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**STUDIES OF A NOVEL METHOD
FOR SOLAR NEUTRINO
NEUTRAL CURRENT DETECTION IN
THE SUDBURY NEUTRINO OBSERVATORY**

by

David John Paterson, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Science

Department of Physics

Carleton University

Ottawa, Ontario

July 31, 1989

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submitted by David John Paterson, B.Sc.

in partial fulfilment of the requirements for
the degree of Master of Science

Thesis Supervisor

Chair, Department of Physics

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ABSTRACT

The Sudbury Neutrino Observatory will study the Solar Neutrino Problem 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 relative NC and CC rates provides a method for observing neutrino oscillations, and may confirm the existence of a neutrino mass. The NC interaction is a critically important aspect of the experiment, which breaks up the deuteron producing a neutron and a proton. The reaction rate is measured by counting free neutrons. This thesis studies the planned capture γ -ray NC detection method and an alternative method in which the thermalized neutrons are captured in (n, α) or (n, p) reactions on light nuclei. The charged products may be uniquely detected using scintillation or proportional counter techniques, completely separating the NC signal from the Čerenkov signals of the CC and ES interaction, thereby improving the significance of the measurement. A Monte Carlo program has been written in order to analyse the neutron capture efficiencies of the two methods. The SNO experiment, NC detection methods, and Monte Carlo program are discussed, and potential detector configurations are identified.

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INTRODUCTION

A discrepancy exists between the predicted [1] and observed [2] solar neutrino flux. This discrepancy, known as the Solar Neutrino Problem (*SNP*), has been known for more than two decades, and theoretical models have been postulated which attempt to account for the discrepancy, but none of these models has received independent observational support. The observations and the physics underlying the predictions have both been substantially refined since the discrepancy was first identified, but the disagreement remains. As well, the observations have recently been independently confirmed [3].

One promising model which attempts to explain the problem suggests that neutrinos oscillate in flavour during their flight from the sun, or while passing through the sun [4], rendering them partially unobservable with existing solar neutrino detectors. Other solar neutrino detectors have been proposed in order to study this problem. Most of the proposed detectors are incapable of solving this puzzle through direct observations of oscillated neutrinos, which could only interact through the neutral current channel. The Sudbury Neutrino Observatory (*SNO*) is one proposed detector [5] which would be capable of observing unambiguously the neutral current interactions, and thereby of demonstrating whether such oscillations actually do occur. However, the *SNO* detector, as proposed, is limited in the accuracy with which it can distinguish observations of neutral current interactions from other types of interactions. *SNO* is also limited in its ability to separate variations in the relative flux of different flavours of solar neutrinos if such variations occur over a relatively short period of time. This may become a significant limitation if the origin of the solar neutrino problem is to be found in the neutrino magnetic moment [6], or in combined effects such as flavour changing neutrino spin rotations (*FC ν SR*) [7]. The planned method is also not capable of separating neutrinos of different flavours while observing a neutrino burst signal from a supernova core collapse event.

An alternative method for observation of neutrino-deuteron neutral current interactions has been proposed [8], which could clearly separate the neutral current

event signature from all other types of events, enabling unambiguous and real time neutral current event detection. In the proposed method, neutrons which are freed from the deuteron by neutral current interactions would thermalize and then capture in discrete detecting elements, causing the emission of charged particles which will produce a signal distinct from the Čerenkov light emitted by the other types of neutrino interactions in the D_2O .

We have studied the various scintillation and proportional counter techniques for implementing this method, and have identified a number of promising solutions. This has involved a survey of neutron capture reactions and the properties of various loaded scintillator materials. In order to study the feasibility of these solutions, a Monte Carlo program has been written which simulates the neutron capture probabilities of the planned and proposed detection techniques, and enables simulation of variations in the detection method design parameters. This thesis discusses the physics of the solar neutrino problem, detectors proposed to study the problem, the SNO detector, neutral current detection methods for the SNO detector, the Monte Carlo, and the results derived from its operation.

THE SOLAR NEUTRINO PROBLEM

I THE STANDARD SOLAR MODEL

The "Standard Solar Model", the theory describing the physics of main sequence stars as discussed by many authors [1,9] predicts that stars fuse hydrogen atoms into helium atoms, with some intermediate heavy products resulting at low concentrations. In simplest terms, the process consumes four hydrogen atoms (mass excess = 7289 keV each) to produce each helium atom (mass excess = 2425 keV), with the nuclear binding energy liberated in the process being 26.7 MeV ($4 \times 7289 - 2425 \text{ keV}$). With two fewer protons and two additional neutrons in the resulting helium atom, weak interaction theory requires the concurrent emission of two positrons and two electron neutrinos (ν_e) in order to conserve both charge and lepton number. It is predicted that there will be one neutrino emitted by the sun for each 13 MeV of energy released. Detailed analysis of the proton-proton (*pp*) chain of reactions suggests a complex neutrino energy spectrum.

Deuterons, ^3He , ^7Be , and ^7Li or ^8B are intermediate products of the *pp* fusion chain. Reaction probabilities, given in Figure 1 as predicted by Bahcall and Ulrich [1], are derived from laboratory measurements of reaction cross sections, while solar luminosity and age, the equation of state, elemental abundances, and solar opacity to photon radiation are used to predict reaction rates and solar temperature profiles.

In addition to the *pp* chain, a small amount of carbon in the solar core will act as a catalyst for the CNO cycle of reactions. This sequence, shown in Figure 2, also produces helium from hydrogen, again liberating two neutrinos and 26 MeV of radiant energy. The CNO chain contributes 1.6% of the total radiant flux [1], and solar neutrinos originate from the CNO chain in this same proportion.

TABLE I: Solar Neutrino Flux at Earth Surface [1]

Source	Flux ($\times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$)	Energy (E_ν) MeV
pp	6.0	≤ 0.42
pep	0.014	1.44
Hep	8×10^{-7}	≤ 18.8
${}^7\text{Be}$	0.47	0.86 (90%) 0.38 (10%)
${}^8\text{B}$	0.00058	< 15.0
${}^{13}\text{N}$	0.061	< 1.71
${}^{15}\text{O}$	0.052	< 2.25
${}^{17}\text{F}$	0.00052	< 2.25
Total	6.598 (+2%)	

The energy liberated in these hydrogen burning chains is radiated away or carried away by the escaping neutrinos. The neutrinos carry away approximately 2.1% of the total liberated energy [1]. The radiant energy also ultimately escapes the sun, but not in the same prompt timeframe as the neutrinos. Photons have a mean free path measured in centimetres in the sun, and experience a three dimensional random walk lasting nearly 10^6 years before escaping. Neutrinos, on the other hand, have a mean free path much greater than the solar diameter, and escape the sun unscattered. Averaged over time, the standard solar model predicts emission of two electron neutrinos for each 26 MeV of radiant energy. The luminous energy arriving at earth from the sun is $1.4 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$, indicating a solar luminosity of $3.9 \times 10^{33} \text{ erg s}^{-1}$, or $8.5 \times 10^{11} \text{ MeV cm}^{-2} \text{ s}^{-1}$ at the earth's surface. At the rate of one neutrino for each 13 MeV of luminous energy, neutrino emissions are predicted to be $1.8 \times 10^{38} \text{ s}^{-1}$ at the sun, or a flux of $6.6 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ at the earth's surface. Due to the predicted reaction probabilities (Figures 1 and 2) and the kinematics for two body and many body final states, the detailed neutrino energy spectrum is predicted to be as shown in Table I and Figure 3, listed according to the parent nucleus [1].

Attempts have been made to measure this flux, and a large discrepancy is evident between predicted and measured values. As will be discussed below, two underground detectors have observed solar neutrinos. The ^{37}Cl detector of Dr. R. Davis [2] has observed solar neutrinos since 1968. After 61 complete runs between 1970 and 1984, an observed flux of 2.0 ± 0.3 SNU is reported [2] ($1 \text{ SNU} = 10^{-36}$ captures s^{-1} per target atom). The predicted rate derived from the standard solar model is $7.9^*(1 \pm 0.33)$ SNU [1]. Recently, the Kamiokande II collaboration has reported [3] observations of solar neutrino electron scattering experiments in a tank of water, confirming the results reported by Davis. Theories which attempt to explain the discrepancy fall into two broad classes. In the first group are theories which propose non-standard models of solar physics, such as solar core mixing which results in a lower core temperature, changing the reaction probabilities from those of Figure 1. In the second group are theories which suggest changes in the neutrinos themselves. Examples include neutrino magnetic moments which render neutrinos undetectable after interaction with the solar magnetic field [6], or suggestions that the neutrinos born deepest in the core of the sun (^8B neutrinos) oscillate from electron flavour to other neutrino flavours [4a,4b]. It should be noted that the existing detectors are most sensitive to only that 2% (or less) of electron neutrinos of the highest energies.

Given the 15% uncertainty in the measured value and the 33% uncertainty in the theoretical value for the solar neutrino flux, and the fact that existing experiments are sensitive to such a small portion of the solar neutrino flux, the discrepancy would not be a serious challenge to solar fusion physics but for two facts. The first is that both the theory and the measurements have been so thoroughly conducted. The measurements have been so frequently made and so thoroughly scrutinized that there is little likelihood of unaccounted systematic error. The recent Kamiokande II confirmation of the Homestake results underlines the fact that the observed ^8B neutrino flux is not as predicted by the standard model. On the other hand, the theory is thorough and rigorous, having been fully modelled in Monte Carlo programs, and the 33% uncertainty reflects the extent of the error which may result from a wide

range of possible variations in the solar models (99.7% confidence). Even allowing for maximum error in both the model and the Homestake results, so that the discrepancy is minimized, the remaining discrepancy is near 50% of the predicted flux. The solar neutrino experiments and reported results will be discussed below, following a discussion of the range of standard model variations accounted for in the 33% uncertainty above.

The second point which amplifies the seriousness of the discrepancy is that, while the existing detectors are sensitive to only a small part of the expected flux, the flux under observation results from the final reaction in a branch of the *pp* chain and which occurs in the solar core at the highest of expected solar temperatures. Therefore, the "solar neutrino problem" may in the absence of new neutrino physics, point out a very real misunderstanding in solar fusion physics. A discussion of the possible implications regarding solar core temperatures and neutrino oscillations follows the detector discussion below.

The final section of this chapter will focus on the neutral current measurement which is so essential in distinguishing between the two types of solution to the solar neutrino problem.

II MODEL UNCERTAINTY

Theoretical predictions of solar neutrino flux are based upon stellar evolution theories and nuclear reaction dynamics as measured in laboratory experiments. The method for predicting the spectrum of solar neutrinos has involved Monte Carlo modelling of the zero age main sequence sun, and then iterating the model to account for the evolution in its composition which results from the progression in its nuclear fusion reactions. Acceptable models correctly exhibit the currently observed luminosity and elemental abundances after the appropriate 4.6 billion years of evolution. Other input parameters to the models include primordial hydrogen (X), helium (Y), and heavy element (Z) abundances, opacity to photon radiation, and the equation of state.

The method of Bahcall and Ulrich [1] is to numerically estimate the " 3σ " (99.7% confidence level) neutrino flux and uncertainty. To accomplish this, randomly generated values for the input parameters (reaction cross sections, elemental abundances, opacity, etc.), which are within the 3σ uncertainty range of accepted values for such parameters, are input to the Monte Carlo routines. With 1000 successful models generated, the range of values for the estimated neutrino flux emitted spans the full 3σ uncertainty range. The probability that the solar neutrino flux is not within the range estimated by this method is 0.3% unless there is an error in the accepted input parameters, or an error in the solar model, or unknown physics affecting the sun or the neutrinos. Ongoing scrutiny of the input parameters over the years has resulted in revisions to the predicted rates, but the impacts of these revisions have been quite minor over the past two decades, suggesting that the model parameters are mature. There is little likelihood that the model is in error in any significant way.

The reaction cross sections and uncertainties used in the Monte Carlo simulations are determined from the low energy cross section factors and first derivatives as shown in Table II for the pp chain reactions. The pep reaction rate is calculated from the pp rate according to the formula indicated.

The Monte Carlo simulations assume that the sun is homogeneous on arrival on the main sequence, taking light element abundances to be primordial. As well,

fractional abundances of elements heavier than carbon are assumed, as shown in Table III [10], to be as currently observed on the surface of the sun. Uncertainties employed in the Monte Carlo simulations are taken to be triple the 1σ values determined in [10].

Opacity is closely connected to heavy element abundances, and was therefore derived from the Table III data using programs of the Los Alamos Opacity Library.

TABLE II: Proton-Proton Chain Reaction Parameters [1,11]

Reaction	Q (MeV)	$\langle q_{\nu_e} \rangle$ (MeV)	S_0 (keV-barns)	dS/dE (barns)	Lifetime (yrs)
$^1H(p, e^+ \nu_e)^2H$	1.44	0.26	$4.07(1 \pm 0.05) \cdot 10^{-22}$	$4.52 \cdot 10^{-24}$	10^{22}
$^1H(pe^-, \nu_e)^2H$	1.44	1.44	see Equation 1 below.		10^{12}
$^2H(p, \gamma)^3He$	5.49	-	$2.5(1 \pm 0.16) \cdot 10^{-4}$	$7.9 \cdot 10^{-6}$	10^{-6}
$^3He(p, e^+ \nu_e)^4He$	19.80	9.63	$8 \cdot 10^{-21}$		10^{12}
$^3He(^3He, 2p)^4He$	12.86	-	$5.15(1 \pm 0.17) \cdot 10^3$	- 0.9	10^5
$^3He(^4He, \gamma)^7Be$	1.59	-	$0.54(1 \pm 0.06)$	$-3.1 \cdot 10^{-4}$	10^6
$^7Be(e^-, \nu_e)^7Li$	0.86	0.86	see Equation 2 below.		10^{-1}
	0.38	0.38			
$^7Li(p, \alpha)^4He$	17.35		$52(1 \pm 0.5)$	0	10^{-5}
$^7Be(p, \gamma)^8B$	0.137	-	$2.43(1 \pm 0.22) \cdot 10^2$	$-3 \cdot 10^{-5}$	10^2
$^8B(e^+ \nu_e)^8Be^+$	17.98	6.71			10^{-6}
$^8Be^+(\alpha)^4He$					

$$\text{Equation 1) } R_{pp} = 5.51 \cdot 10^{-5} \rho(1+X)T_6^{-\frac{1}{2}}(1+0.02T_6) \cdot R_{pp} \text{ [12]}$$

$$\text{Equation 2) } \lambda = 4.62(B)10^{-9}(\rho^{\frac{1+X}{2}})T_6^{-\frac{1}{2}}(1+0.004(T_6-16)) \text{ [13]}$$

TABLE III: Solar Heavy Element Abundances [10]

Element	Number Fraction
C	0.29661
N	0.05918
O	0.49226
Ne	0.06056
Na	0.00129
Mg	0.02302
Al	0.00179
Si	0.02149
P	0.00017
S	0.00982
Cl	0.00019
Ar	0.00230
Ca	0.00139
Ti	0.00006
Cr	0.00028
Mn	0.00017
Fe	0.02833
Ni	0.00108
Total	1.00000 $Z/X = 0.027 \pm 19\%$

Monte Carlo simulations of different opacities are accomplished through variations in the heavy element abundances from those observed on the solar surface (Table III), and also by varying the primordial helium abundance used as one of the Monte Carlo initial conditions. The objective of such variations in Monte Carlo input parameters is to vary the temperature predictions for the interior of the sun, changing the predicted reaction rates from those shown in Figure 1, and thus predicting a neutrino spectrum which more closely matches the observations. Reduced heavy element abundances within the sun would increase opacity and produce the necessary reduction in the ^8B

neutrino flux predictions, though it is not obvious why heavy elements should be less plentiful within the sun than what is observed on its surface. Increased primordial helium abundance would increase the predicted ${}^8\text{B}$ neutrino flux. Alternatively, it is not obvious why the sun's primordial helium abundance should be less than that predicted by big bang theory, given that the sun is at least a second generation star, yet this is what would be required in order to explain the solar neutrino problem through a non-standard model of solar helium abundance.

III THE DETECTORS

Homestake Detector And Results

The heart of the Homestake detector is a tank containing 3.8×10^5 liters of perchlorethylene (C_2Cl_4). The detector is located in the Homestake gold mine in South Dakota, at a depth of 1400 metres below 4000 mwe of 2.84 g cm^{-3} of rock. (1mwe = 1 metre of water equivalent = 1000 g cm^{-2}) This overburden reduces the secondary cosmic ray background (muon) rate to $1.5 \times 10^3 \text{ m}^{-2} \text{ y}^{-1} \text{ sterad}^{-1}$, which gives a background counting rate in the detector of $0.08 \pm 0.03 \text{ d}^{-1}$. In the detection reaction, a neutrino ($E_\nu \geq 0.814 \text{ MeV}$) impinging on a chlorine nucleus will interact through the charged current channel, to convert a neutron into a proton, thus creating a ${}^{37}\text{Ar}$ atom from a ${}^{37}\text{Cl}$ atom. ${}^{37}\text{Ar}$ decays through electron capture with a 35 day half life, so the tank must be purged and the argon atoms separated and counted sufficiently frequently to ensure significance of the measurements. The purging process involves circulation of helium gas through the detector, which on extraction carries with it the argon. Added to the perchlorethylene, 0.2 cm^3 of ${}^{36}\text{Ar}$ or ${}^{38}\text{Ar}$ aid as a carrier of the ${}^{37}\text{Ar}$ during extraction. The gas mixture is cleaned and sieved before being frozen in a liquid nitrogen cooled charcoal trap at -196°C (argon freezing point -189°C), and the volume measured to determine the amount of argon extracted. The isotopes are separated to determine the ${}^{37}\text{Ar}$ volume. The isotope separation process is demonstrated to be 95% efficient at removing the carrier atoms. The remaining argon, essentially the ${}^{37}\text{Ar}$ atoms created by the solar neutrinos, is then observed for

eight months and decays are directly counted.

