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Through-going muons in the Sudbury Neutrino Observatory

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Abstract. We present results from observing through-going cosmic ray muons in the Sudbury Neutrino Observatory (SNO). Most of these events are very high energy downward muons produced by meson decay in the atmosphere. These yield information on the rate, energy spectrum and atmospheric interactions of cosmic rays. The remainder are horizontal and upward muons produced by the interaction of atmospheric neutrinos in the rock surrounding SNO. We are uniquely able to see neutrino-induced muons coming from above the horizontal. The angular distribution of these muons is sensitive to neutrino oscillations and very insensitive to the details of flux calculations.

1 Introduction

1.1 The Sudbury Neutrino Observatory

The SNO detector is a large volume water-Cherenkov detector of charged particles with a very low electron energy threshold of about 5 MeV (Boger 2000). It is sited at the 6800 ft level in INCO's Creighton Mine in Sudbury, Ontario. The heart of the detector is 1000 tonnes of D_2O, a material chosen specifically for solar neutrino detection. For the detection of cosmic-ray-induced muons the heavy water is indistinguishable from light water. The mean minimum through-going muon energy is 2.9 GeV.

The geological environment of SNO is shown in Fig. 1. The overburden is essentially flat and uniform and the centre of SNO is at a depth of 6010 metres water equivalent (m.w.e.). The two local rock types, known as the hanging wall and foot wall, are similar in density and composition to within a few % and are relatively straightforward to model in the analysis of muon events.

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1.2 Downward Muons

Solar neutrinos detectors like SNO are placed deep underground precisely to reduce the intensity of atmospheric cosmic ray muons. Muons can give backgrounds to the solar neutrino signal in the form of neutrons and decays of spallation products. Only very high energy muons (>4 TeV) have sufficient energy to reach SNO; the rate of through-going downward muons detected is about 3 per hour.

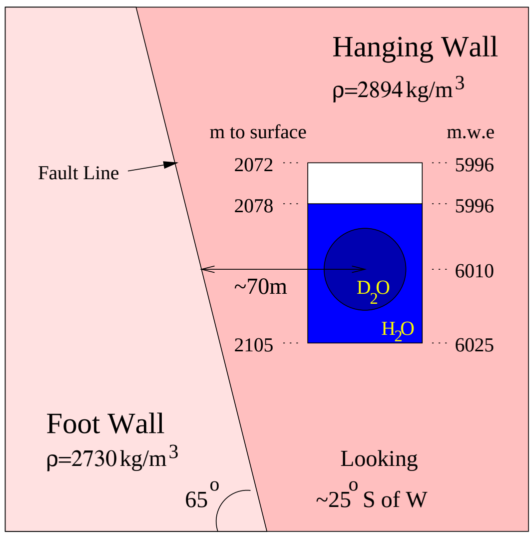

Fig. 1. The geological environment and position of SNO. The hanging wall is norite, a dense gabbro; the foot wall is a less dense mix of gabbro and granite. The depths of various parts of the detector are given in metres of rock and metres water equivalent (m.w.e).

Downward muon rates deep underground have been investigated many times, most recently by the Fréjus (Berger et al. 1989), MACRO (Ambrosio et al. 1995) and LVD (Aglietta et al. 1999) experiments. They have measured the intensity as a function of depth, the spectral index of muons at the surface, and set a limit on the "prompt" component from charmed-meson decays. In our study of downward muons, we repeat

