Atmospheric neutrinos in Soudan 2

Maury Goodman, for the Soudan 2 collaboration
Argonne, Illinois 60439

Soudan 2 has measured the atmospheric neutrino flavor ratio with 4.2 fiducial kiloton-years of exposure. It measures a flavor ratio of $0.66 \pm 0.11(stat)$, inconsistent with the expected ratio but consistent with the hypothesis of neutrino oscillations and the Super-Kamiokande data. In a sample of events with good angular resolution, fits to the L/E distribution suggest that $\Delta m^2 > 10^{-3} eV^2$.

I. INTRODUCTION

The measurement of the atmospheric neutrino flavor ratio is of interest due to the apparent anomaly in some reported experiments [1–6] and the explanation of that anomaly in the context of neutrino oscillations. The double ratio

$$R \equiv \left(\frac{\nu_\mu}{\nu_e}\right)_{data} \Big/ \left(\frac{\nu_\mu}{\nu_e}\right)_{MC} \sim \left(\frac{tracks}{showers}\right)_{data} \Big/ \left(\frac{tracks}{showers}\right)_{MC}$$

allows a measurement which is independent of an absolute flux or exposure calculation.

Soudan 2 is an iron calorimeter with different experimental systematics from the water Cherenkov detectors and with a different geometry and detection technique from from the Frejus experiment. A large veto shield placed against the cavern wall allows the identification of particles entering the detector from the interactions of cosmic ray muons in the surrounding rock. We use these "rock" events to show that our low value of R is not due to contamination from such events.

II. DETECTOR AND FLAVOR RATIO ANALYSIS

The 963 metric ton Soudan 2 experiment is located in the Soudan Underground Mine State Park, Soudan, Minnesota, USA 710 meters underground. About 85% of the mass of a module is provided by 1.6 mm thick sheets of corrugated steel. The sheets are stacked to form a hexagonal 'honeycomb' structure. Plastic drift tubes (1.0 m long and 15 mm in diameter) fill the spaces in the honeycomb. An 85% argon/15% CO_2 gas mixture is recirculated through the modules. Ionization deposited in the gas drifts toward the closer end of the tube in an 180 volt/cm electric field. The average density is 1.6 g/cc. Further details of module construction may be found in Reference [7]. The calorimeter is surrounded by an active shield designed to identify particles which enter or exit the detector cavern.

We have analyzed data from 4.2 fiducial kton-year exposure taken between April 1989 and October 1998. During this period the detector was under construction, starting with a total mass of 275 tons and ending with the complete 963 tons. The goal of the data reduction is to obtain a sample of 'contained events', defined as those in which no primary particle in the event leaves the fiducial volume of the detector. The fiducial volume is defined by a 20 cm depth cut. Triggered events are passed through a software filter to reject events with tracks entering or leaving the fiducial volume (mostly cosmic ray muons) or events which have the characteristics of radioactive background or electronic noise. Approximately 1 event per 1500 triggers passes this filter.

The selected events are then double scanned to check containment and to reject background events, using an interactive graphics program. Monte Carlo events equivalent to 5.9 times the exposure of the real data were inserted randomly into the data stream and processed simultaneously with the data events, ensuring that they are treated identically. The neutrinos were generated using the BGS flux [8].

The lepton flavour of each event is determined by second level scanners who flag them as 'track', 'shower' or 'multiprong'. Tracks which have heavy ionization and are straight are further classified as 'protons'. Proton recoils accompanying tracks and showers are an additional tag of quasi-elastic scattering and are ignored in the classification. Any second track or shower in the event results in a multiprong classification. Results are shown in Table I. Events with (without) shield hits are labeled "rock" ("gold") events. The quality of the flavour assignment was measured using the Monte Carlo data. We found that 87% of events assigned as tracks have muon flavour and 96% of showers electron flavour.

