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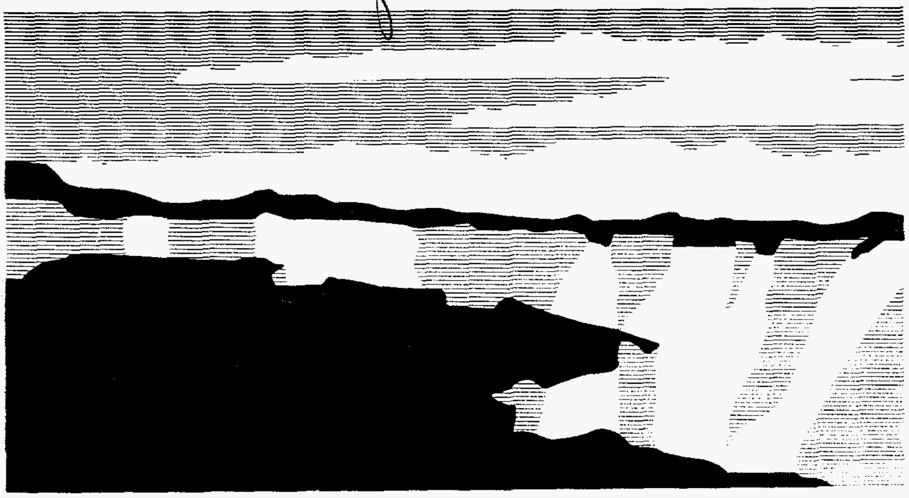

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THE SUDBURY NEUTRINO OBSERVATORY

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and

ON BEHALF OF THE SNO COLLABORATION *

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A report is given on the status of the Sudbury Neutrino Observatory, presently under construction in the Creighton nickel mine near Sudbury, Ontario in Canada. Focus is upon the technical factors involving a measurement of the charged-current and neutral-current interactions of solar neutrinos on deuterium.

1 Introduction

Existing data from the four pioneering solar neutrino experiments, Chlorine [1], Kamiokande [2], SAGE [3], and GALLEX [4], combined with results from Standard Solar Model (SSM) calculations [5] over a spectrum of solar neutrino energies, constitutes what is now well known as the *Solar Neutrino Problem.* In all cases, the experimental neutrino fluxes are significantly low compared to SSM predictions and this deficit appears to be energy dependent. Indeed, by combining the existing experimental results there seems little room for any ^{7}Be neutrinos despite the fact that ^{8}B neutrinos are observed, albeit at about one third of the expected rate [6]. This latter effect, refered to as the ^{7}Be/^{8}B anomaly makes it difficult to render an astrophysical solution to the solar neutrino deficit. On the other hand, the energy dependent suppresion of the solar neutrino spectrum is beautifully accomodated through the mechanism of matter-enhanced neutrino (MSW) oscillations [7].

The existence of neutrino oscillations requires non-zero neutrino masses and a violation of lepton flavor conservation, yielding profound implications for elementary particle physics, astrophysics, and cosmology. The interpretation of the existing solar neutrino problem relies both on our confidence in the existing solar neutrino results as well as in the details of SSM calculations. Hence, it is of paramount importance to test the hypothesis of solar neutrino oscillations in a model-independent manner.

The Sudbury Neutrino Observatory (SNO) is a new generation, real time, experiment that will exploit a heavy water (D_2O) target to carry out two basic measurements on the ^8B solar neutrino spectrum:

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

If electron neutrinos created in the solar core are truly experiencing flavor transitions to the muon and/or tau states then a ratio of the total neutrino flux to the electron neutrino flux at earth offers a model independent test of the oscillation hypothesis. In addition, detailed studies of the shape of the electron neutrino energy spectrum in the SNO detector can be used to probe different solutions to the solar neutrino problem.

