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Solar Neutrino Physics

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Abstract

With its heavy water target, the Sudbury Neutrino Observatory (SNO) offers the unique opportunity to measure both the 8B flux of electron neutrinos from the Sun and, independently, the flux of all active neutrino species reaching the Earth. A model-independent test of the hypothesis that neutrino oscillations are responsible for the observed solar neutrino deficit can be made by comparing the charged-current (CC) and neutral-current (NC) rates. This LDRD proposal supported the research and development necessary for an assessment of backgrounds and performance of the SNO detector and the ability to extract the NC/CC-Ratio. Particular emphasis is put upon the criteria for deployment and signal extraction from a discrete NC detector array based upon ultra-low background ³He proportional counters.

Background and Research Objectives

During the past thirty years extensive theoretical and experimental research has elucidated our understanding of how the Sun shines and has culminated in what we refer to as *the Solar Neutrino Problem* [1,2]. Data from the pioneering experiments, namely the Chlorine experiment, Kamiokande, SAGE, and GALLEX have provided a coarse spectroscopy of the solar neutrino spectrum, including the low energy and dominant pp-flux[2]. In all cases, the measured flux of neutrinos falls significantly short of the predictions of the Standard Solar Models (SSM). Moreover, this deficit appears to be energy dependent. What is particularly surprising is the apparent absence of 7Be neutrinos while 8B neutrinos are observed, albeit at about half the predicted rate. This situation seems difficult to remedy based upon any reasonable modification to the astrophysical models that predict the solar neutrino production rates[3]. If the Sun is powered by nuclear fusion then it is impossible to produce 8B neutrinos at all without first producing 7Be. On the other hand, the data can be beautifully reconciled with theoretical predictions if neutrinos have mass and are allowed to change flavor through matter enhanced or vacuum oscillations[4]. This tantalizing hint of neutrino mass & mixing would mark the first departure from the standard model with profound implications for the fields of elementary particles, astrophysics, and cosmology. Focus is now upon new generation experiments that will search for the direct manifestation of solar neutrino oscillations using techniques that do not rely on SSM calculations for their interpretation.

The Sudbury Neutrino Observatory (SNO) is presently in the commissioning phase at the 6800 foot level of the Creighton Nickel Mine in Sudbury, Ontario, Canada by collaborators from twelve institutions in Canada, the United States, and the United Kingdom. By exploiting a 1000 tonne target of heavy water (D₂O), SNO aims to carry out two basic measurements of the 8B solar neutrinos, namely:

1. the flux and energy spectrum of electron neutrinos reaching the Earth above a threshold energy of 5 MeV through the charged-current (CC) interaction on deuterium, and
2. the total integrated flux of all active neutrinos reaching the Earth with energy above the 2.22 MeV binding energy of the deuteron through the neutral-current (NC) interaction.

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 to a proton in the inverse beta decay interaction with the emission of a fast electron that produces Cerenkov radiation. The Cerenkov light is collected in a spherical array of 9800 photomultiplier tubes (PMTs) surrounding the D₂O vessel. The pattern and number of PMTs that are triggered can then be used to deduce the energy and direction of the neutrino and this information is used to recover the CC-spectrum. On the other hand, NC-disintegration of the deuteron can proceed with equal probability via all active neutrino species,

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

To extract the NC-signal one must accurately detect and count the number of free neutrons liberated in the heavy water. The ratio of the NC-to-CC flux (NC/CC-Ratio) will thus provide the *smoking gun* for flavor conversion of solar neutrinos and does not rely on solar model calculations for its interpretation. In addition, detailed studies of the shape of the CC-spectrum can be used to probe different solutions to the solar neutrino problem, such as matter enhanced or vacuum oscillations. The extraction and separation of these signals and the associated backgrounds in the SNO detector form the central focus of this LDRD effort. Particular emphasis is given to the recovery of the NC-signal using an array of ultra-low background ³He proportional counters deployed throughout the heavy water vessel.