The Homestake detector has been operating since 1968, and the results as reported [2] are shown in Figure 4. The mean solar neutrino interaction rate reported by the detector for all tests up to 1986 [2a] is $2.0(\pm 0.3)$ SNU, where Bahcall and Ulrich [1] have calculated an expected rate of $7.9(1+0.33)$ SNU for this detector based upon the standard solar model. This 2.0 SNU result may indicate an ${}^8\text{B}$ neutrino flux of $2.0 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ versus the predicted value of $5.8 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$. Alternatively allowing for a 3σ uncertainty in the observations, a conservative upper limit to the ${}^8\text{B}$ neutrino flux is $2.7 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ [1]. Since the lower limit of the predicted ${}^8\text{B}$ flux is $3.7 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, the Homestake results substantiate a conservative conclusion that the observed ${}^8\text{B}$ solar neutrino flux is less than one half the predicted flux. Considering that the Homestake energy threshold is 0.814 MeV, and that 77% of the predicted rate is attributed to ${}^8\text{B}$ neutrinos, these results are consistent with a complete absence of ${}^8\text{B}$ neutrinos. More recent results [2b] suggest some cyclic variations in solar neutrino flux, with a period comparable with that of the sun spot cycle. While this observation is statistically significant but inconclusive [14], a mechanism has been identified [6] which would cause such flux variations.

Kamiokande Detector And Results

The Kamiokande detector was originally built to observe nucleon decay. Modified for electron neutrino detection, it is located at a depth of 1000 meters (2700mwe) below a mountain and has a total mass of 3000 tons of H_2O , but a fiducial mass for solar neutrino detection of only 680 tons. In the detector, Čerenkov radiation generated by scattered electrons is detected by 1071 50 cm. diameter spherical photomultiplier tubes. Of these, 123 are aimed outward as a veto, leaving 948 aimed at the fiducial volume. The energy threshold is greater than 7.5 MeV. Timing and angular resolution allow for accuracies of 1.7 meters in locating the position of the reaction, and 28° in the direction of the scattered electron [3b].

Backgrounds have been an ongoing concern at Kamiokande, with cosmic ray muon rates of 0.3 s^{-1} , and total backgrounds of 0.8 s^{-1} . With an expected ^8B solar neutrino interaction rate of 0.33 d^{-1} , substantial data manipulation is required in order to extract the signal from the backgrounds. The steps in the data reduction are described below.

Large events (eg. through-going muons) are eliminated by discarding all events registering energies exceeding 25 MeV. Stopping muons are eliminated by vetoing all events which are observed by any of the outward focused photomultiplier tubes. To eliminate muon decay electrons, events which occur within 100 μs of a previous event are discarded.

Pulse shape discrimination is used to eliminate photomultiplier tube noise. In this scheme, tube signals are rejected where the peak of the signal (number of photoelectrons) falls below .125 of the total number of photoelectrons in the pulse.

To eliminate backgrounds in the detector originating with the surroundings, events not reconstructed to have occurred within the central fiducial volume of 680 m^3 are discarded.

To eliminate events possibly resulting from fragments of muon collisions on oxygen nuclei (spallation), events are analysed and compared to the γ -ray signatures of the possible fragments of such collisions (^{12}N , ^{12}B , and ^8B), and data are rejected where

appropriate.

Finally, for surviving events, those not showing appropriate directionality with respect to the sun are rejected.

While statistics are not yet plentiful, results [3b] are that the solar neutrino flux

$$\Phi_{\text{B}} = 0.46 \pm 0.13 (\text{stat}) \pm 0.08 (\text{syst})$$

of the SSM predicted rate, indicating that the ${}^8\text{B}$ neutrino flux is less than $2.6 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, and confirming the Homestake results.

IV IMPLICATIONS OF THE SOLAR NEUTRINO PROBLEM

Many explanations have been offered for the solar neutrino problem, including some which directly contradict the physics employed in the standard solar model. An example of such contradictory physics would be the suggestion that the sequence of nuclear fusion reactions is terminated for unknown reason before the ${}^8\text{B}$ reaction is able to occur. Ignoring such 'non-physical' proposals, two possible causes for the solar neutrino problem are apparent.

It is possible that the temperature within the core of the sun is somewhat different from that predicted by the standard model. This may be attributed to an opacity to photon radiation which is different from that predicted, or to some other method which extracts or redistributes the energy from the core of the sun. One such energy redistribution method proposed is an as yet undiscovered particle known as a *WIMP* (Weakly Interacting Massive Particle), which mixes the solar core. The reduction in temperature will reduce the probability of occurrence of the ${}^3\text{He}({}^3\text{He}, 2\text{p}){}^4\text{He}$ reaction, and all subsequent reactions including the ${}^8\text{B}$ decay which emits the neutrinos being studied by the operating detectors. Unless there is evidence to support some other cause for the discrepancy between predicted and observed rates, reduced ${}^8\text{B}$ neutrino flux must be attributed to reduced solar core temperature. The flux of ${}^8\text{B}$ neutrinos is predicted by the Monte Carlo simulations to be a sensitive function of temperature. At any given point in the solar core, the local production rate of ${}^8\text{B}$ neutrinos will be proportional to temperature to the power 13 [1]. Integrating from the central core

outward, the total ${}^8\text{B}$ neutrino production rate varies with the eighteenth power of the central temperature within 1% over the range of temperatures predicted by the standard model [1]. If the measured flux is determined to be representative of the ${}^8\text{B}$ neutrino production rate, this flux will therefore provide a sensitive monitor of the solar core temperature, with a two thirds reduction in ${}^8\text{B}$ neutrino flux resulting from a 5.9% reduction in solar core temperature from the predicted 15.6×10^6 °K value.

Other possible explanations for the solar neutrino problem are founded in theories about the physical properties of the neutrino itself. While the neutrino is generally assumed to be massless and to have a vanishing magnetic moment, these properties are measured to limits which may not preclude the neutrino itself as the cause of the solar neutrino problem. It has been proposed that the neutrino which we observe from weak interactions is in fact a two (or more) component particle, which oscillates between forms which are and are not detected by the existing detectors. This theory proposes that electron flavour neutrinos are emitted in the solar fusion reactions, but the neutrinos are oscillated to muon or tau flavours while travelling from birth location to the detectors. This oscillation is theorized to be a function of distance, or a function of the lepton density through which the neutrinos pass while escaping from the sun [4a,4b]. An alternative theory to explain the solar neutrino problem is that the neutrino has a small magnetic moment which is sufficient to interact with the solar magnetic field and flip the neutrino into a form which does not interact with the operating detectors [6]. These theories will be more fully explored below.

V NEUTRINO PHYSICS

Today's standard model hypothesizes that the most basic constituents of matter include families of fermions which interact through the exchange of bosons. The fermions all have spins measured at $\pm \frac{1}{2}$ unit, and are subdivided into three families each of quarks and of leptons. The quark families include the up and down particles, the charm and strange particles, and the top and bottom particles. Each of these particles has its antiparticle. All have been observed except the top particle and its antiparticle. Among the leptons, the three families proposed include the electron family, the muon family, and the tau family, each of which includes its namesake charged particle and a corresponding neutrino. Again, each particle has its antiparticle. All lepton particles mentioned have been observed, with the exception of the tau neutrino. It is noteworthy that the neutrino is the only fundamental fermion having a neutral electrical charge, a fact which leads us to a fundamental question in neutrino physics.

An antiparticle is commonly defined to be the charge conjugate (charge reversed state) of a particle. For a neutral particle, charge conjugation will not yield a change in polarity, and the distinction between the particle and its antiparticle is less obvious. For neutrinos, further distinction between the particle and its antiparticle is found in their respective helicities, with the neutrino observed to be "left-handed" and the antineutrino observed to be "right-handed". Handedness, in similarity with the more classical use of the term in the analysis of inductance between electric and magnetic fields, refers here to the sense of the particles spin with respect to the direction of travel of the particle. A neutrino therefore will spin in the direction pointed by the fingers of the left hand when the thumb is pointed in the direction of motion. The question arises when we imagine the neutrino or antineutrino being subjected to each of two types of fundamental transformations, those being a Lorentz transformation and a CPT (charge conjugation - parity inversion - time reversal) transformation. (Interaction of a neutrino with an electric or magnetic field may cause a transformation of the Lorentz type. This would require that the neutrino have

an electric or magnetic moment, which implies some internal structure.) Invariance under CPT transformation is assumed. While CP invariance is known to be violated in the case of K_s decay, CP invariance is generally expected, and the intrinsic charge and parity of an antifermion are known to be opposite those of the respective fermion.

Given an energetic neutrino, spinning in the above mentioned "left-handed" sense, then an observer whose rest frame overtakes the neutrino rest frame will observe that the neutrino changes to a right handed particle on passing. This of course presumes that the neutrino has mass, or somehow travels at a speed less than that of light. The question posed in this case is whether the Lorentz transformed particle is actually the antiparticle, or just a spin reversed neutrino. If the antineutrino is in fact just a Lorentz transformed neutrino (Figure 5b), then it is what is known as a Majorana neutrino, and must have a mass. If, however, the helicity reversed version of the neutrino is indeed distinct from the antineutrino, then there may be as many as four particles (Figure 5a), being the neutrino and antineutrino each having left-handed and right-handed versions. Such a particle is known as a Dirac neutrino. In the case of Majorana neutrinos, a CPT transformation will result in an inversion of the neutrino to its antiparticle, in similarity with the Lorentz transformation. In the case of the Dirac neutrino however, CPT transformation will generate a spin reversed antiparticle, while Lorentz transformation will generate particle spin reversal. The fundamental question then is whether the neutrino is best described by the Majorana or Dirac model?

Of course, if the neutrino is massless, the Lorentz transformation cannot be employed to reverse helicity. The distinction between the Majorana and Dirac models then diminishes except in so far as the Dirac model allows for two additional but otherwise unnecessary and unobservable particles. The question of the correct model of the neutrino and antineutrino is intertwined with an equally fundamental question of whether neutrinos have mass.

Further, Dirac neutrinos may be composed from linear combinations of charge conjugate Majorana neutrinos. Such particles may exhibit magnetic and possibly

even electric dipole moments, although such moments would be exceedingly small, with one model (SO(10)) predicting a Dirac neutrino magnetic moment of $\mu_\nu = 3 \cdot 10^{-19} m_\nu (\text{eV}) \mu_B$.

While observation of a neutrino magnetic moment would provide conclusive evidence for Dirac neutrinos, available evidence has suggested an upper limit on the neutrino magnetic moment which is six orders of magnitude larger than the SO(10) prediction [15] but perhaps two orders of magnitude below that necessary to explain the solar neutrino problem. This evidence may be sufficient to rule out the magnetic moment as the cause of the solar neutrino problem.

VI NEUTRINO OSCILLATIONS [9]

The above discussion applies within any one neutrino flavour, while the standard model currently assumes the three flavours of electron, muon, and tau neutrinos. The unstated assumption underlying the above discussion was therefore that lepton flavour is conserved. It is possible, however, that lepton flavour is not conserved between emission in the sun and detection on earth, while lepton quantum number is conserved. This would allow for the known flavours of neutrinos (ν_e , ν_μ , ν_τ) to be Dirac neutrinos for example, composed from more fundamental neutrinos. As an example, restricted to only two flavours and two neutrino components, with wave functions mixing at an angle θ

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

With time evolution of these component neutrinos described by:

$$|\nu_1(t)\rangle = e^{i(E_1 t)} |\nu_1(0)\rangle$$

$$|\nu_2(t)\rangle = e^{i(E_2 t)} |\nu_2(0)\rangle$$

where each particle's energy is given by,

$$E_i = \sqrt{p^2 + m_i^2}$$

Then

$$|\nu_e(t)\rangle = \cos(\theta)e^{[-iE_1t]}|\nu_1(0)\rangle + \sin(\theta)e^{[-iE_2t]}|\nu_2(0)\rangle$$

The probability of finding a ν_e oscillating to a ν_μ in time t is then given by:

$$\langle\nu_\mu(t)|\nu_e(t)\rangle^2 = \frac{1}{2}\sin^2(2\theta)[1 - \cos(\frac{(m_2^2 - m_1^2)}{2p}t)]$$

where m_1 and m_2 are the masses of the constituent neutrinos. Assuming the particle escapes any collisions, it will travel at constant velocity, and will exhibit oscillation over the oscillation length

$$L_{osc} = 2\pi \frac{2p}{[m_2^2 - m_1^2]}$$

This describes the possibility of non-conservation of lepton flavour through the oscillation of neutrinos between various flavours as a function of energy and the masses of the constituent neutrinos. This oscillation would therefore be evident over the characteristic distance (L_{osc}) from the neutrino's point of origin.

Similarly, analysis of the Majorana model will reveal the possibility of flavour oscillations, and therefore non-conservation of flavour along with the possible transformation of neutrinos into antineutrinos

Considering this possibility of neutrino flavour oscillation, some Grand Unification Theories predict a dominant massless left-handed Majorana neutrino participating in weak interactions, and a sub-dominant heavy right handed Majorana neutrino with a mass of as much as 10^{14} GeV. Neutrino oscillations would also make sense of the solar neutrino problem. As a result, the search for neutrino oscillations has become as fundamental a challenge as is the neutrino mass question.

VII NEUTRINO OSCILLATION TESTS

From the previous discussion on neutrino oscillation, it was concluded that the probability of finding a ν_ℓ oscillating into a $\nu_{\ell'}$ was given by:

$$P_{\ell\ell'} = \frac{1}{2} \sin^2 2\theta [1 - \cos(\frac{\Delta m^2}{2p} t)]$$

where t is related to the oscillation length

$$L_{osc} = 2\pi \frac{2p}{\Delta m^2}$$

and

$$\Delta m^2 = m_2^2 - m_1^2$$

It can be shown that these relations are equivalent to an expression for the probability of a ν_ℓ oscillating into a $\nu_{\ell'}$ as given below:

$$P_{\ell\ell'} = \sin^2 2\theta \sin^2 \left[\frac{(1.27 \Delta m^2 L)}{E_\nu} \right]$$

where

$$\ell \neq \ell'$$

$$\Delta m^2 \text{ is in } eV^2$$

$$L \text{ is in meters}$$

$$E_\nu \text{ is in MeV}$$

The probability of no oscillation, of course, is

$$P_{\ell\ell} = 1 - P_{\ell\ell'}$$

Numerous experiments have been conducted to explore various values of Δm^2 and $\sin^2 2\theta$. Such experiments can be split into the two broad categories of low energy experiments and high energy experiments.

There were two notable low energy neutrino oscillation experiments conducted at nuclear reactors. In both cases, the reaction under study was the collision:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

If electron neutrinos oscillate into another form of neutrino, then at some distance from the neutrino source, the yield of coincident positrons and neutrons could be expected to decrease by a measurable amount. This is known as a "disappearance" reaction. At the Gosgen and Bugey reactors, the neutrino target and the positron detector were both achieved by use of a mineral oil based liquid scintillator. Neutron detection was achieved through the use of ^3He multiwire proportional chambers. The Gosgen experimental results are consistent with an absence of oscillations in the parameter space (Δm^2 , $\sin^2 2\theta$) attributable to the experiment (see Figure 6). The Bugey experiment explored similar parameter space to the Gosgen experiment, measuring the flux at 13.6 and 18.3 meters from the reactor, but the results from Bugey showed a 10% decrease in flux at the greater distance, not attributed to the geometry of the apparatus. These contradictory results are displayed in Figure 6.

Neutrino oscillation experiments have also been conducted at high energy accelerators where "appearance" searches are used to test for oscillation from muon to electron flavours. CERN has been the site of the CHARM collaboration and the European Bubble Chamber (BEBC) experiments, the results of which are displayed in Figure 7 [9]. For these two experiments, the negative results only serve to eliminate the possibility of neutrino oscillations in the parameter space indicated, that being for $\Delta m^2 > 0.2 \text{ eV}$ and $\sin^2 2\theta > 3 \times 10^{-2}$. An electron neutrino appearance experiment was also carried out at Brookhaven National Laboratory, with similar negative results, but extending the eliminated parameter space by an order of magnitude in $\sin^2 2\theta$, as shown in Figure 7 [9].

Fermilab conducted an appearance experiment to search for oscillations of ν_μ to ν_τ , also with negative results, and eliminating much of the parameter space eliminated in the three ν_μ to ν_τ experiments. The FNAL results are similarly given in Figure 7 [9]. Experiments have also been conducted to search for ν_μ disappearance at the CERN and Fermilab accelerators. Both the CHARM and CDHS groups operated at CERN, and again the results served only to eliminate some parameter space as shown in Figure 8 [9]. The CCFR collaboration at Fermilab had equally disappointing results,

but eliminating some probability of oscillation at higher Δm^2 than the CERN groups, as shown in Figure 3.

There have been no conclusive results providing proof of neutrino oscillations, although there have been some tantalizing claims of the disappearance of atmospheric neutrinos, based on a sample of approximately 200 events. Such results have not been substantiated.

VIII MATTER OSCILLATIONS, THE MSW EFFECT

The neutrino oscillations discussed above are known as vacuum oscillations, since the probability of oscillation is independent of the environment. However, it was initially recognized by Mikheyev and Smirnov [4a], based on the formalism of Wolfenstein [4b], that oscillation probability could be influenced by the lepton density through which neutrinos may be passing. The argument proceeds as follows.

The time evolution of a neutrino wave function is governed by

$$\exp[i(pnx - Et)]$$

where n is the index of refraction (for leptons) of the medium through which the particle passes. In a vacuum, $n=1$ and for energetic neutrinos the exponential term reduces approximately to

$$\exp\left[\frac{itm^2}{2p}\right]$$

In matter, however, the index of refraction is given by:

$$n_\ell = 1 + \frac{2\pi N}{p^2} f_\ell(0)$$

where ℓ is the lepton flavour, N is the number density of scatterers, and $f_\ell(0)$ is the forward scattering amplitude, which can be approximated by its real part due to the low probability of absorption of the neutrino. Due to this change in neutrino time evolution in the presence of matter, there is a different probability of oscillation and a different oscillation length (L_m) for neutrinos as they pass through matter, than those determined above. Consequently one must consider a mixing angle for

the matter oscillations (θ_m). Wolfenstein defined a "characteristic matter oscillation length" (in meters), which was independent of neutrino energy, as follows:

$$L_o = 1.7 \cdot 10^7 \frac{A}{Z} \rho$$

where A and Z are the atomic number and nuclear charge, and ρ is in g cm^{-3} . The oscillation length for an energetic neutrino in matter is then given by:

$$L_m = L_{osc} \frac{\sin 2\theta_m}{\sin 2\theta}$$

where θ_m is determined from:

$$\tan 2\theta_m = \tan 2\theta \left[1 + \frac{L_{osc}}{L_o} \sec 2\theta \right]$$

The probability of oscillation of a ν_e to a ν_μ in a distance x, is then given by:

$$P_{e\mu} = \sin^2 \theta_m \sin^2 \frac{\pi x}{L_m}$$

The mixing angle, θ_m , and the oscillation length in matter, L_m , depend on the vacuum mixing angle θ , the vacuum oscillation length L_{osc} , and through it on Δm^2 , and through L_o on the density of the medium.

