Measuring the Cosmic Ray and Atmospheric Neutrino Fluxes at the Sudbury Neutrino Observatory

J. A. Formaggio
Massachusetts Institute of Technology
(for the SNO Collaboration)
Measuring the Cosmic Ray and Atmospheric Neutrino Flux at the Sudbury Neutrino Observatory

- Physics from Cosmic rays
- The Environment (SNO)
- Event reconstruction & selection
- Verification methods
- Backgrounds & Systematics
- Preliminary results & Summary

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What Can SNO Measure?

- At 5900 meters water equivalent, SNO can measure the primary flux for muons of very high energies.

- Below \(\cos(\theta_z) < 0.4\), cosmic ray muons are well below the neutrino-induced muons. Neutrino-induced muons become the dominant signal.

- Sensitive to oscillating and non-oscillating portions of the neutrino-induced spectrum (above the horizon).

- Other physics also open:
  - Cosmogenic neutron production from muons.
  - All sky map of muons searching for point sources.
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The Environment

- Location in Sudbury, Canada, in Canadian shield

- Local flat landscape near sea level (309 m above sea level with 50 m local variations)

- Active nickel mine; local rock mostly norite or granite.

- Rock density measured via bore samples and surface gravity measurements.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Norite</th>
<th>Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Density (g/cm$^3$)</td>
<td>2.83 ± 0.05</td>
<td>2.83 ± 0.10</td>
</tr>
<tr>
<td>$&lt;Z/A&gt;$</td>
<td>0.491</td>
<td>0.495</td>
</tr>
<tr>
<td>$&lt;Z^2/A&gt;$</td>
<td>6.01</td>
<td>5.84</td>
</tr>
</tbody>
</table>
Over 2092 m (5900 m w.e.) of rock overburden

The Sudbury Neutrino Observatory
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PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

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7 ktons of light water shielding

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A 12 m acrylic vessel

1 kton of heavy water (neutrino target)

7 ktons of light water shielding

The Sudbury Neutrino Observatory
Three-phase experiment

- Experiment conducted in three phases (with different sensitivities to solar neutral current flux).

- Experiment completed third and final phase on Nov. 28th, 2006.

- Heavy and light water volume drained from cavity; all D$_2$O returned.
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0.2% of NaCl added
Enhanced sensitivity to neutral current reactions

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Discrete $^3$He counters added for best CC/NC separation.
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- Salt Phase. 0.2% of NaCl added. Sensitive to neutral current reactions.
- NCD Phase. Discrete ³He counters added for best CC/NC separation.
Reconstructing Events

- Reconstruction algorithm makes use of SNO's spherical symmetry to simply reconstruction of events.
  - Events look identical under rotational transformation.

- Use of both charge and timing information to reconstruct direction and distance of closest approach (can also be used separately).

- Corrections due to reflections, multiple hit PMTs, etc. accounted for in reconstruction.
**Event Selection**

- A total of 1229 days of livetime analyzed across all three phases of the experiment.
- Through-going muons leave distinct signature passing through detector.
- Use of low level and high level cuts for instrumental background removal.
- Cuts highly efficient in retaining candidate through-going muons.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Low Level Cuts</th>
<th>High Level Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing &amp; Burst Cuts</td>
<td>Calibrated Tubes</td>
<td>Impact Parameter</td>
</tr>
<tr>
<td></td>
<td>Raw Charge</td>
<td>Number of fit p.e.’s</td>
</tr>
<tr>
<td></td>
<td>Raw Timing</td>
<td>Cone In-Time Ratio</td>
</tr>
<tr>
<td></td>
<td>Neck Tubes</td>
<td>dE/dX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cone Tube Fraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear Discriminant</td>
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Through-going muon efficiency: \( \varepsilon_\mu = 99.3\% \)
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### Backgrounds

- High PMT hits numbers also characteristic of instrumental backgrounds. Removed by cuts on topology and timing cuts.
- Bifurcated and cut-based analyses performed to determine level of contamination.
- For atmospheric-induced events, primary cosmic rays also a background. Less than 1 event/year expected after zenith cut.
- Small amount of internal neutrino interactions also contribute, but considered part of the fit.

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<th>Background</th>
<th>Expected Rate (events/year)</th>
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<tr>
<td>Instrumental Activity</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Cosmic Ray Contamination</td>
<td>1.2 ± 1.1</td>
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</table>
Validity Checks

- No direct calibration (controlled muon source) to verify validity of muon reconstruction. Rely on four key measurements:
  - Data/Monte Carlo comparisons of cosmic ray muons.
  - Comparisons of charge-only/time-only track reconstruction.
  - $\chi^2$ tests at high impact parameter.
  - An independent track calibration using an external muon detector.
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- Impact Parameter Reconstruction: < 830 cm (216.4 m^2)
- Impact Parameter Uncertainty: ± 4 cm
- Angular Resolution: 0.6°
## Systematic Uncertainties

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<thead>
<tr>
<th>Neutrino Interaction Model</th>
<th>Variation</th>
<th>Atmospheric Flux Error</th>
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<tbody>
<tr>
<td>Axial Mass</td>
<td>$\pm 150$ MeV/c$^2$</td>
<td>$\pm 1.1%$</td>
</tr>
<tr>
<td>Quasi-Elastic Cross-Section</td>
<td>$\pm 10%$</td>
<td>$\pm 0.8%$</td>
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<td>$\pm 20%$</td>
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<td>$\pm 3%$</td>
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<td>Total Model Uncertainty</td>
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Preliminary Systematic Uncertainty (atmospherics) ± 5.4%
Current Status

- Blind analysis of data performed. Data from 1229 days now opened.
- Data looks at both downward muon rate and atmospheric neutrino flux.
- Paper in preparation and undergoing collaboration review.
Summary

• Muon analysis for full 3-phase data set near complete. Variety of validity checks have reduced systematic uncertainties to less than 5.5% for neutrino-induced flux.

• Access to atmospheric neutrino spectrum above horizon and without neutrino oscillation effects.

• Full range of muon analyses now being explored.
Thank you

- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- University of Pennsylvania
- University of Texas at Austin
- University of Washington
- University of British Columbia
- Carleton University
- University of Guelph
- Laurentian University
- Queen’s University
- TRIUMF
- University of Oxford
- LIP, Lisbon, Portugal