2 The SNO Detector

2.1 History

The idea to use heavy water in a solar neutrino experiment was first proposed by H.H. Chen [8] in 1984. Upon visiting the Creighton mine in Sudbury during discussions for a proton decay experiment he became aware of the existence of heavy water at AECL and pursued the possibilty to borrow about 1000 tonnes of D_2O. The SNO collaboration was formed shortly thereafter and funds from NSERC in 1985 allowed a feasibility study [9] to evaluate the capabilities and practicality of building such a detector.

In 1986 an exploratory drift was located along with a site wherein a 20 m diameter cavity could be constructed at the 6800 ft level of the INCO mine. A detailed proposal for the laboratory [10] was reviewed in June 1988 by an international scientific and technical review committee that recommended that SNO be approved and funded as proposed. Capital funds for the construction of the Observatory were committed in Januray, 1990. The SNO project is presently under construction by collaborators* from twelve institutions located in Canada, the United States, and the United Kingdom.

2.2 Detector Design

The design of the SNO detector has evolved since the original proposal [10] of 1987. Neutrinos will be detected in 1000 tonnes of 99.92% isotopically pure D_2O contained in a 12 m diameter acrylic sphere. At 2070 m (6200 mwe), this acrylic sphere is suspended in a barrel-shaped cavity some 22 m in diameter and 30 m high. The 12 m acrylic vessel will be the largest sphere of its kind in the world, constructed of some 200 (5 cm thick) panels, initially machined and thermoformed before assembly underground. About 7500 tonnes of ultrapure light water (H_2O) acts to shield the D_2O volume from backgrounds original to the surrounding (norite) rock enviroment.

Cerenkov radiation is detected in an array of 9800, 20 cm photomultiplier tubes (PMTs) that are uniformly distributed in the light water shield 2.5 m outside of the acrylic vessel and supported by a geodesic frame (PSUP). Each PMT is facilitated with a reflector to enhance light collection to reach an effective photocathode coverage of about 60%.

Neutrinos interact in the detector to produce relativistic electrons and free neutrons. Signals from the PMTs are exploited to determine the location, energy, and direction of the electron based upon the time of arrival of Cerenkov photons at the PMTs and the number of PMTs that trigger in a given event. Neutrons are detected via their subsequent capture in discrete neutron counters and/or by the Cerenkov light produced by neutron capture on chlorine dissolved in the D_2O.

2.3 Neutrino Interactions in SNO

2.3.1 Charged Current with Electron Neutrinos

Only electron neutrinos can interact with the deuteron via the charged current (CC) interaction,

$$\nu_e + d \rightarrow p + p + e^- - 1.44 \text{ MeV}, \tag{1}$$

wherein a neutron is transformed into a proton with the emission of a fast electron. The recoil proton does not have sufficient energy to create a signal in the detector but the relativistic electron will produce Cerenkov light to be collected in the PMT array. The number of PMTs that trigger in any given event is a measure of the incident neutrino energy so that the SNO detector is capable of obtaining information (with about 20% resolution) on the CC spectrum shape. This spectral shape can then be studied for spectral distortions predicted for MSW effects or neutrino oscillations in vacuum (refer to ref.[6]). Some directional information is present in the CC signal, although limited by the standard dependence for the inverse β decay interaction.

2.3.2 Neutral Current Interaction

Neutral current (NC) disintegration of the deuteron can proceed by all active neutrino species with energy above the binding energy of the deuteron (2.22 MeV):

$$\nu_x + d \rightarrow p + n + \nu_x - 2.22 \text{ MeV}. \tag{2}$$

Consequently, the SNO detector is capable of measuring the total solar neutrino flux from the ^8B spectrum. A comparison of the total flux obtained in a NC measurement to the electron neutrino flux obtained in a CC measurement (the NC/CC ratio) thus allows a model independent test of the neutrino oscillation hypothesis. A measure of the NC signal requires one to capture and count the number of free neutrons liberated in the heavy water. Techniques to extract the NC signal are discussed in section 4 below.

