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NEUTRAL-CURRENT DETECTION IN THE SUDBURY NEUTRINO OBSERVATORY

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ABSTRACT

The Sudbury Neutrino Observatory (SNO) will have the capability of detecting all active species of neutrinos with energies greater than 2.2 MeV by the neutral-current disintegration of deuterium. The comparison of this rate with the rate of inverse beta decay of the deuteron will yield a nearly model-independent answer to the question of whether electron neutrinos from the sun oscillate into mu or tau neutrinos. The signal of a neutral current interaction is the liberation of a free neutron in the heavy water detector, and we discuss a technique employing ^{3}He proportional counters for registering these neutrons, particularly from the standpoint of the ultra low backgrounds needed.

1 INTRODUCTION

The Sudbury Neutrino Observatory (SNO) is a laboratory to study the properties of neutrinos and to resolve the "solar neutrino problem" [1, 2]. The heart of the detector is 1000 tonnes of 99.92% isotopically pure heavy water (D_2O) in a specially excavated chamber 2100 m below ground in the INCO Creighton nickel mine near Sudbury, Ontario.

Deuterium has unique nuclear properties that make it ideal for the study of neutrino interactions. There are four principal modes by which neutrinos can interact with heavy water:

$$d + \nu_e \rightarrow p + p + e^- - 1.44 \text{ MeV} \quad (CC : 9750 \text{ yr}^{-1})$$
$$d + \nu_x \rightarrow p + n + \nu_x - 2.22 \text{ MeV} \quad (NC : 5000 \text{ yr}^{-1})$$
$$d + \bar{\nu}_e \rightarrow n + n + e^+ - 4.03 \text{ MeV} \quad (CA : 0 \text{ yr}^{-1})$$
$$e^- + \nu_x \rightarrow e^- + \nu_x \quad (ES : 1100 \text{ yr}^{-1})$$
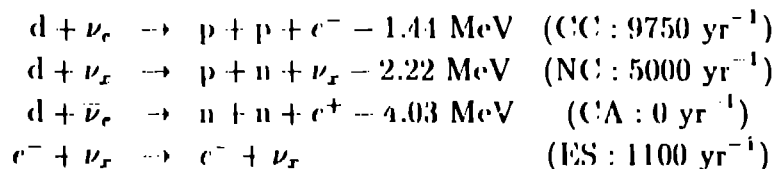
The first of these reactions proceeds by the charged-current (CC) interaction of electron neutrinos specifically. The second is the neutral-current (NC) disintegration of deuterium and can be initiated with equal probability by any of the left-handed neutrinos (ν_e, ν_μ or ν_τ) and their antiparticles. The third is the charged current interaction of electron antineutrinos (CA). The fourth is the elastic scattering of neutrinos (ES). While all flavors can scatter, the cross section for electron neutrinos is about 6 times that for other flavors as a result of the additional charged current channel. In the standard models of the sun (SSM; [3]) and of particle physics, only electron neutrinos are produced by the sun. However, if neutrino oscillations occur, then the neutrinos may reach the Earth as other flavors.

SNO therefore has the capability to reveal the presence of neutrino oscillations largely independent of solar properties. If the NC rate exceeds the CC rate (suitably normalized for cross sections), then neutrinos must be oscillating. If the CC energy spectrum differs from the known ^{8}B spectrum, then neutrinos must be oscillating via the MSW mechanism [4] or the Voloshin Vysotsky Okun' mechanism [5]. Unlike the kinematically convolved ES spectrum, the CC electron spectrum measured in SNO directly reflects the incoming ν_e spectrum (with quite good energy resolution) simply shifted down by 1.44 MeV.

SNO is a high rate experiment. The interaction rates listed with the reactions above are for a ^{8}B ν_e flux of 6×10^6 cm^{-2} s^{-1} and a detection threshold of 5 MeV electron kinetic energy (the NC threshold is the binding energy of the deuteron).

