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NEW RESULTS FROM THE K2K EXPERIMENT

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The K2K long-baseline neutrino oscillation experiment has analyzed all data including the period ending in February 2004. The total data sample is from 8.9 x 10^{19} protons on target. We observe 108 events at the far detector, Super-Kamiokande, when 150.9 +11.6 -10.0 were expected. Further, we observe a distortion of the neutrino energy spectrum which is consistent with ν_μ to ν_τ oscillation. The probability that we would observe these results if there is no neutrino oscillation is 0.011%, a 3.9 σ significance.

Keywords: neutrino; neutrino oscillation; long-baseline.

1. Introduction

The KEK to Kamioka (K2K) experiment is the first long-baseline accelerator experiment to study the same oscillation parameters as atmospheric neutrinos [1,2]. We look for the disappearance of ν_μ, which is presumed to oscillate to ν_τ, the likely explanation for the deficit in atmospheric neutrinos seen by many experiments. Instead of neutrinos from cosmic rays, we look for the disappearance of ν_μ from a neutrino beam produced at the KEK accelarator. We see both a deficit of events and a distortion of the energy spectrum consistent with neutrino oscillation.

2. The experiment

The KEK accelerator produces protons with an energy of 12 GeV which hit an aluminum target. Positively charged pions are selected by the magnetic horn which then decay in the 200 m decay pipe. Most of the muons are absorbed by the rock so that only neutrinos remain.

The properties of the neutrino beam is first measured by a set of near detectors which see a flux of approximately 10^{11} neutrinos every 2.2 seconds (the time between beam spills) within a 100 m^2 area. A tiny fraction of neutrinos interact here; the rest continue on for 250 km to the Super-Kamiokande detector[3], located under a mountain in Gifu Prefecture, Japan. The neutrino flux at Super-K is about 10^6 neutrinos within a 40 m x 40 m area every beam spill. Events from the beam are selected with a 1.5 μs cut using timing information from the global positioning system and the expected background is 2×10^{-3} in the whole sample.

The total data sample used for this analysis is 8.9×10^{19} protons on target, accumulated in several runs between 1999 and 2004, nearly twice the sample as the previous analysis[4]. The data sample is divided into two separate periods, K2K-I and K2K-II. During the earlier period 40% of the surface of the Super-K inner detector was covered with photomultiplier tubes and the near detectors consisted of a 1 kilo-ton water Cerenkov detector (1KT), a scintillating fiber and water detector (SciFi), a lead glass detector, and a muon range detector (MRD). The second period had photo-multiplier coverage of 19% in Super-K and the lead glass detector was replaced: first with the prototype, and then with the full scintillating bar (SciBar) detector. The interaction medium for this analysis is water for Super-K, 1KT, SciFi, and scintillator for SciBar. For charged-current events, this means neutrons in oxygen and carbon nuclei.

3. Analysis

The suite of near detectors measures the properties of the neutrino beam, in particular the flux and the shape of the neutrino energy spectrum. We divide the data into into eight neutrino energy regions. We perform a fit for the flux in seven of the eight energy bins (the region 1.0 to 1.5 GeV is fixed) and for the non-QE to QE ratio, relative to our baseline Monte Carlo.

The lower energy data is from the fully-contained, one-ring muon-like sample of the 1KT detector. For these events we measure the momentum and the angle of the muon and, assuming CC-QE kinematics, we can estimate the neutrino energy. In the energy regions from 0.75 to 1.5 GeV, data from all near detectors contributes significantly to the fit, while at the higher energies, the fit is based primarily on the SciFi and SciBar detectors.

For SciFi and SciBar, the data is subdivided into three samples. We use events in which there are one or two tracks, and require that at least one, usually the muon, penetrates into the lead glass detector or the muon range detector. The two track sample is further divided. For CC-QE kinematics, we can predict the direction of the recoil proton. If the measured second track agrees with this prediction within 25 degrees, we put it in the QE enhanced sample. If it disagrees, more than 30 degrees for SciFi, 25 degrees for SciBar, then it goes into the non-QE sample.

When we compare the Monte Carlo with the data, for all near detectors, we see the Monte Carlo has too many events at small angle with respect to the beam. This is especially true for the non-QE samples of SciFi and SciBar. Events at small angle also correspond to events with a low value for the square of the momentum transfer, q^2, the relevant parameter in the interaction models.

