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Measuring Cosmic Ray and Atmospheric Neutrinos in the Sudbury Neutrino Observatory

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High energy muons and neutrinos are produced by the interaction of primary cosmic rays in the Earth's upper atmosphere. These primary interactions produce mesons that decay into muons and neutrinos. SNO is in a unique position amongst underground experiments in the world. At the depth of over 6 km water equivalent, it is the deepest underground laboratory currently in operation. SNO can make a number of novel measurements using muons. First, SNO is sensitive to the downward muon rate coming from primary cosmic ray interactions. Second, SNO's great depth makes possible the detection of atmospheric neutrinos (via the detection of neutrino induced muons) from the nadir to inclinations as large as $\cos(\theta_{\mathrm{zenith}}) \simeq 0.4$ above the horizon. Although SNO is a modest-size Cherenkov detector, SNO's unique niche allows it to make important model-independent checks of atmospheric neutrino oscillations.

Keywords: Atmospheric neutrinos; muon; cosmic ray flux.

1. The SNO detector

The Sudbury Neutrino Observatory (SNO) uses 1 kton of ultra pure D_2O as a target to study ν_e+d $\rightarrow e^- + p + p$ and ν_x+d $\rightarrow \nu_x$+n+p reactions[a] from solar neutrinos [1]. The heavy water is contained in a 12 m diameter transparent acrylic shell as shown in Figure 1. Cherenkov light emitted as charged particles pass through the detector is gathered by 9456 photomultiplier tubes mounted on the 17.8 m geodesic sphere encasing the detector (PSUP). An additional 91 outward-looking tubes are used to tag high energy particles, such as cosmic muons, entering from outside the detector.

Located in Sudbury, Ontario, Canada, SNO is the deepest underground laboratory currently in operation. Having a depth of 2092 meters (or 6010 meters water equivalent) reduces the number of cosmic rays seen within the detector to $\sim$ 80 events/day. The low cosmic ray activity allows SNO to be highly sensitive to solar neutrinos and upward-going neutrino-induced muons, while the high slant depth favors high-energy cosmic rays.

[a]Where ν_x refers to any active flavor of neutrino.

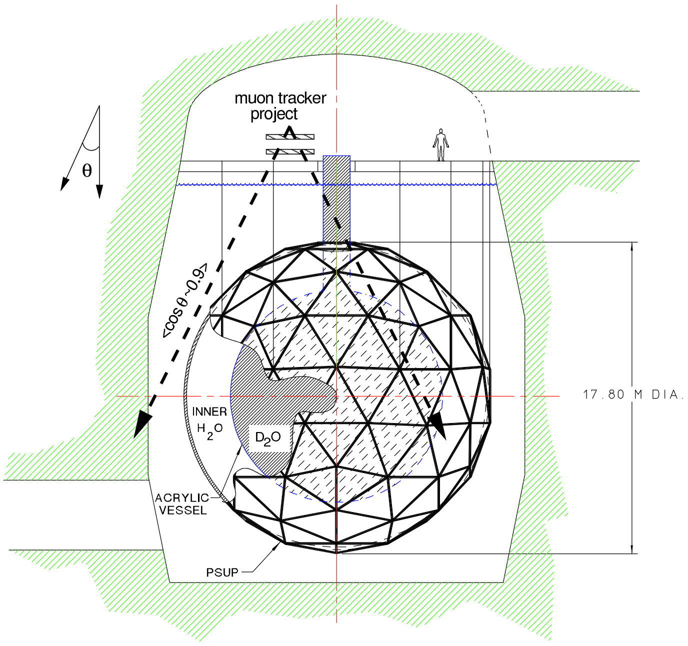

Fig. 1. Schematic view of the SNO detector 6800 ft underground. A proposal for a muon tracker is discussed in Section 3.

2. Atmospheric neutrinos in SNO

Figure 2 shows the expected zenith angle distribution of the muon flux at SNO[2]. At this depth, cosmic muons at zenith angles below $\cos(\theta_{\mathrm{zenith}}) \simeq 0.4$ are attenuated. Any muons recorded at a lower zenith angle are due to neutrino interactions in the rock surrounding the detector. While the neutrino flux is symmetric about the horizon, only events coming from below the horizon may oscillate. SNO can thus perform a direct measurement of the absolute atmospheric neutrino flux. By studying the muon flux as a function of zenith angle, it is also possible to study neutrino oscillations. The effect of oscillation scenarios[b] involving $\nu_\mu \rightarrow \nu_\tau$ or a sterile neutrino is also shown on the figure.

2.1. *Reconstruction*

On average a muon passing through the detector will deposit an energy of 2–3 GeV. It is characterized by a large number of photomultiplier tubes (PMT) recording a signal. The muon exit location is determined by clustering the PMTs with high charge. This point is used to bootstrap an iterative fit using the PMTs timing to determine the muon direction. Systematic effects such as radial bias are corrected.

The analysis and reconstruction algorithm performance for through-going muons

[b]Based on best-fit measurements reported by the Super-Kamiokande collaboration (SK) in [3].

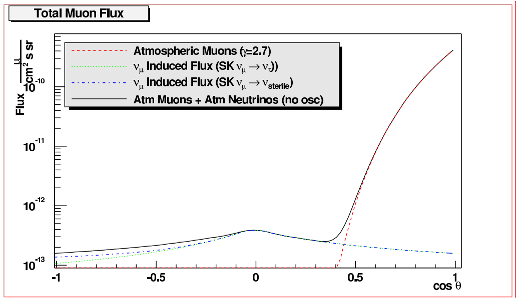

Fig. 2. Zenith angle distribution of muons predicted at SNO location. The curves below the horizon correspond to different oscillation scenarios. See full text for details.

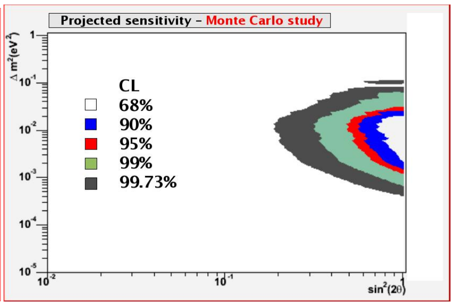

Fig. 3. Projected atmospheric-neutrino-oscillation sensitivity for through-going muons for 730 days livetime at SNO. See full text for details.

are currently being optimized.

2.2. *Sensitivity*

Figure 3 shows the projected atmospheric-neutrino-oscillation sensitivity for SNO's accumulated 730-day data set (as of Winter 2003). The fit uses a loose normalization constraint reflecting the current uncertainty on the primary cosmic flux, and assumes oscillations given by $(\Delta m^2, \sin^2 2\theta) = (5 \times 10^{-3}\ [\mathrm{eV}^2], 1)$. The color bands show the signal for different confidence levels (CL). Only statistical uncertainties are included in this figure.

The reconstruction and sensitivity reach of low energy muons that stop in the detector is being investigated as well.

3. Prospects for muon calibration

In order to acquire independent calibration data, the installation of a set of reconditioned tracking chambers at SNO is being assessed.

A portable design consisting of a small number of planes of a size between 4–8 m^2 would allow the recording of 3–6 muons/day with an angular resolution on three-dimensional tracks better than 1 degree. Such a sample is of particular interest in the determination of the systematics in the simulation and track reconstruction.

Figure 1 shows the angular coverage of such a tracking device. There is also the perspective to improve the acceptance for muons at large impact parameters where the current reconstruction algorithm becomes less efficient.

References

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