First Neutrino Observations from the Sudbury Neutrino Observatory

R.L. Helmer for the SNO Collaboration[a]

[a]TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

The first neutrino observations with the Sudbury Neutrino Observatory are presented. Based on preliminary analyses, the location, direction, and energy of the observed events are consistent with detection of ^{8}B solar neutrinos by charged current absorption on deuterium and elastic scattering off electrons, with little background. Water assays indicate radioactivity levels are falling and are within a small factor of the level necessary for measurement of the flux of all active neutrino flavors via the neutral current reaction on deuterium.

1. Introduction

The Sudbury Neutrino Observatory (SNO) is a 1000 tonne, real time, heavy water Cerenkov detector built to investigate the observation that fewer neutrinos are measured to be coming from the sun than are predicted [1]. It has been noted that a possible solution to this problem - the Solar Neutrino Problem (SNP) - is that electron neutrinos produced in the sun oscillate to another flavor while in transit to the earth [2]. The detector is designed to measure both the flux of electron neutrinos alone and the total flux of all active neutrino flavors originating from the beta-decay of ^{8}B in the sun [3]. Observation of fewer electron neutrinos than the total number of all neutrinos would be unambiguous evidence of oscillations. This paper presents the first observations of these neutrinos with the SNO detector.

Solar neutrinos are observed in three detection reactions. First, the total flux is measured by detecting the neutron from the neutral current (NC) disintegration of the deuteron,

$$\nu_x + d \rightarrow \nu_x + p + n \qquad (1)$$

where ν_x refers to any active neutrino flavor. This reaction is equally sensitive to all active flavors.

Second, the flux of electron neutrinos is measured independently by detecting the electron from charged current (CC) absorption on deuterium,

$$\nu_e + d \rightarrow p + p + e^- \qquad (2)$$

Comparison of the fluxes measured with reactions (1) and (2) will enable SNO to make an essentially solar model independent determination of whether all the electron neutrinos produced in the sun reach the earth as the same flavor, or whether some have oscillated into other flavors. A flux of electron neutrinos measured with reaction (2) that is less than the total flux measured with reaction (1) would be unambiguous evidence that oscillations to an active neutrino flavor are occurring. In addition, the kinematics of reaction (2) are such that the electron energy is highly correlated with that of the incoming neutrino. It will therefore be possible to look for the distortions of the neutrino energy spectrum which are predicted to occur under certain oscillation scenarios [4].

A summary of a number of the possible results from SNO, based on the NC and CC reactions, is given in Table 1. The entries in this table are of a qualitative nature only. For entries with a question mark, and in fact for all the entries, whether or not a given signal would be seen depends in a detailed way on the precise values of the masses and mixing angles and on the sizes of the statistical and systematic uncertainties. For example, it is likely a spectral distortion would be seen if small angle MSW oscillations to a sterile neutrino occur, but observation of a distortion is improbable if the solution is large angle MSW. Note that CC/NC=1 combined with observation of a distortion would be diagnostic of oscillations to a sterile neutrino. Note further that for the oscillation solutions, each line of the table is unique. Hence,

Table 1
Some possible signals in SNO for various proposed solutions to the solar neutrino problem.

		oscillation signal			
		CC/NC	spectral distortion	seasonal variation	earth effects
SNP solution	SSM wrong	1	no	no	no
	sterile neutrinos	1	?	?	?
	large angle MSW	< 1	no	no	yes
	small angle MSW	< 1	yes	no	no
	vacuum	< 1	yes	yes	no

given sufficiently small statistical and systematic uncertainties, SNO has excellent resolving power to discriminate among the possible solutions.

The third reaction by which solar neutrinos are detected is via elastic scattering (ES) off electrons,

$$\nu_x + e^- \to \nu_x + e^- \tag{3}$$

While this reaction is primarily sensitive to electron neutrinos - the cross section for $\nu_e e$ scattering is about six times larger than for $\nu_\mu e$ or $\nu_\tau e$ scattering - the small sensitivity to these other flavors will provide a valuable check on conclusions drawn from comparisons of fluxes measured with the CC and NC reactions. A comparison of the fluxes measured with the CC and ES reactions must be consistent with those conclusions.

