SOLAR NEUTRINO NEUTRAL CURRENT DETECTION METHODS IN THE SUDBURY NEUTRINO OBSERVATORY

C. K. Hargrove
National Research Council of Canada, Ottawa, Ontario
and
D. J. Paterson
Carleton University, Ottawa, Ontario

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ABSTRACT

The SUDBURY NEUTRINO OBSERVATORY *(SNO)* will study the Solar Neutrino Problem *(SNP)* through the detection of charged current (CC), neutral current (NC), and elastic scattering (ES) interactions of solar neutrinos with heavy water. The measurement of the NC rate relative to the CC rate provides a nearly model independent method of observing neutrino oscillations. This difficult measurement is therefore a critically important aspect of the experiment. The NC interaction breaks up the deuteron producing a neutron and a proton. Its rate in the nominal design is measured by observing Čerenkov light from showers produced by neutron capture γ rays from the capture of the NC neutrons by a selected additive to the heavy water. These signals from the neutron capture γ ray showers overlap the CC and ES signals and are indistinguishable from them. Therefore the measurement of the NC rate requires a complicated subtraction of two low statistics signals. In this paper we describe the investigation of an alternate detection method in which the thermalized NC neutrons are captured by (n,α) or (n,p) reactions on light nuclei. The resulting charged particle products are uniquely detected by scintillators or proportional counters, completely separating this NC signal from the CC and ES Čerenkov signals and thereby simplifying its measurement, improving its significance and allowing observation of otherwise unobservable short term NC fluctuations. The method is described and its implications for the NC measurement are discussed.

INTRODUCTION

A deficit in the measured flux of solar neutrinos relative to predictions was first observed at Homestake by Davis *et al.* [1] and more recently confirmed at Kamiokande II by Hirata *et al.* [2]. These detectors are sensitive to only the highest energy solar neutrinos, detecting primarily electron neutrinos (ν_e) from the decay of ^8B. Results from both detectors are consistent, reporting that the high energy ^8B flux is less than half that predicted by the Standard Solar Model (SSM) of Bahcall & Ulrich [3]. A new generation of solar neutrino detectors are being proposed or are under construction [4]. One of these is the SNO detector [5]. It is a copy of the successful H_2O Čerenkov detectors [2,6] with the sensitive medium changed to 1 kilotonne of D_2O. The D_2O will be contained in a spherical acrylic vessel, and surrounded by H_2O to shield against backgrounds. Photomultiplier tubes immersed in the H_2O will detect Čherenkov light from the interactions. The detector site will be excavated at the 6800' level of INCO's Creighton nickle mine near Sudbury, Ontario.

The use of D_2O will allow SNO to observe CC, NC, and ES reactions with solar neutrinos. The CC reaction is just the inverse β decay reaction of the solar ν_e on the neutron of the deuteron. The ES reaction is the elastic scattering of neutrinos off the electrons of the D_2O. The NC reaction disintegrates the deuteron producing a proton and a neutron. Since the cross section for this latter reaction is independent of neutrino flavour, a difference in the calculated flux of neutrinos from the measured rates of CC and NC reactions would imply a significant flux of solar ν_μ or ν_τ, and provide definitive evidence of neutrino flavour oscillations and massive neutrinos. The measurement of the NC rate is therefore of crucial importance to our understanding of the nature of neutrinos and their weak interactions. It is also an independent check of the total neutrino flux from the sun.

The NC reaction $\nu_x + d \rightarrow \nu'_x + p + n$ occurs for solar neutrinos having energies in excess of the deuteron binding energy (2223 keV). In the SNO detector, this reaction rate is predicted [5] to be 6380 per kilotonne-year assuming the SSM neutrino flux [3]. The ^8B solar neutrino kinetic energy endpoint of 15 MeV will result in a total recoil energy endpoint of 12.8 MeV. Since protons of such low energies will produce little signal, detection of NC events can only occur through neutron capture.

The currently planned NC detection method would look for the Čerenkov light from electrons in the showers produced by neutron capture γ rays from capture by the deuterium of the D_2O or from selected additives. The light from these γ rays would be indistinguishable from the light from the CC and ES interactions. The NC measurement therefore requires careful subtraction of two signals of similar energy with relatively low statistics.