The majority of the events classified as contained are due to the interactions of neutral particles (neutrons or photons) produced by muon interactions in the rock around the detector. Calculations show that only a few percent of such events will not have an accompanying charged track traversing our shield, which was placed as close to the cavern wall and as far away from the detector as possible to maximize the probability of detecting the accompanying charged particles. The efficiency of the shield has been measured using cosmic ray muons detected in the main detector. It ranges from 81% during the early data runs before the geometrical coverage was complete to 93% at the end of this data period. Also, 8.9% of Monte Carlo events had a random shield coincidence.

Our large sample of rock events enables us to investigate this potential background by studying the depth distribution of the events in the detector. This allows us to simultaneously measure any backgrounds due to either shield inefficiency or contained events due to neutral particles entering the detector without being accompanied by charged particles in the shield. Neutrino events will be distributed uniformly throughout the detector, while background events will be attenuated towards the center. We define a measure of the proximity of the event to the detector exterior by calculating the minimum perpendicular distance from the event vertex to the detector edge.

In using the depth distribution of the rock events to correct for background, we note that the measured flavor ratio as a function of shield multiplicity is observed to be a constant value of 0.76 ± 0.07. We then correct the track to shower ratio in the data by fitting the track and shower depth distribution to a sum of those in the rock events and Monte Carlo, constraining the flavor ratio of the rock events to its observed value. The result of the fit gives the corrected neutrino induced rate of 83.6 tracks and 119.7 showers. From this we calculate $\mathrm{R} = 0.66 \pm 0.11$, where the error includes the statistical error on the data, the statistical error on the Monte Carlo, and the error on the fit.

TABLE I. Classifications for the contained events before corrections.

	Track	Shower
Data: gold	105	159
Background corrected "ν"	83.6	119.7
MC	847	805

III. THE HIGH RESOLUTION SAMPLE

If the low value of R is the result of neutrino oscillations, the L/E distribution will be sensitive to Δm^2. The ability to identify an oscillation signature in an L/E distribution is mainly limited by the measurement of the incident neutrino direction. The neutrino directional measurement is smeared by detector resolution, target Fermi motion, and the failure to image all final state particles. We have found that by placing energy cuts on the data, we can obtain a subsample of events which have the potential for good directional measurement, and hence better sensitivity to oscillation parameters. In Soudan 2, the identification of a recoil proton greatly enhances the ability to identify the neutrino direction. The cuts that isolate this sample are:

- **Tracks and Showers**
  $p_{lept} > 150 MeV/c$ if a recoil is present
  $p_{lept} > 600 MeV/c$ if no recoil is present
- **Multiprongs**
  $E_{vis} > 700 MeV/c$
  $p_{vis} > 450 MeV/c$
  $p_{lept} > 250 MeV/c$

Because it has the highest statistics with the lowest systematic error, the quasielastic sample is the best sample with which to make the hypothesis test, *"Is there an atmospheric neutrino anomaly?"* The high resolution sample includes about 40% of the quasi-elastic events, but also most of the high energy multiprongs. This sample is preferable to use for neutrino oscillation parameter measurements, which depend on L/E resolution. The zenith angle distribution of the high resolution sample is shown in Figure 1. The ν_μ deficit is clearly seen at all zenith angles.