It is planned to collect data in three phases. In the first phase, pure D_2O will be used as the detection medium. This phase is primarily sensitive to the charged current reaction, but there is some sensitivity to the neutral current reaction through neutron capture on deuterium followed by emission of a 6.25 MeV gamma ray. In the second phase, NaCl salt will be introduced into the heavy water in order to enhance the neutron capture probability from 25% in pure D_2O to 83% by capture on chlorine. Capture on chlorine is followed by a cascade of gammas up to 8.6 MeV. The relative response of the detector expected in these two phases is shown in Fig. 1. Finally, because of the importance of the neutral current result, a third phase is planned in which the salt will be replaced in the heavy water by an array of ^{3}He proportional counters. The array has

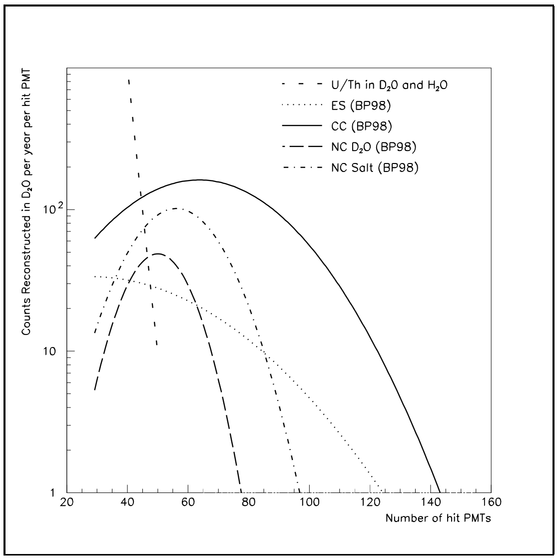

Figure 1. Simulations of spectra obtained with the three detection reactions (NC,CC,ES) for neutrino fluxes as calculated [5] by BP98. Spectra from the NC reaction are shown for pure heavy water and with added salt. The expected counting rate from U and Th radioactivity in the water is also shown. An MeV of electron energy corresponds to about 9 hit photomultipliers.

good capture efficiency for neutrons (45%), but more importantly the neutral current measurement during this phase will be subject to completely different systematic effects than during the salt phase. Thus, results obtained with the array will provide an excellent consistency check with results obtained with the salt. In addition, there will be no Cerenkov light associated with the neutron capture and hence this phase will provide the best measurement of the charged current spectrum shape, important for disentangling the various oscillation scenarios.

Data collection for phase one of the experiment began in November, 1999, and is continuing at the present time. A brief description of the experiment is given in the following section, and a summary of observations to date and a discussion of backgrounds are presented in subsequent sections.

2. Description of the Experiment

The detector is housed in a barrel shaped cavity 22 m in diameter at the widest point and 34 m high. The cavity is located 6800 feet below the earth's surface in Inco Ltd.'s Creighton Mine in Sudbury, Ontario. The heavy water is contained within a 12 m diameter, 5 cm thick, spherical acrylic shell. This volume is viewed by 9438, 20 cm diameter photomultiplier tubes (PMTs) mounted on an 18 m diameter geodesic sphere which surrounds the acrylic sphere. The space between the acrylic and the cavity walls is filled with 7300 tonnes of ultrapure light water, including 1700 tonnes in the space between the acrylic and the phototubes, to shield against radiation emanating from the walls, PMTs, and construction materials. The volume between the geodesic sphere and the cavity walls is viewed by 91 PMTs mounted on the outside of the sphere.

Several techniques and sources are used to calibrate the response of the detector. Some 600,000 electronic constants are calibrated regularly with built-in pulsers. The constants have proven to be stable. Optical properties of the detector have been studied using a light diffusing ball fed by a pulsed laser system providing wavelengths between 337 nm and 700 nm. Energy calibration is provided by a nearly mono-energetic ^{16}N gamma ray source. The neutron response of the detector has been studied with an acrylic-encapsulated ^{252}Cf source. A number of other sources are being prepared to extend the energy calibration to both higher and lower energies, and to study backgrounds and the efficiencies with which the latter are being identified.

Finally, there are separate water systems for the light and heavy water. Both systems provide means for monitoring the water for radioactive impurities and for purifying it. A comparison of the purity requirements with radioassay measurements is given in Section 4.

A full description of the detector can be found in [3].