In this paper we propose another method. The neutrons would be captured on light nuclei which have very large neutron capture cross sections and charged reaction products in the final state. Such a process can be considered because of the long mean free path of the neutron in the D_2O. The

large cross section ($\sim 1000b$) means that one needs only a small amount of the element to capture a significant fraction of the neutrons. The charged particles in the final state allow the NC signal to be detected in scintillators or proportional wire chambers. Since these signals will be unique, NC event detection could then be completely separated from the CC and ES reactions, improving the quality of the NC measurement.

This paper will discuss NC detection methods in section II, Monte Carlo simulations in section III, detecting element composition in section IV, detecting element purity in section V, and statistical analyses in section VI and give the conclusions in section VII. Potential capture nuclei and scintillation materials will be addressed in the body of these sections.

II NEUTRAL CURRENT DETECTION METHODS

i The Capture γ-ray Detection Method (CGRD)

The currently favoured NC detection method for SNO (called in this paper the Capture Gamma Ray Detection Method) relies on the detection of the shower produced by the neutron capture γ rays which result from capture of the NC neutron on suitable target nuclei added to the D_20. Depending on the choice of additive, the maximum energy of the γ rays is about 8 MeV. The γ rays will convert into a shower made up of a large number of lower energy electrons. These electrons will produce Čerenkov light which can be detected in the photomultipliers of the SNO detector.

A survey of neutron capture nuclei was made and three likely candidates were identified [5]. These are the deuterons of the D_2O itself, gadolinium, and chlorine. The first has a capture probability of 24% for neutrons born in the D_2O volume and gives a 6.25 MeV γ ray. The other two can be introduced in sufficient quantity to capture more than 80% of the neutrons.

Over 81% of neutron captures in natural gadolinium would occur on ^{157}Gd, resulting in 7937 keV being released in an average of 3.4 capture γ rays. Only 46.5% of the primary capture γ rays have $E_\gamma \geq 5.0\ MeV$ (36% have $E_\gamma \geq 5.5\ MeV$) [7], with the balance of the energy distributed over the γ rays from the balance of the cascade. (Secondary γ rays all have $E_\gamma \leq 2.2\ MeV$.)

In natural salt, over 98% of neutron captures occur on ^{35}Cl, resulting in 8579 keV being released in capture γ rays. Over 57% of the primary capture γ rays from salt have $E_\gamma \geq 5.0\ MeV$ (55% have $E_\gamma \geq 5.5\ MeV$) [8], and consequently fewer low energy secondary capture γ rays are emitted in the cascade. The higher energy Cl capture γ rays generate a shower containing more electrons which have energies above the Čerenkov threshold, and therefore more Čerenkov light results from the Cl capture γ rays than from the Gd capture γ rays. Since this produces a better signal to background ratio, NaCl is currently the favoured detection material [5].

The CGRD chain has a number of difficulties. These include:

1. The energy detected from a NC event will typically overlap the spectrum of energies of the CC and ES signals and be indistinguishable from them. This means that the NC signal can only be extracted by a series of complicated subtractions.

2. The detection efficiency for NC events is inherently limited to near 50% because of the SNO detector's high threshold relative to the capture γ ray energy, required to eliminate background events.

3. The materials have to be dissolved in the 1,000 tonnes of D_2O and subsequently removed in order to return to taking CC measurements. Removing the material from 1,000 tonnes of D_2O will be difficult, time consuming and expensive.

4. A serious drawback of the planned measurement method is the need to make sequential CC and NC measurements. A statistically significant CC measurement will require a full year of data taking with a neutron absorber added to the D_2O in order to suppress the NC signal. After filtering out the neutron absorber, perhaps another year of data taking will be required to collect statistically significant NC results. Short to medium term variations in CC and NC rates will not be separately distinguishable. Potentially relevant data separating seasonal flux variations or short term variations associated with sun spot cycles for neutrinos of different flavours may be lost.

ii Charged Particle Detection Method(CPD)

The search for a better detection method has led us to consider light nuclei with high thermal neutron capture cross sections, which emit charged particles following neutron capture (called the Charged Particle Detection Method). The two necessary conditions for this technique are a high neutron capture cross section which allows the use of a small amount of material to absorb the neutrons, and charged particle products which are uniquely observable using standard particle detection techniques. The CPD method makes it possible to separate the NC events from the CC and ES events. Three suitable nuclei, ^3He, ^6Li, and ^{10}B, with cross sections of the order of thousands of barns and charged particle emission energies of the order of MeV, are known to exist. For detection methods we have considered scintillation methods, gas counter, and solid state counter techniques. The CPD method would have the following advantages and disadvantages for detecting NC neutrons.