Figure 1 depicts the result of a Monte Carlo simulation of the Cerenkov spectrum in SNO for signals reconstructed within the 6 meter radius of the D2O volume. Apart from the neutrino induced signals, a Cerenkov background wall rises steeply below a threshold of about 5 MeV, and arises primarily from beta and gamma activity from the long lived uranium (U) and thorium (Th) contamination in the D2O itself. In principle, the NC-signal can be determined from the neutron capture rate on deuterium which provides a Cerenkov signal from the 2.22 MeV gamma rays producing light in the detector. This approach is plagued, however, due to the fact that the signal is largely buried in the background wall. In order to boost the signal out of the background, another approach is to dissolve about 2.5 tonnes of salt into the heavy water. This then provides a Cerenkov signal from 8.6 MeV gamma rays that can be safely separated from the background wall. Nonetheless, the NC and CC signals are now significant backgrounds to one another and, in the simplest scenario, the detector would have to be run with and without salt in order that both signals could be separated. While techniques have been developed to separate the NC and CC signals on a statistical basis using pattern recognition techniques in the dissolved salt option, it is desirable to implement another option that can directly distinguish the two signals on an event-by-event basis and in real time. Such a method requires that the neutral-current signal be measured by a means that does not rely upon Cerenkov radiation. To this end, we have focused upon the design, research and development, construction and commissioning of an array of discrete neutral-current detectors (NCDs) using ultra-low background ^3He proportional counters[5].

Importance to LANL's Science and Technology Base and National R&D Needs

LANL has a long and impressive history in the arena of neutrino physics, starting with the seminal discovery of the neutrino by Cowen and Reines, a strong accelerator based neutrino physics program, precision measurements of tritium beta decay and the direct search for an electron anti-neutrino mass. LANL is also the leading US institution on the SAGE solar neutrino experiment, the results from which were first to observe the low energy pp-flux and to elucidate the $^7\text{Be}/^8\text{B}$ anomaly. The SNO experiment promises to resolve the solar neutrino problem through its unique ability to determine the NC/CC-Ratio and represents one of the highest priority experiments in nuclear physics in the nation. Our participation in the SNO experiment, and particularly in the development of a discrete NC-detector array, draws on the unique capabilities of our weak interactions team at LANL and will play a critical role in resolving the solar neutrino problem.

Scientific Approach and Accomplishments

Commissioning the SNO Detector

A Web-Based Logbook

The Los Alamos team has designed and developed a series of web based logbooks used for archiving, sharing, and disseminating information within the SNO collaboration. The web logbook is intended to provide the same basic functionality as a paper logbook with the key enhancements that information is entered and retrieved using a standard web browser, the contents are fully searchable, email can be sent out and received, and special document types such as meeting agendas and minutes are available. In addition, the logbook includes automatic procedures that provide reminders of important events, analyze and redistribute incoming email, and create condensed summaries of new or modified documents. We developed the logbook because of the perceived need to enhance communication within the collaboration especially with the collaborators dispersed over three countries.

Email has long been used to facilitate communication amongst scientists and is a significant component of the web logbook. However, email has the drawback that documents are not shared; each person has their own copy. The web logbook takes the next step beyond email by placing all the documents in centralized repositories that are easily accessible. This functionality permits the collaboration to always work from the same set of documents. Any document can be emailed out with the email including a URL style link back to the original document. Paper logbooks also have the disadvantage that information is difficult to retrieve once it has been entered. The web logbook is fully searchable, including documents which are attached to log entries. Finally, a paper logbook is passive. It cannot remind you of upcoming meetings or inform you about new entries by colleagues. The web logbook provides such timely information through the use of automated procedures.

The SNO web site consists of over a dozen individual logbooks each directed at a particular aspect of the SNO experiment including the logging of all shift related activity. The basic logbook actually consists of a series of modules, which are easily modified to provide special purpose logbooks. SNO uses several of these derivative designs as part of the full web site. Currently the web logbook has expanded beyond its SNO roots and is being used by other groups at the Laboratory. A talk covering the logbook is scheduled for presentation at the 2nd DOE GroupWare/Symposium Workshop.

PMT Data Analysis & Event Recognition

The group's work on SNO PMT data analysis has fallen into two categories: the analysis of detector commissioning data, and the construction of event identification algorithms for neutrino data. The former has been of immediate use in diagnosing anomalies in the 9800 channels of electronics and the latter will be a key part of the SNO physics extraction in the longer term.