The Cerenkov light from charged current and elastic scattering events is detected in SNO by an array of 9,500 photomultipliers surrounding the acrylic sphere that holds the D_2O.

Neutral current interactions release a free neutron, and a number of strategies for detecting the neutron can be devised. One is to dissolve in the heavy water a fraction of a percent of chloride ion. When a neutron captures on 75% abundant ^{35}Cl, it emits an 8.6 MeV γ, which showers. The resulting Cerenkov radiation can be detected by the PMT array in the same way CC events are detected.

Another method, the one discussed here, is to detect the neutron in ^{3}He proportional counters dispersed in the heavy water so that the NC and CC events become completely distinct and no longer represent "backgrounds" to each other. Because of the central importance of SNO's neutral-current capability to the potential discovery of new physics, there are strong incentives to develop independent techniques.

2 ^{3}He DETECTORS FOR SNO

The use of ^{3}He proportional counters for neutron detection is a well-established technique that relies on the exothermic reaction,

$$^3\text{He} + \text{n} \rightarrow \text{t} + \text{p} + 0.764 \text{ MeV},$$
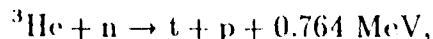
for which the thermal-neutron cross section is enormous, 5330 b. As heavy water is an excellent moderator, it is possible to distribute counters sparsely and still realize high capture efficiencies.

The planned arrangement for SNO is approximately 900 m of 5-cm diameter tubular detectors organized end-to-end in strings anchored to the bottom of the acrylic vessel on a square 1-m lattice. On average, 15% of the light from Čerenkov events is obstructed by the detector array, which somewhat degrades the energy resolution and increases the threshold.

2.1   THE SIGNAL

In the usual mode of operation of proportional counters, the total charge collected at the anode wire is converted to a voltage in a charge sensitive (integrating) preamplifier, and gives a measure of the energy deposited in the gas. More information than just the total charge is actually available, however. The primary ionization from a track drifts in and is multiplied over a period of time that depends on track length, track orientation, and the drift velocity. Thus the ionization density projected onto a plane perpendicular to the wire can be deduced from the current profile of the pulse. This information reveals a great deal about the event that created the track. An example is shown in Fig. 1. The ionization density peaks near the end of an α particle track (the "Bragg peak"). That part of the track arrives first at the wire, creating a sharp initial maximum in the current followed by a period of decreasing current terminating after 4 μs when the most distant ionization reaches the wire. The signal shown is the digitized output of a current preamplifier. (The total energy can be derived from the integral.) By contrast, the ^{3}He(n,p)T event displays the double peak produced by the back to back proton and triton tracks. Each event has a distinctive ionization "fingerprint." In the simplest analysis, the maximum drift duration of a ^{3}He(n,p)T event is 2.9 times that of an alpha of the same energy, and it is possible merely by sorting with respect to current pulse duration and total charge to obtain a subset of neutron events, more than 50%, that are completely free of α competition.
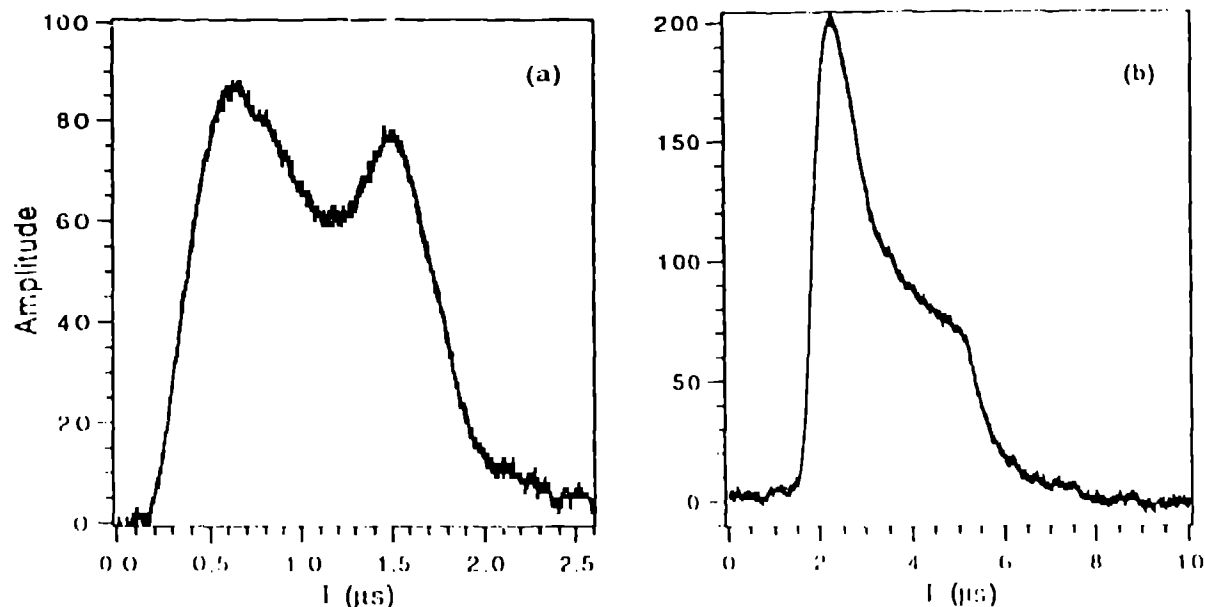
Figure 1: (a): Current pulse from ^{3}He(n,p)T event in a 30-cm proportional counter. (b): Pulse from 5.4 MeV α.