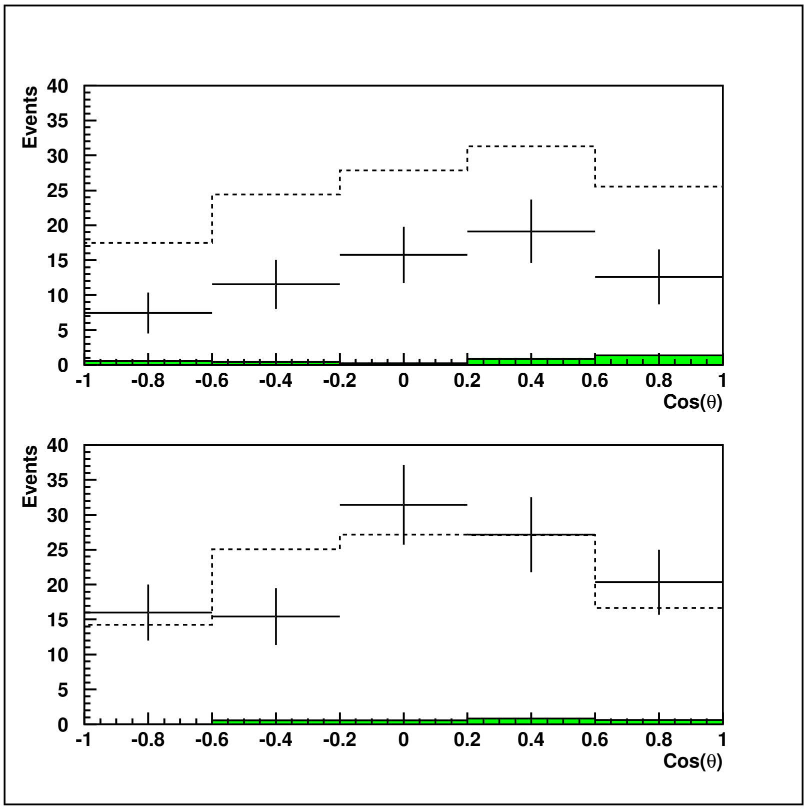

FIG. 1. The zenith angle distribution of the data (points), neutrino Monte Carlo without oscillations (dashed line) and the rock background (shaded). The upper curve is for ν_μ events and the lower curve for ν_e's. The rock and Monte Carlo curves are normalized to the data.

For the high resolution sample the flavor ratio is $R = 0.52 \pm 0.09$. This lower value of the ratio is consistent with our value from the quasi-elastic sample, but is inconsistent with the possible value 0.75 at 90% CL. This value implies a higher value of Δm^2 just because neutrinos from both sides of the earth have to be contributing to the ν_μ disappearance. This conclusion is born out by the L/E fits.

In Figure 2, we show the L/E data for both ν_μ and ν_e without oscillations. In Figure 3, we show the ν_μ data with oscillation fits for maximal mixing and $\Delta m^2 = 10^{-3} eV^2$ and $5.0 \times 10^{-3} eV^2$. In Figure 4, we show the ν_μ data with a oscillation fits for maximal mixing and $\Delta m^2 = 1.1 \times 10^{-2} eV^2$ and $10^{-1} eV^2$. $\Delta m^2 = 1.1 \times 10^{-2} eV^2$represents our best fit, but the value of χ^2 for larger mass values does not give a bad fit. However, values of Δm^2 below $10^{-3} eV^2$ are ruled out.

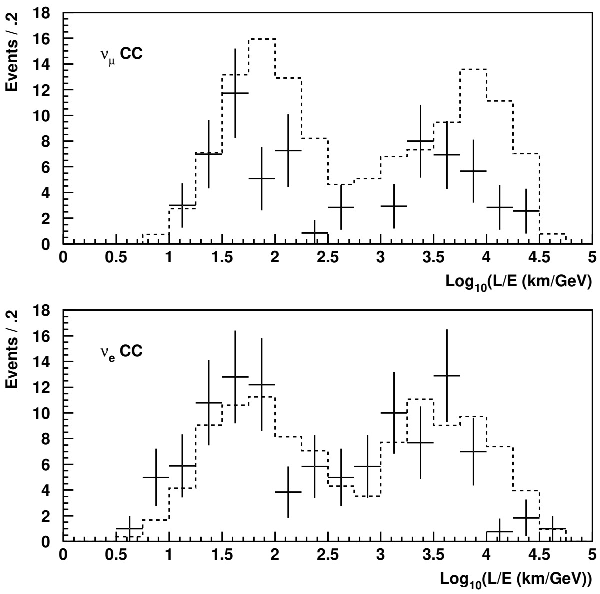

FIG. 2. L/E distributions for ν_μ CC and ν_e CC background subtracted data (crosses) and the Monte Carlo expectation without oscillations (dashed histogram). The MC is normalized to 4.2 kiloton-years data.