1. Since the neutron capture cross section in pure D_2O is a fraction of a millibarn, the increase in cross sections for such a charged particle emitting nucleus is a factor $> 10^6$. Therefore about a millionth of the capture agent (ie kilograms) will be required to capture the same number of neutrons as the D_2O and its additives.

2. Since the charged products of these reactions have energies of the order of MeV, one can detect them either in scintillators or gas counters. This will provide a signal which is completely distinguishable from the CC and ES Čerenkov light eliminating the necessity of making tedious sub-

tractions.

3. The elements of such a detecting system are solid and can be introduced and removed easily and quickly, thus allowing elimination of the difficult and time consuming removal of the additives from the D_2O.

4. Since the NC signal would be independent of the other signals, one could separately monitor short term variations of the NC and CC signals, which makes possible analyses of short to medium term variations in the relative rates.

One obvious difficulty of the CPD method is its sensitivity to radioactive contaminants in the materials themselves. In both the scintillation and the proportional counter methods, radioactive contaminants in their materials will produce signals comparable with that of the NC neutron capture signal. This is to be compared with the CGRD method where direct backgrounds from radioactive materials are below the thresholds of the SNO detection system. Therefore the purity of the materials must be greater for the CPD method than for the CGRD method.

Another potential drawback of the CPD method is the longer neutron capture mean free path as a result of the smaller amount and discrete nature of capture material. This longer mean free path, and hence poorer spatial resolution may reduce the ability of the CPD method to distinguish the NC neutrons produced uniformly in the D2O, from the background neutrons which are produced preferentially around the outside of the D2O by external background γ rays. This is expected to be only a small drawback.

The above mentioned advantages are so attractive that we have decided to study the implementation of this method in enough detail to estimate its feasibility. In this paper we report the details and early results of this study.

III MONTE CARLO SIMULATION

A Monte Carlo program has been written to simulate the neutron capture process in the SNO detector for both the CGRD and the CPD methods. In this program the incident ^8B neutrino energy spectrum is simulated and neutrons produced by their NC interaction with the D_2O are generated uniformly throughout the D_2O, thermalised, and scattered. Probabilities are calculated for the neutron's capture in detectors, in water and its additives, and for its escape from the D_2O. The program is able to simulate the addition of various solutes to the D_2O, and to allow for location of absorbing elements of simple geometries in a regular matrix. Appropriate values of the capture and scattering cross sections are employed for the D_2O with or without additives, while the detecting element neutron mean free path can be defined as appropriate for the detector materials employed.

This Monte Carlo program has been used to calculate the neutron capture probabilities for deuterons, gadolinium, and chlorine additives in SNO. The results agree with those of other calculations of the SNO collaboration [9], and with other analytical and numerical [10] estimates of neutron capture probabilities for discrete detecting elements, thus confirming the accuracy of the routines. It has been used to determine the optimum mass, shape, and spacing of discrete neutron absorbing elements, and the photon losses on insertion of the elements, as discussed in the balance of this paper.

IV DETECTING ELEMENT COMPOSITION

The only three stable isotopes with sufficiently high thermal neutron capture cross sections and with final state charged particles are ^3He, ^6Li and ^{10}B. The details of their reactions are given in Table I. The use of these isotopes for neutron capture, in conjunction with appropriate charged particle detection materials, is analysed below.

i ^3He

^3He has the largest cross section of the three alternatives (5327 b) and therefore warrants consideration even though it is a noble gas and has the lowest Q-value (0.77 MeV). There are two possible ways of implementing the CPD method using ^3He.

The ^3He gas is itself a scintillator [11]. However, the low energy of the proton resulting from the neutron capture and the need for the use of wavelength shifters to move the light into a detectable spectral range make this method of detection less promising.

It is also a reasonable counting gas and hence the introduction of ^3He proportional counters into the D_2O is an interesting possibility. The Monte Carlo simulation has shown that 35 g of ^3He at 1 atm arranged in 2.1 cm diameter tubes on a 1.0 m grid is sufficient to capture 25% of the neutrons produced. The neutron mean free path in the gas of the tubes is $\lambda = 7.009\ cm$. Detailed studies of this method of detection are being carried out by SNO collaborators from Los Alamos Scientific Laboratories (LASL), see Bowles et al [10].