The effort of the group on detector commissioning data analysis has been important in the shakedown of the detector's performance and in the verification of the detector's behavior. The analysis has formed one part of a cycle where data from detector runs has been analyzed and any problems found have been fed back to the hardware experts. Subsequent runs verify that the problems have indeed been fixed and then the cycle begins again. This feedback loop and the work of the Los Alamos group within it has brought the detector electronics to the point where more than 99% of the channels are operating in a stable condition. This goal having been met, the commissioning analysis moved on to the task of dealing with events in the detector caused by light and/or electronic pickup from discharges in the PMTs known generically as *flashers*. Whilst other groups within the collaboration have worked on the elimination of such events, the Los Alamos group has used its expertise in simulation and analysis to obtain demonstrably robust and efficient cuts to remove these events before subsequent neutrino analysis. Much progress in this area has already been made, with the projected signal to background ratio already down to of order unity, a significant achievement in a detector expecting about 10 events per day. A lot of work remains to be done, however, particularly in carefully checking the purity and efficiency of all cuts using radioactive source calibration data.

The second major focus of the group in PMT data analysis has been on the longer term task of neutrino event identification. In the dissolved salt option, the CC and NC interactions of neutrinos produce characteristically different patterns of Cerenkov light. These different patterns can be used to separately extract the number of CC and NC events in a detector data sample. This enables SNO's key measurement, the NC/CC-Ratio, to be made in a way that is complementary to the discrete NCD technique and has largely different systematics. The Los Alamos group has led the way in constructing these event ID algorithms. With Monte Carlo data these algorithms have been shown to work almost down to the limit determined by counting statistics and, as with the flasher cuts, they now await proper verification using calibration data from radioactive sources.

Analysis of Air-Fill Data

As part of the commissioning phase of the SNO detector, a substantial amount of data has been taken without water in the detector. One of the main purposes for this air-fill data is to study backgrounds and compare them with expectations. The background events can be separated into two broad categories: physics and instrumental backgrounds.

Physics background events are produced by particles losing energy in the volume of the detector and producing detectable amounts of light. Cosmic ray muons are an example of such background. In an air-filled detector, muons produce detectable light through Cerenkov radiation in the wall of the acrylic vessel. The rate of muon events is very low (tens a day) because of the deep location of the detector. The study reported here is another type of physics background due to radioactive alpha decay of Radon isotopes and their progeny. Radon alpha decays produce light through scintillation in air. Because of the large volume of the detector and the naturally occurring content of Radon in the air, these type of events are expected to dominate the spectrum at the low energy end (single Radon decays produce very few hits in the detector).

Early air-fill data showed a larger number of events with a large number of hits than expected. Previous studies of the expected event yield from Radon decays did not include the possibility of pileup. Pileup events could, in principle, be responsible for some of those large energy events through several alpha decays happening in random coincidence. To study the yield (in hits) of Radon events, a set of the data taken with a pulsed trigger was used. This trigger makes no requirement on the numbers of hits and it is therefore extremely useful for understanding high-rate backgrounds with small light yield, such as Radon decays (about 10^{11} alpha decays are expected in the detector volume for 6.5 picocurie/liter Radon concentration). Using these data, the Monte Carlo simulation of Radon decays was tuned to produce the same hit spectrum as observed.

The next step involved the Monte Carlo simulation of pileup events. For each level of pileup (2,3,4, and up to 9 decays in an event) a Monte Carlo sample was generated. Using the distribution of hits of each of these samples together with the Poisson probability of such a pileup to happen an estimate of the yield of high hit events was done. About 2000 events per day with 40 or more hits were observed in the air-fill data and about 330 with 50 or more hits. The Monte Carlo calculation of Radon pileup yielded about 900 events with 40 or more and only 18 with 330 or more. In conclusion, radon pileup was found to be an important component of the signal at intermediate energies, but it is not an important event source at the large energy part of the spectrum.

