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The atmospheric neutrino anomaly in Soudan 2

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Based on a preliminary analysis of 1.01 fiducial kiloton-years of Soudan 2 data, we measure $(\text{track/shower})_{\text{measured}}/(\text{track/shower})_{\text{predicted}} = 0.64 \pm 0.17(\text{stat}) \pm 0.09(\text{sys})$. We discuss the implications of a neutrino oscillation interpretation of the atmospheric neutrino anomaly.

1. INTRODUCTION

The Soudan 2 detector is accumulating data on atmospheric neutrinos. Previous experiments have found fewer ν_μ events (relative to ν_e) than expected based on calculations of neutrino production in the atmosphere.[1] Results are usually expressed by the ratio:

$$R \equiv \frac{(\nu_\mu/\nu_e)_{\text{measured}}}{(\nu_\mu/\nu_e)_{\text{predicted}}} \quad (1)$$

with R found to be less than 1. Here we report on a preliminary analysis of 1.01 kT-year of data in Soudan 2.

2. THE SOUDAN 2 DETECTOR

The Soudan 2 detector is a tracking drift calorimeter that consists of 224 modules each weighing 4.3 tons. The detector was partially operated during installation from 1987 until fall of 1993. At the present time (June 1994) data from 1.83 fiducial kiloton-years of exposure has been collected. Preliminary analysis from the first 1.01 kiloton-years is presented here. The calorimeter is surrounded by a cavern-liner proportional tube active shield, which is used in the analysis.

Each module is $1 \times 1 \times 2.5\text{m}$ (high). The bulk of the mass consists of 1.6-mm thick corrugated steel sheets which are interleaved with detection elements. In each module there are 3780 15-mm diameter by 1 m long plastic drift tubes in a honeycomb matrix. Information along the drift direction is pulse height analysed and time digitized with a clock running at 5 Megahertz. Tubes

are oriented to line up with vertically running anode wires and horizontally connected rows of cathode pads. The information from each event then consists of anode channel versus time and cathode channel versus time pulse profiles. Pulse height in each time bin is digitized by a 6-bit flash ADC. Time information and pulse shape profiles are then used to match anode and cathode pulses and give a full three dimensional reconstruction for each gas crossing in the event.

The three corresponding views of an ν_μ candidate are shown in Figure 1. In the Figure, the space between channel numbers is used to indicate the pulse height profile. The event picture is blown up around the reconstructed position of the event. In the full detector, the number of pixels is about 10^9 . The typical occupancy from noise and random radioactivity is about 30 hits per event.

2.1. Calibration

In order to understand the response of the detector to low energy charged tracks, a module was calibrated at the Rutherford Laboratory's ISIS pulsed neutron source. Beams of positive and negative π 's, μ 's, and electrons at momenta between 140 and 400 MeV/c, and protons at 700 and 830 MeV/c, were used. The detector was oriented at several angles of incidence for the calibration. Detector resolution, ionization response and particle identification have then been compared to Monte Carlo simulations and calculations. For the neutrino flavor ratio, e/μ separation is an important factor. We found separation was greater

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than 95% efficient at all momenta except the lowest one where it fell to about 70%. Further details can be found in [2-4].

3. CONTAINED EVENT ANALYSIS

Processing of 17 million triggers yielded 25000 possible contained event candidates which were scanned by physicists. Containment is defined as no track coming closer than 20 cm to the outside of the detector. For each of the contained events, the topology was defined as either single track, single shower, or not being due to a quasi-elastic interaction ($\overline{QE}$). The single track and single shower events are mostly quasi-elastic interactions, according to our Monte Carlo simulation. In this separation, an observed recoil nucleon or muon decay were allowed in addition to the single lepton for QE track and shower events. Events which appeared to be neutral current or inelastic interactions were classified as ($\overline{QE}$). A summary of the Monte Carlo results are as follows:

- 3.72 kT-year simulated and scanned
- Gaisser-Stanev-Barr flux at Solar Max used
- After programs run:
 - 30% Quasielastic ν_μ
 - 26% Quasielastic ν_e
 - 13% Inelastic ν_μ
 - 15% Inelastic ν_e
 - 2% neutral current elastic
 - 14% neutral current inelastic
- Scanning efficiency
 - 96% correct track/shower
 - 76% correct track/shower/ $\overline{QE}$

Certain kinds of noise in the detector can appear to be similar to low energy showers. We have identified and eliminated such events. Nevertheless, at this stage we have applied an additional cut that showers must have more than 200 MeV of visible energy.

