Title: NEUTRAL-CURRENT DETECTORS FOR THE SUDBURY NEUTRINO OBSERVATORY

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ABSTRACT

With its heavy water target, the Sudbury Neutrino Observatory has the unique opportunity to measure both the $^8$B flux of electron neutrinos from the Sun and the flux of all active neutrino species independently, thus offering a direct and model-independent test of a neutrino oscillation solution to the solar neutrino problem. We report on the physics intent and design of a discrete method of neutral-current detection in the Sudbury Neutrino Observatory that will utilize ultra-low background $^3$He proportional counters dispersed throughout the heavy water volume. Projections of background in all components of the detector are considered in an analysis of our ability to extract the neutral-current signal and the neutral-current to charged-current ratio.
1. Introduction

At this conference we had the opportunity to review and reflect upon thirty years of solar neutrino physics, both with respect to a theoretical understanding of how the Sun shines\(^1\), and the experimental data offered by the pioneering experiments\(^2\), namely Chlorine, Kamiokande, SAGE, and GALLEX. Taken together, these results provide tantalizing hints that solar neutrinos experience flavor transitions before their arrival at Earth. Focus is now upon new generation experiments that will endeavour to resolve the solar neutrino problem using techniques that do not rely upon solar-model calculations for their interpretation and/or are directly sensitive to the physics manifest in neutrino oscillations.

The Sudbury Neutrino Observatory (SNO) is presently under construction\(^3\) at the 6800 foot level of the Creighton Nickel Mine in Sudbury, Canada, by collaborators from twelve institutions in Canada, the United States, and the United Kingdom. By exploiting a 1000 tonne heavy water (D\(_2\)O) target SNO aims to carry out two basic measurements on the \(^6\)B solar neutrino spectrum:

1. the flux and energy spectrum of electron neutrinos reaching the earth above a threshold energy of 5 MeV, and
2. the total integrated flux of all (left-handed) neutrinos reaching the earth with energy above the 2.2 MeV binding energy of the deuteron.

A ratio of the neutral-current (NC) flux to the charged-current (CC) flux offers a direct test of the neutrino oscillation hypothesis, independent of solar model calculations. In addition, detailed studies of the shape of the CC-energy spectrum can be used to probe different solutions to the solar neutrino problem, such as matter enhanced or vacuum oscillations. In this paper we focus on methods of NC-measurement in SNO and, in particular, a method of discrete NC-detection using an array of ultra-low background \(^3\)He detectors, which would allow a simultaneous and independent measure of the CC and NC-signals.

Only electron neutrinos can interact with the deuteron via the CC-interaction,

\[
\nu_e + d \rightarrow p + p + e^- - 1.44 \text{ MeV},
\]

wherein a neutron is transformed into a proton with the emission of a fast electron. The relativistic electron will produce Cerenkov light to be collected in an array of 9800 photomultiplier tubes (PMTs). The number of PMTs triggered by an event is a measure of the incident neutrino energy so that the SNO detector is capable of recording the CC-energy spectrum. This spectrum can then be examined for spectral shape distortions that are predicted for different neutrino oscillation scenarios.

NC-disintegration of the deuteron can proceed by all active neutrino species with energy above the binding energy of the deuteron:

\[
\nu_x + d \rightarrow p + n + \nu_x - 2.22 \text{ MeV}.
\]

To extract the NC-signal one must accurately detect and count the free neutrons liberated in the heavy water by the neutral-current disintegration of deuterium. In principle,
Figure 1: A simulation of the Cerenkov spectrum in SNO with Pure-D$_2$O showing the charged-current (CC), neutral-current (NC) and elastic-scattering (ES) signals, along with the $\beta/\gamma$ activity from various detector components. The NC-signal and background refer to neutrons captured on deuterium. The NC-signal is also shown for the case where 2.5 tonnes of salt are dissolved in the D$_2$O.
these neutrons can be detected by the Cerenkov light produced after their subsequent capture on deuterium. This approach is appealing only because it would not require any modification to a “pure-D2O” detector used to measure the CC-spectrum. This method of NC-detection is plagued, however, because the Cerenkov signal produced is largely masked by the CC-signal itself as well as a background wall created by intrinsic radioactivity in the SNO detector (see Figure 1). In order to “boost” the NC-signal away from the Cerenkov background wall, an approach involves dissolving about 2.5 tonnes of salt (in the form of MgCl2) into the heavy water, permitting neutrons to be captured on 35Cl. This process produces an 8.6 MeV γ-ray which produces Cerenkov light predominantly through Compton scattering. The result is a Cerenkov spectrum that can be safely separated, at least in part, from the background wall. Nonetheless, the NC and CC-signals still represent “backgrounds” to one another in the dissolved salt option. In the simplest scenario, the detector would be operated first without salt and then with salt, and a subtraction of the two spectra would allow one to separate the CC and NC-signals.

