Studying Muons and Atmospheric Neutrinos with the Sudbury Neutrino Observatory

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on behalf of the SNO Collaboration

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The SNO Experiment

The **S**udbury **N**eutrino **O**bservatory uses 1 kton of ultra pure D_2O as a target to study $\nu_e + d \rightarrow e^- + p + p$ and $\nu_x + d \rightarrow \nu_x + n + p$ reactions from solar neutrinos. The heavy water is contained within a 12-m diameter transparent acrylic shell. 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. An additional 91 outward-looking (OWL) tubes are used to tag high energy particles, such as cosmic muons, entering from outside the detector.

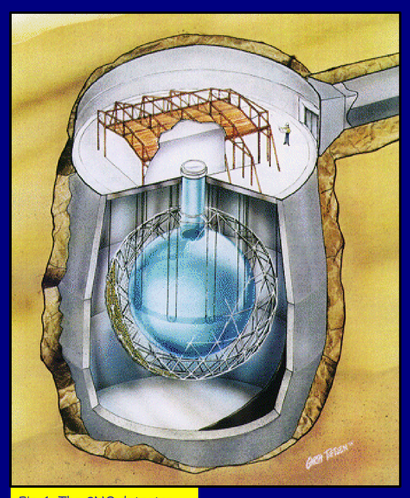

Fig. 1: The SNO detector.

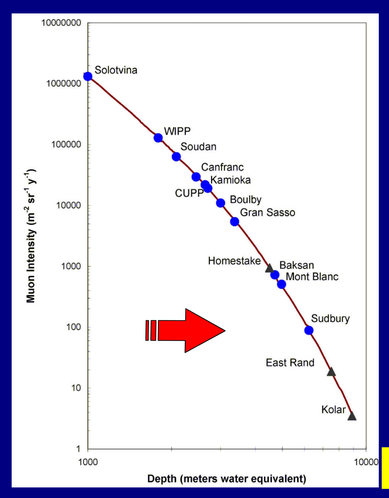

Fig. 2: Vertical muon flux as a function of depth with current (circles) and closed (triangles) underground facilities.

The Location

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 ~80 events/day. The low cosmic ray activity allows SNO to be highly sensitive to solar neutrinos, high-energy cosmic rays and upward-going neutrino-induced muons.

Atmospheric Neutrinos

For zenith angles less than 66°, the high energy cosmic ray muons are attenuated. Any muons recorded at larger zenith angles are due to neutrino interactions in the rock surrounding the detector. By studying the muon flux as a function of zenith angle, it is also possible to study neutrino oscillations.

Although SNO is a modest-size atmospheric neutrino detector, its deep location permits direct measurement of the absolute atmospheric neutrino flux. While the neutrino flux is symmetric about the horizon, only events coming from below the horizon may oscillate. SNO's depth provides a robust check on neutrino oscillations.

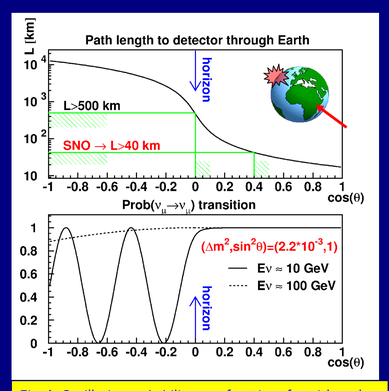

Fig. 4: Oscillation probability as a function of zenith angle.

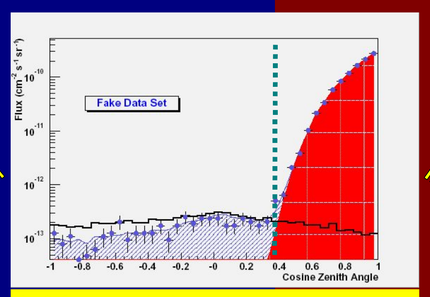

Fig. 3: Cosmic muons (red) and neutrino-induced muons (blue) as a function of zenith angle. Points come from a simulated data set.

Muons

For zenith angles greater than 66°, the muon flux is entirely dominated by muons resulting from primary interactions in the upper atmosphere.

Measurement of the muon flux at many depths (as done by other underground experiments such as MACRO, LVD, Frejus, and others) provides a test of the primary surface flux as well as the muon transport mechanism.

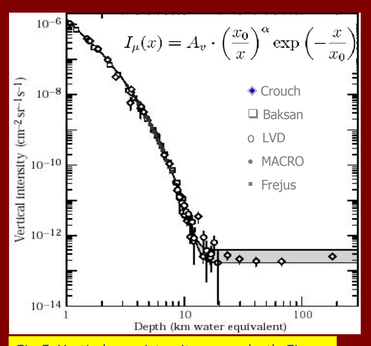

Fig. 5: Vertical muon intensity versus depth. Figure from PDG 2002.

