Sudbury Neutrino Observatory: Status and Progress

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ABSTRACT

The Sudbury Neutrino Observatory (SNO) has been designed to study solar neutrinos using 1 kiloton of heavy water (D_2O) as both the interaction and detection medium. The D_2O gives SNO sensitivity to ν_e's exclusively through a charged current (CC) reaction as well as sensitivity to all other weakly interacting neutrino flavors through a neutral current (NC) reaction. SNO has so far taken engineering data in both Air Fill and Partial Fill configurations, beginning our understanding of the detector behavior as well as observing cosmic ray muons and background radioactivity.

1. Physics Motivation and Experimental Approach

The main goal of the Sudbury Neutrino Observatory (SNO) is to study the Solar Neutrino Problem. The measured deficit of neutrinos from the Sun relative to the predictions of the Standard Solar Model, combined with the apparent energy dependence of this deficit, argue strongly that ν_e's from the Sun are changing into another flavor before their arrival at the Earth. The recent atmospheric neutrino measurements from the SuperKamiokande Collaboration strongly support the idea that neutrino oscillations from one flavor to another do occur (in this case, probably $\nu_\mu \leftrightarrow \nu_\tau$). However, for the case of solar neutrinos, no single measurement as yet has demonstrated definitively that the flux of neutrinos from the Sun contains anything other than ν_e's.

SNO is designed to resolve this question through the direct comparison of the solar ν_e flux with the flux of all weakly interacting neutrino flavors. The comparison is done using heavy water (D_2O) as both the interaction and the detection medium. neutrinos interact in three ways in D_2O:

- $\nu_e + d \rightarrow p + p + e^-$ (Charged Current—CC)
- $\nu_x + d \rightarrow p + n + \nu_x$ (Neutral Current—NC)
- $\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e^-$ (Elastic Scattering — ES)

The CC reaction is sensitive only to ν_e's while the NC reaction occurs for all weakly interacting neutrino flavors. Therefore comparison of the neutrino flux measured via the NC reaction and that measured via the CC reaction tells us directly whether the solar neutrino flux contains a significant fraction of non-electron neutrinos.

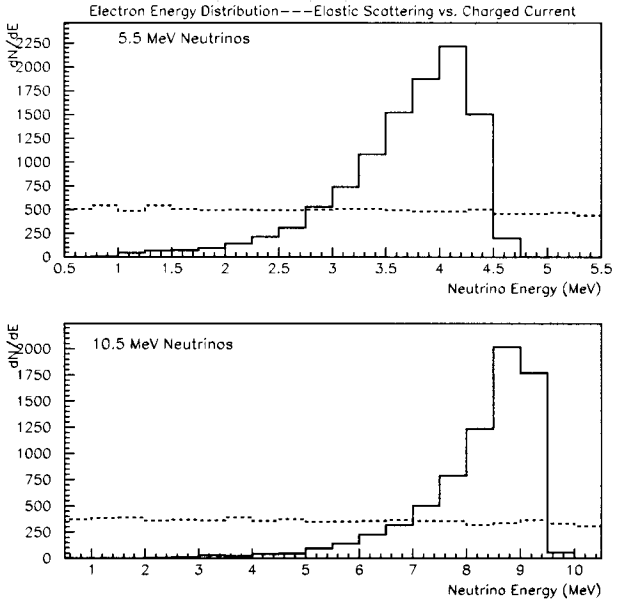

Fig. 1. Comparison of energy resolution of charged current and elastic scattering reactions. The ordinate is labelled in arbitrary units.

There are further advantages to this method, however. As is shown in Figure 1, the CC reaction is a sensitive measure of the incident neutrino energy—far more so than the elastic scattering reaction which produces a recoil electron energy spectrum that is nearly flat. SNO will therefore be able to produce a high resolution measurement of the solar ν_e spectrum (above about ~ 5 MeV). Optimistically, a sensitive measurement of this spectrum can tell us whether neutrino oscillations are occurring in an energy-dependent way, thereby distinguishing different oscillation scenarios.

