DOE/ER/40479--T1

DE92 011021

SUDBURY NEUTRINO OBSERVATORY

Annual Technical Progress Report
For the period July 1, 1991 - June 30, 1992

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March 1992

Prepared for

THE U. S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-FG02-89ER40479

TECHNICAL PROGRESS REPORT
to the
Department of Energy
for the
Sudbury Neutrino Observatory Project

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March 9, 1992

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1 The Sudbury Neutrino Observatory Project

This document is a technical progress report on work performed at the University of Pennsylvania during the current year on the Sudbury Neutrino Observatory project. The motivation for the experiment is the measurement of neutrinos emitted by the sun.

The Sudbury Neutrino Observatory (SNO) is a second generation dedicated solar neutrino experiment which will extend the results of our work with the Kamiokande II detector by measuring three reactions of neutrinos rather than the single reaction measured by the Kamiokande experiment. The collaborative project includes physicists from Canada, the United Kingdom, and the United States. Full funding for the construction of this facility was obtained in January 1990, and its construction is estimated to take five years.

The motivation for the SNO experiment is to study the fundamental properties of neutrinos, in particular the mass and mixing parameters, which remain undetermined after decades of experiments in neutrino physics utilizing accelerators and reactors as sources of neutrinos. To continue the study of neutrino properties it is necessary to use the sun as a neutrino source. The long distance to the sun makes the search for neutrino mass sensitive to much smaller mass than can be studied with terrestrial sources. Furthermore, the matter density in the sun is sufficiently large to enhance the effects of small mixing between electron neutrinos and mu or tau neutrinos. This experiment, when combined with the results of the radiochemical ^{37}Cl and ^{71}Ga experiments and the Kamiokande II experiment, should extend our knowledge of these fundamental particles, and as a byproduct, improve our understanding of energy generation in the sun.

The experiment is similar to the Kamiokande experiment in size and design, but utilizes as a target one kiloton of heavy water, D_2O , which permits detection of the neutrinos through the reactions

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad (1)$$

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

$$\nu_x + d \rightarrow \nu_x + p + n \qquad (3)$$

The elastic scattering of neutrinos from electrons is highly directional, and establishes the sun as the source of the detected neutrinos. The absorption of ν_e on deuterons produces an electron with an energy offset from the neutrino energy by approximately the threshold energy for the reaction. This reaction is sensitive to the spectrum of ν_e and any deviations from the parent spectrum which might be induced by traversing the high density matter in the sun. The disintegration of the deuteron by neutrinos is independent of neutrino flavor and has a threshold of 2.2 MeV. Measurement of the rate of this reaction determines the total flux of ^{8}B neutrinos, even if their flavor has been transformed. Measurement of this reaction makes the interpretation of the results of the experiment independent of theoretical calculations, unlike all other solar neutrino experiments.

The University of Pennsylvania group's responsibilities to the SNO collaboration are in the area of data handling and include characterization of photomultiplier tubes in the prototype and production stages of the experiment, development and acquisition of photomultiplier tube bases, signal processing electronics, and software organization and development. Our work on the characterization of the detector response and extraction of physics results, and our past experience with the Kmaiokande detector have led us to do a modest amount of R&D on radioactive sources for detector calibration this year.

Many of our activities are in collaboration with other institutions in the collaboration, but our group brings experience which does not exist elsewhere in the collaboration in many areas of study.

2 Technical Progress During the Current Year

2.1 Photomultiplier Tube Measurements

During 1991 the PMT test and measurement set up was used to verify a number of measurements made at Queen's University. As a result of this work, our confidence in the Queen's measurements is quite high. Until quite recently there were few production tubes available to measure, so the principal use of the set up was to optimize and tune the PMT voltage divider chain design and to verify the suitability and stability of a single cable PMT base design.

2.2 Photomultiplier Bases

The initial Hamamatsu design for a two cable base was changed to a single cable version (HV and signal on the same coaxial cable) in order to save costs and to reduce complexity. The electrical design of this base was then verified in the PMT test and measurement set up. Once semi-production tubes were available from Hamamatsu, the last three dynodes were provided with zero cancelling networks tuned to the pole caused by the finite capacitance and impedance of the dynode structure. In the tuned base, the post pulse ringing and damped oscillation is reduced by about a factor of eight. After some experimentation it became clear that tube to tube differences are sufficiently large that further cancellation (without manual tuning) would be difficult if not impossible.

A production version of this design was layed out and sent for prototype manufacture. The base material was chosen to be 0.005" Kapton film to reduce the radioactive burden. The resistors and small energy storage capacitors are all surface mount devices to keep the total mass as small as possible. The high voltage capacitors (one filter and one back termination capacitor) are implemented as wrapped film dielectric capacitors (Philips components) with very low mass and radioactivity. These capacitors were then tested for high voltage compatibility at Queen's and for high frequency response at Penn. They were found to be superior to ceramic equivalents and less expensive.

About one hundred prototype bases have been produced to test various assembly and test scenarios. A small (500 pc,) assembly order is presently underway.