The gas containment and high voltage electrode materials of the detecting elements will contribute additional mass in this method. Material purity requirements for the containment vessel will be more stringent than for the ^3He alone, since there will be approximately 3 kg [10] of containment materials within the range of the spectrum of α and β backgrounds in those materials. This method shows promise of being the NC detector of choice for SNO.

ii ^{10}B

The ^{10}B scintillating alternatives are impractical largely due to their low light yield in the sensitive range of the photomultiplier tubes. The light emitted by borated organic scintillators, for example, would not be well separated from the 1200 to 1400 Čerenkov photons emitted by a 10 MeV β particle from a CC event. On neutron capture, ^{10}B would release 2.3 MeV (93% branch) into the scintillator via its α and ^7Li reaction products. Allowing for a large pulse height defect [11] for heavy particles (eg. a factor of 20 for these α, ^7Li products), fewer than 1200 photons will be produced by a typical organic scintillator having an efficiency 65% that of anthracene.

Proportional tubes containing $^{10}BF_3$ are commonly used for neutron detection. However only a small amount of Boron can be used in the tubes because the $^{10}BF_3$ has a strong affinity for electrons in the gas, thus killing the signal if it is included in the counter in large amounts. While lower pressure would reduce this effect, larger and more massive counters would be required and the benefits would be lost.

iii ^6Li

Lithium is to our knowledge not used in proportional counters and we have therefore only considered the scintillation and solid state counter options. Loaded scintillator combinations which have been considered for lithium include ^6LiI, ^6Li loaded cerium activated glass, ^6Li dispersed in ZnS, and liquid scintillators loaded with ^6Li. Other interesting options include a thin foil of ^6Li sandwiched between scintillators, solid state counters, or proportional chambers. These sandwiches would let one detect the coincidence between the α and the triton, thereby allowing one to distinguish between the signal and the background.

Lithiated organic scintillators have not generally been successful. Loading levels tend to be low in order to minimise quenching, leading to larger overall scintillator masses in order to achieve the same neutron capture probabilities as compared to other alternatives.

Lithiated inorganic scintillators give good hope of achieving high neutron detection efficiency. They present a challenge, however, in reaching sufficiently high purity levels to achieve acceptable signal to background ratios. The charged decay fragments of uranium and thorium chain daughters largely overlap the signal produced from ^6Li on neutron capture. Lithium loaded cerium activated glass displays background activity rates many times the tolerable level for this detector. Of the scintillators and loading elements mentioned above, then, the most practical choices appear to be ^6Li loaded ZnS, ^6LiI, or the ^6Li foil sandwich alternatives.

a) ^6LiF in $ZnS(Ag)$

Neutron capture in compounds of ^6LiF, $ZnS(Ag)$, and a lucite carrier in the ratio 1:2:1 (wt.) have been analysed and reported in the literature [11, and references within]. High efficiencies (relative to NaI) have been reported together with good γ ray discrimination (10^{-3} or better). Light yields as high as 188,000 photons on neutron capture have been reported [12] for such compounds. Zinc sulfide attenuates the light signal at a thickness greater than 25 $mg\ cm^{-2}$. At this thickness, the probability of capturing incident thermal neutrons in such a ^6LiF:$ZnS(Ag)$ compound will be 15%. Thin acrylic plates or disks containing ^6LiF loaded ZnS are therefore envisaged. The scintillation light signal from the 4.76 MeV given to the alpha and triton by the neutron capture on the ^6Li will differ from the Čerenkov light of other types of events in several ways. It will be isotropic, and the amount of light generated in the spectral range of the photomultiplier tubes will greatly exceed the signal from the ES and CC Čerenkov events and it will have fast and slow decay components of 0.1 μsecond and 1 μsecond respectively [11].

With such a strong light signal, negligible photon losses in the D_2O, and 75% photocathode coverage of the SNO fiducial volume, there will be a high multiplicity of photomultiplier tubes detecting each event.