Contained events with hits in the active shield are due to interactions of neutral particles produced by muon interactions in the surrounding rock. A study of such events indicates that the efficiency of detecting at least one charged particle passing through the active shield is high. The shield efficiency and random rate were continuously monitored using the 0.3 Hz of throughgoing muons and random pulser trigger events. The 0 shield hit sample then must be corrected for backgrounds from shield inefficiency and losses due to random shield hits. As seen in Tables 1 to 3, the corrections are rather small. The shield grew between the first and second halves of the data, so the corrections were applied separately.

We are undertaking a re-analysis of our Monte Carlo simulation. The statistics of the preliminary Monte Carlo sample which has been analyzed to date is not large. The Monte Carlo has been improved to include more accurate low energy scattering for nucleons, more realistic representations of the detector geometry, intranuclear scattering of produced hadrons, and the variation of the neutrino flux with the solar cycle. The collaboration is presently comparing the Monte Carlo simulations to the results of our ISIS calibration running. When the Monte Carlo programs have been verified, a high statistics analysis will be conducted. Some aspects of the data event selection may be modified as a result of Monte Carlo analysis as well.

In addition to the flavor ratio, other aspects of atmospheric neutrino reactions can be measured in the Soudan 2 detector. The rate of quasi-elastic recoil protons is one handle on whether the possible neutrino anomaly is due to neutrino oscillations or proton decay.[5] In Soudan 2, recoil protons appear as highly ionizing and very straight short tracks (see Figure 1). Separation of the $\overline{QE}$ sample into ν_e charged current, ν_μ charged current, and neutral current samples would provide additional information with which to study the possible atmospheric neutrino deficit.

Table 1

First 0.5 kT-year; $R' = 0.59 \pm 0.28 \pm 0.10$

	Tracks	Showers	Not-quasi
<i>Data</i>	13	14	11
<i>Corrected Data</i>	11.8	14.0	
<i>Monte Carlo</i>	132	92	105

Table 2

Second 0.5 kT-year; $R' = 0.68 \pm 0.22 \pm 0.10$

	Tracks	Showers	Not-quasi
<i>Data</i>	21	20	21
<i>Corrected Data</i>	21.7	21.3	
<i>Monte Carlo</i>	158	106	125

Table 3

Combined data; $R' = 0.64 \pm 0.17 \pm 0.09$

	Tracks	Showers	Not-quasi
<i>Data</i>	34	34	32
<i>Corrected Data</i>	33.5	35.3	
<i>Monte Carlo</i>	158	106	125

4. DISCUSSION IN THE CONTEXT OF NEUTRINO OSCILLATIONS

For the measured flavor ratio of quasi-elastic neutrino interactions, we define:

$$R' \equiv \frac{(\text{track/shower})_{\text{measured}}}{(\text{track/shower})_{\text{predicted}}} \quad (2)$$

From Table 3, our preliminary measurement is

$$R' = 0.64 \pm 0.17(\text{stat}) \pm 0.09(\text{sys}) \quad (3)$$

The common expression for the atmospheric neutrino flavor ratio is given by R in equation 1. If the apparent atmospheric neutrino ν_μ deficit is due to neutrino oscillations $\nu_\mu \rightarrow \nu_\tau$ with an average oscillation probability $\langle P \rangle$, then one would expect $R = 1 - \langle P \rangle$. (For the case $\nu_\mu \rightarrow \nu_e$, one gets a similar but slightly more complicated relation.[6]) R and R' differ to the extent that there is neutral current background in the single track and single shower samples. For Soudan 2, this is about 10%. This background is different for each experiment.

The measured values of R' are shown in Table 4 including the preliminary result from Soudan 2. For the water Cerenkov detectors IMB

and Kamiokande, ring analysis and decay analysis are shown separately. Statistical errors for the two analyses of each experiment are correlated, while systematic errors are not. For the Frejus experiment, the data for the contained events and for their uncontained events are shown separately.

The preliminary Soudan result does not show a significant neutrino deficit by itself. Nevertheless, we find it interesting that our value of R' is below 1, as are the data from the high statistics Cerenkov detectors. If this is interpreted as being due to $\nu_\mu \rightarrow \nu_\tau$ oscillations, then the mixing angle needs to be large.

At the present time (June 1994), the Soudan experiment has 1.83 kiloton years of exposure, which will be fully analysed as the Monte Carlo analyses are done. By 1999, the expected duration of the experiment, we will have accumulated about 5.0 kiloton-years of data. This does not exceed the present exposures of the water Cerenkov detectors. However it will allow an independent check of the apparent atmospheric neutrino anomaly with a different detector technology and strong systematic controls.

