The Sudbury Neutrino Observatory*

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Designed and constructed to address the solar neutrino problem by measuring the charged and neutral current interactions of solar neutrinos, SNO began full operation after the completion of the water fill in April 1999. The detector is currently accumulating data under stable conditions.

1. INTRODUCTION

The Sudbury Neutrino Observatory (SNO)[1] is a second generation water Čerenkov detector with a detection medium of 1000 tonnes of heavy water (D_2O). The advantages of D_2O, along with a location at a depth of 2070 m (5900 m.w.e.), and scrupulous attention to the radiopurity of materials and cleanliness during the construction phase, position SNO to make unique contributions to the measurement of fundamental neutrino properties. In particular, SNO was designed to address the problem of the apparent deficit of solar neutrinos observed in other experiments[2], when compared to solar model predictions[3], by having sensitivity to all flavours of neutrinos (ν_x), and not just ν_e. Thus, an explanation of the deficit, in terms of massive neutrinos and oscillations to other flavours, may be tested independent of solar ν_e flux model calculations.

With an energy threshold of several MeV SNO is sensitive only to neutrinos from the 0.01% ^{8}B branch, $^8B \rightarrow 2\alpha + e^+ + \nu_e$, with $E_\nu \leq 14.8$ MeV, and the smaller ($\approx 10^{-5}$%) hep branch, $^3He{+}p \rightarrow \alpha + e^+ + \nu_e$, with $E_\nu \leq 18.77$ MeV.

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Energetic neutrinos interact in the D_2O of SNO through one of three principle reactions. Electron neutrinos may interact via the Charged Current (CC) reaction, $\nu_e + d \rightarrow p + p + \mathbf{e}^-$, which has $Q = -1.44$ MeV, and an electron angular distribution wrt the initial ν_e direction of $W(\theta_e) = 1 - \frac{1}{3}\cos\theta_e$. All non-sterile neutrinos may interact via the Neutral Current (NC) reaction, $\nu_x + d \rightarrow \nu_x + p + \mathbf{n}$, which has $Q = -2.22$ MeV. The detection of the free neutron following a NC reaction is a key feature of SNO and will be elaborated upon later. With a smaller cross-section all non-sterile neutrinos may also interact via the Elastic Scattering (ES) reaction, $\nu_x + e^- \rightarrow \nu_x + \mathbf{e}^-$, however the ν_e CC diagram dominates leads to a cross section for ν_e scattering which is 6–7 times larger than for ν_x. The angular distribution is strongly forward peaked.

In addition to these principle reactions SNO is also capable of detecting anti-neutrinos through the charged current reaction ($Q = -4.03$ MeV), $\overline{\nu}_e + d \rightarrow \mathbf{n} + \mathbf{n} + \mathbf{e}^+$, where the coincidence, temporal and spatial, of final state particles provides a unique signature. While the Sun is not expected to be a source of anti-neutrinos, galactic sources, such as supernovae, could prove interesting.

2. THE SNO DETECTOR

The SNO detector was constructed in a barrel-shaped cavity with a maximum diameter of 22 m and a height of 34 m. Throughout the extended detector construction period this volume was maintained as a Class 2500 cleanroom. Two principle structures comprise the detector as shown in

Figure 1, a spherical acrylic vessel with a 12 m diameter and 5.5 cm wall thickness and a concentric 17.8 m geodesic PMT support structure (PSUP) around the acrylic vessel. The acrylic vessel holds the 1000 tonnes of D_2O and is surrounded by 1700 tonnes of ultrapure light water. The PSUP holds 9438 inward-looking 20 cm Hamamatsu PMTs, equipped with reflectors, providing a coverage of 65% of 4π. The outer volume of 5300 tonnes of ultrapure light water shields the D_2O from neutrons and gammas from the cavity walls.

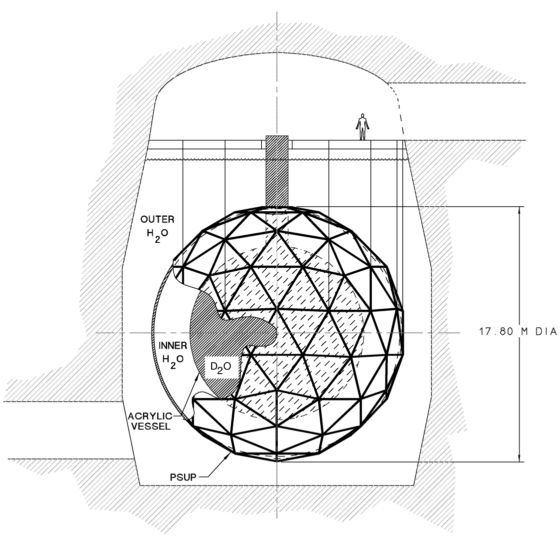

Figure 1. Cross-section of the SNO cavity.

The SNO electronics provides three charge measurements for each PMT covering a dynamic range of 0.05–3000 photoelectrons. PMT timing resolution of 1.7 ns permits event reconstruction with of order 30 cm precision. The primary "NHIT" trigger is an analog sum of all discriminated PMT channels with equal weighting. A second analog sum of all shaped PMT pulses gives the "ESUM" trigger with greater weighting accorded to greater PMT energy. A prescaled low NHIT and a zero-bias pulsed trigger provide continuous measurement of low energy backgrounds and noise.