2.2 Efficiency

Monte Carlo neutron-transport calculations indicate that the counter array, filled with 3 atm of ^{3}He and 0.75 atm of CF_4, has a raw capture efficiency of 45% for neutrons generated in the 99.92% enriched heavy water.

2.3 Energy Resolution

Short counters with the ^{3}He — CF_4 gas fill have yielded 2.5% FWHM. However, gas gains must be restricted to values less than about 10 to avoid space charge effects with alphas, and electronic noise becomes a significant factor. Under actual running conditions (long cables, long counters, capacitor termination), a resolution of 10% is expected.

2.4 Wall Effect

For pure ^{3}He in a semi infinite detector, in 31% of captures, either the triton or the proton strikes the wall before the end of its range. The wall effect drops with the addition of an other gas, because the ratio of neutron capture range to charged particle range increases. The choice of CF_4 as an additive is motivated by its high stopping power, low Z, and good counting properties. In the 80:20 ratio selected, the wall effect is 18%. Wall effect events can be used since the spectrum is known, but the signal to background ratio is worse in that part of the spectrum.

2.5 Position Coordinate

Position information is required in order to reconstruct the radial distribution of events from NC interactions and from the acrylic-vessel background, as well as to establish connections between Čerenkov events and related neutrons (e.g., in the detection of $\bar{\nu}_e$ interactions).

To reduce the amount of material in the heavy water, to minimize interference with Čerenkov light, and to minimize the number of cables running through the neck of the vessel, a single-ended readout is highly desirable. A group at Nagoya University [6] has developed an ingenious solution which is essentially charge division, but in which the charge delivered to one end (the remote end) is stored in a capacitor to leak back into the line with a long time constant. Position information is derived from the ratio of charges in the fast and slow components, and can be extracted from the digitized pulse profiles.

In tests carried out at LANL on this method a position resolution of 1.6% FWHM was obtained. (The position-resolution requirements are modest, since the mean distance to capture is 113 cm.) Position readout by this technique can be combined with fast measurement of the current-pulse shape by adding a resistance in series with the termination capacitor. This effectively lengthens the detector electrically and allows pulse-shape information to be derived for the entire active length of the device.