The Monte Carlo simulations indicate that in order to achieve 25% capture of thermal neutrons on the proposed detecting elements immersed in a one kilotonne sphere of 99.85% D_2O, 9.71 kg of $^6LiF{:}ZnS$ would be required. The detecting element geometry simulated was 0.006 cm thick by 2.9 cm square elements on a 25 cm cubic lattice. These elements would have a mean free path for incident neutrons of $\lambda = 0.037cm$.

b) ^6LiI

With suitable encapsulation, ^6LiI crystals are also promising, achieving neutron blackness near a thickness of 2 mm. The scintillation efficiency of $^6LiI(Eu)$ on neutron capture is reported [12] to be 12 times that of ^6Li loaded, cerium activated glass. The light yield on neutron capture in $^6LiI(Eu)$, by comparison with the yield of such glass [11], is expected to be 57% of that from $^6LiF{:}ZnS$, or 108,000 photons. The use of Sm as the activator may reduce the scintillation light decay time from the 1.4 μseconds typical of $LiI(Eu)$ to 0.25 μsecond, at a small (12%) reduction in light yield [11]. Crystals of ^6LiI are hygroscopic, but proper encapsulation should provide reasonable moisture protection.

Monte Carlo simulations indicate that in order to achieve 25% capture of thermal neutrons on the proposed detecting elements immersed in a one kilotonne sphere of 99.85% D_2O, 38.7 kg of ^6LiI would be required, given a detecting element geometry of 1 mm diameter by 23.5 cm long tubes on a 25 cm cubic lattice. (A geometry similar to that proposed for the $^6LiF : ZnS$ discussed above would require a smaller amount of LiI, but would present a greater surface area for moisture permeation into the scintillator.) The neutron capture mean free path in this material is $\lambda = 0.058cm$.

c) ^6Li Foil Sandwich

Other options which are of interest include the use of scintillators, solid state counters, or proportional counters sandwiched about a thin foil of ^6Li. The $^6Li(n,\alpha)t$ reaction produces a 2.04 MeV α particle and a 2.72 MeV triton, which are emitted back to back. Therefore a ^6Li foil sandwiched between two counters could uniquely detect this reaction by observing coincidences between the two particles. This method would improve discrimination against background α's in the bulk of the counters since such backgrounds would produce only α signatures in one half of the sandwich. Bulk material purity requirements might therefore be relaxed. We are actively studying this possibility.

iv Discussion

The options investigated in this section are summarised in Table II. In this table we list the detector composition, required mass, purity, volume and geometric configuration used in the Monte Carlo calculation. The purity requirements shown include consideration of the necessary acrylic carrier or enclosure materials, and are based upon the sum of the masses of the detection materials and the enclosing acrylic which is within α-particle range of the scintillator. It is apparent from this table that the amount of material in the CPD detectors is relatively small, and therefore possible in a practical case.

a) Event Analysis

The long scintillation light pulses of these lithiated inorganic scintillators will not increase the possibility of false signals resulting from random photomultiplier tube noise. A reliable event trigger can be composed, since there will be a great multiplicity of photomultiplier tubes providing signals during each event. The random coincidence rate will be predictable once final design decisions are made regarding the number of photomultiplier tubes and their random noise rates. The number of photomultiplier tubes which constitute an event trigger can then be set above the level which would present any significant probability of random coincidence. Event reconstruction can be accomplished through analysis of hit distributions and arrival times at detecting tubes. Photon arrival times as a function of photomultiplier tube position, hit distributions, and scintillator decay time can be employed to determine the event origin with reasonably good accuracy, through the use of numerical fitting routines.

b) Capture Distribution

The Monte Carlo simulations indicate that, at 25% neutron capture efficiency, neutrons will be captured on detecting elements with a mean displacement of 2 metres from their birth location, though they experience a 130 metre random walk between birth and capture. This is to be compared with a 10 metre random walk in the CGRD method using the Gd or NaCl additives, where the greater neutron capture efficiency yields 50% detection efficiency but with similar measurement uncertainty. With such a long mean distance to capture, it is apparent that such detectors cannot fully replace the CGRD method since the reduced spatial resolution will result in reduced separation of the background neutrons produced by external γ rays peaking near the outside of the D_2O sphere, from the signal neutrons which are uniformly distributed through the volume. Distinguishing this background at such low detection efficiency may require temporary concentration of the detecting elements near the surface of the sphere, or alternatively require the addition of the NaCl or Gd while making this measurement. Additional elements could be added if higher detection efficiency is desirable and they would overcome any loss in resolution.

c) Signal Loss Due To CPD Elements

The Monte Carlo simulations also indicate a probability that such detecting elements will intercept Čerenkov photons, or photons from other scintillating elements at the rates of 5%, 7%, and 4% respectively for the ^3He, $^6LiF{:}ZnS$, and ^6LiI detecting element geometries discussed. In each case the loss of signal due to insertion of the elements is small.