2.3 Signal Processing Electronics

2.3.1 Bipolar Integrated Circuit

During the summer of 1991, a detailed design and layout was made of a large dynamic range preamplifier for the front end of the charge measuring signal processing chain. This device was designed in the AT&T CBIC-U complementary bipolar process and was layed out on a standard AT&T array tile. The preamp simulation indicates better than 11 bits of dynamic range and a full scale output corresponding to a 10 pC input integrated over 30 nsec can be achieved - more than meeting the SNO specification.

The tile array layout was done with the intent of having some prototypes run by AT&T along with other internal projects at no cost to SNO - the AT&T internal runs have not yet materialized and so no silicon has been fabricated. However, experience with, and our confidence in the AT&T models is sufficiently great that we do not believe that this is a significant problem and are going ahead with the full integrated SNO bipolar design.

The full bipolar chip will have, per channel, two charge preamps (one for the "high gain" channel, $\sim$0.1 photoelectron (p.e.) per bit, and one for the "low gain" channel, $\sim$1.0 p.e. per bit), one discriminator, and timing logic which will establish the width of the charge integration gate (for both high and low gain channels). All of these components are then duplicated for each of the channels on the chip. We are not, at the moment, certain whether to try to put two or four channels on a single chip - this will depend upon the configuration of the full custom layout and the availability of packages with suitable number and configuration of pins.

In addition to the detailed preamp simulation, the major advance on the bipolar chip was to initiate the fabrication order for the chip and to begin to install the CAE/CAD tools necessary to complete the layout. Contrary to the array products where layout can be done either by hand or using a small PC based tool, the relatively complex full SNO device requires the use of a highly complex set of coupled schematic, simulation, and layout tools. Penn is fortunate to have already installed and to have had experience in the same high end tool that AT&T has chosen to use (Cadence). We have been occupied for the past several months, since the first part of the fabrication order was placed, in installing, correcting, and learning the AT&T variations to the basic Cadence toolset. We now have completed several "test" cycles on the tool and are beginning to tackle the full chip. We hope to have complete files to AT&T for checking and approval in April of 1992. If the design passes all of the design checks, the first wafers of bipolar chips would be available to us at the end of the summer.

2.3.2 CMOS INTEGRATED CIRCUIT

Initial testing of the full custom SNO 1.6 micron multi-sample integrator for the time measurement has been encouraging. Initial testing of a model Time to Voltage Converter with Analog Memory Unit (TVC/AMU) has also been encouraging. (The model development is part of the Penn SSC electronics development program and is not part of the SNO effort, but the circuitry is very similar to that required by SNO.)

2.3.3 PHOTOMULTIPLIER TUBE HIGH VOLTAGE CONTROL

In accordance with the single cable base decision, not only the PMT base, but also the dry end of the HV system required redesign. We now have an elegant and manufacturable design for the HV distribution, HV readback (being prototyped at Queen's), impedance preservation, and cable connect/disconnect. We are examining whether or not it is reasonable to include active HV control to handle PMT gain changes, although off-line software gain adjustments are likely to be the standard procedure for small gain adjustments.

2.3.4 SYSTEM DESIGN ISSUES

Considerable progress has been made in detailing the overall system including interconnections between subsystems and standards to use for the various subsystems. These design decisions will be reflected in a revised Design Criteria Document to be issued in March 1992. We are now in a position to begin detailed designs of all of the subsystems.

2.4 Software Management and Development

Software efforts during the past year fall in two categories; utilizing the existing detector simulation code to make engineering design decisions, and organizing the structure of the software to be used throughout the entire collaboration when data becomes available. Penn has contributed to both these efforts.

As an example of the use of existing software to understand the performance of the SNO detector, Penn performed solar neutrino signal extraction using simulated data and background in a study of the effect of different levels of background producing materials in the acrylic vessel which contains the D_2O . This study showed that the tolerable limits of these materials were higher than in the design criteria, providing a margin of safety for the experiment. No change has been made in the design criteria as a result of these studies.

In the organization of the SNO software, we have, with our collaborators, identified three areas where development of software which is platform independent can proceed. We are fortunate that professional programmers have been made available to assist physicists in the initial phases of the project. The three areas are the definition of the control structure for the data analysis code, the code version management, and interactive graphics for data analysis. When the control structure is distributed, the physicists will interact through the version management system and write code which interacts only with the control structure, and not with other physicist supplied code. In this way, efficient management of the code in a collaboration that spans eight time zones should be tractable. The Penn role is to oversee and coordinate these efforts, now that they are defined.

2.5 Detector Response and Calibration

The combination of experience with the Kamiokande II detector, our work in PMT characterization and testing, and software simulation of the detector response have involved the Penn group in a variety of issues relating to detector response and calibration. The development of a compact, high rate light source using a frequency doubling laser and the development of a neutron free gamma ray sources are discussed below.