While techniques to separate NC and CC-signals in the dissolved salt method using pattern recognition techniques could, in principle, make such subtractions obsolete, it is desirable to have a method that directly distinguishes between the two signals in real time. Such a method requires that the neutrons produced by the NC-interaction be detected in a way that does not involve the production of Cerenkov light. To this end, a proposal was put forth to construct an array of ultra-low background 3He proportional counters to be deployed inside of the heavy water vessel with the capability of detecting neutrons simultaneously with, and independent of the CC-signal.

2. Neutral-Current Detector Design

The use of 3He proportional counters for neutron detection in nuclear and particle physics represents a well practiced art. Nonetheless, to realize their potential as a neutral-current detector (NCD) in SNO, one must develop many novel ideas and overcome a multitude of challenging and competing constraints. In particular, since only about 14 neutrons are predicted to be produced in the heavy water per day, the NCDs, like any other material placed in the SNO detector, must be extremely low in natural radioactivity, placing substantial constraints on the materials employed in constructing the counters and on the methods of handling and deployment.

A schematic diagram of the counter design is shown in Figure 2. The dominant mass used in the construction of counters is that employed in producing the cathode-tubing for the counters. With a total mass of about 500 kg, for example, photodisintegration γ-rays from U and Th would produce a background signal equivalent to 10% of the standard solar model signal if in equilibrium at the level of 12 parts-per-trillion by weight. Consequently, ultra-pure nickel produced by chemical-vapor deposition (CVD) is used to construct the tubing as well as the endcaps that are laser-welded into the ends of counter segments. Recent radioanalysis of CVD nickel used to construct prototype NCDs indicates that the bulk material can be produced with intrinsic radioactivity about an order of magnitude below this level. Due to the smaller total mass, less stringent requirements apply to the other detector components such as the copper anode wire, and components for fabricating the counter feed-thru assemblies.
Figure 2: Schematic diagram of a neutral-current detector (NCD) string.
U and Th in the NCD construction materials will also produce $\alpha$ and $\beta$ activity which can enter and ionize the proportional counter gas, creating background to the signal of interest, namely the 764 keV $^3$He(n,p)$^t$ neutron-capture signal. In order to mitigate these backgrounds, techniques of pulse-shape discrimination have been developed wherein the current-pulses from the anode wire are digitized on an event-by-event basis. The result is a “background-free” region (see Figure 3) wherein neutron-capture events are safely separated from other internal activities. To minimize backgrounds in the D$_2$O volume, the preamplifiers are placed outside of the main detector and at the end of a counter string via a readout cable up to $\sim$15 m in length. This configuration places further constraints on the design of the readout electronics and cable to ensure low-noise and signal integrity. In addition, delay lines are mounted at the remote end of each counter string to allow extraction of event position along a counter by exploiting pulse-reflection and time-delay.

Heavy water is an effective neutron moderator. Together with the high capture cross-section for $^3$He, neutrons can be detected with high efficiency in a relatively sparse array and thus with little interference with the Cerenkov light produced via the CC-process. The full array will employ $\sim$800 m of 2-inch diameter proportional counters dispersed symmetrically throughout the heavy water vessel on a 1 m square-lattice. In this case, the array provides a total neutron-capture efficiency of $\sim$50%. The absolute neutron-capture efficiency is a necessary input for a robust extraction of the NC-signal and will be determined from calibration data obtained by inserting neutron sources into the SNO detector. The physical size of these counters places further constraints on their mechanical and electrical design and they must operate in a reliable and stable fashion whilst immersed in water for a period of up to ten years. The NCD array will consist of a total of 96 independent strings varying up to 11 m in length. These strings are fabricated from segments of three different lengths which are to be laser welded together above the SNO detector during the NCD deployment phase. The strings are then deployed with a remotely operated vehicle (ROV) and anchored to the bottom of the acrylic vessel using a ball-and-socket arrangement.