Depending on how L_{osc} compares with L_o , it is possible that matter could suppress oscillations, or that matter may have no effect on the oscillations. However, for neutrinos passing from regions of extremely high density to regions of very low density, it is possible that they will pass through a density at which $L_{osc} = L_o$, and oscillation will be enhanced. This critical density is a function of the neutrino energy, but it is possible that for a Δm^2 between 10^{-7} and 10^{-4} eV^2 , the solar neutrino problem could be explained. Potentially, "matter oscillations" of the neutrinos which are emitted from the ${}^8\text{B}$ decay in the solar core, on passage through less dense regions of the sun, could result in the disappearance of much of the ν_e flux, and the appearance of ν_μ and ν_τ flux.

IX SOLAR NEUTRINO NC INTERACTIONS

The interactions of solar neutrinos with ^{37}Cl nuclei are exclusively through the charged current channel. Such reactions are of the 'inverse β -decay' type, and occur with neutrinos of the electron flavour only. The reactions evident in the Homestake detector therefore do not measure the total solar neutrino flux if flavour oscillations do occur either in the vacuum between the sun and the earth, or through the MSW mechanism within the sun.

Solar neutrino electron scattering reactions, as in the Kamiokande II detector, occur through either the neutral current channel or the charged current channel. Neutrinos of all flavours participate in neutral current scattering interactions with electrons, while neutrinos of only the electron flavour participate in the charged current channel. This results in interaction probabilities which are 6 to 7 times greater for ν_e -electron scattering than for ν_μ or ν_τ scattering off of orbital electrons in the detector. Since the predicted (SSM) event rate for the Kamiokande II detector is only 190 events per year [1] above an 8 MeV threshold, and the results quoted to date reflect 18 months of observation above a 7.5 MeV threshold, statistical uncertainties are large relative to the potential contributions of neutral current interactions to the total event rate.

A third reaction type which has not yet been studied by existing detectors is the ν -nucleon neutral current interaction. This neutrino scattering interaction may dissociate a nucleon from a nucleus when the neutrino supplies enough energy to overcome the binding energy of the dissociated nucleon. This reaction channel is available to neutrinos of all flavours at comparable cross sections, and is therefore insensitive to neutrino oscillations. A solar neutrino flux measurement which employs the neutral current interaction mechanism will therefore measure the total solar neutrino flux. Comparison of results of such a neutral current interaction rate measurement with those of a concurrent charged current interaction rate measurement will reveal the probability for ν_e oscillation into other neutrino flavours since there are no solar emissions of ν_μ and ν_τ . Since there is information to suggest that the solar ν_e flux varies

temporally with a period measured in months to years, resolution of the solar neutrino problem may therefore require concurrent and real time charged current and neutral current ^8B solar neutrino flux measurements.

UNDERGROUND NEUTRINO DETECTORS

The first underground neutrino observatory, built in 1968 to verify solar neutrino flux predictions, was the Homestake detector of Dr. R. Davis and collaborators [2] at Brookhaven National Laboratory. This detector, discussed in the previous chapter, was the first to identify the solar neutrino problem. A second neutrino observatory, a scintillation telescope for observing stellar collapse and solar flare neutrinos, has operated since 1980 in the Baksan Valley in the Caucasus Mountains, and did detect the SN1987A event. A new radiochemical solar neutrino detector is being constructed at Baksan by the SAGE collaboration, employing gallium as the target material. A liquid scintillation detector (LSD) at Mont Blanc has operated since 1984 in search of stellar core collapse neutrinos and atmospheric neutrinos created by cosmic radiation. Mont Blanc registered some unexplained activity on the day of the SN1987A event. Two light water Čerenkov detectors which were originally built as proton decay detectors have also observed neutrinos of cosmic origin. The Kamiokande detector (Kamioka, Japan) was upgraded, with a reduced energy threshold and reduced background contamination, to enable it to observe the solar neutrino flux. These Čerenkov detectors, operated by the Kamiokande II and Irvine-Michigan-Brookhaven collaborations also observed core collapse neutrinos from supernova SN1987A. The Kamiokande detector, described in the previous chapter, has also reported observations of the solar neutrino deficit, supporting the Homestake observations. As well, the Gallex collaboration is building a gallium detector at Gran Sasso Italy, for solar neutrino observations. The Sudbury Neutrino Observatory will be discussed in detail in subsequent chapters.

I GRAN SASSO [16,17]

The Gallex collaboration is currently assembling the Gran Sasso European Underground Laboratories gallium radiochemical solar neutrino detector. Gran Sasso is located at a depth of 3500 metres of water equivalent below a mountain in Italy. This experiment will be capable of observing the *pp* neutrinos, and those of higher energies. The target consists of 30 tons of gallium, containing 39.6% ^{71}Ga , which has approximately 20 times the neutrino capture probability of ^{37}Cl . The gallium is in the form of GaCl_3 . When a neutrino interacts through the charged current channel with the ^{71}Ga , the atom is converted to ^{71}Ge , and the molecule captures another chlorine atom to become germane (GeCl_4). The germane is swept out of the detector tank with air or helium, and extracted by gas scrubbers, then with CCl_4 , and water. The extracted gaseous germane is purified and then delivered to proportional counters for determination of the volume. The ^{71}Ge decays back to ^{71}Ga by electron capture with a half life of 11.43 days, with the emission of x-rays, which are observed to determine the number of atoms converted. The tank must be purged approximately 25 times each year to optimize detection of the ^{71}Ge . The standard Solar Model predicts a result of 123.5 ± 4.4 SNU, while a model consistent with the Homestake results, assuming a deficiency in ^8B neutrinos, will produce an expected result of 94.3 ± 2.1 SNU. Since the experiment has no energy resolution capability, the difficulty will be in interpreting any other result, since oscillations and rotations will not be observable.

The detector is expected to be completed in late 1989, followed by a year of calibrations with a ^{51}Cr source. Data taking is scheduled to begin in 1990. First results are then expected two years later, with more statistically significant results requiring at least two additional years in the event that oscillations impact on the total detected neutrino flux.

II THE BAKSAN NEUTRINO TELESCOPE [18]

The Baksan neutrino telescope, operated at a depth of 850 mwe since June 30, 1980, consists of 3156 separate detectors, each consisting of a volume 70 cm x 70 cm x 30 cm., containing a hydrocarbon scintillator with the H:C ratio 20:9. Each scintillating cube is observed by a photomultiplier tube. The detectors, weighing 330 tons, are arranged into four horizontal planes and four vertical planes to form a cube with two fully enclosed horizontal planes. The cube dimensions are 16 m x 16 m x 11 m. The telescope is intended to observe stellar core collapse and solar flare neutrinos through the capture reactions:

The energy thresholds for these charged current reactions are 30 MeV for the ν_e , 12.5 MeV for the $\bar{\nu}_e$, and 120 MeV for the ν_μ and $\bar{\nu}_\mu$. These thresholds are substantially higher than the kinetic energy of solar neutrinos from any of the branches of the pp or CNO cycles. The charged fragments from the interactions generate scintillation light in the detectors.

The external detector planes are used as a veto to distinguish entering muons, while the three lower horizontal planes form the fiducial volume, consisting of 130 tons in 1200 detectors. With background count rates reduced to 0.014 s^{-1} , the detector is sensitive to a flux of $2 \cdot 10^{11} \bar{\nu}_e \text{ cm}^{-2}$, and is expected to be able to observe a galactic center supernova through capture of 11 to 24 $\bar{\nu}_e$.

The detector reported in 1986 that no core collapse events had been detected since going live, and that there had been no detectable signals associated with solar flares,

above the background rate. This places the neutrino flux from solar flares ($F_{\text{fl}} > 100 \text{ MeV}$) at below $1.7 \cdot 10^9 \nu_e \text{ cm}^{-2}$ and $0.8 \cdot 10^9 \nu_\mu \text{ cm}^{-2}$. Above a 30 MeV threshold, the upper ν_e flux limit is $1.4 \cdot 10^{11} \text{ cm}^{-2}$. This is significant in light of suggestions that the cyclic variations reported by the Homestake detector may be connected with solar flares. The SN1987A event was detected at Baksan [19] concurrent with the Kamiokande detection.

III THE BAKSAN SAGE EXPERIMENT [20]

The Soviet American Gallium Experiment is a solar neutrino observatory being built to observe and measure the solar neutrino flux at the very low neutrino energy threshold of 233 keV. Such a low threshold will make the detector sensitive to even the pp neutrino flux which accounts for over 90% of the predicted solar neutrinos. As with Gallex, this detector will be capable of determining if there is a deficiency in solar neutrino pp flux, while observations to date have focused only on a higher energy branch of the spectrum. The experiment will employ metallic ^{71}Ga as the target for the solar ν_e , the charged current detection reaction being:

The resulting ^{71}Ge decay by electron capture has an 11.43 day half life. This charged current interaction will only be sensitive to neutrinos of electron flavour, and will therefore not directly observe neutrino oscillations or rotations.

The ^{71}Ge is extracted from the ^{71}Ga by a chemical procedure. The ^{71}Ga , which melts at 29.5°C , will be mixed with HCl and hydrogen peroxide and stirred. This will cause the ^{71}Ga to form globules, and the ^{71}Ge will rise to the surface of these globules. After some further processing, the ^{71}Ge is extracted in the form of germane (GeCl_4), and analysed in a way similar to that employed by GALLEX. The germanium will be extracted after a 21 day exposure, and the resulting sample will be observed for 3 to 6 months to count decays of the products. It is anticipated that 8.3 ^{71}Ge atoms should be present after each 21 day cycle.

The detector consists of up to 10 reactors (initially four are to be operated), each containing six tons of metallic gallium. The reactors are located in a 60 m x 10 m x 12 m cavity under a mountain at the Baksan laboratories. The cosmic ray shielding afforded by the 4800 mwe overburden reduces the cosmic ray background to less than 1% of the SSM predicted signal rate. The detector is expected to produce results in 1989 to verify the SSM total solar neutrino flux prediction to an accuracy of 12% to 15% using 30 tons of ^{71}Ga .

IV MONT BLANC [21,22]

The Liquid Scintillation Detector (LSD) located under 5200 mwe at Mont Blanc consists of 72 counters, containing a total of 90 tons of liquid scintillator with 3 photomultiplier tubes in each counter. Each counter is shielded with 2 cm thick iron, for a total weight of 200 tons of iron. The counters are arranged in a cube, and the energy threshold for each counter is adjusted to 7 MeV except for the inner 16 counters where the threshold is set at 5 MeV. The charged current detection reaction being sought from supernova neutrinos is:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

and then

$$n + p \rightarrow d + \gamma$$

where the mean neutron capture time is 170 μs , and the γ -ray energy is 2.2 MeV. Scintillation light from the positron and the γ -ray are observed at the photomultiplier tubes. The background counting rate is 100 to 1000 s^{-1} above a 0.7 MeV threshold, but falls to $6.2 \times 10^{-3} \text{ s}^{-1}$ above a threshold of 5 MeV. The detector is intended primarily for detecting galactic supernovae, and atmospheric neutrinos resulting from cosmic radiation. The detector is expected to see as many as 36 antineutrinos from a $2M_{\odot}$ supernova at a distance of 10 kpc. An event involving five neutrinos was detected on the day of SN1987A, but 4.7 hours in advance of the event detected at IMB, Kamiokande, and Baksan. [23] While the observation is questioned, coincident signals

from gravitational wave detectors at Rome and Maryland are claimed to corroborate that an event did occur.

V IMB [24,25]

The IMB detector consists of a tank containing a fiducial volume of 3300 tons ($2 \cdot 10^{33}$ atoms) of H_2O , observed by 2048 photomultiplier tubes. It is set at a depth of 1570 mwe in a salt mine in Ohio, and was originally constructed to observe nucleon decay. Observable neutrino interactions in the detector are primarily electron scattering events, and the scattered particles are observed through the Čerenkov light they emit. The detector is subject to a background cosmic ray muon rate of 2.7 s^{-1} and cosmic ray neutrinos of approximately 1 d^{-1} , two thirds of them ν_μ . Approximately 3% of the muons stop in the detector.

The IMB detector is used to observe atmospheric neutrinos, distinguishing between down and up going neutrinos for the purpose of making neutrino lifetime measurements. Down going neutrinos will reach the detector in 1 to 2 μs , while upgoing neutrinos will take more than 33 ms. Any difference in flux will indicate a decay time of less than 33 ms (lab frame). The data is used to establish that the lifetime of the muon neutrino exceeds 0.1 s. Comparison of up and down going neutrino flux is also used to evaluate mixing angles for matter enhanced neutrino oscillations by observing for appearance/disappearance of ν_e/ν_μ fluxes. The results of this analysis indicate, using Bethe's prediction of $\Delta m^2 = 1.1 \cdot 10^{-4} \text{ eV}^2$ based on the solar neutrino problem, that $\sin\theta_\nu \leq 0.14$ (90% confidence). Other IMB activities include attempts to observe vacuum oscillations, searches for point neutrino sources, and geomagnetic effects on neutrino flux which would indicate a neutrino magnetic moment.

VI PROPOSED DETECTORS [1]

Two additional radiochemical detectors have been proposed. Both detectors would monitor solar neutrino flux through charged current reactions. The detection reactions proposed are:

In the case of the bromine detector, the threshold for neutrino interaction is 471 keV, which allows detection of all but the low energy pp neutrino flux. The threshold for the lithium interaction is 862 keV, which permits the detector to observe CNO cycle neutrinos, as well as ^7Be , pep , ^8B , and Hep neutrinos. Resulting isotopes are extracted in both cases by chemical means, which are conducted significantly after the interaction, so that neither detector will produce a real time signal.

Two geochemical experiments have been proposed as well. Product isotopes are proposed to be extracted from underground ores following the reactions:

In both cases, the product isotopes have half lives of the order of millions of years, so that the experiments measure the total solar neutrino flux over the past few million years. Again, both proposed experiments investigate charged current reactions only.

Two real time direct counting experiments have been proposed which would monitor charged current reactions by observing for γ -rays emitted by excited products following the reactions:

As well, electron scattering interactions with solar neutrinos may be observable. Given the greatly reduced interaction cross section for ν_μ and ν_τ relative to ν_e , this interaction provides a less than ideal monitor of neutral current interactions. The energy

threshold for the indium experiment permits observation of pp neutrinos, while the argon experiment is sensitive to the ^8B neutrinos.

An experiment has been proposed [26,27,28] which employs an ^{11}B based scintillator (TMB or TMBX) which interacts with solar neutrinos through both the charged and neutral current channels, as well as through electron scattering as follows:

$$^{11}\text{B} + \nu_e \rightarrow ^{11}\text{C} + e^- + \gamma$$

$$^{11}\text{B} + \nu_\tau \rightarrow ^{11}\text{B} + \nu_\tau + \gamma$$

$$\nu_\tau + e^- \rightarrow \nu_\tau + e^-$$

This detector would provide the most complete measure of solar neutrino flux of those discussed thus far, regardless of neutrino oscillations, since the neutral current reaction channel is sensitive to neutrinos of all flavours. This detector would require scintillator purities of femtograms per gram (fg/g) for charged particle emitting contaminants in order to maintain reasonable background rates.

SUDBURY NEUTRINO OBSERVATORY

The Sudbury Neutrino Observatory (*SNO*) will study the Solar Neutrino Problem through the detection of charged current (CC), neutral current (NC), and elastic scattering (ES) interactions of solar neutrinos with heavy water (D_2O). *SNO* makes use of the successful light water Čerenkov technology [3,24], with the sensitive medium changed to heavy water. It is similar to the Kamiokande II detector, except that the use of heavy water will allow *SNO* to observe CC and NC reactions with solar neutrinos. The CC reaction is just the inverse beta decay reaction of the solar ν_e on the neutron of the deuteron.

$$\nu_e + d \rightarrow p + p + e^-$$

The ES reaction is the elastic scattering of neutrinos off the electrons of the heavy water.

$$\nu_\tau + e \rightarrow \nu_\tau + e^-$$

The NC reaction breaks the deuteron into a proton and a neutron.

$$\nu_\tau + d \rightarrow n + p + \nu_\tau$$

The measurement of the NC rate relative to the CC rate will provide a model independent method of observing neutrino oscillations since the cross section for the NC reaction is independent of neutrino flavour. A difference in the relative rates of CC and NC reactions would imply a significant flux of solar ν_μ or ν_τ , and would imply the existence of massive neutrinos.

The measurement of the NC rate is therefore of crucial importance to our understanding of the nature of neutrinos and weak interactions. It is a critically important aspect of the *SNO* experiment.

I THE SNO DETECTOR [5]

In the SNO detector (Figure 9), solar neutrinos interact with the deuterons of the heavy water, which is contained in a transparent acrylic vessel at the centre of the detector. In the reference SNO design, these interactions always result in fast electrons, which produce an electron shower. These fast electrons and shower electrons cause the emission of Čerenkov photons into a cone about the path of the electrons. These Čerenkov photons are detected by a spherical annulus of photomultiplier tubes which surround the heavy water. The electron path length, and therefore the number of Čerenkov photons, is proportional to the electron energy. The spherical pattern of the Čerenkov light surrounds the axis of the electrons path, and hence defines the direction to the point of interaction. The relative arrival times of the Čerenkov photons at the various photomultiplier tubes will be proportional to the distance from the tubes to the electron path. Therefore the location of the interaction, the direction of the electron, and the energy of the electron may be determined.