V DETECTING ELEMENT PURITY

Substantial efforts are directed at minimising sources of background contamination throughout the SNO detector. Contaminants of greatest concern are the isotopes in the ^{238}U and ^{232}Th chains. Purity requirements are most stringent for the water, at 10^{-14} to 10^{-15} g/g uranium and thorium (secular equilibrium assumed) and with the acrylic vessel surrounding the D_2O at 10^{-12} g/g. For detecting elements where all contained α and β particle emissions will be directly registered in the elements, a 1 d^{-1} background rate would result from as little as 67pg of ^{238}U or 280pg of ^{232}Th, again assuming secular equilibrium.

In the case of ^{6}LiI scintillators, it is reported [13] that the signal resulting from neutron capture is larger than that from background α's of similar energy, due to the difference in pulse height defect for the triton versus that for the α. As well, energy resolution was reported at 7%. Considering background α's originating from the ^{238}U and ^{232}Th chains, a number of background events will be observed in rapid succession (eg. $^{224}Ra \rightarrow {}^{220}Rn$ (56s) $\rightarrow {}^{216}Po$ (0.14s) $\rightarrow {}^{212}Pb$). These facts can be used to discriminate against much of the ^{238}U and ^{232}Th decay chain activity of contained contaminants.

Other charged particle emitting contaminants must be considered as well, notably ^{40}K, with a half life of $1.3 * 10^{9}$ yrs., 0.0118% natural abundance, and an 89.3% branching ratio to energetic β's. A 1 d^{-1} rate will result from 80pg of ^{40}K, or 0.7μg of natural potassium.

These amounts of natural potassium, ^{238}U, ^{232}Th require impurity concentration limits for ^{3}He of $2 * 10^{-8}$ g/g, $2 * 10^{-12}$ g/g, and $8 * 10^{-12}$ g/g respectively. Similar background contributions will be seen from these same contaminants in $^{6}LiF{:}ZnS$ at $\frac{1}{300}^{th}$ of the above levels, or in ^{6}LiI (considering background discrimination methods discussed above) at $\frac{1}{100}^{th}$ of the above levels, given the geometries and masses discussed above.

VI STATISTICAL ANALYSIS

In this section we show that with a much smaller neutron capture probability for the CPD method (about 25%) than for the CGRD method (about 83%) we can achieve the same statistical accuracy in the measurement of the NC rate. This is possible because all neutrons captured through the CPD method are observed due to the strong light signal, while for the CGRD method event detection efficiency is reduced from the neutron capture efficiency as a result of the intrinsic efficiency of the SNO detector for Čerenkov light. As well, the CPD method is independent of the CC and ES signals, which removes the necessity of making subtractions of a relatively small number of statistically equivalent signals. In doing these calculations, we have included our best estimates for the backgrounds to the two methods.

The results are given in Table III. The SNP has had two popular explanations. The first is that there are neutrino flavour oscillations, in which case the NC signal may be up to three times stronger than that predicted by the CC signal. The second is that the SSM is wrong, in which case the NC signal would be that predicted by the measured CC rates. Therefore in the table we have given the statistical analyses for these two cases, without assuming improved confidence in the results based upon the shape of the observed spectrum relative to expectations. Columns 2 and 3 give the rates and the errors for the SSM case assuming flavour oscillations while columns 4 and 5 give the same numbers on the assumption that the SSM is wrong. The top half of the table gives the numbers for the CGRD method while the bottom half of the table gives the results for the CPD method.

Neutron background to the NC signal is predicted to be 2167 events per kilotonne year $(kt - y)^{-1}$ [5]. One major source of NC background is photodisintegration of deuterons by γ rays from sources external to the D_2O, such as the surrounding rock, photomultiplier tubes, support structures, and acrylic vessel. Such sources will contribute 30% of the total background [14], and this will be distinguishable by the high concentration of neutrons near the surface of the D_2O sphere. External background sources will therefore contribute about 325 events per kilotonne year $(kt - y)^{-1}$ in the CGRD case (50% detection efficiency), or about 163 events $(kt - y)^{-1}$ for the CPD method at 25% detection efficiency.