3. Observations to Date

There are several phenomena other than interactions of neutrinos, muons, and radioactivity which can satisfy the data taking trigger requirements. Some of these phenomena involve the emission of real light in the detector while others satisfy the trigger conditions by virtue of pickup in the electronics systems. A raw collected data spectrum is shown as the solid line in Fig. 2, along with the results of a series of cuts to remove these instrumental backgrounds. The data shown are only a fraction of the total data collected. The spectra are plotted as a function of Nhit, the number of hit PMTs in each event. The two peaks at lowest Nhit arise from auxiliary triggers which sample activity in the detector. The peak at Nhit=21 is a convolution of trigger threshold effects with the rapidly rising spectrum from the decays of uranium and thorium noted in Fig. 1. The energy scale is such that approximately 9 hit PMTs correspond to 1 MeV of deposited energy. The dashed line shows the residual spectrum after events identified as a flashing PMT are removed. Such events are characterized by a large charge in the PMT which flashed, light observed 70 ns (one transit time) later in the PMTs across the detector, and pickup signals in several channels surrounding the flashing PMT. These characteristics are quite different from a normal Cerenkov event, and are easily identified.

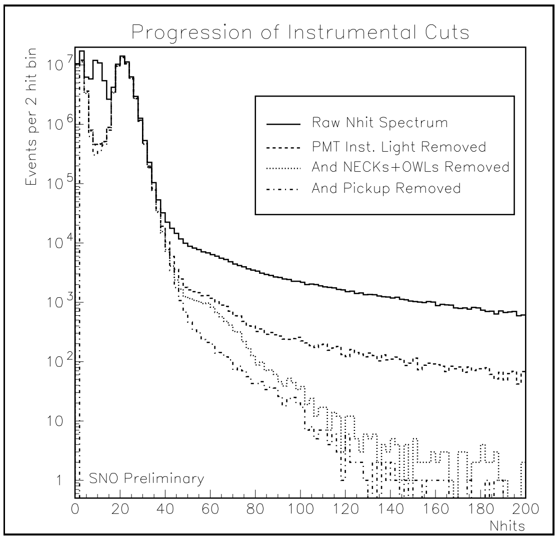

Figure 2. Progression of instrumental cuts.

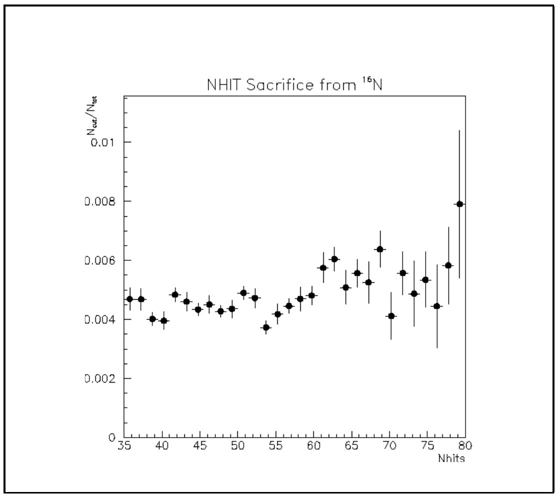

Figure 3. Signal loss as measured with ^{16}N.

Light can also be generated in the neck of the AV, possibly by static discharges of insulating materials. Such events are characterized by light seen by PMTs in the bottom part of the detector preceded by PMTs hit in the neck. In fact, the latter PMTs were placed in the neck for the purpose of identifying these events. The neck PMTs are generally not hit by legitimate events taking place in the detector, as determined from calibration sources. The spectrum remaining after these events are removed is shown as the dotted line in Fig. 2. Finally, the dot-dash line shows the residual spectrum after events identified as originating from electronic pickup are removed.

The result of applying these instrumental background cuts to data collected with the ^{16}N source is shown in Fig. 3. It can be seen that only a small fraction of the ^{16}N events are removed, thus ensuring that few neutrino events will be sacrificed by application of the cuts. Leakage through the cuts has not yet been fully quantified but has been shown to be small, even before application of event reconstruction.

Algorithms based on hit PMT spatial and timing information were used to reconstruct the position and direction of events remaining after application of the above cuts. The distribution of events is shown in Fig. 4. It is apparent there is a substantial excess of events in the heavy water (the D_2O volume corresponds to $\frac{r}{600} < 1$), indicative of CC absorption, reaction (2), on deuterium. The energy threshold for the events shown in this figure is quite high in order to remove low energy backgrounds.

The direction of events in the heavy water with respect to the sun is shown in Fig. 5. Even with a lower energy threshold allowing in more radioactive events, a peak from the elastic scattering reaction (3) is evident. A similar plot for events occurring in the light water is shown in Fig. 6. The ES peak is more evident here since there are only a few background events and no competing CC events.