3 BACKGROUNDS

At the design levels of radiopurity (4 pg/g maximum each of U and Th), the principal backgrounds are approximately 140 neutrons per year released in the heavy water by photodisintegration, and approximately 1000 α events from the walls of the detectors. To achieve these levels, the counter bodies will be constructed of pure Ni formed by chemical vapor deposition from $Ni(CO)_4$. [One sample of tubing made this way was assayed recently at 7.4(4) pg/g Th and < 0.8 pg/g U.] The photodisintegration background will be measured *in situ* from Čerenkov light produced by the 2.6 MeV and 2.44-MeV gammas at the bottom of the Th and U chains, while the alpha backgrounds can be determined directly from the spectra recorded in the counters. An additional source of alphas is ^{210}Pb deposited on the inner surface of the counter from radon, which sets a limit in the range 10 1000 hours for unprotected exposure to room air during construction.

4 STATISTICAL CONSIDERATIONS

The possible presence of MSW distortions (and possible time variations therein) in the CC spectrum make it prudent to avoid assumptions about the shape of that spectrum In that case, the CC spectrum must be derived by subtraction of all non CC contributions, and the statistical advantages of separate detection of NC and CC interactions are self evident.

Assume a detected CC rate of C per year, a detected NC rate of N per year, and a detected neutron background rate of B per year. A likely running scenario would be t_1 years with pure D_2O, followed by t_2 years with salt or ^3He counters for a total of t years. Defining the fractional precision in quantity i as σ_i, for the ^3He method, one has:

$$\sigma_C^2 = \frac{1}{Ct}$$

$$\sigma_N^2 = (1 + \frac{B}{N})^2 \frac{1}{(N+B)t_2} + (\frac{B}{N}\sigma_B)^2,$$

Then the fractional precision in the ratio is:

$$\sigma_R = (\sigma_N^2 + \sigma_C^2)^{1/2}.$$

With the salt technique, statistics for CC alone are accumulated only to the end of interval t_1:

$$\sigma_C^2 = \frac{1}{Ct_1}.$$

Thereafter, statistics accumulate in the sum N + C = T:

$$\sigma_T^2 = (1 + \frac{B}{T})^2 \frac{1}{(T+B)t_2} + (\frac{B}{T}\sigma_B)^2$$

$$\sigma_R = (\sigma_T^2 + \sigma_C^2)^{1/2}$$

The ratio (N+C)/C must be determined approximately twice as accurately to achieve a desired precision in the ratio N/C, as illustrated in Table 1. For these calculations, B $= \eta(1176 + 294[\text{salt}]$ or $140[^3\text{He}])$ and $\sigma_B = 0$ (σ_B represents additional, non-statistical sources of error; η is the neutron detection efficiency).

Table 1: Fractional precisions needed in SNO for a 5-σ demonstration that, when the SSM flux is present, 1/3 is ν_e, and 2/3 ν_μ or ν_τ.

Method	η	N	C	N/3	Data Ratio N/C or T/C		
					No Osc	SSM + Osc	For 5σ
^{3}He	0.4	2000	2200	667	0.303	0.909	σ_R 14.7%
Salt	0.5	2500	2200	833	1.379	2.136	σ_R 7.1%

The foregoing equations are illustrated graphically in Figure 2, with t_1 0.5 years. The necessary precision for a 5 σ effect is achieved very rapidly in both cases. After one year total the salt and ^{3}He methods achieve 10 and 19 σ significance, respectively.

The magnitude of any photodisintegration background present must be determined by some auxiliary measurements. For example, if the heavy water contains 11 fg/g each of Th and U, and 2.5 tonnes of added NaCl contains 1 pg/r each of those isotopes [7], then the detected background neutron rate is B $\eta(1176 + 294)$ per year above 6 MeV, to be compared to the SSM rate of N $\eta(5000)$. If the background can be determined to a precision of only 50%, then the ^{3}He and salt methods become dominated by that uncertainty, and differ little in their ultimate statistical precision (in this rather pessimistic example, still a 5 σ effect after a year).