At this time, we can not identify the source of this discrepancy. Two possible sources are the amount of resonant pion at low q^2 and the amount of coherent pion in the Monte Carlo. Using a phenomenological fit to the SciBar non-QE sample, we

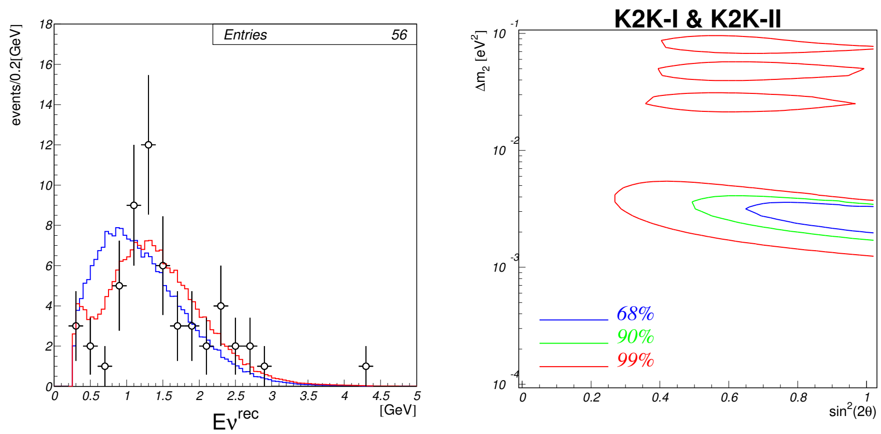

Fig. 1. Left: the preliminary energy spectrum at Super-K showing the data, the best fit in the physical region and the no-oscillation prediction. Both expectations are normalized by the total number of events. Right: the allowed region for the preliminary analysis of the combined data.

find the data agree with the MC if we suppress resonant pion production by $q^2/0.10$ for $q^2 < 0.1$ $(\mathrm{GeV/c})^2$, with no suppression above this value. An alternative which also gives agreement is to choose zero coherent pion. There is no difference in the final analysis when these two choices are compared.

In order to avoid a bias due to this when we fit for the seven neutrino flux parameters, we first fit the near detector data without events near the direction of the beam. Then, fixing the flux at these new values, we apply one of the two suppressions in the previous paragraph, use all the data, and then fit for the nQE/QE ratio. These final parameters are applied to the Monte Carlo which is then transformed using the "far to near ratio". This accounts for the large section of the beam seen by the near detectors and the small part near the center seen by Super-K. This result is the prediction for the shape of the neutrino energy spectrum at Super-K, and can be compared with the data.

4. Results

We have completed the preliminary analysis of the data through Feburary 2004. We observe 108 fully contained events in the Super-K fiducial volume and predict 150.9 +12 -10 if there is no neutrino oscillation. The probability that we would obtain this result if there is no oscillation is 0.33%, based on ΔLog(likelihood). We also observe a significant distortion of the shape of the energy spectrum, using 56 one-ring muon like events in SK, shown in the left plot of Fig. 1. Also using ΔLog(likelihood) for the energy distortion alone, we find this result has a probability of 1.1%. When these two results are combined, the probability is 0.011% (3.9 σ) that we would observe these data if there is no oscillation.

We have analyzed the data with a two-flavor model with ν_μ oscillating to ν_τ using a maximum likelihood fit that accounts for the total number of events, the shape of the spectrum, and systematic errors: $L_{\rm total} = L_{\rm norm} \times L_{\rm shape} \times L_{\rm syst}$. The best fit point within the physical region is $\Delta(m^2) = 2.73 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1.0$. The 90 percent confidence contours from this preliminary analysis are shown in the right-hand plot of Fig. 1. When we analyze the K2K-I and K2K-II data separately, the results are in agreement. Likewise, the contours based on the total number of events, or the shape alone are also in agreement. These results are not affected by the choice of resonant pion or coherent pion suppression described in the analysis section.

5. Conclusion

We present the latest results from the K2K experiment. These preliminary results confirm the ν_μ disappearance observed by atmospheric neutrino experiment. We observe a distortion of the shape of the energy spectrum consistent with ν_μ to ν_τ oscillation. Our best fit gives $\Delta(m^2) = 2.73 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) = 1.0$, which is consistent with atmospheric measurements. This is the first confirmation of the atmospheric neutrino oscillation with a long-baseline accelerator-based experiment.

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