The other source of background neutrons is photodisintegration caused by γ rays from contaminants internal to the D_2O, particularly from ^{208}Tl (2.4 MeV) and ^{214}Bi (2.6 MeV) which are produced in the ^{232}Th and ^{238}U decay chains respectively. This background will not be distinguishable from true NC events and the magnitude of this background will be known based only on measurements of the purity of the D_2O. For the CGRD method, this will contribute a background rate of about 758 events $(kt - y)^{-1}$ while in the CPD case, this background will contribute about 379 events $(kt - y)^{-1}$. A large systematic uncertainty in this background may result from the uncertainty in the ^{208}Tl and

^{214}Bi concentrations, which may be as high as 25% of the predicted internal background rate [14].

For the CPD method we further assume that, in addition to these backgrounds, α and β emitting contaminants contained in the detecting elements and in the surrounding matter will increase the background rate, and we assume that this increase can be limited to 4 d^{-1}. Since the energy loss in thin detectors for β particles is much less than that of the heavy p, t, and α particles which result from neutron capture, good pulse height resolution can distinguish this background from the signal. These contributions to background resulting from contaminants internal to SNO will be measureable before and during operation of SNO with the initial H_2O fill. While contaminants in the loaded scintillating materials will contribute backgrounds with 100% detection efficiency, the background due to intercepted low energy $\beta's$ and $\gamma's$ will be a function of the background spectrum, the thickness of the detectors used, and the proportion of the fiducial volume occupied by neutron detectors.

With the ^{238}U and ^{232}Th concentrations in the D_2O being near 10^{-14} g/g each, contaminants from these chains will emit fewer than 10^5 $\beta's$ per day. Since the electron range in the D_2O is near 10^{-4} that of a neutron, the rate of such $\beta's$ encountering a detecting element is comparable to that for neutrons. However, potassium contamination in the D_2O will contribute in excess of 10^6 $\beta's$ d^{-1} per gram, and therefore a signal much greater than that of the neutrons. Reducing the potassium contamination to a milligram (10^{-12} g/g) will reduce this background to negligible levels. Similarly, the range of background γ rays in water is near four orders of magnitude below that of thermal neutrons, so γ-ray encounters with detecting elements is also improbable for impurity levels similar to those mentioned above. In any event, thin scintillating elements will minimize the amount of scintillation light to result from encounters of $\beta's$, $\gamma's$, and scattered electrons with the detecting elements, providing adequate discrimination against these backgrounds.

It is apparent (Table III) that 25% detection efficiency, achieved by an independent detection method will result in similar or reduced errors in the NC event rate measurement, despite an increase in detected background due to contained and intercepted radiation. The rate of such contained and intercepted background events may reach 4 d^{-1} without appreciable deterioration in the NC rate measurement uncertainty for the full SSM flux scenario, and while achieving a modest improvement in the measurement uncertainty for the 1/3 SSM scenario. Background contributions from intercepted β's and γ's will be small, and can be separated. The rate of 4 d^{-1} will not be exceeded by activity from contaminants contained in the detecting elements, given impurities in the amounts mentioned above.

VII CONCLUSIONS

The feasibility of employing light elements which have a large cross section and charged particle emission in the final state, as a method of detecting the NC neutrons in SNO has been investigated. The large capture cross section means that only relatively small amounts of the detecting materials are required to capture a large fraction of the neutrons. The charged particle final states make it possible to detect the neutron captures using standard particle detection techniques like proportional or scintillation counters in such a way as to completely separate them from the CC and ES signals.

It has been shown that ^3He, ^6Li and ^{10}B are the likely nuclei. Further, 35 gm of ^3He would be sufficient to provide a 25% capture probability in SNO and this amount could be used in a proportional counter mode to give a unique signal. The other competitive schemes we have considered are ^6Li mixed with ZnS scintillator or as ^6LiI scintillators. In these two scintillator scenarios, only 10 and 40 Kg respectively of the combined scintillator and neutron absorber would be required to again provide a 25% capture probability.