2.3.3 Elastic Scattering

The neutrino-electron elastic scattering (ES) interaction is sensitive to all neutrino flavors but the electron neutrino mode is ~6 times stronger due to the presence of both charged and neutral current channels.

$$\nu_x + e^- \rightarrow \nu_x + e^-. \tag{3}$$

The ES reaction is strongly forward peaked thus giving excellent directional information, and the capability to separate this signal from the CC and NC signals.

2.3.4 Charged Current with Electron Antineutrinos

A fourth reaction is possible in the SNO detector via the charged current interaction of electron antineutrinos (CA). While we do not expect electron antineutrinos to be produced in the sun, this reaction is unique with the emission of a fast positron (which creates Cerenkov light) in coincidence with two neutrons.

$$\bar{\nu}_e + d \rightarrow n + n + e^+ - 4.03 \text{ MeV}. \tag{4}$$

This reaction provides a unique signature for the study of atmospheric antineutrinos, cosmic relic antineutrinos, as well as the antineutrino content from a supernova burst.

2.3.5 Reaction Rates

The reaction rates anticipated for solar neutrinos in the SNO detector are outlined in Table 1. CC and ES rates are derived from the Bahcall SSM and assuming a detector threshold of 5 MeV for electrons. NC rates are listed as the total number of neutrons produced in the D_2O per kt-yr. A more detailed discussion of NC detection techniques and efficiency follows later in this paper.

3 Detector Response

3.1 Backgrounds

With signal rates of order 10 events per day, the SNO detector requires an extremely low background enviroment. Due to the depth of the SNO facility in the INCO mine, cosmic ray activity is negligible. Background radiation is thus dominated by any

Case	Charged Current	Elastic Scattering	Neutral Current
SSM	9750	1100	5000
Vacuum Oscillations	3260	480	5000
MSW (Adiabatic)	3750	645	5000
MSW (Non Adiabatic)	3750	488	5000
SSM/3	3250	366	1667

Table 1: The predicted event rates per kt-yr for an electron energy threshold of 5 MeV, according to the Bahcall SSM. NC rates are for the total number of neutrons produced in the D_2O by neutrinos with energy above 2.22 MeV.

naturally occuring radionuclides in the materials used to construct the detector and in the rock surrounding the detector.

The long lived isotopes, ^{232}Th and ^{238}U, are most troublesome since the beta and gamma activity will produce a background to the Cerenkov spectrum. At the bottom of these chains, the subsequent decay of ^{208}Tl and ^{214}Bi yield gamma rays above the binding energy of the deuteron, which can photodisintegrate the deuteron to yield a neutron that is indistinguishable from those created via the NC interaction of neutrinos.

Due to the large mass, the most stringent requirements on background fall on the D_2O, H_2O, acrylic vessel, and PMTs. Specifically, Th and U in the D_2O must be kept below the 10^{-14} level by weight in order that the backgrounds do not exceed $\sim$10% of the expected SSM signal rate. Owing to its smaller mass, tolerable levels in the acrylic vessel are $\sim 10^{-12}$ grams per gram. Since the PMTs are 2.5 m away from the D_2O, the β-γ activity is attenuated in the H_2O shield. To keep the background levels at a tolerable level, the PMTs are constructed of a low radioactivity glass with Th and U levels some 5 to 10 times lower than in standard glass.

3.2 Cerenkov Spectrum

Monte Carlo simulations have been performed to assess the performance of the SNO detector to various signals in the presence of backgrounds (see Fig.1). Below an electron energy threshold of $\sim$5 MeV the Cerenkov spectrum rises steeply (the Cerenkov background wall) due to β-γ activity internal to the D_2O and from events reconstructed within the acrylic vessel volume but original to the PMTs and support structure (PSUP).

An additional background associated with the NC interaction must also be considered, even in the presence of pure D_2O. Neutrons produced via the NC interaction of neutrinos on deuterium will subsequently capture on deuterium with the emission of a 6.25 MeV γ-ray. The subsequent shower is evident in the Cerenkov spectrum and is labeled as the NC signal in the presence of pure D_2O. This signal should be distinguished from the NC background mentioned above, which arises from the photodisintegration of deuterium by γ-emitters at the bottom of the Th and U chains.