As described, the ^{3}He counters also in general have a continuous α background un derlying part of the neutron capture spectrum. If the fraction of events free of alpha
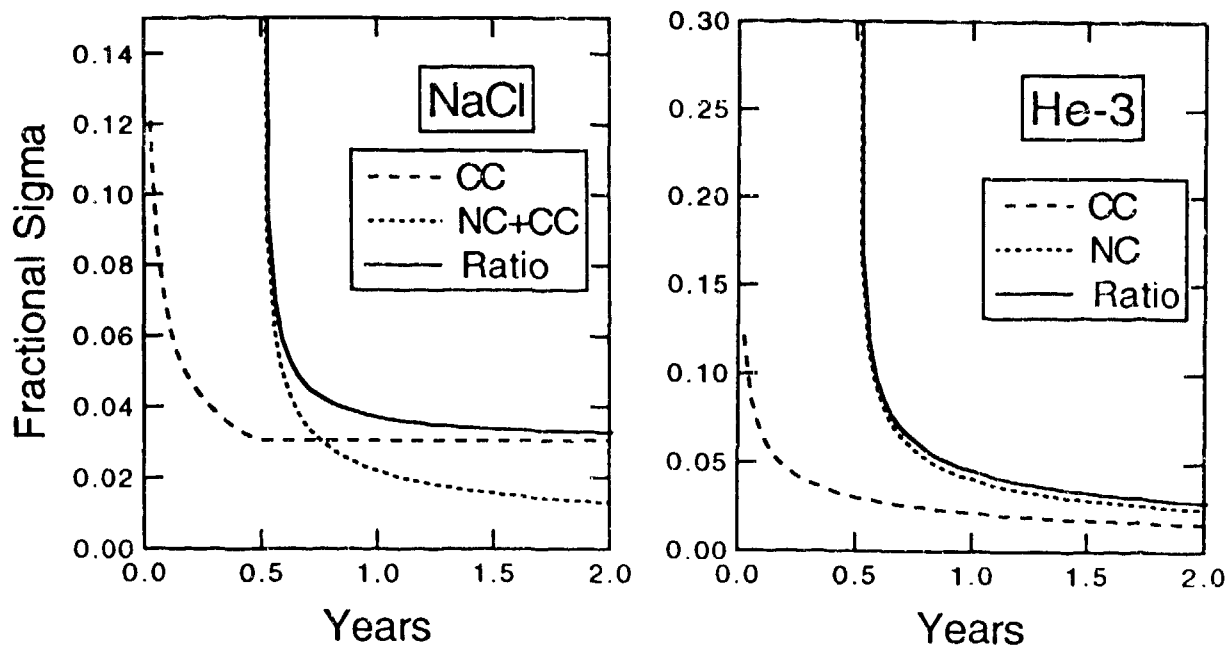
Figure 2: Statistical precisions in experim ts starting with 6 months of pure D_2O followed by installation of either salt (left) or ^3He counters.

background is f and the ratio of the alpha rate (after energy cuts) to the total neutron rate (including photodisintegration neutrons) is α, then it may be shown that

$$\sigma_N^2 = (1+\frac{B}{N})^2 \left\{ \frac{1}{(N+B)t_2} \left(\frac{1-f+\alpha}{1-f+f\alpha} \right) + \alpha^2(\Delta f)^2 \left(\frac{1-f+\alpha(2f-1)}{1-f+\alpha} \right)^2 \right\} + (\frac{B}{N}\sigma_B)^2,$$

where Δf is the uncertainty in f. The value of f is of order 0.5. The effects of alpha backgrounds are minor as long as $\alpha \lesssim 1$.

5   CONCLUSION

The value of a measurement of the neutral-current interaction rate of solar neutrinos in distinguishing astrophysical and particle physics solutions to the solar neutrino problem cannot be overstated. Analysis and measurements of neutron-detection efficiencies and backgrounds indicate that SNO will be capable of detecting the neutral-current process with good efficiency and low backgrounds. Two quite different approaches, dissolved salt and ^3He proportional counters, will be used as a check on systematic effects. The latter approach has the desirable feature that NC interactions will be distinguishable event by event from other types of interaction.

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