Lastly, the ES reaction, which is sensitive predominantly to ν_e's but also to other neutrino flavors (with a much-reduced cross section) provides a nice consistency check of the total flux—both with other experiments and with SNO's own flux measurements from the CC and NC reactions.

2. The SNO Detector

The SNO detector is located 2 km underground in the Creighton Mine near Sudbury, Ontario. One kiloton of D_2O is contained in a transparent acrylic vessel, and

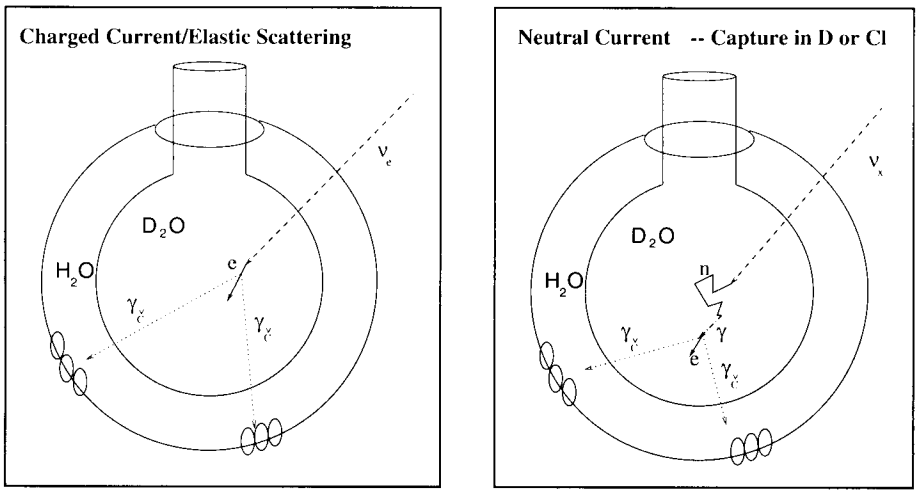

Fig. 2. Neutrino detection mechanisms in SNO.

is surrounded by a geodesic sphere upon which are mounted roughly 9500 8" photomultiplier tubes (PMTs). The entire cavity volume outside the acrylic vessel is filled with $\sim$ 7 ktons of ultrapure H_2O, and the cavity is sealed with a radon impermeable material.

As is shown in Figure 2, SNO detects neutrinos in two ways. For both the CC and ES reactions, a relativistic electron is produced directly, and the resultant Cerenkov light is detected by the surrounding PMTs. Detection of the NC reaction, however, is a multistep process. With pure D_2O inside the acrylic vessel, the neutron liberated by the neutrino reaction is captured by another deuteron, with the emission of a 6.25 MeV gamma. The γ then Compton scatters, producing one or more relativistic electrons which produce detectable Cerenkov light. There are other detection options for the NC reaction, however. Chlorine (in the form of $\sim$ 2 tons of MgCl) can be added to the D_2O, enhancing the capture probability of the neutrons by more than a factor of three as well as boosting the energy of the emitted γ to 8.6 MeV, making it easier to seperate from low energy backgrounds, and allowing a comparison of chlorine-in and chlorine-out rates. A second option is the addition of discrete, ^{3}He proportional

counters, which will detect the neutrons directly.

3. Suppression of Backgrounds

SNO's success depends critically on the understanding and elimination of backgrounds. If we simply assume that the neutrino flux from the Sun is reduced by a factor of three (that is, no oscillations), then SNO would expect a NC event rate of three events per day, a CC rate of 9 events per day, and an ES rate of just 1 event per day. Each event typically has only 50 detected photons, and so any small amount of radioactive contamination which produces detectable light is a potential danger. Radioactivity which leads to the production of a free neutron (through photodisintegration of deuterium, for example), is particularly dangerous, as the capture of such a neutron cannot be distinguished from a neutron produced by a neutrino, regardless of the choice of neutral current detection method. The uranium and thorium decay chains are therefore the greatest concern, since they contain γ's of high enough energy to disintegrate deuterons in the detector.