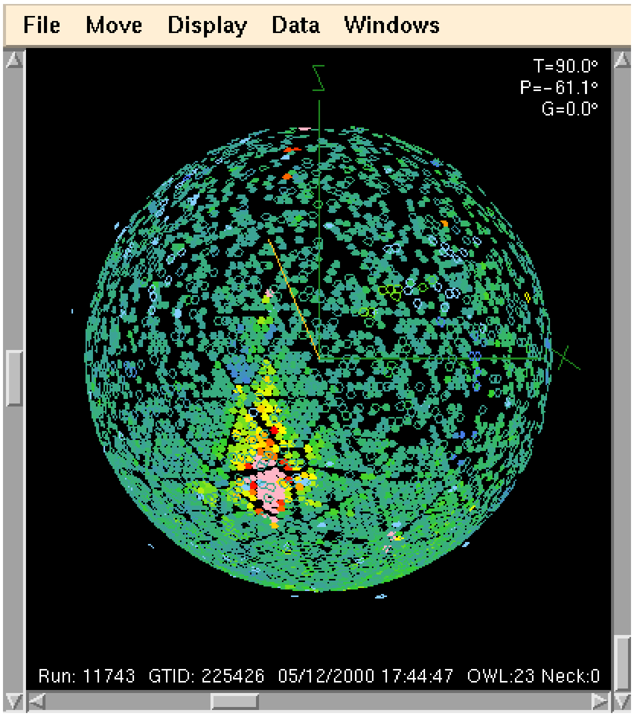

Fig. 2. Through-going downward muon event in SNO. The geodesic frame is that of the PMT support structure (diameter 17 m). The PMTs registering at least one photon are shown; unfilled hexagons for those in the near hemisphere, filled for the far hemisphere. In the graphical display they can be colour-coded either with the total charge measured or or the time of hit. This muon traversed SNO close to the edge; the bright spot shows PMTs closest to the track which received the highest charge.

this analysis, and show that we see no atmospheric muons from an angle below $\sim 24^\circ$ ($\cos\theta = 0.4$) above the horizon.

1.3 Neutrino-Induced Muons

Atmospheric muon neutrinos can interact with the rock around SNO. They produce penetrating muons which travel up to about 10 km.w.e. and can be detected by SNO. We expect and find the rate of detection of distinguishable neutrino-induced muons to be about 120/y. This rate is tiny compared with the downward muon rate, but SNO's angular resolution is sufficient to obtain a clean sample with $\cos\theta < 0.4$.

Existing data on atmospheric neutrinos, of which neutrino-induced muons are a part, principally from Super-Kamiokande (SK) (Fukuda et al. 1999), point to a $\nu_\mu \rightarrow \nu_\tau$ oscillation with a mass difference squared of $\Delta m^2 \approx 0.003$ eV^2 and a mixing angle $\theta \approx 45\,\mathrm{deg}$. One signal for this oscillation is the angular distribution of neutrino-induced muons. The geometry of the earth and putative neutrino properties dictate that neutrinos with these parameters coming from above the horizon do not oscillate, but those coming from below the horizon do oscillate. This leads to a distortion of the angular distribution, with the signal from below the horizon reduced by almost a factor two. Thus SNO's unique contribution to this area of neutrino oscillation physics is to detect both oscillated and unoscillated neutrino-induced through going muons at the same time. Those seen coming from above the horizon provide a good test of the flux models, unhampered by oscillation effects. In effect we can make a self-normalizing measurement of the high energy atmospheric neutrino flux with a baseline of between 20 and 13,000 km. Without oscillations, the angular distribution is expected to be almost symmetrical above and below the horizontal. The only other effect which can disturb this symmetry is that of the geomagnetic field. However at SNO's high magnetic latitude (Tserkovnyak 2001) it can be shown that the primaries which give rise to through-going muons with $E > 2.9$ GeV experience very little distortion.

2 Through-Going Muon Analysis

We present here the analysis of 149 live days during the time from November 1999 to June 2000. Figure 2 shows a through-going muon event in SNO. To reconstruct muon position and direction from PMT times and charges required a model of Cherenkov light generation and an event fitter (Tagg 2001). The event fitter first searched for the muon exit position, which was identified by locating a group of PMTs with high charge (the bright spot on Fig. 2). The algorithm assumed that light was emitted at the Cherenkov angle from a straight-line muon track, and it computed a goodness-of fit measure based upon the timings of the individual PMTs recorded in the event.

Two figures of merit were then used to evaluate the reliability of the fit. These were a probability density function of PMT time residuals computed using all the PMTs recorded in the event (i.e. re-using data rejected in the fit stage) and the ratio of all PMTs in the forward Cherenkov cone that did fire to those that should have fired (given the fitted track). Events that passed a cut on each of these parameters were labelled as good fits. The r.m.s. angular error of the fitter was 2.1°, and the r.m.s. position error was 0.1 m.

Events near the edge of the detector exhibited poor reconstruction (due to short contained track lengths) and so a cut on the impact parameter (radius of closest approach) was made, accepting all events that reconstructed within ~7.5 m of the centre of the detector. The fiducial area, 175.5 m^2 was defined with an error of 2.65%. The final muon sample after these cuts consisted of 7579 events.