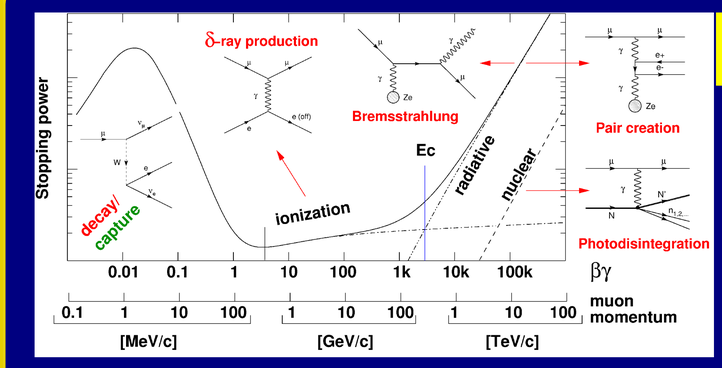

Fig. 7: Processes involved in the description of the energy loss of muons in the SNO simulation.

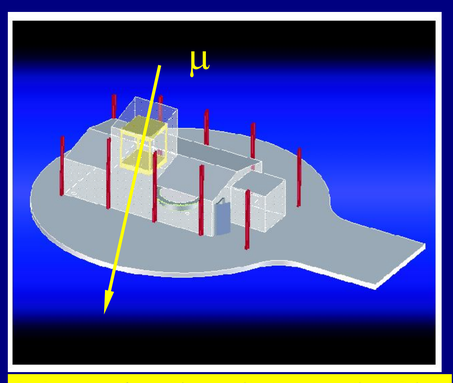

Fig. 8: Mock-up of a possible muon calibration setup on the SNO deck.

Software - Muons Simulation

The energy spectrum of cosmic muons spreads over 4 decades, from O(100 MeV) to O(10 TeV). The processes to be simulated by the SNO collaboration software for the solar neutrino analyses range from 5 MeV (threshold) to around 20 MeV (hep events).

The SNO Monte Carlo has been complemented with a full set of processes describing the energy loss of muons.

Down to explicit thermalization of spallation products, the same data structure successfully accomodates the simulation of physics processes over 15 orders of magnitude in energy.

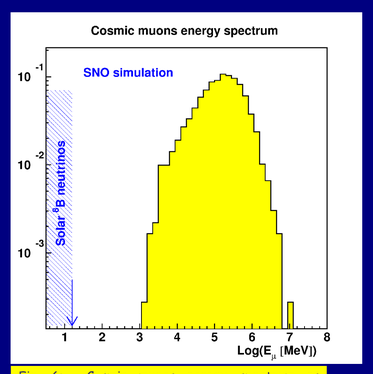

Fig. 6: Cosmic muons energy spectrum as simulated in the SNO Monte Carlo.

Hardware - Muons Direction Calibration

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

A portable design consisting of 2 XY stations of size between 4-8 m² would allow the recording of 3-6 muons/day with an angular resolution on 3D tracks better than 1 degree.

Such a sample is of particular interest in the determination of the systematics in the simulation and track reconstruction.

Selecting Muon Candidates

On average, a muon passing through the entire detector will deposit 2-3 GeV of energy, resulting in a large number (>2000) of photomultiplier tubes to record a signal. Large PMT charge measurement and activity in the OWL tubes are typical of muon events.

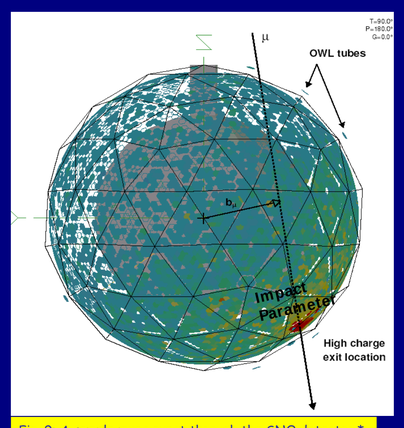

Fig. 9: A sample muon event through the SNO detector *.

Event Reconstruction

Muon events are reconstructed using a goodness-of-fit χ^2 function that makes use of the timing of each valid photomultiplier tube:

$$\chi^2 = \frac{1}{N}\sum_i^N \frac{\left[t_i - t_f(b_\mu, \nu_\mu)\right]^2}{\sigma_t^2}$$

The fit time (t_f) is a function of the direction (ν_μ) and impact parameter (b_μ) of the muon, each of which is determined by the fit. Two variables are used to determine the quality of the fit.