SNO is designed to suppress the physics background from natural radioactivity as much as possible. The 5 km.w.e. depth reduces the rate of cosmic rays (and in turn their associated spallation products) to roughly one an hour through the D_2O. The $\sim$ 4.5 m of light water between the cavity walls and the heavy water provides shielding from neutrons and high energy γ's from the surrounding rock, and the 2.5 m of light water between the photomultiplier tubes and the heavy water shields the radioactivity from the tubes themselves. In addition, the glass for the phototubes is custom made and has radioactivity levels five times lower than standard glass. The acrylic and the bonding material used to build the heavy water containment vessel are also very low radioactivity materials.

Ensuring and maintaining cleanliness of the water itself (both the light and heavy water) is one of the largest efforts undertaken by the SNO collaboration. The entire underground laboratory is maintained as a clean room ('class 2000') to prevent contamination from mine dust, which can have high levels of uranium and thorium. The water systems continually clean and purify the water, removing radioactivity through reverse osmosis and seeded ultra-filtration, killing off bacteria, and removing radon gas. The ultimate design goals for uranium levels in the H_2O and D_2O are $< 1 \times 10^{-12}$g/cm^3 and $< 4.5 \times 10^{-14}$g/cm^3, respectively; for thorium the goals are $< 1.3 \times 10^{-13}$g/cm^3 for H_2O and $< 3 \times 10^{-15}$g/cm^3 for the D_2O.

4. Rejection of Backgrounds

In addition to keeping radioactive contamination low, SNO has several handles on rejecting backgrounds, from both natural sources and from the detector itself. Most backgrounds associated with radioactivity (the exception is the photodisintegration

of deuterium mentioned earlier) produce events whose energies lie well below the energies of ^{8}B neutrino events, and therefore measurement of energy alone (through the number of phototube hits) is a powerful discriminant itself.

The measurement of charge from each phototube in an event is also an important tool for eliminating backgrounds. For example, tube radioactivity may produce a large charge in a single tube, far more than would be anticipated from the number of total tube hits in that event. By the same token, detector backgrounds such as 'flasher events' can produce charge distributions which will look very different from the 1 photoelectron/phototube expected for a typical neutrino event.

By far the best handle on the rejection of background, however, is event reconstruction. As much of the backgrounds originate from outside the D_2O volume (and no signals except those from the ES reaction), rejection of events whose positions are inconsistent with an origin inside the acrylic vessel reduces the background substantially. For this to be effective, good phototube timing is critical. In addition, the ES reaction produces electrons which are forward peaked with respect to the Sun, while the CC reaction produces an angular distribution which falls as $1 - \frac{1}{3}\cos\theta$, peaked away from the solar direction. The reconstruction of direction is therefore a very powerful tool for identifying the solar signal statistically.

5. Detector Specifics

SNO's heavy water is surrounded by 9522 8" phototubes, each with a light concentrator, providing 55% photocathode coverage. The electronics for the detector provide three independent measurements of charge: two high gain measurements (one a $\sim$ 60 ns integration time and the other $\sim$ 400 ns) and a low gain measurement, for a full dynamic range of 0.1 to 3000 photoelectrons. Each channel also provides a relative tube time with a resolution $\sim$ 120 ps. The system as a whole provides a million event buffer with a burst capability slightly higher than 2 MHz, and each event is time-stamped with an absolute time from the Global Positioning System accurate to $\sim$ 300 ns.

The primary trigger for SNO is a based upon the number of tubes hit in a time window of programmable length, nominally set to 100 ns. The trigger is implemented as a fast analog sum of discrete signals from each tube originating with the firing of each channel's discriminator. In addition to this 'NHIT' trigger, there is a direct sum of shaped PMT pulses (thus giving greater weight to those tubes in a given event which see more light). Although the efficiency of such a trigger is naturally less than that of the NHIT trigger, it provides an excellent monitor of the status of all 9522 phototubes with a single oscilloscope trace. In addition, this 'ESUM' (for 'energy sum') trigger will aid SNO in looking at some of its more exotic backgrounds. Other triggers include a pre-scaled version of a low-threshold NHIT trigger and a zero-bias pulsed trigger for looking at very low energy backgrounds, and a reduced-volume

trigger using a tighter coincidence (20 ns rather than 100 ns) for looking at low energy backgrounds near the center of the detector or at 'hot spots' in the detector through the use of programmable channel-to-channel delays.