Table 4

The contained event data on the atmospheric neutrino anomaly. Kamiokande and Soudan are still running. NUSEX did not quote a fiducial exposure, so one has been estimated. (*-unavailable)

Experiment	Exposure kT-year	R'	$track^{see}$ (ν_μ^{see})	$track^{MC}$ (ν_μ^{MC})	$shower^{see}$ (ν_e^{see})	$shower^{MC}$ (ν_e^{MC})
IMB1[7]	3.8	0.68 ± 0.08	104	136	297	265
Kamiokande ring[8]	7.70	0.60 ± 0.06	234	356.8	248	227.6
Kamiokande decay		0.69 ± 0.06	182	277.5	300	313.9
IMB-3 ring[9]	7.70	0.54 ± 0.05	182	268	325	257.3
IMB-3 decay		0.64 ± 0.07	208	261.5	402	348.5
Frejus contained(2.0)[10]	2.0	0.87 ± 0.13	94	100	89	82
Frejus uncontained(2.0)	2.00	1.04 ± 0.13	78	*	10	*
Frejus contained(1.56)[11]	1.56	0.87 ± 0.16	66	90	56	66.8
Frejus total(1.56)	1.56	1.06 ± 0.17	42	35.8	1	3.8
Soudan	1.01	0.64 ± 0.19	33.5	42.1	35.3	28.7
NUSEX[12]	~ 0.4	0.99 ± 0.29	32	36.8	18	20.5

5. LONG BASELINE OPPORTUNITY

The Soudan collaboration has been working with Fermilab to plan a long baseline neutrino oscillation experiment using the potential high neutrino flux from the Fermilab Main Injector. The combination of Main Injector energy ($< E_\nu > \sim 15 \text{ GeV}$) and distance from Fermilab to Soudan (730km) provides a range of L/E similar to that for the atmospheric neutrinos, but at an energy above ν_τ charged current threshold. The large distance does suppress the event rate by $1/L^2$. However the ability to run the Fermilab Main Injector in tandem with either a collider program or Tevatron fixed target program leads to realistic consideration of long high intensity running. That possibility has already led to the approval of a short baseline neutrino experiment, E803, which could share the beam with a long baseline experiment.

The Soudan collaboration has considered two options for such an experiment. In our proposal P822,[13] we have shown what can be done with the existing 1 kiloton very fine-grained Soudan 2 detector. A two detector measurement of the neutral current to charged current ratio, could achieve a systematic precision on the mixing angle

approaching 1%. However the statistical sensitivity is 10%. Still, with a two year run, this could confirm a $\nu_\mu \rightarrow \nu_\tau$ signal with an 11σ effect if the atmospheric deficit is due to 35% mixing. In addition, there are 8 other statistically independent signals for $\nu_\mu \rightarrow \nu_\tau$ which could be detected, such as the shape of the charged current energy distribution, and quasielastic τ production followed by e or μ decay.

Using the existing detector, the statistics of 750 events per year are low compared to the systematic sensitivity of neutrino oscillation tests. The Soudan collaboration has also submitted an expression of interest to Fermilab[14] to build a 16kT iron calorimeter to greatly increase the statistics of a long baseline experiment. Some of the parameters of an experiment with this detector at the Fermilab Main Injector are listed in Table 5. Such a detector could be sensitive to neutrino oscillations with a mixing angle of 3%. Cost estimates are approximately \$30M for the beam and \$40M for the large new detector at Soudan.

6. SUMMARY

The preliminary result from Soudan 2 on the atmospheric neutrino flavor ratio is $0.64 \pm 0.17 \pm 0.09$ based on 1.01 kiloton

Table 5
Soudan long baseline beam and running assumptions

Protons per spill	5.0×10^{13}
Repetition rate	1.9 s
Hours per week	100
Operating weeks per year	39
Protons per year	3.7×10^{20}
New far detector mass	16 kT
Far detector distance	730 km
Average neutrino event energy	14 GeV
Neutrino event rate per kT-year	1200
Charged current event rate for ν_τ (Maximal Mixing) per kT-year	100
Charged current event rate for ν_τ ("") in single τ decay channel per kT-year	20
Neutrino events in 4 years	81,600
Fully measured neutrino events in 4 years	62,000
Near detector distance	0.5 km

years. We are in the process of reanalyzing the Monte Carlo and expect to have a result from our current 1.83 kiloton years soon. By 1999, we will have 5.0 kiloton years of data. In addition to the flavor ratio, we will measure the fraction of multi track events and the fraction of events with recoil protons, which would be further evidence for or against a neutrino oscillation hypothesis.

We are working with Fermilab on a long baseline neutrino oscillation experiment in conjunction with the Main Injector. Such an experiment could begin taking data in the year 2000.

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Figure 1. A candidate ν_μ quasi-elastic interaction. The μ track is 394 gm/cm^2 , corresponding to $645 \text{ Mev}/c^2$ Kinetic Energy. Three projections of the muon track are shown, with two views near the vertex blown up to show a clear recoil proton. All scales are in cm. lines show module boundaries.