The frequency doubling laser light source reported last year was improved by the use of a Potassium Niobate crystal (Virgo Optics) which produces (at 430 nm) well over 1000 photo electrons in less than 2 nanoseconds. Such a device has potential advantages over other light pulsers in that it is directional (like Čerenkov light) or isotropic (using a diffuser), and it can operate at a much higher rate than a conventional nitrogen laser (making low light level calibration runs shorter). The major disadvantage of the Potassium Niobate is that it is more temperature sensitive than crystals previously used at Penn. In order to improve further the performance and turn the source into a usable calibration tool for the SNO detector as a whole, we are presently engaged in adding a temperature control system to the pulser, and trying to design a compact package which will allow conversion to a submersible form.

Gamma ray calibration of the energy response of the detector is planned using radioactive sources. One of the goals of SNO is to keep the detector operating continuously, even during source calibration runs.

A calibration source utilizing the radiative capture of thermal neutrons was used by Kamiokande II, and variations on this approach are being considered for SNO. These sources typically have neutrons associated with the gamma production which capture on detector materials and trigger the detector at high rates. This is incompatible with running the detector for normal data during the calibrations. Calibrations using a thermal neutron capture source are needed to understand the neutral current response of the SNO detector, but do not have the spatial localization desired in an energy calibration. A study of neutron free gamma sources has been initiated by the Penn group to address this problem.

One idea is to use ^{16}N produced by high energy neutrons from a source, or preferably, a commercially available (d,t) generator, through the ^{16}O(n,p)^{16}N reaction. The ^{16}N has a 7.13 second half life, so that by illuminating water with neutrons external to the detector the excited nitrogen can be pumped through a transparent tube into the detector. The β^- decays of ^{16}N produce a 10.4 MeV electron 26% of the time and a low energy β accompanied by a 6.13 MeV γ 69% of the time. This technique has some promise for producing a low intensity source which can be used for both energy and spatial reconstruction calibration. Further, over 90% of the γ's have a unique energy (6.13 MeV) unlike the neutron activitated source used in Kamioka, where six different gamma energies must be simulated in the analysis of the calibration. Preliminary tests at Penn will be followed by tests using a deuteron beam and tritium target at the Queen's University Van de Graff to produce high energy neutrons and form ^{16}N.

2.6 Project Management and Coordination

Penn is also playing an important role in project management and coordination. E.W. Beier is the U.S. spokesman and project R&D manager. He and W. Frati have contributed to understanding and calibrating the detector response. The Penn electronics group (F.M. Newcomer and R. Van Berg) has been especially active in defining interfaces for the mechanical and electrical engineering efforts at the project management and engineering firm, Monenco Consultants, Ltd. Some of this effort was in the normal course of the design - for instance: information on PMT cables, power requirements, and grounding requirements for the cavity construction. An additional large effort was involved with the SNO Cost Reduction Task Force which managed to trim and rationalize the project costs by over 2.4 million dollars. A large fraction of this cost reduction was brought about either directly or indirectly by the efforts of the Penn group.

3 Publications and Reports

1. *The Solar Neutrino Opportunity*, E.W. Beier, Proceedings of the 4th Conference on the Intersections between Particle and Nuclear Physics, Tucson, Arizona, May 1991, AIP Conference Proceedings 243, pp. 3-19, American Institute of Physics, New York, 1992.

2. *Status of Solar Neutrino Experiments*, E.W. Beier, et al., Proceedings of the Twelfth International Conference on Particles and Nuclei: PANIC XII, Nucl. Phys. **A527**, 653-62 (1991).

3. *Extraction of CC, NC, and ES Signals in SNO - III: Multi-Year, Three Parameter Maximum Liklihood Analysis*, W.Frati and E.W. Beier, **SNO-STR-91-025**.

4. *Measurements of the Charge Ratio and Polarization of 1.2 TeV/c Cosmic Ray Muons with the Kamiokande II detector*, Kamiokande II Collaboration, Phys. Rev. **D44**, 617-21 (1991).

5. *Mass Limits on Dark Matter Particles Derived from High Energy Neutrinos from the Sun*, Kamiokande II Collaboration, Phys. Rev. **D44**, 2220-2240 (1991).

6. *Search for Fractionally Charged Particles in Kamiokande II*, Kamiokande II Collaboration, Phys. Rev. **D43**, 2843-6, 1991.

7. *Real Time, Directional Measurement of ^8B Solar Neutrinos in the Kamiokande II Detector*, Kamiokande II Collaboration, Phys. Rev. **D44**, 2241-60 (1991).

8. *Unusual Event Uncovered in a Search for Neutrino Induced Low Energy Electron Event Clusters in Kamiokande-II*, Kamiokande-II Collaboration, to be published in Phys. Rev. **D**.

9. *Observation of a Small Atmospheric ν_μ/ν_e Ratio in Kamiokande*, Kamiokande-II Collaboration, to be published in Phys. Lett. , 1992.

10. *Survey of Atmospheric Neutrino Data and Implications for Neutrino Mass and Mixing*, Kamiokande-II Collaboration, submitted to Phys. Lett. , 1992.

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5/14/92