The water systems continually purify and cool both the heavy and light water, and also provide the capability for periodic assays to determine the radioactive contamination which can be compared with the background levels determined through analysis.

6. Detector Calibrations

For understanding the detector's response to the neutrino signal, and for the efficient rejection of background, SNO needs a variety of calibration sources. These calibrations fall into a few categories: optical calibrations for the measurement of reflection coefficients, scattering lengths and attenuation; energy calibrations to obtain the energy scale (number of phototube hits/MeV) and resolution; and calibrations of the resolution of SNO's reconstruction algorithms.

A nitrogen/dye laser with a diffuser is the main source used for the optical calibrations. The laser's intensity can be varied over several orders of magnitude through the use of several neutral-density filters, and its wavelength is varied using several different dye units to study the wavelength-dependence of the detector's optical properties.

The primary source for energy calibrations is ^{16}N, which emits a 6.13 MeV γ. The subsequent Compton scattering of the γ provides Cerenkov electrons with a known energy spectrum which can then be used to determine both the energy scale and the energy resolution. For the higher energy scales, a 'pT' source— $^{3}\mathrm{H}(p,\gamma)^{4}\mathrm{He}$—yields a 19.8 MeV γ which can be used in the same way. In addition, a ^{8}Li source will be used to provide a spectrum of electron energies very similar to that of the electrons produced through the CC reaction of ^{8}B neutrinos in the detector.

For determination of the resolution of event reconstruction, all of the above sources will be used. In addition, an array of LED sources fixed to the phototube sphere will provide a check on the overall detector geometry. To measure the phototube timing to high accuracy, SNO employs a unique sonoluminescent source (in addition to the laser source). The sonoluminescent source uses resonant acoustic waves to create a sub-micron sized source of light with a time spread less than 50 ps. It is a high rate (23 kHz), isotropic source with very high intensity, and its combination of small size and short emission time make it particularly useful in measuring the phototube timing, as well as checking some of the optical properties measured by the laser.

7. Recent Data

The majority of the data taken up to the time of these Proceedings has focused on understanding detector behavior. While construction was ongoing, several sets of

runs were made both in a completely dry detector ('Air Fill' data) and in a partially filled detector ('Partial Fill' data). The advantage of the Air Fill data is that it provided a 'beam off' view of backgrounds as well as experience with running the detector.

Most of the sources mentioned in Section 6 were tested in the detector in one or more of the Air Fill runs. The laser source provided measurements of the current settings of the channel level discriminator thresholds (found to have a mean near 0.4 photoelectrons) as well as the functional form of the charge correction to the measured tube times (to account for the effects of 5 ns phototube risetime). Both the laser and sonoluminescent source showed that the phototube timing matched our expectations, with an rms of $\sim$ 1.7 ns, and reconstruction of the two sources was sensitive enough to see the spreading in resolution of the laser position relative to the resolution of the sono source's position, due to the laser source's larger ($\sim$ 6 cm diameter) size.

In addition to the calibration sources run during Air Fill, a few week's of standard triggered data were taken as well. These data provided our first glimpse of physics events in the SNO detector— radon decays in the air, high energy γ's from the surrounding rock converting in the acrylic vessel, and muons. The detection of muons in the Air Fill data is somewhat unusual, and is illustrated in Figure 3. A μ traveling downward through the detector enters the upper hemisphere and produces Cerenkov light, roughly half of which is trapped inside the acrylic due to total internal reflection. The half that is not trapped creates an arc, rather than a full ring, at the bottom of the detector. As the μ travels further downward, it enters the bottom hemisphere of the acrylic vessel and again produces Cerenkov light, but this time the curvature of the vessel means that it is the other half of the ring which is trapped. Because the μ is closer to the bottom of the detector now, the arc that this second passing creates is much smaller than the first. Finally, as the muon exits the detector, there is a 'splotch' of light due to the production of Cerenkov radiation in the air and in the phototube glass. Figure 4 shows a Monte Carlo simulation of such an event. The view is looking up through the detector, and the two arcs from the top and bottom acrylic vessel crossings is clear, as is the exit splotch. Figure 5 is an example of such a μ event from the Air Fill data. Again the two arcs are visible along with the exit light, though there is also a substantial amount of other, more diffuse light.