Detector Calibration

In SNO there is a need for radioactive sources to test the detector response to known levels of neutron and gamma radiation. The Cerenkov background wall emanates from the naturally occurring U and Th series. Also in these decay series are photons of sufficient energy to photodissociate the deuterium in the heavy water. This dissociation liberates a free neutron and thus mimics the signal that is being used to determine the neutrino NC-signal. In addition to these naturally occurring radiations, we also wish to understand the detector response to "point" sources of free neutrons. For this purpose we have produced sources containing known amounts of the spontaneously fissioning isotope - ^{252}Cf . Upon fission this isotope liberates a known distribution of neutrons that can be used to bench mark and calibrate Monte Carlo calculations of the detector response. Neutron sources will be used to calibrate the overall neutron capture efficiency and topology of events in the SNO detector, an essential ingredient for recovering the NC flux. The low energy gamma sources will be used to calibrate the Cerenkov background wall. Calibration of the Cerenkov background wall is essential for extracting the total level of NC-background arising from photodisintegration of the deuteron and will also play a crucial role in understanding how the Cerenkov wall limits the threshold in SNO and how this background extrapolates into the CC-spectrum (refer to Figure 1).

We have made 5 sources that are multiply encapsulated (see table below). The sources were placed in 1 inch diameter UVT acrylic rod. There are "hot" and "weak" samples of ^{252}Cf and ^{232}U (in equilibrium with daughters) and one source of ^{226}Ra . These sources will be deployed in the SNO detector at the appropriate time using the infrastructure that has been put into place for calibrating all aspects of the SNO detector using a myriad of sources.

Sample	Height (cm)	Aprox. Activity
Hot ^{252}Cf	2.46	~ 45 n/sec
Weak ^{252}Cf	2.93	~ 4.5 n/sec
^{226}Ra	2.99	~ 80 2.45 MeV γ /sec
Hot ^{232}U	2.85	~ 6000 2.6 MeV γ /sec
Weak ^{232}U	2.86	~100 2.6 MeV γ /sec

Neutral-Current Detector Program

Design Criteria & Operating Constraints

The use of ^3He proportional counters for neutron detection in nuclear and particle physics represents a well practiced art. Nonetheless, one must develop novel ideas and overcome a multitude of challenging and competing constraints to realize their potential as a neutral-current detector (NCD) in SNO. The SSM predicts the production of about 14 neutrons per day in the 1000 tonne heavy water target, placing substantial constraints on the radiopurity of any of the NCD construction materials. Since radioactive background forms the central and most pressing constraint in SNO, these issues are discussed further in following sections of this document. In addition to radiopurity, significant constraints enter from electrical and mechanical considerations and the fact that the counters must survive under water for a period of up to ten years.

Heavy water is an effective neutron moderator. Together with the high capture efficiency on ^3He , neutrons can be detected with relatively high efficiency in an array sufficiently sparse that it does not interfere with the Cerenkov light produced in the main SNO detector. Extensive Monte Carlo studies have lead to an 800 m array of 96 strings that are 5 cm in diameter and distributed on a square lattice throughout the D2O vessel. This array provides an overall neutron capture efficiency of about 50 %.

A schematic diagram of an NCD string is shown in Figure 2. As discussed in the following section, the bulk construction materials used in fabricating the cathode tubing and endcaps is low-background nickel produced via chemical vapor deposition. Due to the smaller mass, less stringent requirements are placed on other components such as the anode wire and feed-thru assemblies. The anode wire itself is constrained mainly by electrical and mechanical considerations. In the first place, the wire must withhold a tension of 30 g to overcome droop under gravity and must be low enough in resistance to minimize losses due to the resistive skin effect. Extensive calculations and mechanical tests were performed at LANL before deciding that 2-mil diameter, hard-drawn copper wire is essentially the only choice for the proportional counters. To minimize background in the D2O, the preamplifiers recovering the signals from the NCD strings are placed outside of the detector using readout cables up to 15 m in length. This places further constraints on the design of the readout electronics and operating parameters of the detector to insure low noise and good signal integrity. In addition, delay lines are mounted at the remote end of a detector string to allow the extraction of event position along the string by exploiting pulse-reflection and time-delay.

