalization are the same as those in reference [8]. Events which deposit more than ∼ 100 MeV of energy are used for the measurement of the integrated flux. The measurement has a 5% systematic uncertainty, of which the largest contribution comes from the vertex reconstruction [9]. For the spectrum measurement, further cuts are imposed in order to select 1Rμ events which stop in the detector. Among the events selected for the flux normalization measurement, 53% of the events have 1 ring. The events with a muon exiting from the detector are effectively eliminated by requiring the maximum charge of any PMT to be less than 200 photo-electrons; 68% of the 1 ring events remain after this requirement. The largest systematic uncertainty for the spectrum measurement is an uncertainty on the energy scale. The energy scale is understood to within ±3%, which is confirmed with both cosmic-ray muons and beam-induced π0s.

The FGD is comprised of a scintillating fiber and water detector (SciFi), a lead-glass calorimeter (LG), and a muon range detector (MRD). In the FGD analysis, events containing one or two tracks with vertex within the 5.9 ton fiducial volume of the SciFi are used. The track finding efficiency is 70% for a track passing through three layers of scintillating fiber and close to 100% for more than 5 layers. Three layers is the minimum track length required in this analysis. Events which have at least one track passing into the MRD are chosen in order to select νμ-induced CC interactions. The momentum of the track is measured by its range through the SciFi, LG, and MRD, with accuracy of 3%.

If the proton produced in the QE interaction has a momentum greater than 600 MeV/c, its track may also be reconstructed. In the case where a second track is visible, the kinematic information is used to enhance the fraction of QE events in the sample. Assuming QE interaction, the direction of the proton can be predicted from the muon momentum. The QE enhanced sample is selected by requiring that the direction of the second track agrees with the prediction to within 25 degrees. Events where the direction of the second track differs from the prediction by more than 30 degrees are put into a non-QE enhanced sample. In the QE enhanced sample, 62% of the events are estimated to be QE events from the MC simulation. In the non-QE enhanced sample, 82% of events are estimated to come from interactions other than QE. The SciFi events are divided into three event categories: 1-track, 2-track QE enhanced, and 2-track non-QE enhanced samples.

The 2-dimensional distributions of the muon momentum versus angle with respect to the beam direction of four event categories (the 1KT event sample and the
three SciFi event samples) are used to measure the neutrino spectrum. A $\chi^2$-fitting method is used to compare these data against the MC expectation. The neutrino spectrum is divided into 8 energy bins as defined in Table I. During the fit, the flux in each energy bin is re-weighted relative to the values in the beam MC. These weights are normalized relative to 1.00 for the $E_\nu = 1.0–1.5$ GeV bin. An overall normalization is included as a free parameter in the fit. The parameter $R_{nqe}$ is used to re-weight the ratio between the QE and non-QE cross-section relative to the MC simulation. The systematic uncertainties of the ND are incorporated into the fitting parameters. They are the energy scales, the track finding efficiencies, and the detector thresholds. In addition, the spectrum measurement by PIMON is used as a constraint on the re-weighting factors.

The value of $\chi^2$ is 227.2/197 d.o.f. at the best fit point. All the parameters including the detector systematics are found to lie within their expected errors. The best fit values of the flux re-weighting factors are shown in Table I. The muon momentum and angular distributions of 1R$\mu$ events in the 1KT, and the muon momentum distributions of the 2-track QE enhanced and non-QE enhanced events in SciFi are overlaid with the re-weighted MC in Figure 1. The fit result agrees well with the data. The errors of the measurement are provided in the form of an error matrix. Correlations between the parameters of the fit are taken into account in the oscillation analysis using this matrix. The diagonal elements in the error matrix are shown in Table I.

The uncertainty due to neutrino interaction models is separately studied. In QE scattering, the axial vector mass in the dipole formula is set to a central value of $1.1 \text{ GeV}/c^2$ and is varied by $\pm 10\%$. The axial mass for single pion production is set to a central value of $1.2 \text{ GeV}/c^2$ and is varied by $\pm 20\%$ [14]. This affects both the $q^2$ dependence of the cross-section and the total cross-section. For coherent pion production, two different models are compared: one is the Rein and Sehgal model [11], and the other is a model by Marteau [12]. For deep inelastic scattering, GRV94 [13] and the corrected structure function by Bodek and Yang [14] are studied. For the oscillation analysis the Marteau model and Bodek and Yang structure functions are employed. Varying the choice of models causes the fitted value of $R_{nqe} (= 0.93)$ to change by $\sim 20\%$. In order to account for this, an additional systematic error of $\pm 20\%$ on $R_{nqe}$ is added to the error matrix. The choice of models and axial mass does not affect the spectrum measurement itself beyond the size of the fitted errors.

The F/N ratio from the beam simulation is used to extrapolate the measurements at the ND to those at SK. The errors including correlations above 1 GeV, where the PIMON is sensitive, are estimated based on the PIMON measurements. The errors on the ratio for $E_\nu$ below 1 GeV are estimated based on the uncertainties in the hadron production models used in the K2K beam MC [3]. The diagonal elements in the error matrix for the F/N ratio are summarized in Table I.