The data from the partially filled detector was taken mostly with the water level well below the halfway point of the cavity. This environment is particularly harsh, since in addition to the radon that is still in the air, the γ's and neutrons from the cavity are not yet shielded, and are able to produce Cerenkov light in the water. In addition, the tubes above the water (the majority for all of our partial fill running) were still warm and had higher noise rates than they will ultimately have when the detector is completely full and cooled. Despite the expected high background rates, however, we found that SNO ran very comfortably (about 30 Hz) at a threshold of 30 phototubes, which is expected to correspond to an energy range between 3 and

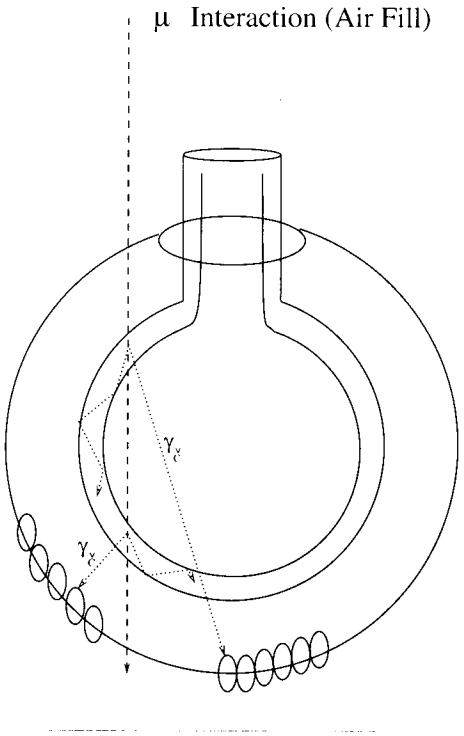

Fig. 3. Muon Detection in SNO Air Fill Data.

5 MeV. For comparison, the maximum sustained rate at which the detector could run at this threshold is roughly 700 Hz.

There have also been a few surprises seen in the data taken during Air Fill and Partial Fill. One of these is the additional light seen in Air Fill muon events, mentioned earlier. This diffuse component of the light relative to what is seen in the simulation can be up to 50% of the total, and is most likely due to the fact that the trapping of light by total internal reflection is not complete due to small imperfections in the acrylic vessel itself. The light bounces around for a while in the vessel but eventually finds a way of getting out. A run of the ^{16}N source during Air Fill showed the same effect, again because the conversion of the γ in the vessel produced an electron whose Cerenkov light was not as trapped as had been anticipated.

In addition to the extra light from the muons and gammas hitting the acrylic vessel in Air Fill, we also found that during the Partial Fill runs, the simple filling

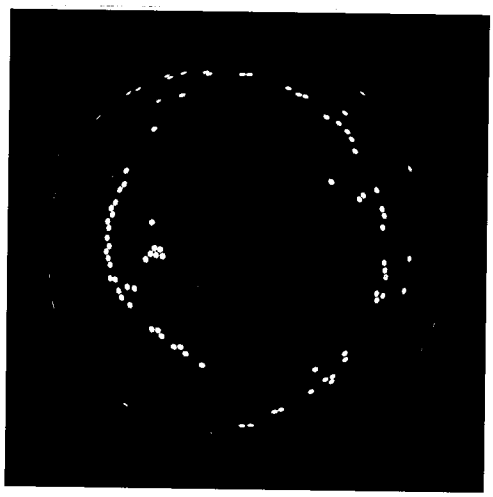

Fig. 4. Simulation of muon event in SNO air fill data. The event is viewed from the bottom of the detector.