The SNO detector will be located 2070 m. (6800 ft.) below the surface in Inco's Creighton nickel mine at Walden Ontario near Sudbury. The rock overburden has a cosmic ray stopping power of 5900 mwe. The cosmic ray signal will be attenuated by the rock, eliminating all but the neutrino and high energy muon components.

The muon rate is predicted to be 24 d^{-1} , with ^{16}O spallation events occurring at a rate near 1.5 d^{-1} , and identifiable by the successive muon and β particle signatures.

The detector (Figure 9) is contained in a cavity, cut into the norite rock, and will have a diameter of at least 20 m. The walls of the cavity will be lined to a thickness of 0.9m to 1.0 m (depending on cavity surface irregularities) with low activity sulfurcrete blocks. The blocks are boron loaded to attenuate the penetration of background neutrons from the rock into the detector. The resulting cavity will then be lined with a 6.4 mm. thick stainless steel tank to contain the detector. A cylindrical acrylic vessel of 5 m. diameter and 5 cm. thickness will be suspended within the cavity, its walls being at least 4.0 m. from the stainless steel tank. The acrylic vessel will be filled with 1000 tonnes of 99.85% D_2O (0.15% H_2O), while the space between the stainless

steel and the acrylic will be filled with H_2O . If a wider cavity is possible, a sphere of 6.0 m radius would give a better geometry and allow the use of a thinner acrylic wall. The H_2O surround will attenuate the penetration of background radiation into the D_2O , reducing the false neutrino signal to tolerable levels. The photomultiplier tubes which detect the Čerenkov light, and their support structures will be contained within the H_2O , such that the photomultiplier tubes will be located at least 2.5 m from the D_2O . Two thousand photomultiplier tubes with 50 cm diameter spherical envelopes (or equivalent) will provide 40% photocathode coverage of the detector.

The 40% photocathode coverage objective was determined in order to achieve acceptable energy, position, and angular resolution. Monte Carlo studies of the reconstruction resolutions were conducted [29] for electrons of various energies. The results of these studies indicate that achievable energy resolution, based on statistical fluctuations in the number of photomultiplier tubes hit, will vary from near 23% for 4 MeV electrons to less than 13% for 20 MeV electrons. Spatial reconstruction efficiency is expected to be nearly constant above 5 MeV, while the analyses indicate that 7 MeV electrons will be located to within approximately 70 cm. resolution. Angular resolution, again based on simulation of 7 MeV electrons, is expected to be about 30° .

II REACTION RATES

Charged current neutrino-deuteron interactions will only occur for ν_e . Cross sections (Figure 10 and [1] Table IX) are of order $10^{-42 \pm 2}$ cm² for neutrino absorption on ²H. Convolving the SSM predicted ⁸B and Hep neutrino spectra with the ²H neutrino absorption cross section will yield a flux prediction of 9750 charged current events per kilotonne year for the SNO detector, for events in which the emitted β particle carries 5 MeV or more energy from the interaction. (Note that the threshold for the charged current interaction is 1.44 MeV.) Since the β particle is significantly less massive than the protons emitted in the reaction, the mean direction of the escaping β particles will show a clear anisotropy favouring the direction of motion of the incident neutrino. The angular distribution of the emitted β particles is predicted to follow the form

$$W(\theta_e) = 1 + \frac{1}{3} \cos(\theta_e)$$

where θ_e is the angle between the incident neutrino and the emitted β particle. As well, the energy spectrum of the emitted β particles is predicted to be largely scaled to the spectrum of the incident neutrinos. The charged current reaction will therefore provide a measure of the energy spectrum of the ⁸B and Hep neutrino flux from the sun, with good statistical accuracy.

Neutrino-electron scattering interactions will occur for all flavours of neutrinos, though only electron flavour neutrinos will scatter via the charged current channel. At the SSM predicted flux (ν_e only), and a threshold of 5 MeV, 1100 neutrino-electron scattering events are predicted to be registered per kilotonne year in the SNO detector. Neutrinos of other flavours would interact with a cross section near 15% that of the electron flavour neutrinos, so that full three neutrino oscillation of the solar flux would produce a signal of fewer than 500 electron scattering events per kilotonne year. Neutrino-electron elastic scattering events will exhibit strong angular correlation with the direction to the sun, but the neutrino energy spectrum will only be a continuum. The neutrino-electron scattering events will be first observed in the detector filled with H₂O. This will distinguish this event rate from the heavy water CC event rate.

During operation of the detector with the D_2O fill, the neutrino electron scattering event rate may be monitored by observation of events in the H_2O surrounding the D_2O vessel.

Neutral current events will occur with equal probability for all neutrino flavours. The threshold neutrino energy for dissociation of deuterons via the neutral current channel is the deuteron binding energy of 2.2 MeV. Based on the SSM, the predicted rate of such interactions is 6380 per kilotonne year. Event detection mechanisms, discussed below, will not preserve any information about the incident neutrino energy spectrum or angular distribution. However, this interaction is the critical measure of neutrino flux, independent of neutrino flavour, and in conjunction with the measurement of charged current interactions, will establish whether solar neutrinos oscillate in flavour.

III CC AND ES EVENT DETECTION

For both the charged current and electron scattering reactions, an energetic electron is produced in the D_2O as a result of the interaction of the deuteron with the neutrino. The direction of travel and the energy of the electron are related to the direction and energy of the incident neutrino. Electrons with kinetic energies in excess of 261 keV will cause the emission of Čerenkov radiation about the direction of travel of the electron. As well, the electron will scatter other electrons along its path, and a shower of electrons will develop, each emitting Čerenkov radiation about their forward directions.

While the scattered electrons will have transverse momenta, there will be a persistence of momentum in the direction of the initial electron, so that there will be an anisotropy in the Čerenkov radiation. This anisotropy will define the direction of motion of the incident neutrino, while the strength of the signal will be proportional to the size of the electron shower, and through that to the energy of the incident neutrino.

Since both types of events are detected through the same mechanism, distinguish-

ing the nature of the separate interaction types will be made more difficult. This can be resolved by measuring the electron scattering event rate first by filling the detector with H_2O , so that charged current events will be prevented. Subsequent replacement of the H_2O by D_2O will permit measurement of the combined event rate, and simple subtraction will separate the two types of events, with some loss in statistical accuracy. Subsequently, variations in the electron scattering event rate may be monitored by observing events in the H_2O surrounding the acrylic tank.

IV PROPOSED NEUTRAL CURRENT DETECTION METHOD

The neutral current reaction occurs for solar neutrinos having energies in excess of the deuteron binding energy (2223 keV). In the SNO detector, this interaction rate is predicted [5] to be 6380 per kilotonne-year assuming the standard solar model neutrino flux [1]. The ^8B solar neutrino kinetic energy endpoint of 15 MeV (neglecting Hep neutrinos) results in a total recoil energy endpoint of 12.8 MeV. The released proton will ionize along its short path, but will produce little scintillation light. Its kinetic energy will be below the Čerenkov threshold of 1.46 GeV. Detection of NC events can therefore only occur through neutron capture. The neutrons resulting from this reaction will thermalize with a mean distance near 14 cm. Thermal neutrons will have a mean free path near 150 metres in the 99.85% D_2O to be used by SNO [30].

The currently favoured NC detection method for SNO relies on neutron capture on a suitable target atom specially introduced into the D_2O , followed by emission of neutron capture γ -rays. These γ -rays will then produce an electron shower, which will be observed through the Čerenkov light emitted. Potential neutron targets include the deuterons of the D_2O and additives such as Chlorine (in salt) and Gadolinium. In one kilotonne of 99.85% D_2O , 24% of neutrons born will capture on deuterons, prompting emission of 6.25 MeV in γ -rays [30]. (As well, 22% of neutrons will capture on ^1H and 4% on oxygen, with the remaining 50% escaping the D_2O .) Capture on deuterons will yield an event rate of only 4 d^{-1} . The alternatives of 4.6 kg of Gd, or 2500 kg of NaCl in additives achieve 83% neutron capture [30]. The SNO detector

threshold will be set above the low energy β and γ backgrounds (eg. ^{40}K), thus reducing overall detection efficiency for this technique to near 50%. One drawback of this method is the relatively large uncertainty in the results since the electron showers generate Čerenkov light of similar intensity to that from CC and ES events. This then requires successive detector runs, first with H_2O , and then D_2O with NC event detection suppressed by a neutron absorbing additive, in order to establish ES and CC event rates. Subsequent measurement of full (unsuppressed) event rates with subtraction of the measured ES and CC rates will yield a NC rate measurement which has a component of its uncertainty resulting from the CC event rate uncertainty.

A more serious drawback of the planned measurement method is the sequential nature of the CC and NC measurements. With perhaps a full year of measurement of the CC rate in order to establish statistically significant results, followed by filtering of the neutron absorber from the D_2O , and then perhaps another year of data gathering for significant NC results, short to medium term variations in CC and NC rates will not be separately distinguished. Potentially relevant data separating seasonal flux variations, or short term variations associated with sun spot cycles for neutrinos of different flavours, will be lost.

The planned method will also result in significant detector lost time due to filtering of the D_2O to remove the additives. It would be preferable to eliminate the need for additives altogether, and to begin real time CC and NC data taking immediately after the initial calibration and background measurements made with the initial H_2O fill.

V BACKGROUNDS [5,31]

External sources of backgrounds include the norite rock, the sulfurcrete, and stainless steel tank. Photomultiplier tubes and support structures, the acrylic vessel, the H_2O , and the D_2O comprise major internal sources of backgrounds. The boron loading in the sulfurcrete will eliminate the neutron signal from the rock, while the sulfurcrete itself will eliminate charged particle radiation from the rock. Ionizing radiation and neutrons from the rock, sulfurcrete, and stainless steel will not penetrate the H_2O . The sulfurcrete will be a strong source of 2.615 MeV γ -rays ($1.4 \times 10^5 \text{ m}^{-2} \text{ d}^{-1}$), which result from the relaxation of ^{208}Pb produced in the ^{232}Th decay chain. The component of this radiation surviving through the H_2O to penetrate the D_2O will be reduced by a factor of 3000. It is estimated that 0.2% of these γ -rays will cause photodisintegration of deuterons, contributing to the 2167 background neutrons in the D_2O per kilotonne year.

The photomultiplier tubes are expected to be the Hamamatsu 50 cm spherical tubes. Background ionizing radiation from the tubes and the support structure will not generally penetrate the 2.5 m to the D_2O surface. Background γ rays are expected to result from $(\alpha, p\gamma)$ reactions in the glass, primarily on ^{27}Al . These events are predicted to occur near a rate of 120 d^{-1} ($E_\gamma > 7.0 \text{ MeV}$), with 0.08 d^{-1} surviving into the D_2O .

Considering all sources, and setting the threshold at 5.0 MeV to mask energetic β particles emitted from ^{238}U and ^{232}Th chain daughters, the charged current background event rate will be limited to 5127 per kilotonne year (including the ES rate of 274 per kilotonne year)[5]. Background γ radiation, expected to penetrate through the H_2O into the D_2O , is predicted to be fewer than 0.2 d^{-1} . It is also expected that fewer than 4 d^{-1} will enter the one meter annulus surrounding the acrylic vessel, thus permitting observation of neutrino elastic scattering events in this portion of the H_2O .

Neutral current background activity is predicted to be 2167 events per kilotonne year [5]. Major sources of neutral current backgrounds include photodisintegration of deuterons induced by γ -rays from sources external to the D_2O primarily from the

H_2O and the acrylic vessel. Such sources will contribute 30% of the total background [31], and this will be distinguished by the high concentration of neutron births near the surface of the D_2O sphere. External background sources will contribute 325 events per kilotonne year (50% detection efficiency).

Photodisintegration will also be induced 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 remaining background will not be distinguishable from true NC events and the magnitude of this background will be known based on measurements of the purity of the D_2O . It is predicted that this will contribute a background rate of 758 events per kilotonne year. 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 [31].

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 α particles of very limited range, and fewer than 100 β 's per day. However, ^{40}K contamination in the D_2O will contribute in excess of 10^8 β 's d^{-1} per gram ($E_\beta = 1.3$ MeV). These backgrounds will not be observed by the detector due to the 5 MeV event threshold.

VI STATISTICAL ANALYSIS

Taking the ES event rate at 274 per kilotonne year (standard deviation $\sigma = 16.6$), the remaining charged current background rate to be 4853 per kilotonne year ($\sigma = 69.7$), and the SSM predicted rate for charged current events (2718 per kilotonne year), and doing the necessary subtractions, the 1σ statistical uncertainty in the charged current rate measurement will be 113.9 events per kilotonne year, or 4.2% of the observed rate. If, however, the observed rate results from a neutrino flux of one third of the SSM predicted rate, which is consistent with the Homestake and Kamiokande observations, the statistical uncertainty will be 104.2 (11.5%) of the observed 906 events per kilotonne year.

These results will be achieved by filling the detector first with H_2O , and observing ES events for a year, and then replacing the H_2O with D_2O . The D_2O will be doped with a neutron absorber to ensure that neutral current events do not provide a background to the charged current observations through neutron captures on deuterons followed by capture γ -rays and a subsequent electron shower. The charged current events will be observed for another year.

A final step involves removal of the neutron absorber, and observation of the combined ES, CC and NC event rate for another year. The predicted NC rate and background are 3122 and 1084 events per kilotonne year respectively. In the scenario in which all types of events occur at the SSM predicted rate, the 1σ uncertainty will be 144.8 events per kilotonne year, or 4.6% of the observed NC rate. The Homestake and Kamiokande results make this scenario unlikely. At an NC rate of only one third the SSM prediction, the 1σ statistical uncertainty will be 137.5 events per kilotonne year, or 12.9% of the observed rate.

The difficulties apparent include deteriorating uncertainty as the observations deviate from the SSM, and the lengthy separation in time between the CC and NC measurements, which renders the two measurements incomparable in the face of short to medium term variations in the underlying solar neutrino emitting activities.

NEUTRAL CURRENT EVENT DETECTION

I NEUTRAL CURRENT EVENT DETECTION METHODS

Solar neutrinos with energies in excess of the deuteron binding energy (2223 keV) interact with deuterons in D₂O through the neutral current reaction

$$\nu_e^* + d \rightarrow \nu_e' + p + n$$

In the SNO detector, this interaction rate is predicted [5] to be 6380 per kilotonne-year assuming the standard solar model neutrino flux [1]. The ⁸B solar neutrino kinetic energy endpoint is 15 MeV [1], resulting in a total recoil energy endpoint of 12.8 MeV. Using the Bethe Bloch formula, the rate of energy loss for the liberated proton is given by:

$$\frac{dE}{dx} \approx \frac{D Z_{med} \rho_{med}}{A_{med}} \left[\frac{Z_{inc}}{\beta} \right] \left[\ln \left(\frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) \right]$$

where

$$D = 0.3070 \text{ MeV cm}^2/\text{g}$$

$$\rho_{med} = 1.1 \text{ g/cm}^3$$

$$Z_{med} = 1, 1, 8 \text{ and}$$

$$A_{med} = 1.008, 2.014, 15.995 \text{ for}$$

$$^1\text{H}, ^2\text{H}, \text{O}$$

$$Z_{inc} = 1 \text{ for protons}$$

$$2m_e c^2 = 1.022 \text{ MeV}$$

$$\gamma = \sqrt{\frac{p^2}{m^2} + 1}$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} = 0.0136$$

This rate of energy loss is therefore near 370 MeV per cm, so that a 12.8 MeV proton will travel less than a millimetre. Its kinetic energy is below the Čerenkov threshold of 1.42 GeV, calculated via:

$$E_{th} = \frac{mc^2}{\sqrt{1 - 1/n^2}}$$

where $n = 1.334$ for D_2O and $mc^2 = 938.3$ MeV for protons. The proton will produce little scintillation light. Detection of these events can therefore only occur through neutron capture. The neutrons resulting from this reaction will thermalize with a mean distance of less than 14 cm. Thermal neutrons have a substantial mean free path in pure D_2O , and near 150 metres in the 99.85% D_2O to be used by SNO [30].

The currently favoured NC detection method for SNO relies on neutron capture on a suitable target atom specially introduced into the D_2O , followed by emission of neutron capture γ -rays. These γ -rays ($\lambda \approx 40$ cm.[32]) will then produce an electron shower, which will be observed through the Čerenkov light emitted. Potential neutron targets include the deuterons of the D_2O and additives such as Chlorine (in salt) and Gadolinium. In a one kilotonne sphere of 99.85% D_2O , where the probability of neutron birth is constant with respect to volume and therefore most probable nearest the surface of the sphere, 24% of neutrons born will capture on deuterons, prompting emission of 6.25 MeV in γ -rays [30]. (As well, 22% of neutrons will capture on ^3H and 4% on oxygen, with the remaining 50% escaping the D_2O .) Capture on deuterons will yield an event rate of only 4 d^{-1} . The alternatives of 4.6 kg of Gd, or 2500 kg of NaCl as additives achieve 83% neutron capture [30]. Over 81% of neutron captures in natural gadolinium will occur on ^{157}Gd , resulting in 7937 keV released in a multiplicity of capture γ -rays. Only 46.5% of the primary capture γ -rays exhibit $E_\gamma \geq 5.0$ MeV (36% have $E_\gamma \geq 5.5$ MeV) [33], with the balance of the energy distributed over the γ -rays from the balance of the cascade. In natural salt, over 98% of captures will occur on ^{35}Cl , resulting in 8579 keV being released in capture γ -rays. Over 57% of the primary capture γ -rays from salt will exhibit $E_\gamma \geq 5.0$ MeV (55% have $E_\gamma \geq 5.5$ MeV) [34], and consequently fewer low energy secondary capture γ -rays will be emitted in the cascade. The higher energy Cl capture γ -rays will generate a shower

containing more electrons which have energies above the Čerenkov threshold, and therefore more Čerenkov light will result from the Cl capture γ -rays than the Gd capture γ -rays. This will produce a better signal to background ratio. The SNO detector threshold will be set above the low energy β and γ backgrounds (eg. ^{40}K), thus reducing overall detection efficiency for this technique to near 50%.