3. Neutral-Current Signal & Backgrounds

At the bottom of the Th-chain, $^{208}$Tl emits $\gamma$-rays above the binding energy of the deuteron. Photodisintegration of the deuteron by these $\gamma$-rays, and to a lesser extent from $^{214}$Bi at the bottom of the U-chain, creates neutrons that are background to the NC-signal. The standard solar model (SSM) signal is shown in Table 1 along with the backgrounds projected from detector components based on various radioassay measurements. The background signal can be separated into two categories, namely neutrons produced isotropically and uniformly in the D$_2$O and those created near the acrylic vessel. The “near-vessel” contributions are easily separated from the isotropic signal by using the radial dependence of neutron-capture distributions in the NCD array. The isotropic background is, on the other hand, indistinguishable from the NC-signal and must be determined independently by a set of in situ measurements. The isotropic NC-background will be measured in the SNO detector by using information in the Cerenkov background-wall (refer to Figure 1) which provides a measure of the total amount of U and Th activity in the SNO-detector including the NCD array. Water
Figure 3: Analysis of digitized pulses from $^3$He test-counters and sources. He(n,p)t events are confined to a window as shown and are easily discriminated against $\beta/\gamma$-activity. Alpha particles emerging from the cathode wall overlap with the He(n,p)t window, however, a background free region exists where neutron capture pulses remain separated on an event-by-event basis.
### Table 1: Neutral-Current Signal and Background in 1 Year of SNO with NCDs

<table>
<thead>
<tr>
<th>Component</th>
<th>Neutrons Captured</th>
<th>Thorium Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM Signal</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>D$_2$O</td>
<td>150</td>
<td>3 fg/g</td>
</tr>
<tr>
<td>NCDs</td>
<td>50</td>
<td>1 µg</td>
</tr>
<tr>
<td>Isotropic BGND</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>25</td>
<td>20 pg/g</td>
</tr>
<tr>
<td>Acrylic Vessel</td>
<td>125</td>
<td>1 pg/g</td>
</tr>
<tr>
<td>NCD-Cable</td>
<td>30</td>
<td>2.5 µg</td>
</tr>
<tr>
<td>NCD-Wet-Connect</td>
<td>15</td>
<td>1.25 µg</td>
</tr>
<tr>
<td>NCD-Delay</td>
<td>15</td>
<td>1.25 µg</td>
</tr>
<tr>
<td>Near-Vessel BGND</td>
<td>210</td>
<td></td>
</tr>
</tbody>
</table>

Assay measurements will allow an independent measure of the D$_2$O background, whereas a number of techniques will be used to tag coincidence events that register ionization in the NCDs and Cerenkov light in the PMT array.

As shown in Table 1, the isotropic background projected for SNO is dominated by Th activity in the D$_2$O and the total isotropic background from the detector including the NCD array (~200 neutrons per year) represents 8% of the NC-signal (~2500 neutrons per year). Studies of the backgrounds using the in situ techniques alluded to above indicate that backgrounds at these levels can be determined with an absolute uncertainty of ~25%. Using the projected level and uncertainty of the background signals, the statistics anticipated for the NC-signal in SNO, and folding in our ability to extract the neutron signal from the NCD array one can project SNO's ability to extract the NC-signal and the NC-to-CC ratio. The results of this analysis are displayed in Figure 4 which indicates that with one year of data from SNO with NCDs the various hypotheses to resolve the solar neutrino problem can be discerned with a high degree of confidence.

### 4. Summary & Status

A method of discrete neutral-current detection in SNO allows simultaneous and independent extraction of the charged-current and neutral-current signals on an event-by-event basis. An array of $^3$He proportional counters has been described that meets the stringent radioactivity purity requirements of SNO and that offers respectable neutron-capture efficiency without deterioration of the Cerenkov signal associated with the charged-current interaction. This event-by-event separation optimizes the use of available statistics and simplifies the analysis and interpretation of the data. Analysis of the NC-signal and background indicates an absolute uncertainty in the NC-flux of about 10% with one year of data. A model-independent test of neutrino oscillations can be made using the NC-to-CC ratio which can be determined with a similar level of certainty.

The NCD project is funded by the United States Department of Energy and is presently under full-scale construction by SNO collaborators at the University of Washington, Los Alamos National Laboratory, Lawrence Berkeley Laboratory, and the University of Guelph.
Figure 4: A simulation of the NC and CC sensitivity (95% C.L.) with one year of data from SNO with the NCD array deployed. The NC-to-CC ratio is defined by the slope in the NC/CC plane and is independent of solar models and only mildly dependendent on the absolute uncertainty in the cross-sections for neutrino interactions on deuterium. Three distinct regions are displayed and labeled in the plane based upon different solutions to the solar neutrino problem. The ratio changes for different neutrino oscillation scenarios but differentiation will require a detailed analysis of the shape of the CC-spectrum in SNO.
References

1. J.N. Bahcall, in these proceedings.
2. See individual contributions from R. Davis, K. Lande, Y. Suzuki, T.J. Bowles, and T. Kirsten, in these proceedings.
3. An overview and status report on the Sudbury Neutrino Observatory is presented in the paper by R. Meijer-Drees, in these proceedings.

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