3 Results

3.1 Downward Muons

To calculate the intensity of muons underground requires (a) the intensity of muons at the surface, as a function of energy and angle, and (b) the survival probability as a function of slant depth of rock traversed. The nominal intensity at the surface in units of (cm^2·s·sr·GeV)$^{-1}$ is as follows (Gaisser 2000).

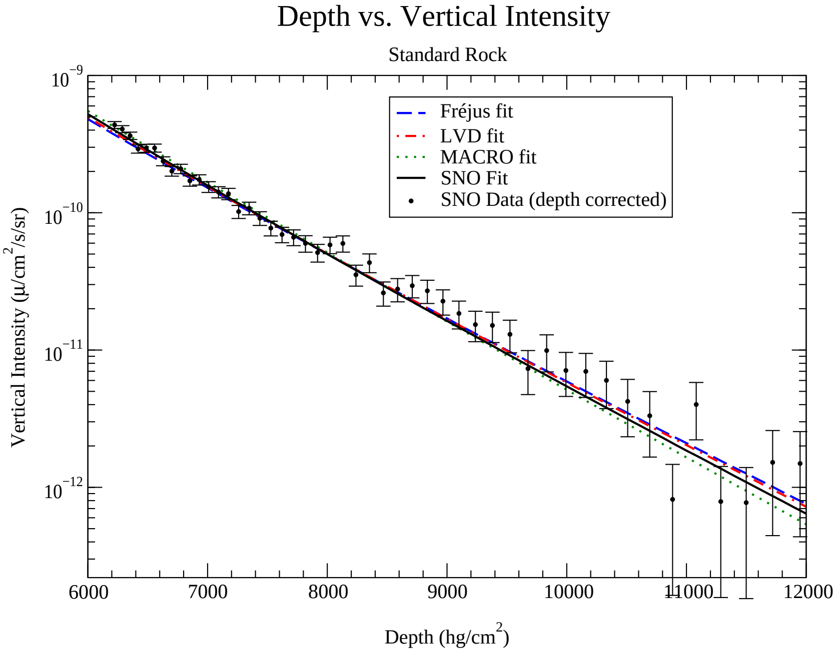

Fig. 3. Depth-intensity relationship for SNO data. The fit shown has the parameters $\alpha = 2$ and $x_0 = 1130 \pm 30$ hg/cm^2. Fits are also shown from Fréjus, MACRO and LVD.

$$\frac{dI_{\mu 0}(E_{\mu 0}, \cos\theta)}{dE_{\mu 0}} = 0.14 \cdot (E_{\mu 0}/\text{GeV})^{-\gamma_\mu}$$
$$\cdot \left(\frac{1}{1 + \frac{1.1 E_{\mu 0} \cos\theta}{115\ \text{GeV}}} + \frac{0.054}{1 + \frac{1.1 E_{\mu 0} \cos\theta}{850\ \text{GeV}}} + R_c \right) \quad (1)$$

The spectral index of muons γ_μ is expected to be close to that of the primary cosmic-rays, $\gamma (\approx 2.7)$. The ratio of prompt muons to pion and kaon decay muons, is handled approximately as a constant, R_c. The muons were tracked through rock using propagation codes MUSIC (Antonioli et al. 1999) and PROP_MU (Lipari 1993).

Using knowledge of the surface intensity, we can convert our measured angular distribution into a depth-intensity plot in standard rock ($CaCO_3$, 2650 kg/m^3) for comparison with other experiments at different depths. The data are shown in Fig. 3, along with a fit to the usual empirical form:

$$I_\mu(vert) = A_v \cdot \left(\frac{x_0}{x}\right)^\alpha \exp\left(-\frac{x}{x_0}\right) \quad (2)$$

A value of γ_μ can be quoted if we assume $R_c = 0$. Theoretical estimates for R_c are in the range $10^{-5} - 10^{-4}$ (Bugaev et al. 1998) and below our current sensitivity.

$$\gamma_\mu = 2.80 \pm 0.04(stat) \pm 0.08(sys)$$

The systematic errors arise from the observation of a small azimuthal asymmetry which is not correlated with our current understanding of the local geology as shown in Fig. 1. The value of γ_μ is consistent with previous results (Ambrosio et al. 1995, Aglietta et al. 1999). There is a very strong correlation between the values of γ_μ and R_c obtained in a free fit to both parameters (see Table 1), but we can give a limit for R_c if we set an upper limit on γ_μ:

$$R_c < 0.005; \gamma_\mu < 2.9$$

The confidence level on R_c is 68%, considering only the statistical error.