One drawback of this method mentioned above is the relatively large uncertainty in the results which occurs because the electron showers generate Čerenkov light of similar intensity to those from CC and ES events. This then requires successive detector runs, and subtraction of the measured ES and CC rates in order to yield a NC rate measurement which has a component of its uncertainty resulting from the statistical uncertainty of the CC event rate.

The more serious drawback of the planned measurement method is the sequential nature of the CC and NC measurements. With perhaps a full year of measurement of the CC rate in order to establish statistically significant results, followed by filtering of the neutron absorber from the D_2O , and then perhaps another year of data taking for 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, will be lost. Separate CC and NC event readouts would, however, assure separation of events on a real time basis.

This NC detection method will also result in significant detector lost time due to filtering of the D_2O to remove the neutron absorbing additives. It would be preferable to eliminate the need for additives altogether, and to begin real time CC and NC data gathering immediately after the initial calibration and background measurements made with the initial H_2O fill.

The search for a better detection method has led to consideration of materials of high thermal neutron capture cross section, and which emit charged particles on neutron capture. With such a neutron capture target loaded in a suitable charged particle detector, the resulting signal can be distinguished from the Čerenkov signals

of the other types of events. If a scintillator is employed for the readout, this signal will be isotropic, and will be more intense than the Čerenkov light, depending upon the neutron capture target used and the characteristics of the scintillator. It will also be readily distinguished from the background of low energy β 's and γ 's which produce Čerenkov signals

II DETECTING ELEMENT COMPOSITION

The only three stable isotopes having suitably high cross sections and which emit charged products are ^3He , ^6Li , and ^{10}B . Their neutron capture reactions are given in Table IV. These three isotopes all have cross sections of the order of 10^3 barns, which is a factor of 10^6 greater than the millibarn cross sections of the deuterons. The mass of detecting material may approach 10^{-6} that of the water, or on the order of kilograms, and still achieve comparable neutron capture efficiency. Scintillating materials which have been considered include the ^3He itself, ^6LiI , ^6Li loaded cerium activated glass, ^6Li dispersed in ZnS , liquid scintillators loaded with ^6Li or ^{10}B , and ^{10}B loaded plastics. As well, ^3He and $^{10}\text{BF}_3$ have been considered in proportional chambers.

TABLE IV: DETECTING ELEMENT LOADING ALTERNATIVES

Detector Type	Composition	Reaction	Cross Section (b)	Q-Value (MeV)	% (wt) Neutron Absorber	τ_d (μsec)	Signal Strength
PWC	^3He	$^3\text{He}(n,p)^3\text{H}$	5327	0.77	100.0	n.a.	2000 e
PWC	$^{10}\text{BF}_3$	$^{10}\text{B}(n,\alpha)^7\text{Li}$	3837	2.79 (7%) 2.30 (93%)	15.0	n.a.	6000 e
Scint.	$^6\text{LiF:ZnS}$	$^6\text{Li}(n,\alpha)^3\text{H}$	940	4.76	8.0	0.1/1.0	188000 γ
Scint.	^6LiI	$^6\text{Li}(n,\alpha)^3\text{H}$	940	4.76	4.5	1.4	108000 γ

The scintillation light from ^3He is largely in the *uv*, requiring wavelength shifting to achieve sufficient signal in the sensitive range of the photomultiplier tubes. Such wavelength shifters would also intercept and shift some of the otherwise undetected

uv light from Čerenkov events; light which would otherwise not penetrate the photomultiplier tube glass envelopes. This would introduce a small, isotropically scattered background to such Čerenkov events. Alternatively, proportional tubes containing ^3He accomplish good neutron detection. BF_3 would be a good alternative to ^3He , since neutron captures in BF_3 will produce triple the number of ion pairs compared with captures in ^3He [35]. However, BF_3 is electronegative, capturing electrons which are migrating toward the anode, and quenching the signal. This would require that the proportional tube operate at low pressure to minimize quenching. Considering that a greater mass of BF_3 would be required than ^3He , resulting in a greater displaced volume and a more stringent material purity requirement, no inherent advantage is seen for BF_3 . In either case, the NC detection signature would be distinct from the CC and ES signatures, satisfying the objective and allowing improvement in the statistical accuracy of the detection method.

Lithiated or borated organic scintillators have not generally been successful. Loading levels tend to be low in order to minimize quenching. This leads to larger overall scintillator masses in order to achieve the same neutron capture objectives, as compared with other alternatives. Further, the light emitted by borated organic scintillators on neutron capture would not be clearly separated from the Čerenkov light of CC events. Ninety three percent of neutron captures in ^{10}B will result in 2.3 MeV being shared between the α and the ^7Li reaction products. Given the large pulse height defect typical of heavy particles in loaded organic scintillators (eg. a factor of 19 for TMB [36]), the light signal from neutron capture on ^{10}B will be of the same intensity as the Čerenkov light from CC and ES interactions (eg. $2.3 \text{ MeV}/19 = 121 \text{ keV}$ equivalent β particle. At 1γ per 100 eV, this yields approx 1210 photons).

Lithiated inorganic scintillators present a challenge to achieve sufficiently high purity levels to maintain acceptable signal to background ratios. The energy spectrum of charged disintegration fragments of uranium and thorium chain daughters largely overlaps the signal produced from ^6Li on neutron capture. Despite this, lithiated inorganic scintillators offer the greatest hope of achieving good neutron detection

efficiency while minimizing detector mass. Lithium loaded cerium activated glass displays background activity at many times the tolerable rate for this detector (at least 20 dpm per 100 grams [37]). Of the scintillators and loading elements mentioned, the most practical choices appear to be ${}^6\text{Li}$ dispersed in ZnS, and ${}^6\text{LiI}$.

Neutron capture in compounds of ${}^6\text{LiF}$ and ZnS(Ag) in a lucite carrier, in the weight ratios of 1:2:1 respectively, have been analysed and reported in the literature [36, and references within]. The scintillation properties of ZnS are generally well known. 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 [35] for such compounds. The wavelength of peak emission of ZnS is $\lambda_{\text{peak}} = 450 \text{ nm}$. [36]. Zinc sulfide attenuates the light signal at a thickness greater than 25 mg cm^{-2} [36]. At this thickness, the probability of capturing a neutron transiting normal to such a ${}^6\text{LiF:ZnS(Ag)}$ compound will be 15%. Thin acrylic plates or disks containing up to $60 \mu\text{m}$. of ${}^6\text{LiF}$ loaded ZnS are therefore envisaged. With the release of 4.76 MeV into the ZnS via the energetic α and triton fragments emitted on neutron capture on the ${}^6\text{Li}$, the scintillation light signal will differ from the Čerenkov light of other SNO detection events in two ways. It will be isotropic, and the amount of light generated in the spectral range of the pmt envelopes will greatly exceed the approximately 1200 to 1400 photons for a typical 10 MeV Čerenkov event. The fast component of the scintillation light decay is reported [36] to be less than $0.1 \mu\text{s}$, with a slow component exceeding $1 \mu\text{s}$. With such a strong light signal, negligible photon losses in the D_2O , and 40% photocathode coverage of the detector, there will be a high multiplicity of photomultiplier tubes detecting each event. Based on the reference SNO design which employs 2000 50 cm. pmt's, and assuming a 10 ns minimum resolving time, the mean rate of photon detection will be as high as 0.38 γ 's per pmt per 10ns using ${}^6\text{LiF:ZnS}$, compared to 0.06 γ 's per pmt per 10ns for Čerenkov detection. Multiple pmt coincidences can provide event triggers since the random coincidence rate will be less than 1 d^{-1} for as few as five

pmts, according to the formula

$$R_c = 2(R)^n t^{n-1}$$

and where the coincidence resolving time t is 100 nanoseconds and the mean random rate $\langle R \rangle$ in the tubes is 10^4 Hz. Event reconstruction can be accomplished through analysis of signals and arrival times at detecting tubes. The index of refraction of heavy water being $n = 1.334$, photon transit times across the 12 metre diameter of the tank will be less than 54 ns. Photon arrival times as a function of photomultiplier tube position, signal angular distributions, and signal size can be employed to determine the event origin with reasonably good accuracy, through the use of numerical fitting routines. With the origin determined, the signals from all pmt's can be fit to the known shape of the light pulse from the scintillator in order to verify that it conforms to the signature of a neutron capture event.

With suitable encapsulation, ^6LiI crystals are equally promising, achieving neutron blackness near a thickness of 2 mm. The scintillation efficiency of $^6\text{LiI}(\text{Eu})$ on neutron capture is reported [35] to be 12 times that of ^6Li loaded, cerium activated glass. The light yield on neutron capture in $^6\text{LiI}(\text{Eu})$, by comparison with the yield of such glass [35], is expected to be 57% of that from $^6\text{LiF:ZnS}$, or 108,000 photons. The wavelength of peak emission is $\lambda_{\text{peak}} = 475$ nm., and the scintillation decay time is $\tau_d = 1.4 \mu\text{s}$ with the Eu activator [36]. The use of Sm as the activator may reduce the scintillation light decay time to $0.25 \mu\text{s}$, at a small (12%) reduction in light yield, while still peaking in the blue region of the spectrum [36]. Crystals of ^6LiI are hygroscopic, but if encapsulated in small diameter acrylic tubes or straws coated to retard water permeation, they would exhibit good neutron detection efficiency and a strong light signal. Photon detection and event reconstruction would be similar to the $^6\text{LiF:ZnS}$ case, with the photon interception rate for $\text{LiI}(\text{Eu})$ [$\text{LiI}(\text{Sm})$] being half [twice] the ZnS rate suggested above.

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

CC = 1/3 SSM:	NC = SSM		NC = 1/3 SSM	
	N	$\sigma(\sqrt{N})$	N	$\sigma(\sqrt{N})$
CGR 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	1063	137.5
		(4.6%)		(12.9%)
PROPOSED 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	531	67.4
		(4.7%)		(12.7%)

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

III DETECTION EFFICIENCY AND BACKGROUND STATISTICS

It is apparent in Table V that with a much smaller neutron capture probability for the proposed method (about 25%) than for the capture γ ray method (about 83%) the same statistical accuracy can be achieved in the measurement of the NC rate. This is possible because the proposed method is independent of the CC and ES signals, removing the necessity of making subtractions of a relatively small number of statistically equivalent signals. Best estimates of the backgrounds to the two methods have been considered in developing the analysis shown in Table V.

As previously discussed, the SNP has had two popular explanations. The first is neutrino flavour oscillations, in which case the NC signal may be up to three times stronger than that predicted from the observed CC signal. The second is that the standard solar model is wrong, in which case the NC signal would be that predicted by the measured CC rate. Table V provides the statistical analysis for these two cases. Columns 2 and 3 give the rates and the errors for the SSM case assuming neutrino 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 results for the capture γ ray method while the bottom half gives gives the results for the proposed method.

Neutron background to the NC signal is predicted to be $2167 \text{ events per kilotonne year (kt-y)}^{-1}$ [5]. One major source of neutral current 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 [31], and will be distinguishable by the high neutron birth rate near the surface of the D_2O sphere. External background sources will contribute $325 \text{ events (kt-y)}^{-1}$ in the capture γ -ray case (50% detection efficiency), or $163 \text{ events (kt-y)}^{-1}$ for the proposed method (25% detection).

The other source of background neutrons is photodisintegration caused by γ -rays from contaminants internal to the D_2O , particularly from ^{205}Tl (2.1 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 on measurements of the purity of the D_2O . For the capture γ -ray method, assuming secular equilibrium and ^{238}U and ^{232}Th contamination in the D_2O and $NaCl$ at 10^{-14} and 10^{-12} respectively, this will contribute a background rate of 758 events $(kt-y)^{-1}$. For the proposed method, this background will contribute 379 events $(kt-y)^{-1}$. A large systematic uncertainty in this background resulting from uncertainty in the ^{208}Tl and ^{214}Bi concentrations may be up to 25% of the predicted internal background rate [31]. A capability to concentrate detecting elements in the D_2O near the acrylic vessel will allow measurement of the profile of neutrons from photodisintegration of deuterons caused by γ -rays from the acrylic to good precision.

The proposed method also assumes that α and β emitting scintillator contaminants, and detection of low energy β and γ activity by the scintillators will increase the background rate by up to $4 d^{-1}$. The contribution to background due to emissions from scintillator contaminants will be a simple function of scintillator mass and purity, with 100% detection efficiency for α 's and β 's. The background due to intercepted and contributed low energy β 's and γ 's will be a function of the background spectrum, the thickness of the scintillators used, and the proportion of the fiducial volume occupied by neutron detecting scintillators. The contributions to the background resulting from contained contaminants will be measurable before and during operation of the detector with the initial H_2O fill. As well, the energy deposited in thin scintillators by β particles, and thus the scintillation light output, will be less than that due to α emissions, distinguishing β particle backgrounds from the signal.

With the ^{238}U and ^{232}Th concentrations in the D_2O being near 10^{-14} g/g each, these contaminants will emit fewer than 100 β 's per day. Since the electron range in the D_2O is near 10^{-4} that of a neutron, the probability of such β 's encountering a detecting element is small. However, 1 gram of ^{40}K contamination in the D_2O will contribute in excess of 10^8 β 's d^{-1} , and therefore a signal 10^3 that of the neutron signal. Achieving a ^{40}K concentration in the D_2O of near 10^{-11} g/g will however reduce this background to negligible levels. Background γ -ray ranges in water are

near three orders of magnitude below those of thermal neutrons, and their encounter with detecting elements is also improbable at source impurity levels similar to those mentioned above. Further, encounter between these γ -rays and thin scintillators is unlikely to result in a detectable signal since photon ranges in such materials are two to three orders of magnitude greater than the scintillator thickness. These sources of background can therefore be considered trivial, providing that the ^{40}K concentration is reduced to the nanogram per gram range.

IV MONTE CARLO SIMULATION

A Monte Carlo program has been written to simulate the neutron capture process in the SNO detector for both the capture γ -ray and proposed methods. In this program, the incident ^8B neutrino energy spectrum is simulated and neutrons are born throughout the D_2O , thermalized, and scattered. Probabilities are calculated for neutron capture in detectors, absorption in the water and its additives, and 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 material employed.

Operation of this Monte Carlo has provided confirmation of the neutron capture probabilities for deuterons, gadolinium, and chlorine additives, against independent predictions [30]. This Monte Carlo has also produced neutron capture predictions in close agreement with other predictions [38] for a matrix of ^3He proportional tubes. This program has subsequently been operated to determine the recommended mass, shape, and spacing of other discrete neutron absorbing and scintillating elements, and the photon losses on insertion of the elements, as discussed below.

NEUTRAL CURRENT DETECTION MONTE CARLO

I PROGRAM OBJECTIVES

The purpose of the Monte Carlo is to simulate neutrino-deuteron neutral current interaction events, including the incident neutrino energy spectrum, the interaction location, the breakup of the deuteron and release of the energetic neutron, and the thermalization and scattering of the particle. The probability of neutron absorption on the components of the water is calculated, and the probability of neutron capture on discrete detecting elements is determined where such detectors are present. (The possible back-scattering of neutrons which have escaped the D_2O is not considered in the Monte Carlo, but will be discussed with the results.) The fiducial volume is taken to be a spherical kilotonne of D_2O . The stipulation of various sets of input parameters, including the D_2O purity and additives, and discrete element geometry and thermal neutron mean free path are required. Determination of the effects of variations of these parameters on neutron detection efficiency is the principal objective of this work.

The detection efficiency is known from another proven Monte Carlo program, for the case of 99.85% D_2O without additives or with NaCl or Gd additives [30]. The D_2O without additives is known to achieve 24% neutron capture on deuterons, 22% neutron capture on ^1H , 4% capture on oxygen, and 50% neutron escape from the fiducial volume. It is also known that adding 2500 kg of NaCl or 4.6 kg of Gd to the heavy water will raise the combined neutron capture efficiency to near 83% for deuterons plus the additives. This will provide a valuable test of the Monte Carlo accuracy for the 99.85% D_2O cases with and without additives, where no discrete detecting elements are present. This prior Monte Carlo does not, however, allow simulation of neutron capture on discrete detecting elements.

The proposed new method for neutral current event detection involves insertion of discrete neutron detecting elements into the fiducial volume. These detecting elements may have various compositions, and simulation of various sizes, shapes, and

spacings will be required in order to optimize the technique. The Monte Carlo is required to accept such possible variations in the geometry of the detecting elements as tubular rods or straws, circular disks, square plates, or cubes and to allow for different compositions of detecting elements through a facility for specifying the thermal neutron mean free path within the detecting elements. As well, the Monte Carlo must permit selection of the inter-element lattice spacing. With such a detecting element matrix specified, the Monte Carlo must then calculate the probability of neutron capture on such detecting elements, while allowing for prior absorption of neutrons in the D_2O or its additives.

Another Monte Carlo was constructed by members of the SNO collaboration from the Los Alamos National Laboratory, specifically for the purpose of determining the neutron capture probability in a matrix of discrete tubular detecting rods containing ^3He gas. The results of this work [38] indicate that 1.0 cm. inside radius detecting tubes, placed on a 100 cm square lattice, with tubes extending the full height of the fiducial volume, and containing ^3He gas at 1 atmosphere pressure, will achieve 20% neutron capture (see Figure 11). A similar configuration, but on a 25 cm square lattice, yields a prediction of near 80% neutron capture. Predictions for other lattice sizes and other gas pressures are also available. These results will serve as a test for the present work, and while this other Monte Carlo is not verified experimentally, corroboration of these results will provide assurance of the accuracy of these routines for other discrete detecting element sizes, shapes, spacings, and compositions.

Results to be provided by the routines include summary data regarding the heavy water and its additives, and the size, shape and spacing of the discrete detecting elements. Incident neutrino energy spectra, neutron birth energy spectra, neutron birth location profiles, and thermalization distance summary results will provide necessary integrity checks for the routines. With neutron scattering distances being random, but fitting an exponential distribution with mean values equal to the known values for the elements involved, summary data on neutron scattering length distributions, accumulated scattered path length and displacement from birth location will provide

other integrity checks. Summary output of the neutron absorption probabilities for each of the elemental components of the heavy water, and capture probabilities for the discrete detecting elements will complete the neutron transport reporting requirements for the Monte Carlo.

Separate calculations of photon losses on detecting element insertion will also be achieved through the use of modified routines.