Finally, the spectrum remaining after application of a fiducial volume cut is shown in Fig. 7. The simulated spectrum for the CC reaction shown in Fig. 1 has been scaled and superimposed on the data. An absolute value for the flux is not given because calibrations are not complete and backgrounds and systematic uncertainties have not been quantified. Nevertheless, it is

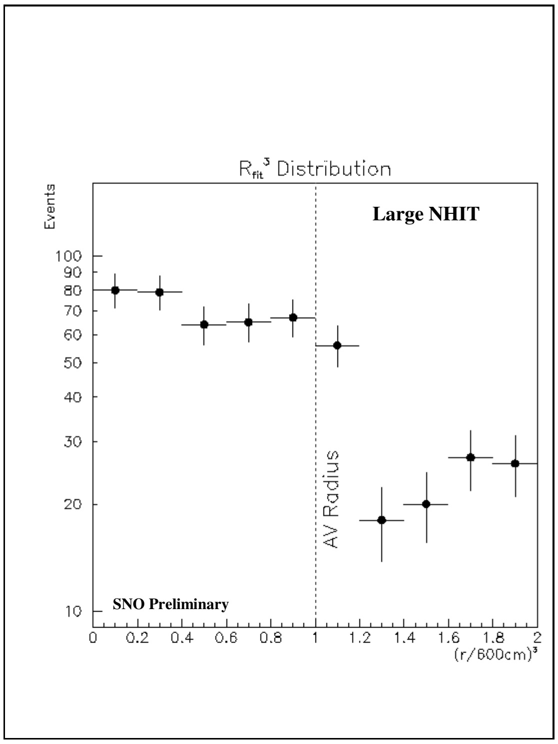

Figure 4. Distribution of events throughout the detector volume.

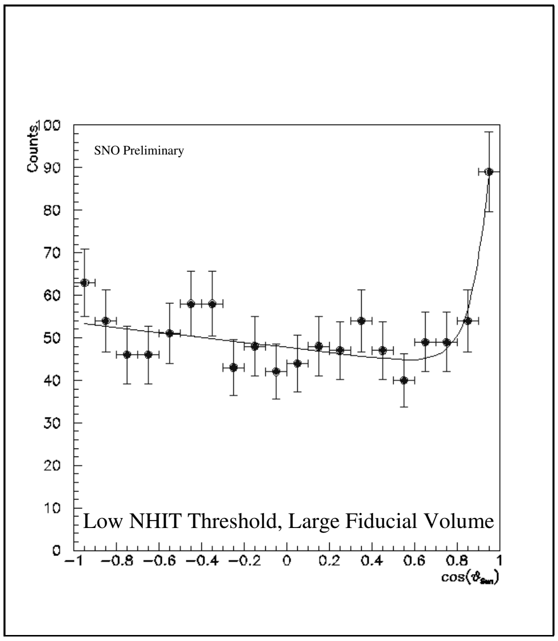

Figure 5. Distribution of events in the heavy water with respect to the direction to the sun.

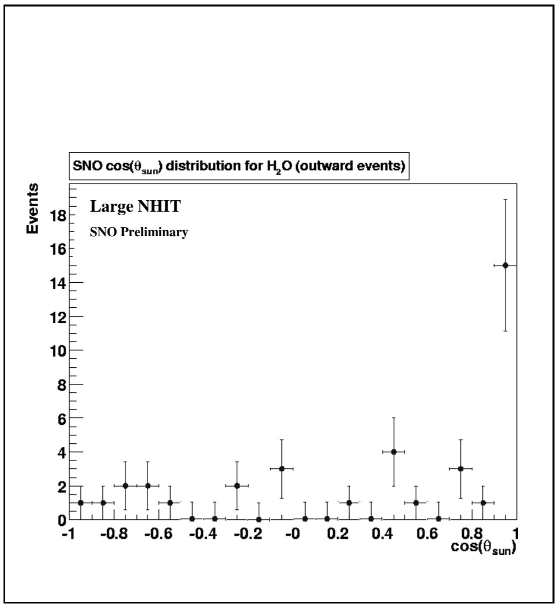

Figure 6. Distribution of events in the light water with respect to the direction to the sun.

