Atmospheric neutrino interactions in Soudan-2

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A new measurement of the atmospheric $\nu_\mu/\nu_e$ ratio-of-ratios, $0.61 \pm 0.15 \pm 0.05$, has been obtained using a 3.2-kty exposure of the Soudan-2 underground detector. This measurement, based upon neutrino reactions in an iron tracking calorimeter of honeycomb-lattice geometry, is in agreement with the anomalously low value reported by the underground water detectors.

1. INTRODUCTION

Soudan-2 is a fine-grained iron tracking calorimeter located 2100 mwe underground in Soudan, Minnesota, USA. The experiment has been taking data since 1989 when the detector was one quarter of its full size; the construction was completed at the end of 1993. The experiment continues to take data with 90% live time, having accumulated 3.6 kty up to the date of this Conference. The first result on the ratio of ratios of the atmospheric neutrinos,

$$R = \frac{[\nu_\mu + \bar{\nu}_\mu]/[\nu_e + \bar{\nu}_e])_{\text{data}}}{[(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

was published earlier this year.\(^1\)

2. THE DETECTOR

The two main components of the Soudan-2 apparatus are the Central Detector and the Active Shield. The Central Detector consists of 224 $1 \times 1 \times 2.5$ m calorimeter modules weighing 4.3 tons each. The bulk of the mass consists of 1.6-mm-thick corrugated steel sheets which are interleaved with drift tubes. Each half of a 1.5-cm-diam., 1-m-long, resistive drift tube is read out by a crossed pair of a vertical anode wire and a horizontal cathode pad that determine two coordinates of a tube crossing; the third coordinate is deduced from the drift time. Readout from the 3.4 million half-tubes is accomplished using 136,000 anode and cathode channels that are multiplexed before the signals are digitized.

The Active Shield covers the walls of the Soudan-2 cavern enclosing the Central Detector as hermetically as possible. Only the calorimeter’s support columns must pass through the shield, adding up to about 5 m², out of the total shield area of 1700 m². The shield consists of 1529 modules with a typical size of 19 cm $\times$ 7 m, each containing a double layer of proportional tubes with a digital readout. A coincidence of two adjacent layers is required for a hit in the off-line analysis.

Detailed descriptions have been published of the design and performance of Soudan-2 calorimeter modules \(^2\) and of the Active Shield system \(^3\).

3. CONTAINED EVENTS

The contained events (CEV) in an underground detector are expected to be atmospheric neutrino interactions, where the neutrinos originate in decays of mesons and muons in cosmic ray showers in the atmosphere. It is these interactions that we model in our Monte Carlo simulation and compare with data. We use the Bartol atmospheric neutrino flux \(^4\), and every MC event is overlayed onto a random pulser event to acquire a realistic
The (mis)identification matrix of the atmospheric neutrino Monte Carlo events. The numbers are percentages; every column adds to 100%.

| Reaction | Track | Shower | Multi | Proton |
|----------|-------|--------|-------|--------|
| $\nu_\mu$ CC | 87.2  | 2.7    | 37.3  | 28.0   |
| $\nu_e$ CC  | 4.3   | 92.8   | 41.6  | 8.8    |
| NC       | 8.5   | 4.5    | 21.1  | 63.2   |

During the period April 1989 through December 1996, we analyzed 75 million triggers, most of which are initiated by throughgoing muons or “noise” (both electronic noise and triggers due to local radioactivity in the cavern). 75% of the Monte Carlo events pass the hardware trigger requirement.

All triggers are processed by a two-stage software filter. The software performs a number of data quality checks, and rejects events that conform to one of the identified noise patterns. To check for event containment, the software requires that (i) no part of the event is within 20 cm of the detector surface, and that (ii) no track is located and oriented in such a way that it could enter the calorimeter undetected (e.g. through a crack between modules). The number of events satisfying the software requirements is 15,000 per kty. About 50% of Monte Carlo events that satisfy the trigger conditions pass the software filter.

The last step in the data reduction chain is a two-stage physicist scan. The resulting CEV sample contains typically 500 events per kty, representing an overall data reduction of $2 \times 10^{-5}$. The Monte Carlo events are injected into the data stream before the scanning stage so that physicists scan data and MC simultaneously without knowing which is which. Of the remaining Monte Carlo events, 70% pass the scan requirements, indicating an overall neutrino CEV detection efficiency of about 26%.

In the last scanning stage, all events are classified into one of three topologies: Tracks, showers, and multiprong. Among the neutrino events, most of the single prong topologies are quasielastic interactions,

$$\nu_l + n \rightarrow l^- + p,$$

and

$$\bar{\nu}_l + p \rightarrow l^+ + n,$$

where $l = \mu, e$. Presence of a proton at the primary vertex is not included in the classification. Single track events are subject to an additional scrutiny: All tracks that pass criteria of straightness and heavy energy deposition are removed from the track sample and reclassified as lone protons. For single shower events, we require that they have nine or more hits to remove a range where, at present, we are less confident in separating signal from certain kinds of noise in the detector. Examination of Monte Carlo neutrino events shows the degree of success of our classification, as summarized in Table 1. We see that most tracks and showers indeed have $\nu_\mu$ and $\nu_e$ flavor, respectively, as expected. Multiprong include interactions of all neutrino flavors as well as neutral current (NC) events, and special selection is needed to determine their neutrino flavor. They are not included in the results presented here.