At Los Alamos a part of our research efforts has involved the construction of a full-scale test-detector (12m in length from 4 X 3m segments) with the mechanical and electrical properties of our design for the longest NCD string. Running as a proportional counter we were able to verify and measure all of the properties of our detector relevant for recovering the signal and demonstrated the feasibility of using unconventionally large proportional counters. With the mechanical, electrical, and radiopurity constraints in hand, one must determine the best choice of gas-fill and operating parameters for running the proportional counters. At least one other component of gas is required to be mixed with ^3He to provide quenching. A gas with high stopping power is desired to mitigate wall effects and the electron drift speed must be increased to allow one to optimize one's ability to exploit digital current pulse information for event-by-event discrimination (discussed further below). In addition, measurements were made to map out the gas-multiplication properties and parameters in order to optimize the gas-fill w.r.t. signal-to-noise and operating voltage while minimizing spurious pulse rates associated with high-voltage micro-discharge and noise. Extensive R&D at LANL lead to He-CF_4 mixtures as the best candidate for gas-fill of the NCD array. These constraints, together with the criteria that the tubes do not collapse under the external pressure of D_2O , and the need for high capture efficiency leads to a constraint on the gas-mixture as shown in Figure 3.

Radioassay Materials

The naturally occurring Th and U series isotopes pose a serious challenge to SNO. Each of these chains has an isotope (^{214}Bi in the U chain and ^{208}Tl in the Th chain) that emits gamma rays having energies that are greater than the 2.22 MeV neutron binding energy in deuterium. Since the detection method for neutrino NC-interactions in SNO is the neutrino inelastic dissociation of deuterium to produce liberated neutrons, these high energy photons can mimic the desired neutrino interactions we wish to study. A total mass of 0.5 μg of Th dispersed in the 1000 tonnes of heavy water will produce neutrons at a rate equal to 1% of the expected neutrino NC signal!

At LANL we have developed techniques that allow us to assay materials that are used in SNO to assure the required radiopurity levels. The most general technique we use is neutron activation on samples and, following irradiation, chemical processing to isolate the characteristic activation products (^{233}Pa for Th and ^{239}Np for U). In specialized cases where it is impractical to directly activate the material to be studied (cases such as the SnAg solder used in NCD construction) we have first performed a chemical separation of the material to remove the Th and U from the sample. For this to be a quantitative procedure

we utilize suitable chemical tracers to determine chemical yields. Once the Th and U fractions are isolated they are then sent to a nuclear reactor for neutron activation. On return to LANL the samples are then counted using high efficiency germanium well detectors.

The required purity levels are dependent on the total mass of a particular material to be used in SNO and its deployment location relative to the heavy water volume. For massive materials, such as the heavy water containing acrylic vessel, purities at the 1 ppt level w.r.t. Th and U are required. Since LANL has a leadership role in the neutral current detection in SNO, we have a very high concern for the purity of the NCDs that we are developing. The primary component of these detectors is ultra high purity chemical vaporization deposition produced Ni. Our goal was to insure that this material had Th contamination at levels below 10 ppt and U at below 100 ppt. This represents a rather intimidating goal since most commercial materials appropriate for constructing proportional are at least 1000 times above this constraint on radiopurity. Results of some of the Ni studies are in the table below.

Sample	U ppt	Th ppt
Ni-200 (High Grade Commercial Ni)	$26,600 \pm 1000$	340 ± 20
Vendor 1 – CVD Ni Plate-A		63 ± 5
Vendor 1 – CVD Ni plate-B		54 ± 5
Vendor 2 – CVD Ni tube-A	17 ± 2	57 ± 3
Vendor 2 – CVD Ni tube-B	5 ± 1	390 ± 16
Vendor 3 – CVD Ni tube-A	≤ 4	≤ 0.9
Vendor 3 – CVD Ni tube-B	≤ 14	≤ 0.5
Vendor 3 – CVD Ni tube-C	25 ± 10	≤ 2.6
Vendor 3 – CVD Ni tube	≤ 9	≤ 2.9

Based on these studies (and many other measurements) vendor C was chosen for producing the nearly 1 kilometer of cathode tubing for the NCD array, as well as for the material in producing the counter endcaps. At the 2 to 3 ppt level in Th, we have reached radiopurity levels 3 to 4 times better than our goals. This is particularly relevant since now the NCD array will not pose as a significant background threat when deployed in SNO and the backgrounds will remain dominated by that intrinsic to the heavy water and surrounding hardware.

