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# INTERACTIONS OF ATMOSPHERIC $\nu_\mu$ AND $\nu_e$ OBSERVED IN SOUDAN 2 *

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ABSTRACT

We present preliminary measurements of the relative rates of atmospheric $\nu_\mu$ and $\nu_e$ interactions from the first 0.5 kton-year exposure of the Soudan 2 experiment. The results are consistent with the deficit of $\nu_\mu$ relative to $\nu_e$ reported by the water Cerenkov experiments, which may be evidence for neutrino oscillations.

## 1. Introduction

Atmospheric $\nu_\mu$ and $\nu_e$ are created in cosmic ray interactions in the atmosphere, and can be detected in underground detectors. The Kamiokande and IMB water Cerenkov detectors have found fewer $\nu_\mu$ interactions (relative to $\nu_e$) than are expected.[1] Results are usually expressed by the ratio:

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

with $R$ found to be less than 1 (see table 1). The Soudan 2 detector is an iron calorimeter, which has different systematic effects than the water Cerenkov counters. Results from the Frejus and NUSEX calorimeters do not suggest a deficit of $\nu_\mu$'s in iron, implying that perhaps there is a systematic effect in Cerenkov detectors or some unexpected nuclear effect. Here we report on a preliminary analysis of 0.5 kton-year of data in Soudan 2. In the next section, some of the issues involving the use of the flavor ratio to search for neutrino oscillations are discussed.

## 2. Searches for neutrino oscillations using atmospheric neutrinos

If neutrino oscillations exist, the probability (P) of oscillation is:

$$P = \sin^2(2\theta)\ \sin^2(1.27\,\Delta m^2\,\frac{L}{E_\nu}) \tag{2}$$

with $\Delta m^2$ in eV$^2$, $L$ in km and $E_\nu$ in GeV. $\Delta m^2 = |m^2_{\nu_1} - m^2_{\nu_2}|$ and $\theta$ is the mixing angle. The atmospheric neutrino spectrum peaks at a few hundred MeV/c momentum, somewhat above thresholds for underground detectors. The distance which the neutrinos travel between production and interaction varies from about 10 km for neutrinos travelling downwards to over 12,000 km for those produced on the far side of the earth. If neutrino oscillations exist, then some fraction of the observed neutrino interactions might be the result of such an oscillation. We can define an average oscillation probability

$$P_{av} \equiv \frac{\int\int P(E,L)\phi_\nu(E,L)\sigma(E)dEdL}{\int\int \phi_\nu(E,L)\sigma(E)dEdL} \tag{3}$$

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where $\phi_\nu$ is the neutrino flux and $\sigma$ is the quasi-elastic cross section. Even for maximal mixing, the range of E and L is large so that $P_{a\tau}$ has a maximum expected value of 0.5. For the case of $\nu_\mu \rightarrow \nu_\tau$ oscillations, we expect a value of $R = 1 - P_{a\tau}$ for quasi-elastic or all charged current events, since the $\nu_\tau$ will have insufficient energy to make charged current events.

## 3. Analysis of Soudan 2 data

The Soudan 2 detector analysis chain has been described elsewhere [2]. The detector is a tracking drift calorimeter that will consist of 224 modules each weighing 4.3 tons. Eight hundred tons are operating at present (November 1992) and detector installation will be completed next year. The calorimeter is surrounded by a cavern-liner proportional-tube active shield.

A total of 1.0 kton-year of data has been recorded and the first 0.5 kton-year has been analyzed. Processing of 17 million triggers yielded 25,000 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. The next step was to classify the topology of the contained events as single track, single shower or not being due to a quasi-elastic interaction($\overline{QE}$). The single track and single shower events are mostly (72%) quasi-elastic interactions according to our Monte Carlo simulation. In this separation an observed recoil nucleon or muon decay was ignored. Events which appeared to be neutral current or inelastic interactions were classified as $\overline{QE}$.