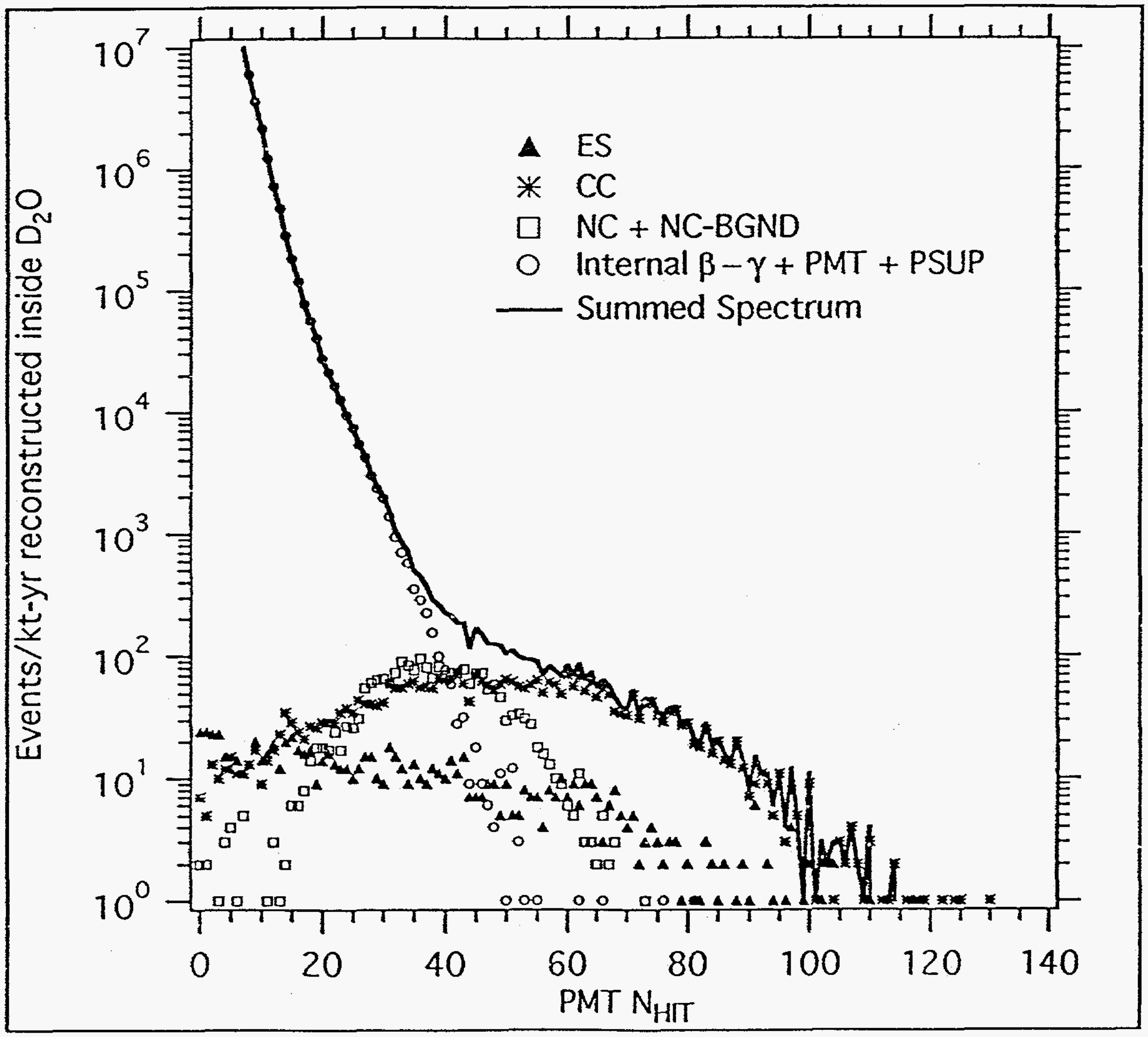

Fig.1 The Cerenkov spectrum anticipated for the SNO detector with pure D_2O. The simulation assumes a full SSM NC rate but a CC rate of 1/3 the SSM prediction. Events are shown that are reconstructed within the 6 m radius of the acrylic vessel in 1 kt-yr. The number of PMT hits (N_{HIT}) is proportional to the energy of the event where 48 N_{HIT} corresponds to an electron energy of ~5 MeV.