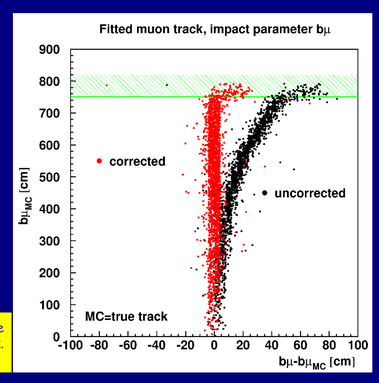

Fig. 10: Impact parameter (b_μ) versus difference between radial position in reconstructed and true track. Shown for events with and without bias correction.

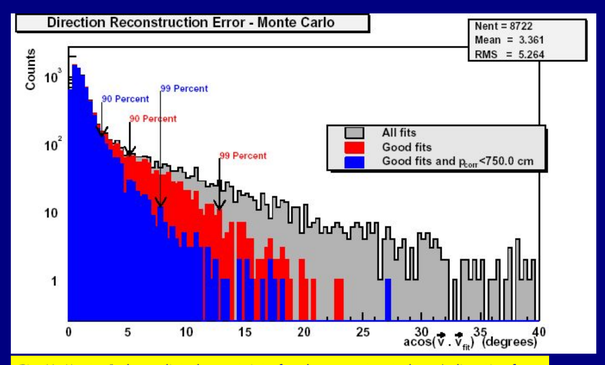

Fig. 11: Monte Carlo predicted uncertainty for the reconstructed track direction for several event selection criteria *.

Systematic effects such as radial bias are corrected as a function of impact parameter. Within an impact parameter of 7.5 meters, the typical error on the directional angle is 1.5° and the error on the impact parameter itself is less than 15 cm.

Data Sample

A preliminary analysis of through-going muons in the SNO detector has previously been reported using the first 149 days of data from the pure D_2O phase. Systematic uncertainties such as angular resolution, fitter efficiency, stopping muons, and effective area have been evaluated. Results (see Figure 12) agree reasonably well with expected yields. The preliminary dataset has also been studied for atmospheric neutrino oscillations, though statistically it cannot distinguish between oscillation and non-oscillation scenarios.

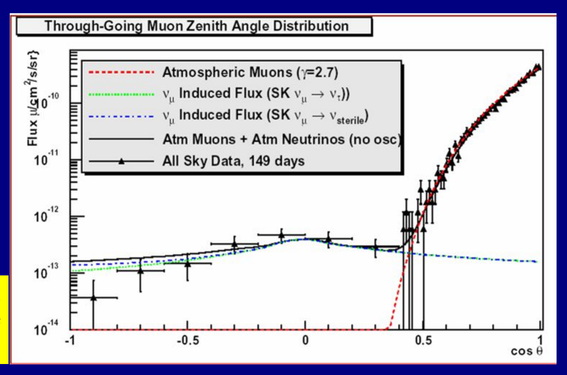

Fig. 12: Muon flux for 149-day dataset as a function of zenith angle. Data and curves normalized by livetime and effective area.*

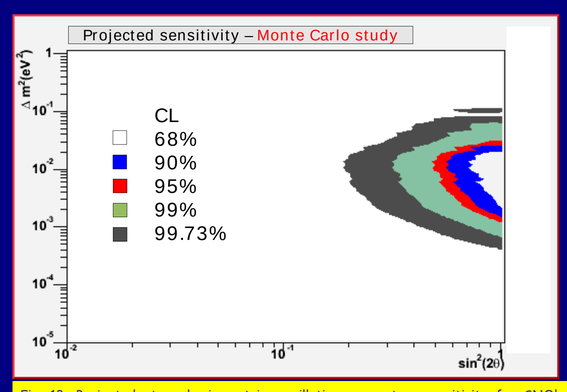

Fig. 13: Projected atmospheric-neutrino-oscillation parameters sensitivity for SNO's accumulated 730 day data set, with flux constraint. Colored bands show signal for different CL. Fit based on current best fit from Super-K. Statistical errors included only.

Projected Sensitivity and Future Goals

Ongoing improvements to the 149-day analysis include:

-> A full comprehensive Monte Carlo of neutrino interactions at atmospheric energies (using NUANCE)

-> Refined input to the fitter to take into account proper PMT timing and charge distributions (multi photoelectrons)

-> Thorough testing of fitter acceptance as a function of impact parameter

The SNO collaboration is currently working on a comprehensive muon analysis that will include the full pure D_2O + salt data sets (~730 live days… a 5-fold increase in statistics).

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