Event Topology and Pulse-Shape Discrimination

The U and Th in construction materials will also produce alpha and beta activity which can enter and ionize the proportional counter gas. This activity produces a background to the signal of interest, namely the 764 keV ${}^3\text{H}(\text{n},\text{p})\text{t}$ neutron-capture signal. In order to mitigate these backgrounds, we have developed techniques of pulse-shape discrimination wherein the topology of an event can be identified and used to discriminate different types of ionizing radiation by analysis of the digitized current waveforms recovered from the detector strings. As Figure 4 demonstrates, the result is a background free region wherein neutrons can be counted on an event-by-event basis. By digitizing events with integrated energy up to 10 MeV we have also shown that the data can be exploited as an *in situ* measure of the intrinsic radioactivity of the counters. The data can be fully exploited to separate *bulk* from *surface* contamination and, in principle, to separate the U *versus* Th content of the intrinsic activity.

In order to fully test the low-background capability of our NCD array, prototype detectors have been run and diagnosed underground at a special test facility put in place at the Waste Isolation Pilot Plant (WIPP). There, a set of first and second generation prototype detectors were tested and yielded the evidence we required to verify and improve the radiopurity of the counters, and that the techniques of pulse-shape discrimination described above work effectively. This low background facility has proven an essential part of our program to realize our goal of extremely low background proportional counters and has allowed the proper environment for refining the analytical tools necessary for extracting the neutron-capture signal in a robust manner.

Chemical Etching & ${}^{210}\text{Po}$

Significant concentrations of ${}^{210}\text{Po}$ (138 day $t_{1/2}$) have been found on internal surfaces of some of the prototype nickel detectors produced for SNO. The mechanism for deposition is not totally known, but it has been strongly correlated with the decay of naturally occurring airborne Rn. Though the energy of this alpha decay (5.3 MeV) is substantially above that liberated in the ${}^3\text{He}$ neutron capture reaction (0.78 MeV), it still can pose a source of background for our very low reaction rates. We have, therefore, investigated methods of removing this unwanted contamination without removing significant quantities of the CVD Ni wall material.

The most successful has been the use of high current density electropolishing. Electrolysis at 200 mA/cm² in 1 M sulfuric acid was found to involve negligible attack on the CVD Ni. A series of three, 5 minute runs per tube was found to have a decontamination factor of at least 100 and, in test samples, usually removed the ²¹⁰Po to below detection limits.

Gas-Handling & Detector Diagnostics

At Los Alamos we were fortunate to have access to the 10000 STP liters of ³He (a commercial value over \$1M) required for filling the NCD array. The fact that the ³He reserve is tritiated made it necessary to research and develop a dedicated gas-handling system capable to purify the gas to proportional counter quality and in reducing tritium levels from 30 mCi/l to 10 nCi/l. The system is based upon a series of charcoal cold traps and getters which actually reduce the tritium levels to the 0.1 nCi/l level. A schematic diagram of the gas-handling system is shown in Figure 5 which also shows the second circuit for mixing and purifying the ³He-CF₄ mixture.

The system was designed to handle volumes of the gas-mixture at the 2.5 atm necessary for filling, simultaneously, the detector components making up the largest (11 m) of the NCD strings. In addition, a dedicated electronics and DAQ station has been implemented by Los Alamos for diagnosing and verifying the performance and integrity of the counters at the production phase. The gas-handling system, electronics & DAQ test-bench, and a detailed set of gas-handling and diagnostic procedures are now in place for the full-scale construction of the detector array.

Data Acquisition & Pulse-Shape Analysis Code

Development of the NCDs has required the development of specialized data acquisition and analysis programs. In particular, waveform analysis has been one of the key tools used to characterize the performance of the NCDs. To implement such waveform analysis we have interfaced two waveform digitizing oscilloscopes to the SNO standard data acquisition system. We have also developed a new self-describing data format for the data acquisition system to simplify implementation of new hardware modules and improve the flexibility of analysis programs.

As part of this effort, the core of a new data analysis program has been written and is being used to analyze characterization data from the NCDs. The architecture of this new analysis program simplifies the development of new analysis algorithms because there

exists a clear separation between data and analysis algorithm objects. Thus it is relatively easy to modify an algorithm object to use whatever data is required to perform an analysis. This system will thus form the boiler plate for implementing the NCD data stream into the main SNO data acquisition system and also forms a versatile system that is now being used widely on other projects in our weak interactions program. In developing the analytical tools and recipes for pulse-shape discrimination, our team at LANL has also developed an object-oriented (C++) code that interfaces with the NCD DAQ and automatically extracts the digitized pulses for analysis. These recipes and code now form the bench-mark in analysis for the NCD experiment and are now presently used in the analysis of data during the *cooldown* phase for NCD array..