Perhaps the most subtle physical distortion in the shape of the CC spectrum arises due to the small angle or non-adiabatic (MSW) solution to the solar neutrino problem. This distortion would be most evident in the electron energy range between the low energy threshold of ~5 MeV and ~8 MeV (50 to 80 N_{HIT} in the Cernekov spectrum of Fig.1). It is clear that two considerations are of paramount importance in making a reliable extraction of the CC spectrum shape in SNO, namely :

(1) a detailed understanding of the detector response to electrons and photons extending over an energy regime from ~2 MeV to 14 MeV, and
(2) an *in situ* determination of the detector backgrounds in real time.

A variety of techniques will be exploited to monitor the background levels in the D_2O and H_2O shield, as well as in any additives deployed for a measurement of the NC interaction. A detailed understanding of the detector response will be made by exploiting a variety of calibration sources, a subject discussed in some detail below.

3.3 Calibration

Calibration of the SNO detector will be obtained by inserting a variety of sources at a variety of positions in the D_2O. These sources cover a wide range of signals to establish the optical properties and response of the SNO detector to relativistic electrons, γ-rays, and neutrons.

3.3.1 Optical Sources

Optical light sources in the form of an N_2 Laser-Ball will be used to determine the light attenuation and scattering in the D2O, H_2O and acrylic vessel. A second sonoluminesence source will offer optical light pulses (with a width smaller than 100 ps) which can be used to achieve accurate PMT timing calibrations.

3.3.2 β-γ Sources

Calibration sources emitting relativistic electrons and γ-rays will be exploited to understand the production of Cerenkov radiation in the D_2O and H_2O, as well as for understanding the detector response to the lower energy backgrounds in the SNO detector. It has been emphasized that detailed knowledge of both the background levels and the detector response is required in order to probe subtle distortions of the CC-shape that can be present for different neutrino oscillation scenarios.

Perhaps the most relevant source for solar neutrino studies is the proposed ^{8}Li β-decay source. With an endpoint energy of ~13 MeV, this source provides an ideal calibration for the CC spectrum. Furthermore, since ^{8}Li is the mirror nucleus of ^{8}B, information from this source will also allow one to assess uncertainties related to the theoretical shape of the ^{8}B neutrino spectrum [11].

At lower energies a ^{228}Th-plated proportional counter will provide 2.6 MeV γ-rays, an ideal source to study the low-energy background wall and photodisintegration of the deuteron. A ^{24}Na source will also provide both 1.3 and 2.7 MeV γ-rays which will be particulalrly useful as a low energy calibration as well as providing information on the response to internal β-γ backgrounds.

A ^{16}N source will provide β's and γ's for calibration at an intermediate energy range with a 6.13 MeV γ-ray and two β-decay branches with endpoint energies at 4.27 and 10.44 MeV, respectively. Calibration and response of the SNO detector can be obtained from such a source by exploiting the convoluted β-γ spectrum and the 10.44 MeV endpoint β-decay spectrum.

Two different (proton) accelerator sources are being developed to yield high energy γ-rays for calibrating the SNO detector above the ^{8}B endpoint. Such sources are also desirable in order to obtain calibration information for neutrinos in the event of a galactic supernova. A ^{3}H(p,γ)^{4}He source will provide 20 MeV γ-rays while the ^{7}Li(p,γ)^{8}Be reaction is a source of γ-rays at 14.2 and 17.3 MeV.