In the CEV analysis, the Active Shield plays a crucial role. Figure 1 displays the shield hit multiplicity distribution for the data and for the Monte Carlo events.
Carlo events. Among Soudan-2 contained events, 80% have one or more associated in-time shield hits. In the terminology used below, events without any shield hits are called *Gold events*, while events with two or more shield hits are called *Rock events*. The former are mostly neutrino interactions, while the latter are due to neutral hadrons or photons created in an inelastic interaction of a cosmic-ray muon in the vicinity of the Soudan-2 cavern. Events with one shield hit are a mixture of the two - they contain neutrino events associated with a random shield hit (see the Monte Carlo distribution in Fig. 1) as well as events originating in the rock. We do not consider these events in our further analysis. Our task is now to ascertain if there are any non-neutrino events in the Gold Sample.

4. NON-NEUTRINO BACKGROUND

The Gold Sample is expected to contain two classes of events:

- neutrino interactions; and

- possible background due to interactions of particles originating in the rock, for one of two reasons: (i) there are charged particles originating in the rock passing through the Active Shield, but there are no hits due to shield inefficiency (a 5% effect); or (ii) there are no charged particles passing from the rock through the shield, called No-shield Rock events.

Rock events include gamma conversions creating showers and neutron interactions creating tracks, showers, and multipronges. We note that the density of the Soudan-2 Central Detector medium is 1.6 g/cm$^3$, the radiation length is 9.7 cm, and the nuclear interaction length is 81 cm. We therefore expect differences between vertex distributions of neutrino and Rock events, the Rock event distribution exhibiting a noticeable attenuation as a function of depth in the detector. We define *Penetration Depth* to be the shortest distance from the event vertex to the detector exterior (excluding the floor). Such definition is necessary as we do not know the direction of the incoming particle in most of the events.

![Figure 2. Penetration Depth distributions for single shower events: (a) Gold data sample, (b) Monte Carlo events, and (c) Rock Events.](image)

The penetration depth distributions are shown in Fig. 2 for single shower events and in Fig. 3 for single track events. In both figures we observe that the Monte Carlo distributions extend over the whole range of the penetration depth, while the Rock distributions are confined to smaller depths. The Gold Data distributions do extend over the whole range, indicating presence of neutrino events, but it is not easy to separate the two components by eye. A hint is perhaps the step down from the second to the third bin which is present in the Gold Data and Rock distributions, but not in the Monte Carlo histogram.

We therefore adopt the following procedure to determine the amount of non-neutrino background in the Gold Data: We fit the Gold Data depth distributions to the sum of the expected neutrino (MC) and background (Rock) depth distributions. We choose the Extended Maximum Likelihood Method, a binned maximum likelihood which is appropriate for low statistics distributions, which preserves the total number of
events in the distributions being fitted, and which takes into account finite statistics of the fit components, the Monte Carlo and Rock distributions. The result is displayed in Fig. 4. Here the Gold Data are depicted by the crosses, the solid-line histogram is the fit, and the shaded areas represent the amount of the Rock related background.

5. ATMOSPHERIC NEUTRINO FLAVOR RESULTS

Our final samples are summarized in Table 2. We see that both track and shower samples have 25 - 30% non-neutrino background. The corrected number of neutrino showers agree with the number of Monte Carlo showers while the corrected number of neutrino tracks exhibits a deficit when compared to Monte Carlo.

In order to measure the $\nu$ flavor composition in an unbiased way as possible, it is customary to use a “ratio of ratios”. We express $R$ defined in Eq. 1 using our number of tracks, $T$, as a measure of $\nu_\mu$ events, and number of showers, $S$, as a measure of $\nu_e$ events:

$$R = \frac{T_\nu/S_\nu}{T_{MC}/S_{MC}}.$$ 

Before the background correction, we obtain $R = 0.66 \pm 0.10$ using the raw Gold sample counts. Using the corrected numbers of neutrino events in our Gold sample from Table 2, we obtain

$$R = 0.61 \pm 0.15 \pm 0.05,$$

where the first error is statistical, and the second is systematic.

Our value of $R$ is consistent with results of underground water detectors reviewed in Ref. 5. The indication is that there are too few single tracks, i.e. too few $\nu_\mu$ and $\bar{\nu}_\mu$ events in the underground neutrino flux, usually explained as due to neutrino oscillations.

Finally, we present lepton energy distributions for our track sample in Fig. 5 and for our shower sample in Fig. 6. In the upper portion of the figures, the crosses represent our Gold Data before
Table 2
Soudan-2 results for 3.2 kty.

|                  | Tracks | Showers |
|------------------|--------|---------|
| Gold, total      | 91     | 137     |
| Rock             | 284    | 401     |
| Bkgd in Gold     | 27.1±11.4 | 33.2±9.9 |
| (fraction of Gold| 29.8% | 24.2%  |
| Monte Carlo      | 588    | 584     |
| (norm. to 3.2 kty)| 101.4±4.2 | 100.7±4.2 |
| ν in Gold        | 63.9±13.1 | 103.8±13.6 |

any correction, and the solid histogram shows the Rock background. The dashed histograms are the Monte Carlo distributions. In the lower portion of the figures we show our corrected data distributions. We note that the background is confined not only to smaller penetration depths, but also to smaller energies than the neutrino event distributions.

Our plans for the near future include the extraction of the neutrino flavor ratio from the multiprong events, and neutrino oscillation analysis of our data.

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