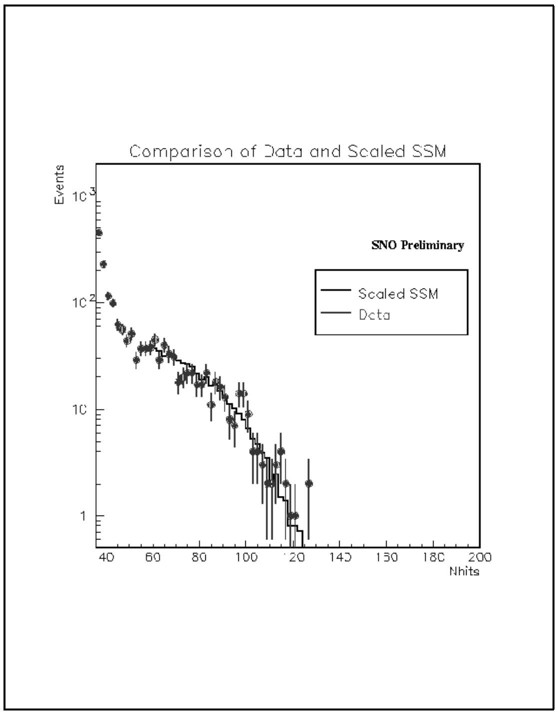

Figure 7. Distribution of events versus the number of hit PMTs.

apparent the spectrum is well defined and so ultimately the flux should be accurately measured.

4. Backgrounds

The most serious sources of radioactive background contributing to the Cerenkov light in the detector arise from the the decay chains of ^{232}Th and ^{238}U impurities in the water and other detector materials. At low energies, impurities in the water dominate. In addition, gammas at the bottom of each of these chains have an energy above the 2.2 MeV photodisintegration threshold of the deuteron. They can therefore liberate neutrons which are indistinguishable from neutrons produced by the NC reaction (1). A variety of systems to purify the water and to provide sensitive radioassays of the impurity concentrations have been developed (see reference [3] for details). Progress in reducing their concentrations in the heavy water is shown in Fig. 8. The goal for each

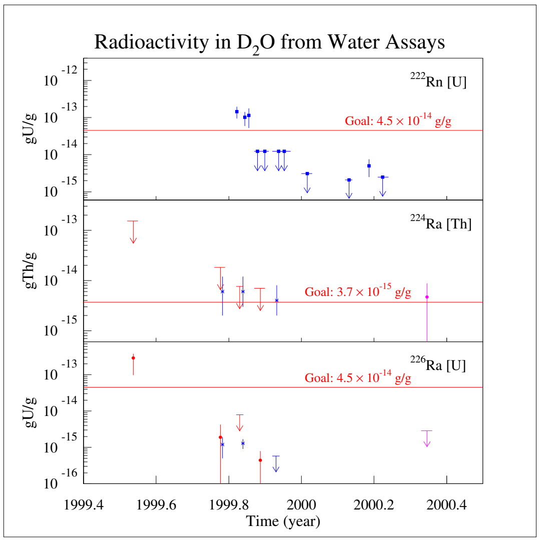

Figure 8. Measurements of radium from the Th and U chains and radon from the U chain in D_2O.

isotope is set by the condition that the neutral current background caused by photodisintegration does not exceed 5% of the signal expected from the neutrino flux of BP98 [5]. It can be seen from the figure that levels of uranium have met the goal while those of thorium are approaching it.

The light water surrounding the acrylic vessel (AV) attenuates higher energy gammas from radioactivity in the phototubes and their support structure and in the rocks in the cavity walls. High energy events reconstructed in the light water volume outside the AV are found to be predominantly inward going and their number falls off rapidly towards the AV. Extrapolations of the number of ^{16}N gammas reconstructing within the D_2O when the source is placed near the PMTs indicate that less than a few percent of the events above nhit=60 in Fig. 7 arise from external high energy gammas.

5. Conclusions

As shown in Figs. 4-7, the distribution of events throughout the detector volume, the angular distributions with respect to the sun, and the agreement of the energy spectrum with the Monte Carlo, all suggest ^{8}B solar neutrino events are being observed with the CC and ES reactions, with little background. It should therefore be possible to obtain an accurate measure of the electron neutrino flux with the CC reaction during the pure heavy water phase of the experiment. Measurements of the radioactivity suggest the total active neutrino flux can be obtained with the NC reaction with only a small uncertainty from the radioactive background.

6. Acknowledgments

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