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 shield hits 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 is continuously monitored using the 0.2 Hz of throughgoing muons. The final sample contains 38 0-shield-hit (neutrino candidate) events and 23 1-shield-hit events which we use to estimate the background. In the 0-shield-hit events we identify 13 tracks, 14 showers and 11 $\overline{QE}$'s. In the 1-shield-hit sample there are 16 tracks, 5 showers and 2 $\overline{QE}$'s. The neutrino event counts have been corrected for losses due to random shield hits and contamination due to shield inefficiencies, giving a final sample of 11.0 tracks, 13.9 showers and 11.5 $\overline{QE}$'s.

In a Monte Carlo exposure of 3.17 kton-years, analyzed in an identical manner, we identified 20.8 tracks, 14.5 showers and 16.9 $\overline{QE}$ events, after normalizing to our exposure. Scanners correctly identified 96% of the single tracks and showers.

## 4. Discussion

The track/shower ratio is 11.0/13.9 = 0.79 ± 0.39 (stat). The Monte Carlo ratio is 1.43. Major systematic uncertainties at this stage are 15% for the Monte Carlo simulation, 14% from the statistics of the Monte Carlo, and 6% from the uncertainty in shield efficiency. Combining these errors in quadrature, we obtain:

$$R' = \frac{(track/shower)_{measured}}{(track/shower)_{predicted}} = 0.55 \pm 0.27(stat) \pm 0.10(sys) \tag{4}$$

For the hypothesis $\nu_\mu \rightarrow \nu_\tau$, this ratio $R'$ must be corrected to obtain $R$ in Equation 1 because 16% of the single track events are due to neutral current interactions, which are unaffected by oscillations. After this correction, R = 0.46 ± 0.23. We note that the correction of $R'$ to $R$ in equation 1 is strongly model dependent and different for each detector. Our preliminary result is included in Table 1 with the results of other experiments. Taken by itself, our result does not preclude $R' = 1.0$, but it is interesting to note that it is close to the low values of $R'$ seen by IMB 3 and Kamiokande. We also note that the fraction of events which are not quasi-elastic is also lower than predicted by the Monte Carlo, as would be expected for $\nu_\mu \rightarrow \nu_\tau$ oscillations.

Table 1. Comparison of results on the atmospheric $\nu$ flavor ratio.
90% CL on $P_{\alpha\nu}$ assumes $\nu_\mu \rightarrow \nu_\tau$ $(0.0 < P_{\alpha\nu} < 0.50)$.
Only the Soudan 2 $P_{\alpha\nu}$ limits includes a neutral current correction.

| Experiment | Exposure | $R'$ | 90% *CL limits on* $P_{\alpha\nu}$ |
|---|---|---|---|
| **Kamiokande** | 4.90 kton-year | $0.60^{+.07}_{-.06} \pm 0.05$ | $0.31 < P_{\alpha\nu} < 0.50$ |
| **IMB 3** | 7.70 | $0.54 \pm 0.02 \pm 0.07$ | $0.37 < P_{\alpha\nu} < 0.50$ |
| **Frejus** | 1.56 | $0.87 \pm 0.21$ | $0.0 < P_{\alpha\nu} < 0.40$ |
| **NUSEX** | ~ 0.4 | $0.99 \pm 0.40$ | $0.0 < P_{\alpha\nu} < 0.50$ |
| **PRELIMINARY** **Soudan 2** | 0.50 | $0.55 \pm 0.27 \pm 0.10$ | $0.24 < P_{\alpha\nu} < 0.50$ |

## References


1. K. S. Hirata *et al.*, *Phys. Lett.* **B280**, 146 (1992); D. Casper *et al.*, *Phys. Rev. Lett.* **66**, 2561 (1991); Ch. Berger *et al.*, *Phys. Lett.* **B227**, 489 (1989); M. Aglietta *et al.*, *Europhys. Lett.* **8**, 611 (1989)
2. Donald Roback Ph.D thesis, *Measurement of the Atmospheric Neutrino Flavor Ratio with the Soudan 2 Detector*, University of Minnesota, 1992 (unpublished).