3.3.3 Neutron Sources

An excessive NC/CC ratio in SNO would provide a direct and model-independent proof of solar neutrino oscillations. Consequently, it is important to have calibration sources to determine the neutron capture efficiency in the SNO detector. Two such sources are being developed, namely a tagged ^{252}Cf fission source which produces an average of 4 neutrons and 20 γ-rays per fission, and a ^{17}N source with a β-n decay branch of ~95%.

4 Neutral Current Detection

Extraction of the total flux of ^{8}B neutrinos requires one to capture and count the neutrons that are liberated in the D_2O through the NC interaction on deuterium. A relatively straightforward approach is to dissolve ~2.5 tonnes of salt ($MgCl_2$) into the heavy water. Neutron capture on ^{35}Cl then provides an 8.6 MeV γ-ray which showers and produces Cerenkov light predominantly through Compton scattering.

Detection of the NC signal via Cerenkov light as described above means that the CC and NC signals are "backgrounds" to one another in the dissolved salt option. In the simplest sense, extraction of the CC and NC signals would thus require a detector running scenario with and without salt so that a subtraction could be performed. While significant progress has been made with respect to separating CC, NC, and ES signals using sophisticated pattern recognition techniques, an approach to deploy discrete neutral current detectors into the D_2O has also been proposed for the SNO detector [12].

In order to enable a simultaneous and independent measurement of the NC and

CC signals, a program to develop ^{3}He proportional counters for NC detection has now progressed into the production phase where some 800 m of such detectors will be constructed and deployed into the SNO detector. The use of ^{3}He proportional counters for neutron detection in nuclear and particle physics represents a well practiced art, however, to realize their feasibility as a NC detector in SNO has meant the development of many novel ideas. In particular, the main materials used in constructing the proportional counters will be produced from ultra-pure nickel formed using chemical-vapour deposition technology. After several years of research and development [13] to establish low radioactivity, mechanical, and electrical constraints the NCD project received capital funds for full scale construction.

As outlined in Table 1, the SSM predicts that ~5000 neutrons would be produced in the SNO detector per kt-yr due to the NC disintegration of deuterium. With a 5 MeV Cerenkov threshold in the dissolved salt option, some 2800 events would be available for analysis from neutron capture on chlorine. Due to the high capture cross-section on 3He, and the fact that D_2O is an efficient neutron moderator, a rather sparse array of discrete counters can still obtain rather high neutron capture efficiency. Specifically, an array of ~800 m of ^{3}He counters distributed in the D_2O with a 1 m lattice spacing will achieve about 50% capture efficiency to yield ~2500 events per kt-yr. The absolute efficiency for neutron capture in either running scenario will be determined using the neutron calibration sources described above.

5 Detector Construction and Schedule

Since the excavation and commissioning of a cavity in the INCO mine, construction of the SNO detector has met many significant milestones. Fig.2 depicts the present status of detector construction. With the upper hemisphere of the PSUP constructed and the PMTs installed and cabled, the upper hemisphere of the acrylic vessel is nearing completion. Upon completion, the acrylic vessel will be cleaned, covered, and hoisted into position with low radioactivity ropes where it will be bonded to the acrylic chimney extending below the deck. At this point construction will commence on the lower hemisphere acrylic vessel and PSUP.

During the physical construction of the detector itself, a number of other activities are in progress, including the development and fabrication of the electronics and data acquisition required to handle the signals and data flow of the 9800 PMTs, and the completion of the D_2O/H_2O water purification systems. In parallel with these activities, the SNO project includes another large scale program in the full-scale production of ^{3}He proportional counters for a neutral-current measurement.

Present projections call for the completion of the SNO detector at the end of February, 1997 with plans for a first D_2O fill towards the end of March, 1997. Studies in the initial phases with a pure D_2O fill will allow a determination of detector backgrounds and stability. The latter results will provide important guidance to the collaboration to make decisions on the running scenario for the SNO detector with respect to the extraction of CC and NC physics.