γ_μ	χ^2 (48 d.o.f.)	R_c Min.	R_c Max
2.70	58.45	-0.0016	-0.00018
2.75	56.77	-0.0009	0.00072
2.80	55.39	-0.0001	0.00184
2.85	54.25	0.0009	0.00324
2.90	53.32	0.0021	0.00502

Table 1. The limits on R_c to given for different fixed values of γ_μ. Errors (68% C.L.) are statistical only.

3.2 Horizontal and Upward Muons

Two theoretical calculations of neutrino-induced muons are shown in Figure 4. In both we use the Bartol neutrino flux (Agrawal et al. 1996), but allow the overall normalization to float. Propagation of muons in rock is calculated as before. There are two lines, one with and one without neutrino oscillations. In the oscillation case, we take $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.003$ eV^2. The overall neutrino flux is fitted to the data; the values of χ^2/d.f. are 6.29/6 for the no oscillation case and 3.90/6 for the preferred SK $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters. This result marginally favours the SK oscillation parameters. However a much more significant result is that the previously unobserved signal above the horizon is as anticipated (Tagg 2001).

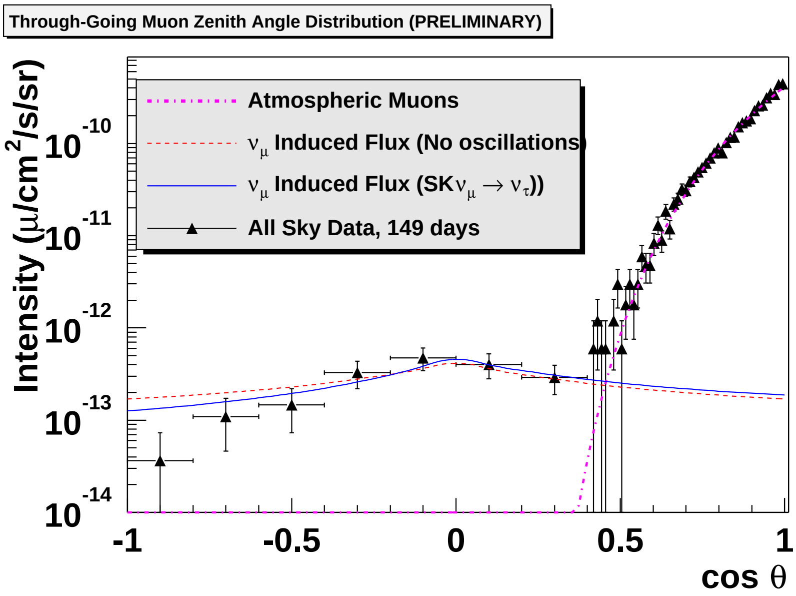

Fig. 4. Complete zenith angle distribution of through-going muons. The theoretical curves are (i) downward muons ($\cos\theta > 0.4$) with the nominal surface distribution and propagation in rock calculated with MUSIC, (ii) neutrino-induced muons ($\cos\theta < 0.4$) with the Bartol neutrino flux, propagation in rock calculated with MUSIC, with (continuous line) and without (dashed line) oscillations. The overall neutrino flux is fitted to the data; the values of χ^2/d.f. are 6.29/6 for the no oscillation case and 3.90/6 for the preferred SK $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters.

4 Conclusions

In this work we have demonstrated that SNO is working as anticipated for high energy events. We have shown that the downward muon intensity and angular distribution is as predicted from extrapolations of results at shallower depths. The downward muon rate is sufficiently small and restricted in angle that a clean set of neutrino-induced muon events can be extracted with a uniquely large range of zenith angles. Preliminary results on the neutrino-induced muon data set are consistent with previously reported neutrino oscillation parameters. However these statistically-limited data are also consistent with no oscillations.

Based on 150 days of data, we predict that a statistically meaningful, self-normalizing neutrino oscillation measurement can be made with SNO in the next year.

5 Acknowledgments

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