The SSM predicted event rate for the SNO detector is 6380 per kilotonne year. Accordingly, operation of the Monte Carlo may involve simulations of as many as 10,000 events in any run, in order to ensure statistical significance. Given the anticipated thousands of scatterings of each neutron simulated, such Monte Carlo runs may involve hundreds of millions of steps. The routines will therefore be required to operate efficiently, and in batch. The programs are intended to operate on a Digital Equipment Corporation VAX computer.

II PROGRAM STRUCTURE

The neutral current event simulation Monte Carlo consists of two principle Fortran 77 programs, a data file containing library information about the potential additives to the heavy water, and two command procedures to manage and sequence the routines. The first command file (NC.COM) initiates the operation of the Monte Carlo, and runs the first fortran program (NCINPUT). This fortran program gathers input information and reads the library data file (ADDITIVES.DAT) to describe the detector parameters, and summarizes these in a temporary data file (RUNPARMS.DAT). The command file then submits the second command file (NCBATCH.COM) to the batch queue. This second command file runs the second fortran program (NCMAIN). This fortran program reads the information in the temporary data file. It simulates the neutron generation, scattering, and detection process, and then creates an output file (NCOUTPUT.DAT) suitable for printing out the results of the simulations. On completion of the second fortran program, the command file deletes the temporary data file. The program listings and detailed program explanations are contained in Appendix 2.

MONTE CARLO RESULTS

The Monte Carlo programs have first been operated in order to verify the accuracy of the routines. Comparison of the results of these trial operations with those produced by the other Monte Carlo programs, for the cases of 99.85% D_2O with and without additives, and for the ^3He detector case, has confirmed their accuracy. Subsequently, the programs have been operated in order to discover practical $^6LiF:ZnS$ and ^6LiI scintillating element geometries. The Monte Carlo output reports for these tests are contained in Appendix 3.

A modified version of the Monte Carlo routines has been operated in order to investigate the probability of photon losses on insertion of the detecting elements. Another modified version of the Monte Carlo has been used in order to study the potential impact of the approximation taken in the Monte Carlo that neutrons which escape the D_2O sphere do not scatter back into the sphere.

I RESULTS COMPARISON WITH OTHER MONTE CARLOS

Neutron Absorption Predictions From ANISN Program

The neutron absorption predictions derived from operation of the ANISN program [30] indicate that, for neutrons born throughout a spherical kilotonne of 99.85% D_2O , 24% of neutrons will be captured on deuterons, while ^1H atoms will capture 22% of the neutrons and oxygen will capture 4%. The present Monte Carlo was operated for 10,000 events, verifying these predictions within the statistical uncertainty, as shown in Report 1 of Appendix 3. The Monte Carlo predicts a probability of neutron capture on deuterons of 24.8%, with capture on ^1H at 22.7% and capture on oxygen at 4.1%. The neutron escape probability is predicted to be 48.4%. While these capture probabilities are slightly greater than those predicted by the ANISN Monte Carlo, the statistical uncertainty is greater than the disagreement.

In addition to the neutron capture probabilities, the Monte Carlo provides information about neutron scattering and about the medium. The neutron scattering

mean free path is calculated to be 2.825 cm. Based on this, and the number of collisions required to thermalize the neutrons, calculated according to Segre [39], the thermalization distance is predicted to be near 14 cm., confirming the ANISN prediction [30]. The Monte Carlo also reports that 1.8% of neutrons escape the fiducial volume prior to thermalization.

The Monte Carlo determines the probability of neutron absorption in the medium by first scattering all neutrons from their thermalization locations to the point of escape from the D_2O . Neutrons are then determined to have been previously absorbed based upon the length of the path they have travelled in reaching the escape point. In this light, the number of neutron scatters and the distances travelled by neutrons, as shown in the Monte Carlo reports, are overstated.

In order to assess the impact of the decision to ignore the potential return of neutrons which scatter out of the spherical kilotonne, a modified version of the program was operated which permitted return of neutrons from up to 6 cm. outside of the D_2O . This program was operated for the case of 99.85% D_2O without additives. The 6 cm. limit was selected on the grounds that the neutron absorption mean free path in H_2O will be approximately 25 cm, and the scattering mean free path will be near 1 cm., as calculated by the Monte Carlo. A random walk which carries a neutron a depth of 5 cm into the H_2O , returning to the D_2O again, will travel one absorption mean free path, while scattering 25 times, and will therefore have a 36.8% ($1/e$) probability of survival. Similarly a neutron which penetrates to a depth of 6 cm. into the H_2O before returning to the D_2O will travel 36 cm within the H_2O , and will have a 24% probability of survival. Making the overestimating but simplifying assumption that all neutrons which penetrate up to a 6 cm. depth in the H_2O and then return to the D_2O will survive, this test yielded a 1.2% increase in neutron absorption, relative to the case shown in Report 1. This is of the same order as the 1% (1σ) statistical uncertainty in the results, so that the actual error attributable to the assumption is only a fraction of the statistical uncertainty in the results and is therefore almost negligible.

The ANISN program was also employed to study the neutron capture probabilities available from the use of additives in the D₂O. The additives considered in the SNO reference design were NaCl (2.5 tonnes) and Gd (4.6 kg), and the neutron capture probability attributed to each of these cases approached 83% combined capture on the Cl or Gd additives plus the deuterons [30]. The present Monte Carlo was operated for both of these cases, and the results, shown in Reports 2 and 3 of Appendix 3 for the NaCl and Gd cases respectively, indicate 2.5% to 2.7% capture on deuterons and 79.4% or 80.2% capture on Cl or Gd respectively. Again, the present results coincide with the ANISN results within the statistical uncertainty. While the neutron scattering mean free path and thermalization distance remain unchanged from the case without additives, the neutron absorption mean free path is reduced by the additives to near 10 m. While the same 1.8% of neutrons escape prior to thermalization, only 14% of thermalized neutrons escape. The neutron losses on ¹H, oxygen, and Na are also small.

These results can be taken as confirmation that the Monte Carlo neutron birth routines, scattering, random walk, and absorption routines operate correctly.

Neutron Capture In ^3He Proportional Tubes

The Monte Carlo written at Los Alamos Laboratory has predicted neutron capture efficiencies for ^3He filled proportional tubes of 1 or 2 cm. radius, maintained at 1 or 3 atm. pressure [38]. Simulations have been studied for tubes extending vertically the full height of the D_2O , on square grids of 25 cm. to 100 cm. lattice constant. The SNO detector geometry simulated was for the cylindrical reference design, rather than the preferred spherical design. The present Monte Carlo was operated for similar conditions (1 cm. radius tubes only), but for the spherical design, and the results are shown in Reports 4 through 7 of Appendix 3. Compared with the Los Alamos results as shown in Figure 11 of Appendix 1, the agreement is excellent for the smaller lattice constants. The differences between the LANL and present Monte Carlo results for the 100 cm. lattice constants exceed 1% (1σ statistical uncertainty) of the present work, but the impacts of the different SNO detector geometries may well account for part of the approximately 3% difference. The LANL model has the principal axis of the detecting tubes parallel with the principal axis of the fiducial volume. This configuration yields an approximately 1.1% greater overall proportional tube length (907 m vs. 897 m), and together with the full extent of a 3σ statistical error, account for the disagreement in the results. The convergence of the results of the two Monte Carlos at smaller lattice constants is reassuring. The results are therefore taken to be in agreement, and the routines simulating neutron encounter and capture on detecting elements are taken to be corroborated.

The impact of the decision to neglect neutron scattering back from the H_2O was not determined for the ^3He detector case, but will be addressed again for the scintillator scenarios.

II DETECTOR SIMULATION RESULTS

The objective taken for this work was to determine efficient and practical detecting element geometries to achieve 25% neutron capture efficiency for the three detecting element materials selected, those being ^3He proportional wire chambers, $^6\text{LiF:ZnS}$ scintillating plates, and tubes or straws of ^6LiI . This was achieved through operation of the Monte Carlo programs for various sets of the input parameters of detecting element lattice spacing and detecting element dimensions. Neutron mean free path lengths within the detecting elements were taken to be 7.009 cm. for ^3He (1 atm. pressure), 0.037 cm. for $^6\text{LiF:ZnS}$, and 0.058 cm. for ^6LiI .

It is intuitively obvious that materials which are diffused throughout the fiducial volume will be most efficient at neutron capture, since such a diffuse scenario will present the greatest accumulated cross section integrated along the full extent of the neutron's path. The requirement that the neutron capture efficiency be maximized despite the concentrating of the absorbing material into discrete detectors demands that the detector lattice size be sufficiently small relative to the neutrons mean free path in the D_2O as to present the neutrons with a high probability of encountering such a detector. Any lattice spacing of the order of a metre or less will satisfy this requirement, given the roughly 150 metre random walk executed by neutrons prior to absorption in the D_2O . The more stringent requirement will then be the need for the detectors not to impede the photons generated by Cerenkov events or in other scintillators. In this case, smaller detectors and smaller lattice spacings will always be preferable because they will present less contiguous obstruction. Finally the practicalities of handling the detectors must limit the quantity of detectors and thus the lattice spacing. The lattice assumed for the ^3He detection scenario was taken to be a 100 cm. square grid in the x-y plane, with detectors extending the full height of the fiducial volume. In the ^6Li loaded scintillator scenarios, the lattice was taken to be a 25 cm. cubic grid. These lattice sizes were considered to be the minimum practical spacing for detector handling.

At the same time, the amount of absorbing material contained in such a detec-

tor must be such that the required capture efficiency is achieved. This does not necessarily require that the detectors be neutron black, or even have a 25% capture probability for a crossing neutron, since detectors which are large relative to the neutrons scattering mean free path will intercept the same neutron numerous times. This 'multiple scattering' effect can be used to limit detector thickness, and thus detector mass, without sacrificing detection efficiency. It will allow the detection efficiency, as a function of detector mass, to approach the best case solution, in which the absorbing material is diffused throughout the D_2O . This calls for a detector thickness which, when taken together with the mean number of neutron crossings of a detecting element, gives a good probability of neutron capture. The product of this probability and the probability that neutrons will locate detecting elements must equal the desired neutron capture efficiency.

With these lattice spacing constraints decided, detecting element dimensions were established such that the neutron capture efficiency predicted by the Monte Carlo was near 25%. Subsequently, the neutron capture efficiency as a function of detector mass was determined by operating the Monte Carlo again with the same mass of detecting material hypothetically taken to be an additive to the D_2O . Where the detection efficiency of the elements approached the efficiency achievable with the same mass of material in a diffuse neutron absorbing additive, the design was taken to be optimized.

^3He Proportional Chamber Detector Results

The Monte Carlo results (Report 8 of Appendix 3) indicate that proportional chambers containing ^3He gas at 1 atm pressure will achieve 24.5% neutron capture efficiency with an inside diameter of 2.1 cm. At this thickness, the probability that a neutron will be captured in a single pass through the detector is 28.3%. In this case, neutrons which encounter detectors travel a mean distance of 130 metres, but are captured on average only 2 metres displaced from their birth locations. The impact of the detectors on the absorption of neutrons on deuterons is to reduce the absorption probability to 17% from the previous 24%.

Such proportional chambers will displace a volume of 311 litres, which will contain 35.3 g of ^3He at 1 atm. pressure. As shown in Report 9 of Appendix 3, 35.3 g of ^3He if dissolved in the D_2O , would achieve 24% neutron capture efficiency, indicating that the proportional tube geometry is optimized.

$^6\text{LiF:ZnS}$ Scintillator Results

The thickness of the $^6\text{LiF:ZnS}$ scintillators was taken to be not more than $60\ \mu\text{m}$ so as to not attenuate the scintillation light signal. This thickness achieves a 27.5% single pass neutron capture probability. At this thickness, 25.2% neutron capture efficiency (see Report 10 of Appendix 3) was achieved by the Monte Carlo at a detector size of 2.9 cm. square. The distances travelled by neutrons prior to capture, and the displacements from birth to capture remain as in the ^3He case. The neutron escape statistics and neutron capture on deuterons are also similar to the ^3He case.

In order to determine if the neutron capture efficiency was optimized for this detector mass (9.71 kg), the Monte Carlo was operated again with the loaded scintillator material treated as a hypothetical set of additives dissolved in the D_2O . The results of this Monte Carlo simulation are given in Report 11 of Appendix 3. The neutron capture efficiency which would be achieved by the ^6Li in such an additive would be 27.1%, compared with the 25.2% achieved by the detectors. This indicates that the geometry chosen is nearly optimized.

The assumption that escaping and returning neutrons will have negligible impact on neutron capture efficiency was verified again for the discrete detector case. The modified Monte Carlo was operated again permitting neutrons to return from as far as 6 cm. into the H_2O , with the above ${}^6LiF:ZnS$ detector configuration. The results indicate an increase in detection efficiency from 25.2% to 26.5% for the detectors and are similar to the previous test.

${}^6LiI$ Scintillator Results

With the lattice spacing selected at 25 cm., the process employed to determine the detecting element geometry for ${}^6Li$ was to first elect a loaded straw shaped design with thickness such as to achieve neutron blackness (0.27 cm.), and then use the Monte Carlo to determine what length of straws would achieve 25% detection efficiency. The diameter of the straws was then reduced in subsequent Monte Carlo simulations, while extending the length of the straws so as to maintain 25% capture efficiency. This process was halted as the straw length approached the 25 cm. lattice spacing. The results (Report 13 of Appendix 3) are for the case of 1 mm. diameter straws of 23.5 cm length, and the capture efficiency achieved was 25.6%.

The mass of ${}^6LiI$ in such a set of detectors would be 38.7 kg. A test of detector efficiency optimization was then conducted by operating the Monte Carlo with the same mass of ${}^6Li$ and I as an additive to the D_2O , and the results (Report 14 of Appendix 3) indicate that this mass of material would capture 53.8% of the neutrons if diffused throughout the volume. This implies that a substantially lesser mass of ${}^6LiI$ could be employed in a different geometry to achieve the required 25% capture efficiency. Now capture probability is largely a function of detector surface area and neutron path length in the D_2O . A design which maintains the surface area of the straw design, while reducing the volume and hence mass of material, maintaining 25% neutron capture efficiency will be more optimized. In order to achieve this reduction in mass, it should be noted that the neutron absorption mean free path in the ${}^6LiF:ZnS$ was 0.037 cm., achieving a mean capture probability of 27.5% for a

neutron transiting the 0.006 cm thickness (integrating over all angles of incidence). In the ${}^6\text{LiI}$ case, the mean free path was 0.058 cm., achieving 85.3% capture probability for neutrons transiting the 1 mm. straws, integrated over all incidence angles around the surface of the straws. In order to better optimize the design for the ${}^6\text{LiI}$ detectors, a flat plate design with a thickness to achieve closer to 25% capture probability on a single transit of the detector would be indicated. Adopting a geometry similar to that employed in the ${}^6\text{LiF:ZnS}$ simulations, with the thickness adjusted to account for the different cross sections of the materials will achieve the required 25% capture efficiency with less scintillator mass.

III PHOTON LOSSES ON DETECTOR INSERTION

Finally, a modified version of the Monte Carlo was employed to determine the photon losses on insertion of these different detector geometries in the D_2O . The extent of the modifications was to eliminate the neutron thermalization routines in order to ensure a constant density of photon births, and to fix the scattering mean free path to a distance greater than the diameter of the D_2O vessel. This would ensure that photons would be born at random throughout the fiducial volume, and then directed at random to escape the D_2O volume without scattering. The routines to test for interception of the photons with 'black' detecting elements would then count photons lost. This modified Monte Carlo was operated for one million events for each of the ${}^3\text{He}$ proportional tube, ${}^6\text{LiF:ZnS}$ plate, and ${}^6\text{LiI}$ straw designs. The results indicate photon losses of 4.7%, 6.7%, and 3.7% respectively.

IV RESULTS SUMMARY

It was shown in Table V that 25% detection efficiency achieved through such a discrete detecting element method would result in a neutral current event rate measurement of comparable accuracy to the presently planned method. This could be achieved despite a 4 d^{-1} increase in detected background from contained and intercepted radiation. These Monte Carlo simulations have shown that 25% capture efficiency can be achieved with the proposed detecting elements. Suggested designs for such detecting elements are 35.3 g of ^3He in proportional wire chambers, 9.71 kg of $^6\text{LiF}:\text{ZnS}$ in detector disks, or 38.7 kg of ^6LiI in straws, taking the geometries to be as listed in Table VI. The ^6LiI design is not optimized, but a design similar to the $^6\text{LiF}:\text{ZnS}$ disks containing less ^6LiI would achieve the detection objectives. Furthermore, the 'straw' design does minimize photon losses on detector insertion.

TABLE VI: SUMMARY OF DETECTION ALTERNATIVES

Detector Composition	Scintillator Mass (kg)	Material Purity Required (10^{-12} g/g)			Volume Displaced (L)	Geometric Configuration
		^{238}U	^{232}Th	^{40}K		
NaCl	2500	1	4	n.a.	115	Added to D_2O
Gd	4.6	1	4	n.a.	0.6	Added to D_2O
^3He in Prop. Tubes	0.0353	0.03	0.14	0.65	263	2.1 cm. diam. tubes, 1 atm. 897 m. long, vertical on 100 cm. square grid.
$^6\text{LiF}:\text{ZnS}$ in Acrylic Plates	9.71	0.005	0.022	0.10	2.7	2.90 cm. square, $60\mu\text{m}$ thick. 54362 plates, 25 cm. cubic grid
^6LiI in Acrylic Tubes	38.7	0.002	0.007	0.03	10.0	1 mm. diam., 23.5 cm. long. 54362 tubes, 25 cm. cubic grid

* including mass of containment/carrier materials

Observable α and β emissions at a rate of 1 d^{-1} will result from impurities in the amounts of 1300 pg of K, 67 pg of ^{238}U , and 280 pg of ^{232}Th . The required impurity

concentration limits for the ^3He , equivalent to these amounts of contaminants are respectively $0.4 \cdot 10^{-10}$ g/g, $1.9 \cdot 10^{-12}$ g/g, and $7.9 \cdot 10^{-12}$ g/g. Similar background contributions will be seen from these same contaminants in the $^6\text{LiF:ZnS}$ at 0.36% of the above levels, or in the ^6LiI at 0.09% of the above levels. While there is no record of these difficult purity levels having been achieved for inorganic scintillators, similar levels have been reported for organic liquid scintillators on distillation [28]. Since the range of β particles is much greater in scintillators than that of the heavy p, t, and α particles resulting from neutron capture, good pulse height resolution of the scintillators will permit distinguishing of the smaller background signals contributed by β particles (eg. ^{40}K) on crossing the thin scintillating elements. Further study may provide pulse shape or rise time distinctions between scintillations from 4.5 MeV to 5 MeV α emissions due to contaminants, and from α -triton emissions from ^6Li on neutron capture.

