Recent atmospheric neutrino results from Soudan 2

T. Kafka

for the Soudan 2 Collaboration
(Argonne National Laboratory, University of Minnesota, Tufts University, USA; Oxford University, Rutherford Appleton Laboratory, UK)

An updated measurement of the atmospheric $\nu_\mu/\nu_e$ ratio-of-ratios, $0.68 \pm 0.11 \pm 0.06$, has been obtained using a 4.6-kty exposure of the Soudan-2 iron tracking calorimeter. The $L/E$ distributions have been analyzed for effects of $\nu_\mu \rightarrow \nu_x$ oscillations, and an allowed region in the $\Delta m^2$ vs. $\sin^2\theta$ plane has been determined.

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 in 1993. The experiment continues to take data with 90% live time. The results presented here were obtained using a 4.6 fiducial kiloton-year exposure. For previous Soudan-2 results on the ratio of ratios of the atmospheric neutrinos,

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

see Refs. [1, 2].

Detailed descriptions have been published of the design and performance of Soudan-2 calorimeter modules [3], and of the active shield system [4].

2. ATMOSPHERIC NEUTRINO FLAVOR RESULT

We analyze fully contained events (all hits more than 20 cm from the nearest detector edge) to determine $R$ using single-track and single-shower events for which the active shield registered no in-time two-layer coincident hits (gold events). This sample contains mostly quasi-elastic neutrino interactions, with a background of photon and neutron interactions originating in cosmic-ray muon interactions in the rock. These rock events are mostly flagged by hits in the active shield, but some are not accompanied by shield hits and constitute a background for our neutrino sample. A correction for this background is determined using distributions of event depth in the detector. For the 4.6-kty Soudan 2 exposure, we obtain a ratio-of-ratios value of

$$R = 0.68 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.})$$

Our full detector simulation of atmospheric neutrino interactions is based on the 1989 Bartol flux for the Soudan site [5]. See Ref. [6] for more information on the quasi-elastic data analysis.

3. HIGH RESOLUTION SAMPLE

We wish to analyze neutrino $L/E$ distributions where the neutrino path length is calculated from the event zenith angle, radius of the Earth, and the neutrino production height. We therefore make data selection designed to optimize our resolution in event angle and in energy. For the quasi-elastic events (tracks, showers) we require the charged lepton momentum to exceed 150 MeV/c if a recoil proton is measured in the event, otherwise we require event visible energy to exceed 600 MeV. For multi-prongs, we require the visible energy to exceed 700 MeV, the vector sum of visible momenta to exceed 450 MeV, and the charged-lepton momentum to
neutrino oscillations. Fig. 2 displays the $\nu_e$ distribution for downgoing neutrinos, while the simulation is shown in cross-histograms. The MC histogram is normalized to the data for $\theta^2=0.0001 \text{ eV}^2$ and $\sin^22\theta=1$ and for four values of $\Delta m^2$. We see that the simulation exceeds the data for $\Delta m^2 = 0.0001 \text{ eV}^2$ and $\Delta m^2 = 0.001 \text{ eV}^2$ for most of the downgoing neutrinos, while the simulation is smaller than the data for $\Delta m^2 = 0.01 \text{ eV}^2$. The best agreement between data and the simulation is obtained for $\Delta m^2 = 0.008 \text{ eV}^2$.

Figure 1. $L/E$ distributions for Soudan-2 $\nu_e$- and $\nu_{\mu}$-flavor HiRes samples (crosses) together with the no-oscillation atmospheric neutrino Monte Carlo (dashed histograms).

4. $L/E$ RESULTS

In Fig. 1 we show the $L/E$ distributions for the HiRes sample. Fig. 1a shows that the $\nu_{\mu}$-flavor data (crosses) follow the shape of the $\nu_e$-flavor no-oscillation Monte Carlo distribution (dashed histogram). The MC histogram is normalized to the $\nu_e$ data. In the $\nu_{\mu}$-flavor sample, shown in Fig. 1b, the depletion of the data vis-à-vis the no-oscillation Monte Carlo is obvious (with the same MC normalization as for the $\nu_e$ sample).

To convert results of our atmospheric neutrino simulation generated under the no-oscillation hypothesis into simulated neutrino oscillation data, we apply to every MC event an $L/E$-dependent weight representing the probability of no oscillation for a given $\Delta m^2$ and $\sin^22\theta$ valid for two-flavor neutrino oscillations. Fig. 2 displays the $\nu_{\mu}$-flavor $L/E$ distribution (crosses) together with the oscillation MC for $\sin^22\theta=1$ and for four values of $\Delta m^2$. We see that the simulation exceeds the data for $\Delta m^2 = 0.0001 \text{ eV}^2$ and $\Delta m^2 = 0.001 \text{ eV}^2$ for most of the downgoing neutrinos, while the simulation is smaller than the data for $\Delta m^2 = 0.01 \text{ eV}^2$. The best agreement between data and the simulation is obtained for $\Delta m^2 = 0.008 \text{ eV}^2$.

To determine the neutrino oscillation parameters $\Delta m^2$ and $\sin^22\theta$ from our data, we fit the atmospheric neutrino Monte Carlo distribution including the effects of neutrino oscillations to the $L/E$ distribution for our $\nu_{\mu}$ data corrected for the rock background, by minimizing $\chi^2$. At the same time we assume that no neutrino oscillations occur in the $\nu_e$ flux, and include only the total $\nu_e$ event counts in our $\chi^2$. In addition to $\Delta m^2$ and $\sin^22\theta$, the neutrino flux normalization factor, $f_\nu$, is the third free parameter in the fit. Errors in both the data and the Monte Carlo are taken into account when calculating $\chi^2$.

Fig. 3 shows our $\chi^2$ surface as a function of $\Delta m^2$ and $\sin^22\theta$. A distinct minimum is observed at $\Delta m^2 = 0.008 \text{ eV}^2$ and $\sin^22\theta = 0.95$ (with $f_\nu = 0.82$). The corresponding confidence-level contours are shown in Fig. 4 for 68% CL and 90% CL. The Soudan-2 allowed region is seen to overlap both the Kamiokande and SuperKamiokande allowed regions [7].

Our plans for the near future are to incorpo-
rate more recent atmospheric $\nu$ fluxes in the Monte Carlo, and to include partially contained events in the analysis. And we certainly plan on taking more data, even through the period of dynamite blasting of the MINOS cavern in the Soudan mine. We expect to reach 5.0 fid. kty by the Millenium.

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