Recirculation and purification of both the light and heavy water maintains the low radioactive background levels. A program of periodic assays of both the light and heavy water systems shows radioactivity levels at or near to design goals.

3. SNO's PHYSICS OBJECTIVES

The principle physics objective of SNO is to measure the ratio of CC/NC events. A cross-section normalized, acceptance corrected ratio $<$ 1 would strongly indicate ν_e oscillations to ν_μ or ν_τ. A measurement of the ^{8}B total flux via the NC interaction represents a test of the solar model predictions (barring oscillations to sterile ν's) and is of considerable interest. A feature of the ν_e CC interaction on deuterium is that, to of order 20% resolution, $E_{e^-} = E_{\nu_e} - 1.44$ MeV. Thus, the kinematics to measure the ν_e energy spectrum via the e^- spectrum are much more favourable than in the ES case. This, together with an anticipated 5 MeV analysis threshold, allows a sensitive fit to any MSW effect induced spectral distortions.

To achieve these objectives it is necessary to both detect the neutron freed in ν-induced NC reactions and to understand and measure the background production rate of neutrons, primarily from photodisintegration of the deuteron. The design specification for radioactivity allows an NC background of 10% of the full Standard Solar Model (SSM) NC signal. The specification for the assay systems is to provide a 20% measurement (i.e. 2% SSM) of the background contribution. In the pure D_2O (present) phase n-capture on deuterium occurs 24% of the time giving a 6.2 MeV γ, as a workable but difficult NC signature. Two methods are foreseen to enhance the NC signal and both will be used in the course of the experiment. One method involves the addition of 2 tonnes of $MgCl_2$ to the D_2O. The resulting 0.2% salt solution would have an 83% efficiency for n-capture on ^{35}Cl with a γ-cascade releasing a total of 8.6 MeV into the detector. The second method involves the installation of an array of 96 4–11 m long ^{3}He n-counters. A total counter length of 770 m will be deployed giving a 38% n-capture efficiency and offering a distinct NC signature.

4. INITIAL DETECTOR PERFORMANCE

In witness to the attention paid to cleanliness and the radiopurity of materials, and indicative of the initial performance of the water systems, the detector is very quiet. At a 0.25 photoelectron threshold the individual PMT singles rates are in general < 800 Hz, due in part to the cooling of the light water volume to 10^oC. The trigger rates are summarized in Table 1. As seen in Table 1

Table 1
Summary of SNO hardware trigger rates during the initial operation of the detector.

Trigger Type	Hardware Threshold	Trigger Rate (Hz)
Pulsed trigger	zero bias	5
100 ns NHIT	17 PMTs	3–5
20 ns NHIT	15 PMTs	2–3
ESUM	~200 p.e.	< 1
Prescaled	12 PMTs	< 1

the typical overall trigger rate is 10–15 Hz, with 5 Hz from the zero-bias trigger alone. The principle physics trigger is the 100ns NHIT, whose 17 PMT hardware threshold translates to approximately 2 MeV. At this point in time > 98% of all PMT channels are fully working and taking data. We observe "flasher" events where a large pulse is seen in one tube, often with electronic cross-talk to its nearest neighbors, and light is seen by the PMTs on the opposite side of the detector. Bursts of these flashers are definitely correlated with seismic activity in the mine, which we monitor independently, however even the isolated single flashers are very distinctive and reliably identified and tagged in a first pass data analysis. Earlier reported problems of HV breakdown in the submerged PMT HV connectors are now understood to be associated with the degassing of the light water volume, a process which was done for the removal of radon and oxygen. The HV breakdown problems have been resolved by regassing the water with pure N_2 after the degassing step.

From early on, physics events were easily found in the data. Cosmic-ray muons are observed at the expected rate of about 3 per hour, with atmospheric neutrinos being much less frequent. Figure 2 shows a clear Čerenkov ring consistent with a solar neutrino interaction.

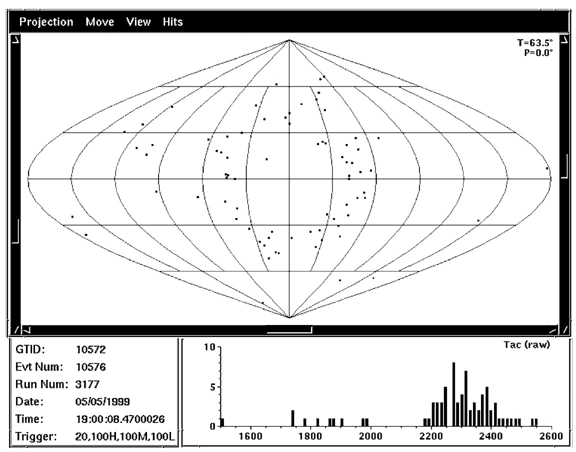

Figure 2. An example neutrino candidate event presented in a flat projection of the detector.

5. CONCLUSIONS

After a challenging construction phase the SNO detector is now routinely taking data. All indications are that the design specifications, and hence the physics objectives, are within reach.

REFERENCES

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2. see for example, C. Gonzalez-Garcia, in these proceedings.
3. see for example, J.N. Bahcall, S. Basu and M.H. Pinsonneault, *Phys. Lett.* **B433**, 1 (1998).