In the case of the ^3He approach, additional mass will be contributed in gas containment and high voltage electrode materials. At 1 atmosphere pressure, 35.3 g of ^3He will occupy a volume of 311 liters, displacing 341 kg of D_2O . (While higher gas pressures would reduce the volume displaced, containment vessel material requirements would become more rigorous.) Material purity requirements may be more stringent by two orders of magnitude than stated above for the ^3He alone, considering the α and β background contributed by the approximately 2 kg of containment materials at the contact with the surface of the gas (surface mass [38]). For the scintillator scenarios, solid plates or small diameter tubes will be required to contain and carry the scintillators. Acrylic materials would be sufficient for these tasks, having a density near that of the heavy water, though a coating to retard water permeation may be required. Purity requirements for these materials would be of the same order of magnitude as the scintillator constituents, since the approximately 1 kg of material within α particle range of the scintillator will not greatly increase the mass of the detectors for either the $^6\text{LiF:ZnS}$ or ^6LiI methods.

CONCLUSIONS

The difference between the predicted and measured ${}^6\text{B}$ solar neutrino flux, known as the Solar Neutrino Problem, may result from a solar core temperature which is different from the predicted value, or from as yet unproven neutrino physics. A difference between predicted and actual solar core temperatures of only 5.9% may be capable of causing the SNP, but such a temperature is outside the 3σ (99.7% confidence level) predictions. Neutrino physics which may be capable of causing the SNP includes vacuum or matter enhanced neutrino oscillations from electron flavour to μ and τ flavour, a non vanishing neutrino magnetic moment which results in neutrino helicity flipping into sterile neutrinos, or a more exotic mechanism such as flavour changing neutrino spin rotations. There is no experimental evidence to support any of these theories, but the most favoured of these alternatives is the case of matter enhanced neutrino oscillations.

Though two solar neutrino observatories have confirmed the deficit in observed solar electron neutrino flux, neither of these observatories is capable of direct observation of evidence of neutrino oscillations. Of the observatories proposed to address this question, only the Sudbury Neutrino Observatory, (SNO) and the proposed BOREX (${}^{11}\text{B}$) detector are capable of observing the essential neutral current interactions which provide direct evidence for or against neutrino oscillations.

The SNO detector, as proposed, is capable of observing these neutral current interactions, but is limited in the accuracy with which it can separate neutral current interactions from other types of interactions. In this work, it was further identified that the SNO detector is not capable of separating periodic variations in the relative rates of charged current and neutral current interactions, though there appears to be evidence that the solar electron neutrino flux varies inversely with the sun spot cycle. This would imply that neutrinos have a non- vanishing magnetic moment and helicity flip into sterile neutrino types, or that neutrinos oscillate in flavour and rotate in spin space. SNO, as proposed, would be limited in its ability to achieve real time separation of the various components of a cyclic neutrino flux.

An alternative neutral current detection mechanism has been proposed for SNO, which would overcome the shortcomings identified above, and may permit earlier completion of SNO calibration, and therefore earlier data gathering. This method replaces the planned neutron capture γ -ray detection method with neutron capture on high cross section materials and subsequent charged particle emission and detection. This work has identified the most practical materials for this scheme as being ^3He in a scintillator or proportional wire chamber, or ^6Li loaded into an inorganic scintillator such as ZnS or LiI . The important properties of these scintillation alternatives for this neutron detection scheme have been identified.

In order to evaluate the detector geometry alternatives with such materials, this work has focused on the writing of a Monte Carlo program. The integrity of this Monte Carlo was first established by its replication of the neutron transport and absorption predictions of the ANISN program employed by Atomic Energy of Canada Limited for the capture γ -ray detection method. The present Monte Carlo was then employed in reproducing the neutron capture predictions of the Los Alamos Laboratory Monte Carlo for the ^3He proportional wire chamber alternative, which was thoroughly studied at LANL. Finally, the present Monte Carlo was operated to evaluate optimized detector geometries for the ^3He and ^6Li alternatives, and to predict photon losses on insertion of the detecting elements.

The results derived from the operation of the Monte Carlo concur with the Los Alamos results, indicating that a practical ^3He alternative which achieves equivalent uncertainty in the NC measurement with that of the planned detection method could involve proportional wire chambers. These chambers would have a diameter of approximately 2.1 cm, extending vertically, located on a 100 cm square grid, and have a gas pressure maintained near 1 Atm. The total mass of the gas would be less than 40 g, plus the mass of the containment and electrode materials. Thin plates containing a ^6Li loaded inorganic scintillator, each having a surface area near 2.9 cm square, and located on a 25 cm cubic grid will achieve similar results, while other untried geometries may also be practical. The mass of material required for such plates would be

of the order of 10^4 g. Such plates would emit more than 10^5 photons on capture of a thermal neutron, which would present an unambiguous signal to the photomultiplier tubes. While these alternatives are practical in terms of the amounts of materials required, they present real challenges in material purity in order to achieve a reasonable ratio of signal to introduced background. The necessary uranium and thorium radiopurity indicated for these detection materials is of the order of feritograms per gram in order to limit the introduced background from α and β emissions to four events per day.

Further efforts to overcome the radiopurity difficulties with this proposed detection scheme are warranted, in order that the essential improvements in the SNO detector identified above can be achieved. Areas warranting study include material purification and purity measurement methods capable of achieving these extreme levels, and techniques capable of distinguishing background α emissions from the α -triton signal characteristic of neutron capture in the ^6Li loaded scintillator. Success on either of these objectives would render this proposed neutral current method the most efficient and practical alternative, yielding the greatest amount of information with the greatest accuracy for the study of the Solar Neutrino Problem.

The detailed studies in this thesis, of both the scintillator and proportional tube detectors seeded with light nuclei of high thermal neutron capture cross section, and exhibiting charged particle emission on neutron capture, have shown the alternatives to be an interesting and advantageous neutral current detection technique for the SNO experiment. The loaded scintillator candidates identified are ^6LiF loaded in ZnS , and ^6LiI . The advantages available through the use of such a technique are shown to include improved measurement accuracy, as well as the important improvement of real time separation of charged current and neutral current measurements. Neutrino flux flavour correlations with short period solar variations, such as flare or core collapse phenomena, may be possible for SNO following the method studied in this work. This makes a strong case for further analyses and measurements, leading to implementation of the technique.

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APPENDIX 1

FIGURES

FIGURE 1: SOLAR pp CHAIN NUCLEAR REACTIONS [5]

FIGURE 2: SOLAR CNO CHAIN NUCLEAR REACTIONS

FIGURE 3: SOLAR NEUTRINO ENERGY SPECTRUM [1]

FIGURE 4: HOMESTAKE DETECTOR RESULTS [2] Crosses are Homestake Yearly Average Neutrino Observations Dots are Monthly Mean Sunspot Numbers (Inverted Plot)

FIGURE 5: LORENTZ & CPT TRANSFORMATIONS OF NEUTRINOS [9] a) Dirac Neutrinos; b) Majorana Neutrinos

FIGURE 6: GOSGEN AND BUGEY EXCLUDED PARAMETER SPACE [9]

FIGURE 7: HIGH ENERGY APPEARANCE TEST EXCLUDED PARAMETER SPACE [9]

FIGURE 8: HIGH ENERGY DISAPPEARANCE TEST EXCLUDED PARAMETER SPACE

[9]

FIGURE 9. THE SNO DETECTOR [5]

FIGURE 10: NEUTRINO ABSORPTION CROSS SECTIONS [9]

FIGURE 11: LANL MONTE CARLO RESULTS FOR ^3He PWC DETECTORS [38] Upper Figure 1 Atm.; Lower Figure 3 Atm.; Lower Curves 2 cm Diam.

APPENDIX 2

THE MONTE CARLO

THE MONTE CARLO

I THE COMMAND FILES

The command procedure that initiates the Monte Carlo is run with the command

`@nc{ret}.`

This command procedure specifies interrupt/abort handling, defines the interactive terminal session as the output and input device, runs the "NCINPUT" program, and submits the second command file, known as "NCBATCH", to the batch queue.

The "NCBATCH" command procedure operates from the batch queue. It also specifies interrupt/abort handling. Since the "NCINPUT" routine outputs the necessary parameters for the main Monte Carlo routine ("NCMAIN") into a temporary data file known as "RUNPARMS.DAT", the "NCBATCH" command procedure defines this data file as the input data. The "NCBATCH" command procedure also defines the output file to be "NCOUTPUT.DAT", and then runs the "NCMAIN" simulation program. Finally, the "NCBATCH" command procedure deletes the "RUNPARMS.DAT" data file. It is possible to submit multiple Monte Carlo jobs, to the limit of the number of batch jobs which can be concurrently executing, provided care is taken to ensure that a submitted job is given the opportunity to collect the information in its "RUNPARMS.DAT" file before another similar file is created. This generally requires no waiting or delays, but does preclude submitting jobs to a waiting queue since its "RUNPARMS.DAT" data file will be deleted by a previous job on termination prior to being read.

II THE INPUT ROUTINE AND DATA FILES

The "NCINPUT" program, listed in this appendix, is substantially commented in the listing and largely self explanatory. The following section will provide definitions for the variables used and explain the flow of the program.

The variable "DET" is used as a flag to indicate the presence of discrete detecting elements, while the variable "TUB" is used as a flag to indicate if the discrete detectors are tubular or circular disks. Two other temporary string character variables, "SYMBL" and "SYMB", are also used. Eight arrays, each having twenty elements, are used to store symbolic names for elements in and additives to the water ("SYMBOL(I)"), atomic masses in amu ("ATOMASS(I)"), fractional elemental composition in the water ("FELECOMP(I)"), thermal neutron absorption cross section in barns ("CROSSECT(I)"), the calculated relative elemental neutron absorption probability ("PRELABS(I)"), the total number of atoms of each element in the doped water ("ATOMS(I)"), the elemental thermal neutron scattering cross section in barns ("SCTCRS(I)"), and the total mass of each element in the doped water ("TELEMASS(I)"). The first three elements are specified in the initialization section as ^2H , ^1H , and Oxygen for $I = 1, 2, 3$ respectively, and the symbols, atomic masses, cross sections, and scattering cross sections are initialized for these three elements.

The D_2O molecular purity (%) is requested of the operator ("DPCT"), and the mass fraction of D_2O molecules ("DPCT") and density ("RHOWATT") are calculated.

The operator is then asked to specify the number of elements added to the water. If the presence of such additives is identified, then the total mass and density of the additives is requested so that the mass of the water can be appropriately reduced to allow for the additives in the fixed fiducial volume. Each additive element is then requested in sequence, and the "ADDITIVES.DAT" data file is checked for each element symbol input in an attempt to provide the atomic mass and cross sections [40] from this data file. If this information is not available in the "ADDITIVES.DAT" file, the operator is asked to supply it. The operator is asked to identify the atomic

```
$ on error then goto end
$ on control_y then goto end
$ on control_z then goto end
$ on control_c then goto end
$ SET NOVERIFY
$ DEFINE/nolog SYSSOUTPUT TT
$ DEFINE/nolog SYSSINPUT TT
$ RUN NCINPUT
$ SUBLONG/nolog_file NCBATCH
$end:
$ EXIT
```

fraction of the total additives which is comprised of each element. This information is then displayed back to the operator in a table on the screen. The scattering cross sections specified are factored to account for the fact that the atoms are in liquid state and not bound in a lattice structure [40]. The absorption ("ABSMFP") and scattering ("SCMFP") mean free paths are then calculated for the doped water. The operator is given the choice of using the calculated scattering mean free path length, or entering another value instead.

The operator is then asked to indicate if discrete detecting elements are to be present in the simulation. If so, the operator is required to supply the lattice spacing and thickness of the detecting elements in each of the x, y, and z dimensions. The operator is asked to indicate if the detecting elements are tubular or disk shaped and to specify the neutron mean free path in the detecting element material. The neutron capture probability for each detecting element is calculated, integrating over all incidence angles. The operator is then asked to indicate the number of events to be simulated.

The program then creates the "RUNPARMS.DAT" file and terminates.

III THE EVENT SIMULATION PROGRAM AND OUTPUT FILES

The "NCMAIN" program, listed in this appendix, is also substantially commented and largely self explanatory. The following section will provide variable definitions and explain program flow.

Many of the variables defined in the "NCINPUT" program carry the same definitions in this program. In addition, new array variables are introduced to store 50 bin histogram data for incident neutrino energies ("JNEUTHST(I)"), neutron birth energies ("INENHST(I)"), neutron birth location radii ("IR1HST(I)"), and neutron scattering distances ("ISCDSHST(I)").

The "NCMAIN" program first reads the "RUNPARMS.DAT" data file to establish the number of events to be simulated, and the number of additives to the water. It also reads the symbols, atomic masses, fractional compositions, scattering cross sections, thermal neutron capture cross sections, and elemental relative neutron absorption probabilities for the water and additives. It then reads the scattering and absorption mean free path lengths in the water, the discrete detecting element neutron capture probability, the sum of all of the individual relative elemental absorption probabilities, and the density of the doped water. The discrete element lattice spacings and dimensions are then read, followed by the percentage heavy water purity, the total mass of the additives, the flags indicating the presence of the detectors and their tubular or circular shape, and the neutron mean free path inside the detecting elements.

The program enters a main loop, in which it generates, and analyses each event. Since execution time is a serious concern given the anticipated number of individual scatterings each neutron will experience, the program tends to be linear and sequential rather than relying on subroutines and calls.

The first task within the loop is to randomly generate an incident neutrino energy. The ^8B solar neutrino energy spectrum of Bahcall & Ulrich [1] is simulated by generating energies randomly, and discarding such random numbers with a frequency function described by the Bahcall & Ulrich [1] spectrum. The sum of two gaussian

envelopes together describe the incident spectrum to within 1% of the values given by Bahcall & Ulrich. Each accepted incident neutrino energy is counted in one of fifty array elements for a subsequent histogram.

The neutrino energy is then reduced by the deuteron binding energy, and the balance is randomly factored, reflecting the three body final state of the interaction, so that the mean neutron birth energy will be one third of the mean energy remaining. Data is also saved for a subsequent histogram of neutron birth energies.

The three cartesian coordinates of the neutron birth location are randomly generated, and discarded if they are found to be outside of the fiducial volume. From these cartesian coordinates, equivalent spherical polar coordinates are calculated. The thermalization distance is then calculated [39], with the direction being random, and the cartesian coordinates are updated. Where these revised coordinates are outside the fiducial volume, the neutron is considered to have escaped before thermalization, the loop terminates, and simulation of another event begins.

If discrete detecting elements are present, the program next determines the closest faces of the eight nearest detecting elements. Since they are located on a regular grid, this amounts to determining two values for each of the three cartesian coordinates. The program then tests to see if the neutron has stopped inside a detecting element, and if so, tests for neutron capture in the element. This last test is accomplished by generating a random number, and comparing it with the neutron capture probability which is based on the mean free path within the element. If the capture probability is less than the random number, the neutron escapes.

Neutrons which survive to this point are scattered. Since they are born in a three body final state, and they generally scatter extensively in thermal collisions, no persistence of momentum will be evident. The scattering distances are generated randomly, but fitting an exponential frequency function [41]. Scattering distances are recorded for a subsequent histogram, and the total distance travelled is recorded. The neutron location cartesian coordinates are then updated. Two substantial tests remain to be done before simulating another scattering collision. They are a test for

encounter with a detecting element, and a test for escape from the fiducial volume.

If discrete detecting elements are present, the program determines if the neutron has scattered beyond one of the nearest faces of one of the detecting elements. If so, it determines if it has intercepted any face of one of the discrete detecting elements within the limits defining the sides of the element. If so, the program tests for neutron capture. Otherwise, the program determines if the neutron has scattered to the next lattice grid, and if so, tests for encounter with and capture within another detecting element. The total path length travelled is kept for all neutrons determined to have been captured within discrete detecting elements, so that the number captured may later be reduced by an appropriate amount to reflect the probability of prior absorption in the water.

Finally, the new neutron location is tested to determine if it is beyond the fiducial volume. If so, the total path length travelled in getting to this point is used to evaluate the probability of absorption in the water prior to escape. The total number of escaped and absorbed neutrons is adjusted accordingly, and if the program has not yet simulated the required number of events, another neutron is simulated. If, however, the neutron has not escaped the fiducial volume, it is scattered again and tested again as described above, until all neutrons have completed scattering and been captured, or absorbed, or have escaped.

The program then proceeds to report results to an output file. The results include information about the water composition and doping, the discrete detecting element spacing and geometry, and the density of the doped water. Mean values are then reported for the incident neutrino energies, the neutron birth energies, the thermalization distances, the scattering free path, the number of scatters per neutron, the absorption free path, and the distances travelled from birth to escape. Values are given for travelled distance and displacement from birth to absorption, and to capture in discrete elements where they are specified.

The program then reports the probability of neutron absorption for each element in the water and the additives, and for neutron capture on discrete detecting elements.