As the detector segments for the NCD array are constructed they are shipped underground at Sudbury where they are stored in a dedicated area and operated as counters for verification and monitoring. A cooldown period of about six months is used for continuous monitoring and verification, and to allow for the decay of cosmogenically produced ^{56}Co . During this phase, the detectors are also monitored for intrinsic radioactivity using the techniques developed at LANL and described previously. At this stage, approximately 15% of the array is underground at Sudbury. Analysis of the first data sets indicate radiopurity levels at about the 3 ppt level of Th, some three times lower than our design goal and in agreement with expectations based upon the radioassay measurements described previously.

Leaching Studies

We have proposed using ^3He proportional counters constructed with ultra high purity, chemical vapor deposition (CVD) Ni. We have performed extensive quality control measures to insure that the individual components that are used as construction materials meet the required purity levels. However, once the detectors have been assembled they will be deployed into the heavy water volume of SNO. Though extreme care is being taken in the construction, shipping and handling phases, any added surface contamination could, in principle, leach off of the detectors and introduce contamination in the SNO heavy water. To test against this effect we are building a "whole body" counter system that can take completed detector elements and measure extremely low levels of radioactive materials that might transfer into the aqueous phase. The required sensitivity for these tests is defined by the desire to not introduce any contamination level that will result in neutron production that is greater than 1% of the expected neutrino NC production rate. This limit requires us to

have less than 2 μg of ^{238}U and 0.6 μg of ^{232}Th in the 1000 tonne heavy water volume (i.e. about 1 part in 10^{15}).

We have developed and tested prototype chemical extraction systems that meet these requirements. They are based on circulating ultra high purity water (that in production systems will flow over the Ni counter bodies) that has been spiked with small amounts of ^{227}Th and ^{223}Ra (on the order of 10^8 atoms). The Ra and Th are trapped using a commercial cation exchanger (Bio-Rad AGMP-50) and subsequently eluted for analysis. Even at these small atom concentrations (comparable to those that would be present at required testing levels for the longer lived ^{228}Th and ^{226}Ra), recoveries of greater than 50% were obtained for each species. These tests imply that we should be able to reach a level of radiation detection that is at least an order of magnitude more sensitive than required for SNO certification.

Deployment Program

A key aspect of the NCDs development is how to deploy the full array in SNO. The detectors are buoyant and possess anchors that must be attached to fixtures on the bottom of the acrylic vessel (refer to Figure 2). Thus the NCD array cannot be deployed until the detector is full of heavy water. Furthermore the NCDs are constructed in segments, the longest not exceeding 3 meters. These segments must be assembled into detector strings, the largest of which are 11 meters in length. Thus we must develop the method for laser welding the NCD segments *in situ* underground and deploying them into the filled SNO detector through the neck of the acrylic vessel.

At our disposal in Los Alamos is a unique resource which is a pool in the shape of a cube with a dimension of 20 feet on a side. At the top of this pool we have built a mockup of the acrylic chimney, which gives access to the interior of the acrylic vessel at SNO. In the pool we have placed fixtures, such as those that will be used for the NCDs, on the bottom and on a slanted acrylic plate. We have also placed a mockup of the "ceiling" portion of the acrylic vessel to observe how the cables connecting the NCDs to the preamps will behave. The current plan for deployment, which has been largely tested using the Los Alamos pool, is to weld NCD segments together above the acrylic vessel chimney. As each segment is welded into place, the entire string would be pulled down using a looped rope that is attached to the bottom of the acrylic vessel. Once completed and tested the entire string of NCDs would be maneuvered to its final position using a remotely operated vehicle (ROV).