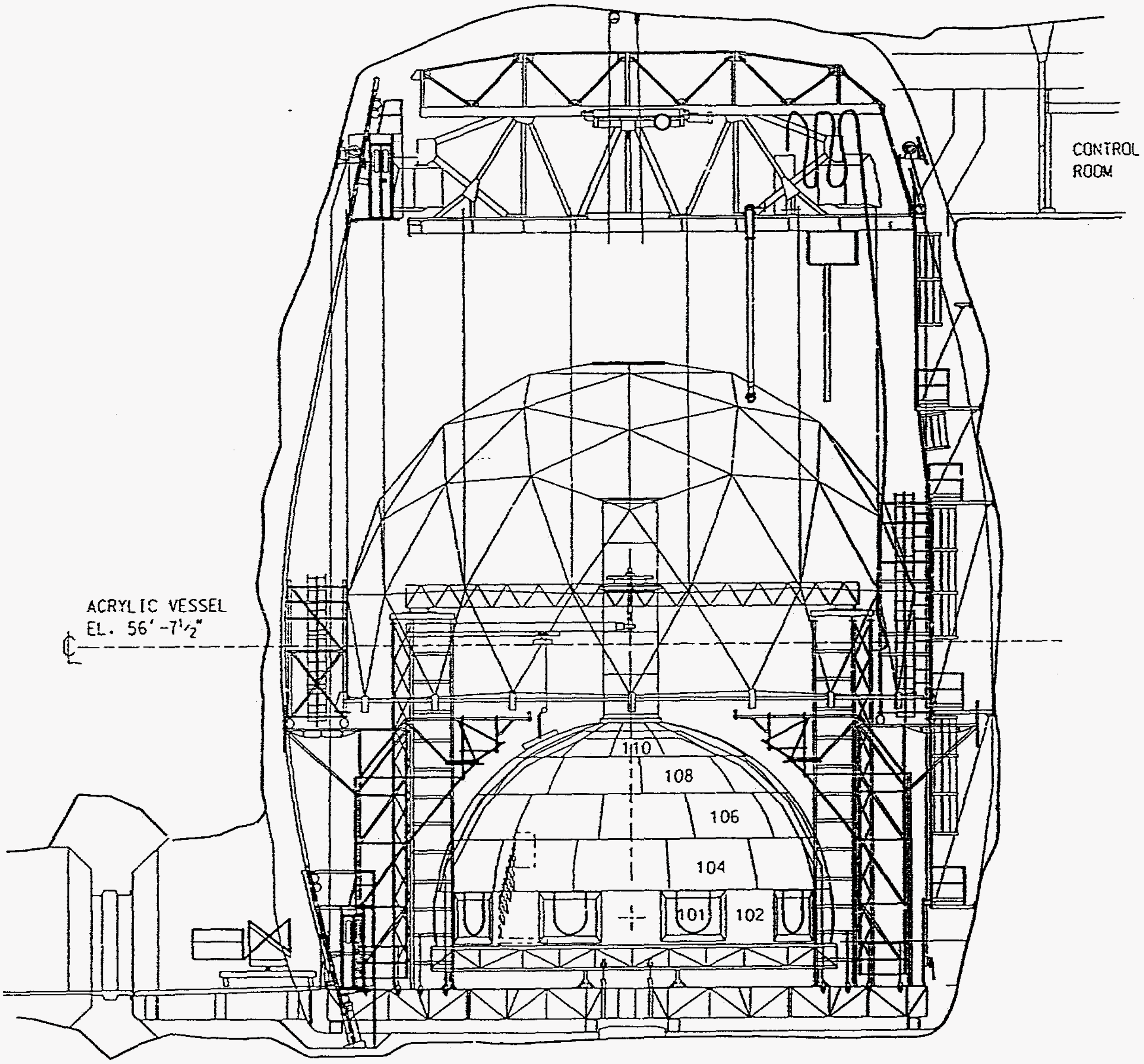

Fig.2 Engineering diagram depicting the present stage of SNO detector construction. With the upper hemisphere of the acrylic vessel under completion, it will be hoisted into place so that work can proceed on the lower hemisphere of the detector.

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