The major problem of the technique is the removal or discrimination against naturally occuring radioactive backgrounds which are directly observable by the detecting materials. These backgrounds require very high levels of purity of the materials, of the order of 10^{-14} to 10^{-15} g/gm of Th and Uranium. Such purities are undemonstrated but not as yet shown to be unachievable. Thin foils of ^6Li sandwiched between ionization detectors (eg. CsI scintillators, solid state detectors, or proportional chambers) are potentially a useful method for observing coincident $\alpha's$ and tritons and thus discriminating against contained α backgrounds.

The statistical accuracy of this method has been compared with the CGRD method for the two likely explanations for the SNP; a problem with the SSM or neutrino matter oscillations. It has been shown that for either case, with sufficient ^3He or ^6Li in the D_2O to capture 25% of the neutrons comparable statistical accuracy can be achieved using this method as with the CGRD method of using neutron capture γ rays.

In summary, we have shown that the CPD methods of detecting NC events in SNO has significant advantages over the the CGRD method in that:

1. It completely separates the NC signal from the CC and ES signals.
2. It can be inserted and removed from the D_2O.
3. Only small amounts of detection materials are required.
4. It permits separate observations of short term fluctuations in the NC and CC neutrino signals.

These advantages over the CGRD method make it very important to pursue this method further and investigate the technical problems to be overcome in implementing this technique.

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TABLE I: DETECTING ELEMENT LOADING ALTERNATIVES

Detector Type	Composition	Reaction	Cross Section (b)	Q-Value (MeV)	% (wt) Neutron Absorber	τ_d (μsec)	Signal Strength (N_γ/n or N_e/n)
PWC	^3He	$^3He(n,p)^3H$	5327	0.77	100.0	n.a.	2000 e^-
PWC	$^{10}BF_3$	$^{10}B(n,\alpha)^7Li$	3837	2.79 (7%) 2.30 (93%)	15.0	n.a.	6000 e^-
Scint.	$^6LiF{:}ZnS$	$^6Li(n,\alpha)^3H$	940	4.76	8.0	0.1/1.0	188000 γ
Scint.	^6LiI	$^6Li(n,\alpha)^3H$	940	4.76	4.5	1.4	108000 γ

TABLE II: SUMMARY OF DETECTION ALTERNATIVES

Detector Composition	Scintillator Mass (kg.)	*Material Purity Required (10^{-12} g/g) ^{238}U	^{232}Th	Volume Displaced (L)	Geometric Configuration
$NaCl$	2500	1	4	115	Added to D_2O
Gd	4.6	1	4	0.6	Added to D_2O
^3He in Prop. Tubes	0.0353	0.03	0.14	263	2.1 *cm.* diam. tubes, 1 atm. 897 m. long, vertical on 100 *cm.* square grid.
$^6LiF{:}ZnS$ in Acrylic Plates	9.71	0.005	0.022	2.7	2.90 *cm.* square. 60μm thick. 54362 plates on 25 *cm.* cubic grid
^6LiI in Acrylic Tubes	38.7	0.002	0.007	10.0	1 *mm.* diam., 23.5 *cm.* long. 54362 tubes on 25 *cm.* cubic grid

* including mass of containment/carrier materials.

TABLE III: PREDICTED EVENT AND BACKGROUND RATES $(kt-y)^{-1}$.

cc = 1/3 SSM:	nc = SSM		nc = 1/3 SSM	
	N	$\sigma(\sqrt{N})$	N	$\sigma(\sqrt{N})$
CGRD METHOD AT 50% DETECTION EFFICIENCY				
Total cc + nc + bkgd	12051	109.8	9992	100.0
Less cc + bkgd	7845	88.6	7845	88.6
=nc + bkgd	4206	141.1	2147	133.6
Less nc bkgd				
external	325	18.0	325	18.0
internal*	758	27.5	758	27.5
Total bkgd	1084	32.9	1084	32.9
=nc rate	3122	144.8 (4.6%)	1063	137.5 (12.9%)
CPD METHOD AT 25% DETECTION EFFICIENCY				
Total nc + bkgd rate	3598	60.0	2534	50.3
Less bkgds				
external	163	12.7	163	12.7
internal*	379	19.5	379	19.5
contained	1461	38.2	1461	38.2
Total bkgd	2003	44.8	2003	44.8
=nc rate	1595	74.8 (4.7%)	531	67.4 (12.7%)

* As well, a systematic error of up to 25% of internal backgrounds may result from contaminant measurement uncertainties.