During the initial testing phase we developed and constructed the nameplates that label each fixture point. Though this task may appear trivial, one must recall that the labels have to be easily visible from several feet away, must survive immersion in ultrapure water, and cannot have a U and Th content higher than a few parts in 10^{12} . We also developed techniques for guiding the ROV. The key concern here is not moving an NCD around using the ROV, but knowing where one is inside the 12 meter diameter acrylic vessel. As part of the investigation we made a movie of the interior of the acrylic vessel prior to its being filled with heavy water. This film clearly illustrated that the uniformity of the photomultiplier tube array could easily lead an operator to become disoriented. Also the fixtures to which the anchors are attached are almost invisible since they are constructed of acrylic. Within the pool we placed black plastic on the walls and floor which reproduced the lack of visual clues observed in the film. Tests with the ROV indicated that a global view camera with an adjustable zoom is essential to the deployment process. Furthermore, a strong recommendation was made to retrofit the ROV with an electronic compass so that that operator knows in which direction he is facing. Our goal is to fully test all of the deployment hardware, and train all of the NCD installers, at Los Alamos prior to beginning installation of the NCD array underground at SNO.

Neutral-Current Signal Recovery

At Los Alamos we have spearheaded the program to understand the various elements in recovering the NC-signal from the NCD array in SNO and to project the ultimate sensitivity in extracting the NC/CC-Ratio. A recipe for extracting the signal has been developing using the following key elements as a guide:

- The total neutron-capture rate is extracted from the NCD array on an event-by-event basis, including a time stamp and 3-dimensional spatial coordinates, by exploiting the digitized pulse-shape and background free region in the $3\text{He}(n,p)t$ window.
- Measurements of the spatial response of the array to neutrons and the overall neutron-capture efficiency are performed using ^{252}Cf calibration sources.
- The *near-vessel* contributions to the neutron signal are separated from the *isotropic* signal using the unique characteristics and radial distributions offered by the discrete NCD array.

- Radioactive *hot-spots* are characterized and eliminated from the data sample using the spatial distribution of events over the NCD array, and also by exploiting coincidences with Cerenkov radiation in the PMT array.
- Using independent measures of the intrinsic radioactivity of the various detector elements, together with the information contained in a well calibrated Cerenkov background wall, the isotropic contribution to the neutron signal from photodisintegration background is deduced.

By utilizing all of this information one can deduce the NC-flux and its uncertainty in a manner that will allow SNO to differentiate between various scenarios to explain the solar neutrino deficit. Based on our present knowledge and projection of backgrounds, and through the techniques and tools described for extracting the various elements of the neutron-capture signal, Figure 6 depicts the result of simulations to project our ultimate sensitivity to the NC-signal after running the SNO detector for one year with the NCD array deployed.

Publications

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A. Hime, *Neutral-Current Detectors for the Sudbury Neutrino Observatory*, Fourth International Solar Neutrino Conference, Heidelberg, Germany, April 8-11 (1997), LAUR-97-2014.

A. Hime, *Exorcising Ghosts-In Pursuit of the Missing Solar Neutrinos*, Los Alamos Science, Celebrating the Neutrino, Number 25 (1997).

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Figure Captions

Figure 1: Simulation of the Cerenkov spectrum in SNO with Pure-D₂O showing the charged-current (CC), neutral-current (NC), and elastic-scattering (ES) signals, along with the beta/gamma activity associated with various detector component backgrounds. 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 into the D₂O.

Figure 2: Schematic diagram of a neutral-current detector (NCD) string.

Figure 3: Constraints placed on the total pressure and CF₄ fraction in filling the NCD array. The optimum choice for gas fill uses 2.5 atm of ³He/CF₄ in the ratio 85:15, and detectors are operated at 1835 V for a gas-multiplication factor of 100.

Figure 4: Analysis of digitized pulses from ³He test counters at LANL. ³He(n,p)t events are confined to a window as shown and are easily discriminated from beta/gamma activity in the counter. Alpha particles emerging from the bulk of the cathode material overlap with ³He(n,p)t window but leave approximately 50% of the region background-free.

Figure 5: Schematic diagram of the gas-handling system designed and constructed at LANL for the purification and preparation of the He-CF₄ gas-mixture used in filling the NCD array.

Figure 6: A projection of the sensitivity (95 % C.L.) to the NC and CC signals after running SNO with the NCD array in place for one year. The NC/CC-Ratio is defined by the slope in the NC v.s. CC plane and is independent of the details of solar model predictions of the independent fluxes. Three distinct regions are discerned with high confidence for the different possible solutions to the solar neutrino problem.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6