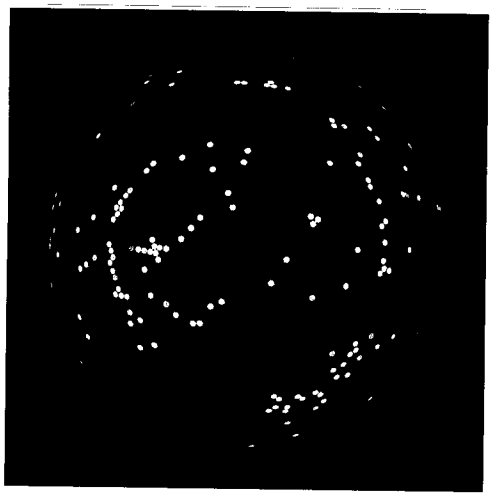

Fig. 5. Real muon event in air fill. The event is viewed from the bottom of the detector.

of D_2O generated enormous quantities of light in the detector. The light from the heavy water is very short time scale (unlike a light leak), high rate (> 100 Hz) and high intensity, lighting up every tube in the detector with several photons each. As yet, this phenomenon remains unexplained, though light from cavitation (the natural counterpart to our sonoluminescent source) and static discharge from falling D_2O droplets have been suggested. The effect has not been seen during the filling with H_2O.

There have also been a couple of unpleasant surprises seen during Air Fill and Partial Fill. The first was the rate of 'flasher events'—these are events in which a phototube spontaneously emits light. The rate of these events in the Air Fill data was found to be far higher—up to a few per minute—than what we had anticipated. These events were particularly worrisome because they produced events in the energy regime in which we expect to see our neutrino signal ($\sim 50-200$ phototube hits) and they are the result of a complex system which is hard to model. However, analysis efforts showed that the flasher events could be eliminated efficiently at the 99.8% level. In addition, once the water had been put into the detector, it was found that the rate of the flashers had become significantly lower, except during mine-related seismic events when typically a burst of flashers occurred. This time-correlation will make the removal of the flashers even easier.

A difficulty that became apparent during the Partial Fill runs was the appearance of high voltage breakdown in the wet-end connectors of the phototubes. This breakdown is intermittent, but can produce large events in the detector and occasionally at high rates, making it difficult to run without turning the tube off. Eventually, the base resistors in some of the tubes showing the problem are destroyed. The breakdown problem is the result of a marginal connector design, and therefore it is unknown how many will show the problem. Of the tubes run under water so far, $\sim 15\%$ have shown some degree of breakdown, which corresponds to $\sim 4.5\%$ of the total in the detector.

8. Conclusions

Over the past year of engineering running, the majority of the SNO detector has shown itself to be in very good shape. Over 99.8% of the 9728 electronics channels are working, very few phototubes ($< 0.2\%$) have been found not to work, the channel thresholds are low (and are likely to get lower with more work) and the trigger rates are low even in the very high background rate environment of Partial Fill. The water has also been found to be in excellent shape, with the levels of uranium in both the D_2O and H_2O ten times lower than the design goal, and the thorium levels in the H_2O already at the design goal. The thorium level in the D_2O is several times higher than the ultimate design goal, though the recirculation and purification of the heavy water has not yet begun and it is expected that when it does, the thorium level will come down significantly.

The wet-end high voltage breakdown is the most serious concern, and that will continue to be monitored. It is likely that some fraction of the tubes will fail due to this problem (in addition to the 0.2% found to be dead at the start) and will have to be turned off.

SNO will begin taking data in a full detector in May, 1999, and expects to begin the full calibration program soon afterward. Roughly two months after turn-on, enough radon will have decayed away to allow neutrino data acquisition to begin.

SNO will soon give us:

- A measure of the solar ν_e flux.
- The first high-resolution measure of the solar ν_e spectrum.
- The first measurement of the faction of non-electron flavor neutrinos from the Sun.