The events in SK are selected using the timing information provided by the global positioning system. Events detected in SK must occur within an expected beam arrival time window of 1.5 $\mu$sec. In addition, the detected events must have no activity in outer detector, and have an energy deposit greater than 30 MeV with a vertex reconstructed within the 22.5 kiloton fiducial volume [3]. This sample of events is referred to as the fully contained (FC) sample. The efficiency of this selection is 93% for CC interactions. Fifty-six events satisfy the criteria. With the timing cut, the expected number of atmospheric neutrino background is approximately $10^{-3}$

| $E_\nu$ (GeV) | $\Phi_{\text{ND}}$ | $\Delta(\Phi_{\text{ND}})$ | $\Delta(F/N)$ | $\Delta(\epsilon_{\text{SK}})$ |
|---------------|----------------|------------------|---------------|------------------|
| 0–0.5         | 1.31           | 49               | 2.6           | 8.7              |
| 0.5–0.75      | 1.02           | 12               | 4.3           | 4.3              |
| 0.75–1.0      | 1.01           | 9.1              | 4.3           | 4.3              |
| 1.0–1.5       | 1.00           | —                | 6.5           | 8.9              |
| 1.5–2.0       | 0.95           | 7.1              | 10            | 10               |
| 2.0–2.5       | 0.96           | 8.4              | 11            | 9.8              |
| 2.5–3.0       | 1.18           | 19               | 12            | 9.9              |
| 3.0–          | 1.07           | 20               | 12            | 9.9              |
\begin{align*}
\mathcal{L} = \mathcal{L}_{\text{norm}} \cdot \mathcal{L}_{\text{shape}}. \quad \text{The normalization term } \\
\mathcal{L}_{\text{norm}}(N_{\text{obs}}, N_{\text{exp}}) \text{ is the Poisson probability to observe } N_{\text{obs}} \text{ events when the expected number of events is } N_{\text{exp}}(\Delta m^2, \sin^2 2\theta, f). \quad \text{The symbol } f \text{ represents a set of parameters constrained by the systematic errors. These parameters are described in detail later.}
\end{align*}

The shape term, \( \mathcal{L}_{\text{shape}} = \prod_{i=1}^{N_{1R\mu}} P(E_i; \Delta m^2, \sin^2 2\theta, f) \), is the product of the probability for each 1\(R\mu\) event to be observed at \( E_{\text{rec}}^i = E_i \), where \( P \) is the normalized \( E_{\nu}^{\text{rec}} \) distribution estimated by MC simulation and \( N_{1R\mu} \) is the number of 1\(R\mu\) events.

In the oscillation analysis, the whole data sample is used for \( \mathcal{L}_{\text{norm}} \), i.e., \( N_{\text{obs}} = 56 \). The spectrum shape in June 1999 was different from that for the rest of the running period because the target radius and horn current were different. The estimation of energy correlations in the spectrum at the ND and in the far/near ratio has not been completed for this period. Thus, data taken in June 1999 are discarded for \( \mathcal{L}_{\text{shape}} \). The discarded data correspond to 6.5% of total POT. The number of 1\(R\mu\) events observed excluding the data of June 1999 is 29, and the corresponding number of 1\(R\mu\) events expected from MC simulation in the case of no oscillation is 44.

The parameters \( f \) consist of the re-weighted neutrino spectrum measured at the ND \( (\Phi_{ND}) \), the F/N ratio, the reconstruction efficiency \( (\epsilon_{SK}) \) for SK for 1\(R\mu\) events, the re-weighting factor for the QE/non-QE ratio \( R_{\text{nqe}} \), the SK energy scale and the overall normalization. The errors on the first 3 items depend on the energy and have correlations between each energy bin. The diagonal parts of their error matrices are summarized in Table 4 as described earlier. The error on the SK energy scale is 3% [3]. Two different approaches are taken for the treatment of systematic errors in the likelihood. The first is to treat the parameters \( f \) as fitting parameters with an additional constraint term in the likelihood (method 1) [9]. The other approach is to average the \( \mathcal{L}(f) \) sampled over many random trials weighted according to the probability density distribution of the systematic parameters \( f \) (method 2) [10].

The likelihood is calculated at each point in the \( \Delta m^2 \) and \( \sin^2 2\theta \) space to search for the point where the likelihood is maximized. The best fit point in the physical region of oscillation parameter space is found to be at \( (\sin^2 2\theta, \Delta m^2) = (1.0, 2.8 \times 10^{-3} \text{ eV}^2) \) in method 1 and at \( (1.0, 2.7 \times 10^{-3} \text{ eV}^2) \) in method 2. If the whole space including the unphysical region is considered the values are \( (1.03, 2.8 \times 10^{-3} \text{ eV}^2) \) in method 1 and \( (1.05, 2.7 \times 10^{-3} \text{ eV}^2) \) in method 2. The results from two methods are consistent with each other. At the best fit point in the physical region the total number of predicted events is 54.2, which agrees with the observation of 56 within statistical error. The observed \( E_{\nu}^{\text{rec}} \) distribution of the 1\(R\mu\) sample is shown in Figure 2 together with the expected distributions for the best fit oscillation parameters, and the expectation without oscillations. Consistency between the observed and best-fit \( E_{\nu}^{\text{rec}} \) spectrum is checked by using Kolgomorov-Smirnov(KS) test. A KS probability of 79% is obtained. The best fit spectrum shape agrees with the observations.

The probability that the observations are due to a statistical fluctuation instead of neutrino oscillation is estimated by computing the likelihood ratio of the no-oscillation case to the best fit point. The no-oscillation probabilities are calculated to be 0.7% and 0.4% for method 1 and 2 respectively. When only normalization (shape) information is used, the probabilities are 1.3% (16%) and 0.7% (14.3%) for the two methods. Allowed regions of oscillation parameters are evaluated by calcu-
FIG. 3: Allowed regions of oscillation parameters. Dashed, solid and dot-dashed lines are 68.4%, 90% and 99% C.L. contours, respectively. The best fit point is indicated by the star.

In conclusion, both the number of observed neutrino events and the observed energy spectrum at SK are consistent with neutrino oscillation. The probability that the measurements at SK are explained by statistical fluctuation is less than 1%. The measured oscillation parameters are consistent with the ones suggested by atmospheric neutrinos. At the time of this letter the K2K experiment has collected approximately one-half of its planned $10^{20}$ protons on target.

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