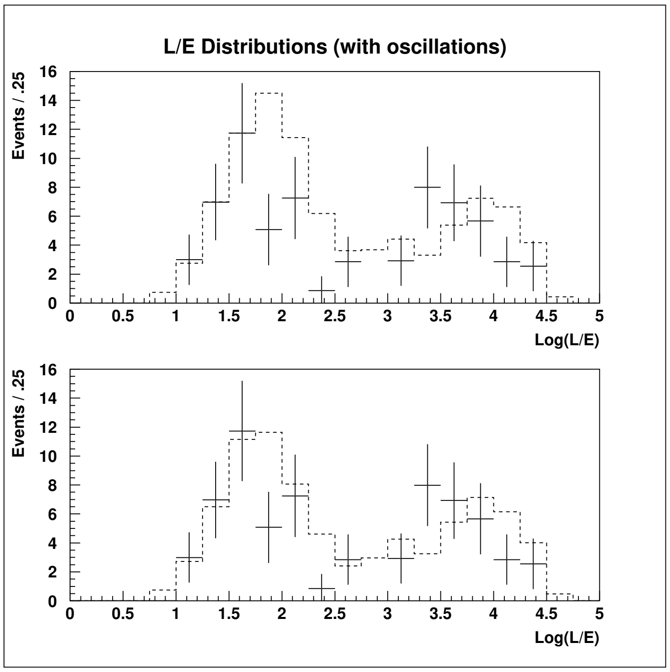

FIG. 3. L/E distribution for ν_μ background subtracted data with Monte Carlo expectation for $\Delta m^2 = 1.0 \times 10^{-3} eV^2$ (top) and $\Delta m^2 = 5.0 \times 10^{-3} eV^2$ (bottom)

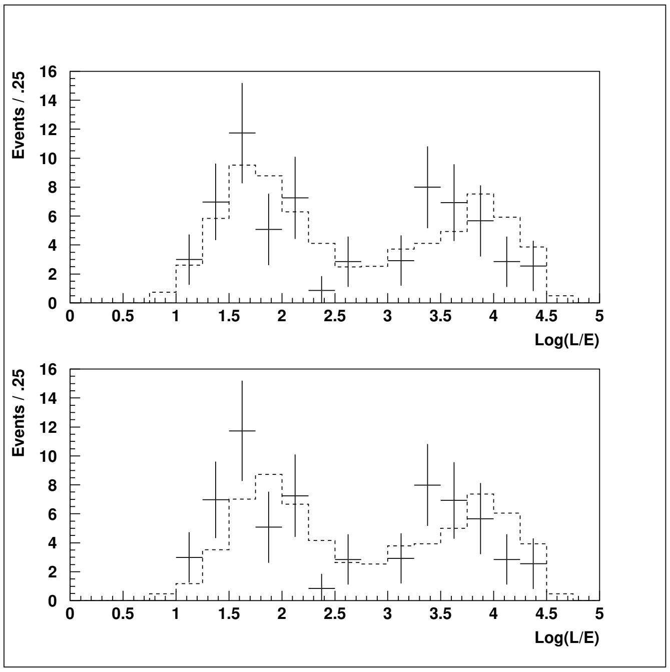

FIG. 4. L/E distribution for ν_μ background subtracted data with Monte Carlo expectation for $\Delta m^2 = 1.1 \times 10^{-2} eV^2$ (top) and $\Delta m^2 = 1.0 \times 10^{-1} eV^2$ (bottom). $1.1 \times 10^{-2} eV^2$ is our best fit for $sin^2(2\theta) = 1.0$.

IV. CONCLUSION

Soudan 2 measures a neutrino flavor ratio $R = 0.66 \pm 0.11(stat)$ inconsistent with expectation, but consistent with the interpretation of neutrino oscillations $\nu_\mu \to \nu_\tau$ in atmospheric neutrinos. A data sample with good angular resolution does not show a zenith angle effect, giving the oscillation parameters $\Delta m^2 > 10^{-3} eV^2$ for $\sin^2(2\theta) = 1$.

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