Finally, the program outputs frequency information for plotting histograms of incident neutrino energy and neutron birth energy, neutron birth radii, and neutron scattering distances. The program then terminates. Examples of the output reports are included in Appendix 3 following.


```
$ on error then goto end
$ on control_y then goto end
$ on control_z then goto end
$ on control_c then goto end
$ SET NOVERIFY
$ DEFINE/nolog SYS$OUTPUT TT
$ DEFINE/nolog SYS$INPUT TT
$ RUN NCINPUT
$ SUBLONG/nolog_file NCBATCH
$end:
$ EXIT
```

```
$ on error then goto end
$ on control_y then goto end
$ on control_z then goto end
$ on control_c then goto end
$ SET NOVERIFY
$ DEFINE/nolog FOR008 RUNPARMS.DAT
$ DEFINE/nolog FOR009 NCOUTPUT.DAT
$ RUN NCMAIN
$ CREATE RUNPARMS.DAT
$ DEL RUNPARMS.DAT;*
$end:
$ EXIT
```

PROGRAM NCOUT

```

*****
*   THIS PROGRAM GATHERS INPUT FOR SIMULATION OF SNO DETECTION OF   *
*   NEUTRAL CURRENT EVENTS.  THIS PROGRAM READS A FILE CALLED       *
*   ADDITIVES.DAT (IF AVAILABLE) FOR INFORMATION ABOUT ADDITIVES IN  *
*   THE WATER.  THIS PROGRAM CREATES A FILE CALLED RUNPARMS.DAT FOR  *
*   LATER USE BY THE BATCH JOB CALLED MCMAIN, WHICH EXECUTES THE    *
*   MONTE CARLO AND CREATES THE OUTPUT FILE                         *
*****

*****
*   DECLARE AND INITIALIZE VARIABLES                                *
*****

CHARACTER*1 DET,TUB
CHARACTER*5 SYMBOL(20), SYMBL, SYMB
REAL ATOMASS(20),FELECOMP(20),CROSSECT(20),PRELABS(20),ATOMS(20),
*   SCTCRS(20),TELMASS(20)
DATA TELMASS/20*0.0/LUN1/8/TPRELABS/0.0/
DATA TMADD,TATOMS,SIGMAN,SIGMAN2/4*0.0/
DATA (SYMBOL(I),I=1,3)/'2D','1H','O'/
DATA (ATOMASS(I),I=1,3)/2.0141,1.0080,15.995/
DATA (CROSSECT(I),I=1,3)/.000456,.278000,.000149/
DATA (SCTCRS(I),I=1,3)/7.6,81.5,4.24/
DATA TUB/'N'/
INTRINSIC MIN
PARAMETER (AVOGAD=6.022045E23,PI=3.141592654)

*****
*   SEED RANDOM NUMBER GENERATOR                                  *
*****

N=10011

*****
*   CLEAR SCREEN                                                  *
*****

DO50, I=1,25
PRINT*,' '
CONTINUE

*****
*   PROVIDE INTRODUCTORY INFORMATION TO THE USER                *
*****

PRINT*,'*****'
PRINT*,' '
PRINT*,'THESE MONTE CARLO ROUTINES SIMULATES CREATION, DIFFUSION,'
PRINT*,'AND EITHER ESCAPE OR CAPTURE OF THERMAL NEUTRONS BORN OF'
PRINT*,'SOLAR NEUTRINO-DEUTERON NEUTRAL CURRENT INTERACTIONS IN'
PRINT*,'THE SNO DETECTOR. INPUT INFORMATION REQUIRED INCLUDES D2O'
PRINT*,'PURITY INFORMATION,AND INFORMATION REGARDING ADDITIVES TO'
PRINT*,'THE WATER, SUCH AS MASS AND DENSITY, AND ATOMIC WEIGHTS,'
PRINT*,'FRACTIONS, AND SCATTERING AND ABSORPTION CROSS SECTIONS.'
PRINT*,'INFORMATION FOR SOME ADDITIVES MAY BE STORED IN A FILE'
PRINT*,'NAMED ADDITIVES.DAT. DISCRETE DETECTING ELEMENTS MAY BE'
PRINT*,'SPECIFIED AS TO GRID SPACING, SIZE, AND CAPTURE FRACTION.'
PRINT*,'OUTPUT WILL BE FOUND IN A FILE NAMED NCOUT.DAT'
PRINT*,' '
PRINT*,'*****'

*****

```

```

*      DETERMINE THE PERCENTAGE D2O H2O IN THE WATER
*****

PRINT*, ' '
PRINT*, 'ENTER D2O PURITY (% D2O)'
READ*, DPCT
DPCT=DPCT/100

*****
*      ESTABLISH DENSITY OF WATER ALONE
*****

H2OMASS=2*ATOMASS(2)+ATOMASS(3)
RHOWAT=1-DPCT*(1-(2*ATOMASS(1)+ATOMASS(3))/H2OMASS)
DPCM=1.0/(1.0-(1.0-DPCT)*(H2OMASS/(2*ATOMASS(1)+ATOMASS(3))))

*****
*      DETERMINE IF THERE ARE ADDITIVES IN THE WATER
*****

PRINT*, 'ENTER NUMBER OF ADDITIVE ELEMENTS (0 TO 17)'
READ*, NADD
NCOMP=3+NADD
IF (NADD.EQ.0) THEN
    ADDENS=RHOWAT
ELSE

*****
*      DETERMINE MASS OF ADDITIVES, AND REMAINING MASS OF WATER
*****

    PRINT*, ' '
    PRINT*, 'ENTER TOTAL MASS OF ADDITIVES (tonnes)'
    READ*, TMADD
    PRINT*, 'ENTER DENSITY OF ADDITIVES (g/cc)'
    READ*, ADDENS
ENDIF

WATMAS=1000-TMADD*RHOWAT/ADDENS
TELMASS(1)=WATMAS*DPCM*2*ATOMASS(1)/(2*ATOMASS(1)+ATOMASS(3))
TELMASS(2)=WATMAS*(1-DPCM)*2*ATOMASS(2)/(2*ATOMASS(2)+ATOMASS(3))
TELMASS(3)=WATMAS-TELMASS(1)-TELMASS(2)
TOTMAS=FELECOMP(1)*ATOMASS(1)+FELECOMP(2)*ATOMASS(2)
TOTMAS=TOTMAS+FELECOMP(3)*ATOMASS(3)

IF (NADD.NE.0) THEN

*****
*      DETERMINE ADDITIVES, ATOMIC WEIGHTS, AND CROSS SECTIONS
*      CHECK FILE ADDITIVES.DAT FOR INFORMATION ABOUT ADDITIVES
*****

    DO100, KTR=4, NCOMP
    PRINT*, ' '
    PRINT*, 'ENTER ELEMENT (ISOTOPE) SYMBOL'
    READ (*, 95000) SYMBOL (KTR)

    OPEN (LUN1, FILE='ADDITIVES.DAT', STATUS='OLD', ACCESS=
*      'SEQUENTIAL', FORM='FORMATTED', IOSTAT=IERFLG)
    READ (LUN1, 96001, IOSTAT=IERFLG) SYMBL, SYMB
    READ (LUN1, *, IOSTAT=IERFLG) ATOMASS(KTR), CROSSECT(KTR),
*      SCTCRS(KTR)
    IF (SYMBOL(KTR).EQ.SYMBL) THEN
        SYMBOL(KTR)=SYMB
        GOTO 90
    ENDIF

```

```

IF (ILPILC EQ 1) GO TO 60

PRINT*, 'ENTER ATOMIC MASS (amu)'
READ (*, 95003) ATOMASS (KTR)

PRINT*, 'ENTER THERMAL NEUTRON CROSS SECTION (barns)'
READ (*, 95002) CROSSECT (KTR)

PRINT*, 'ENTER NEUTRON SCATTERING CROSS SECTION (barns)'
READ (*, 95002) SCTCRS (KTR)

CLOSE (LUN1)
PRINT*, 'ENTER FRACTION OF ADDITIVE WHICH IS ', SYMBOL (KTR)
READ*, FELECOMP (KTR)

PRINT*, ' '
PRINT*, ' '

TOTMAS=TOTMAS+ (FELECOMP (KTR) *ATOMASS (KTR) )

100 CONTINUE

ENDIF

DO 150, K=1, NCOMP
  IF (K.GT.3) TELMASS (K) =TMADD*FELECOMP (K) *ATOMASS (K) /TOTMAS
  ATOMS (K) =TELMASS (K) *AVOGAD*1E6/ATOMASS (K)
  TATOMS=TATOMS+ATOMS (K)

150 CONTINUE

*****
*   DISPLAY ELEMENT DATA
*****

PRINT*, ' '
PRINT*, ' '
PRINT*, 'ELEMENT    MASS (amu)    FRACTION    CROSS SECTIONS (cm)'
PRINT*, 'SCATTERING    ABSORPTION'
PRINT*, ' '

*****
*   DETERMINE NUMBER OF ATOMS OF EACH TYPE
*****

DO 200, J=1, NCOMP
  FELECOMP (J) =ATOMS (J) /TATOMS
  PRINT 95001, SYMBOL (J), ATOMASS (J), FELECOMP (J), SCTCRS (J),
  * CROSSECT (J)

*****
*   THE NEXT LINE REDUCES THE BOUND STATE SCATTERING CROSS SECTION
*   TO ACCOUNT FOR THE FREE (LIQUID) STATE.
*****

  FACTOR= (ATOMASS (J) / (ATOMASS (J) +1) ) **2

*****
*   DETERMINE TOTAL N-SIGMA FOR ABSORPTION AND SCATTERING
*****

  SIGMAN=SIGMAN+ (CROSSECT (J) *ATOMS (J) *3/ (4*PI* (599) **3) )
  SIGMAN2=SIGMAN2+ (SCTCRS (J) *FACTOR*ATOMS (J) *3/ (4*PI* (599) **3) )

*****
*   DETERMINE ABSORPTION PROBABILITIES FOR ELEMENTS
*****

```

```

*****
PRELABS(J)=FELECOMP(J)*CROSSECT(J)
TPRELABS=TPRELABS+PRELABS(J)

CONTINUE

*****
*   DETERMINE DENSITY, AND ABSORPTION AND SCATTERING MEAN FREE PATHS   *
*****

ELEDENS=(WATMAS+TMADD)*1E6*3/(4*PI*(599)**3)
ABSMFP=1E24/SIGMAN
SCFP=1E24/SIGMAN2

PRINT*, ' '
PRINT*, 'Enter Scattering mfp (cm), 0 for Default Value of', SCMFP
READ*, TEMP
IF (TEMP.NE.0) SCMFP=TEMP

*****
*   DETERMINE PRESENCE, LOCATION, AND CHARACTERISTICS OF               *
*   DETECTING ELEMENTS                                                 *
*****

PRINT*, 'WILL THERE BE ANY LOADED SCINTILLATORS PRESENT?'
PRINT*, 'IF SO, ENTER Y (ret), FOLLOWED BY DETAILS.'
READ (*,95004) DET
IF (DET.EQ.'Y'.OR.DET.EQ.'y') THEN
    PRINT*, 'ENTER X-AXIS GRID SPACING (CENTRE TO CENTRE, cm)'
    READ*, XGRID
    PRINT*, 'ENTER Y-AXIS GRID SPACING (CENTRE TO CENTRE, cm)'
    READ*, YGRID
    PRINT*, 'ENTER Z-AXIS GRID SPACING (CENTRE TO CENTRE, cm)'
    READ*, ZGRID
    PRINT*, 'ENTER SCINTILLATOR THICKNESS ON X-AXIS (cm)'
    READ*, DX
    DX=DX/2
    PRINT*, 'ENTER SCINTILLATOR THICKNESS ON Y-AXIS (cm)'
    READ*, DY
    DY=DY/2
    IF (DY.EQ.DX) THEN
        PRINT*, 'ARE ELEMENTS TUBES OR ROUND DISKS (Y/N)?'
        READ (*,95004) TUB
    ENDIF
    PRINT*, 'ENTER SCINTILLATOR THICKNESS ON Z-AXIS (cm)'
    READ*, DZ
    DZ=DZ/2
    PRINT*, 'ENTER NEUTRON MFP IN SCINTILLATOR (cm)'
    READ*, CAPTMFP
    XY=MIN(DX,DY,DZ)
    XYZ=4*XY/CAPTMFP
    IF (TUB.EQ.'Y'.OR.TUB.EQ.'y') THEN
        XYZ=PI*XY/(1.4142136*CAPTMFP)
    ENDIF
    CAPTPROB=1.0-EXP(-XYZ)
    PRINT*, ' CAPTURE PROBABILITY IN DETECTOR = ', CAPTPROB
    DET='Y'
ENDIF

*****
*   DETERMINE NUMBER OF EVENTS TO RUN (=NNEUT)                       *
*****

PRINT*, 'ENTER THE NUMBER OF NEUTRON EVENTS TO RUN'
READ*, NNEUT

```

```

      PRINT*, ' '
      *****
      *      CREATE RUNPARMS.DAT FILE FOR SUBMISSION OF BATCH JOB      *
      *****

      OPEN (LUN1, FILE='RUNPARMS.DAT', STATUS='NEW', ACCESS='SEQUENTIAL',
      *      FORM='FORMATTED')
      WRITE (LUN1, *) NNEUT, NCOMP
      DO 9500, KTR=1, NCOMP
         WRITE (LUN1, 96002) SYMBOL(KTR)
         WRITE (LUN1, *) ATOMASS(KTR), FELECOMP(KTR), SCTCRS(KTR),
      *      CROSSECT(KTR), PRELABS(KTR)

9500 CONTINUE
      WRITE (LUN1, *) SCMFPP, CAPTPROB, ABSMFPP, TPRELABS, ELEDENS
      WRITE (LUN1, *) XGRID, YGRID, ZGRID, DX, DY, DZ
      WRITE (LUN1, *) DPCT, TMADD
      WRITE (LUN1, 96003) DET
      WRITE (LUN1, 96003) TUB
      WRITE (LUN1, *) CAPTIMFP
      CLOSE (LUN1)

      *****
      *      FORMATS      *
      *****

95000 FORMAT(A5)
95001 FORMAT(2X, A5, 3X, F9.5, 4X, F9.7, 4X, F7.3, 2X, F12.6)
95002 FORMAT(F13.6)
95003 FORMAT(F11.4)
95004 FORMAT(A1)
96001 FORMAT(A5, 1X, A5)
96002 FORMAT(1X, A5)
96003 FORMAT(1X, A1)
      END

```

```
*****  
*****  
*   THIS PROGRAM SIMULATES SNO DETECTION OF NEUTRAL CURRENT EVENTS *  
*   INCLUDING INCIDENT NEUTRINO ENERGY SPECTRUM SIMULATION, ENERGETIC *  
*   NEUTRON BIRTH, THERMALIZATION, AND DIFFUSION. ABSORPTION AND *  
*   ESCAPE PROBABILITIES ARE DETERMINED. NEUTRON BIRTH LOCATION, *  
*   ENERGY, AND DIRECTION ARE RANDOM WITHIN THE LIMITS PRESCRIBED FOR *  
*   8-BORON NEUTRINO COLLISIONS, WITHIN A 1 KILOTONNE D2O SPHERE. *  
*   THERMALIZATION DIRECTION (DISTANCE AS PER SEGRE ,1977) IS *  
*   RANDOM. ESCAPE EXITS VOLUME; ABSORPTION IS ON D2O OR H2O OR *  
*   ADDITIVE. DETECTION MAY BE WITHIN N-CAPTURE SCINTILLATOR ELEMENTS. *  
*   THIS ROUTINE TAKES INPUT FROM FILE RUNPARMS.DAT AND OUTPUTS TO *  
*   FILE NCOUTPUT.DAT *  
*****  
*****
```

```

*****
*
* DECLARE AND INITIALIZE VARIABLES
*
*****

```

```
CHARACTER*1 DET
CHARACTER*5 SYMBOL(20)
REAL ATOMASS(20), FELECOMP(20), CROSECT(20), PRELABS(20), SCTCRS(20)
INTEGER ITHRMHST(50), INENHIST(50), IENUTHST(50), IR1HST(50),
*      ISCDSHST(50)
INTRINSIC SIGN, SQRT, MIN, MAX, ABS, SIN, COS
DATA ITHRMHST/50*0/, INENHIST/50*0/, IENUTHST/50*0/, IR1HST/50*0/,
*      ISCDSHST/50*0/LUN1/8/NUMDET, NUMABS, NESC, NTHESCC, ITEMPTOT/5*0/
*      ENUMEAN, ENMEAN, XNL, YNL, ZNL/5*0.0/LUN2/9/TCAPDIS, TESCDIS,
*      TCAPDSPL, TESCDSP/4*0.0/
PARAMETER (PI=3.141592654)
```

```
*****
* SEED RANDOM NUMBER GENERATOR
*****
```

N=10011

*****
 * READ RUNPARMS.DAT FILE TO COLLECT INPUT DATA *
 *****

```

OPEN (LUN1, FILE='RUNPARMS.DAT', STATUS='OLD', ACCESS='SEQUENTIAL',
*      FORM='FORMATTED')
READ (LUN1, *) NNEUT, NCOMP
DO 950, KTR=1, NCOMP
    READ (LUN1, 96002) SYMBOL(KTR)
    READ (LUN1, *) ATOMASS(KTR), FELECOMP(KTR), SCTCRS(KTR),
*      CROSSECT(KTR), PRELABS(KTR)

```

```

50  CONTINUE
    READ (LUN1,*) SCMFPP,CAPTPROB,ABSMFPP,TPRELABS,ELEDENS
    READ (LUN1,*) XGRID,YGRID,ZGRID,DX,DY,DZ
    READ (LUN1,*) DPCT,TMADD
    READ (LUN1,96003) DET
    READ (LUN1,96003) TUB
    READ (LUN1,*) DETMFP
    CLOSE (LUN1)

```

```
*****  
*****  
*/-----\\  
*<<<<<<<<<<<< MAIN ROUTINE >>>>>>>>>>>>*  
/*-----\\
```



```

C *****
C *****
C
1000 DO 90000, I=1,NNEUT
C
C *****
C *      GENERATE NEUTRINO ENERGY SPECTRUM (=ENU) .      *
C *
C *      THIS ROUTINE GENERATES THE INCIDENT 8B NEUTRINO ENERGY SPECTRUM      *
C *      AS PER BAHCALL AND ULRICH, 1988      *
C *      THE METHOD IS TO GENERATE A RANDOM ENERGY UP TO 15 MEV, AND THEN      *
C *      ACCEPT OR DISCARD THESE ENERGIES WITH FREQUENCIES CALCULATED      *
C *      AT LINES 2500 AND 2501, WHICH APPROXIMATELY DESCRIBES (WITHIN      *
C *      1% OF TOTAL FLUX FOR ANY GIVEN BIN) THE B&U PREDICTED SPECTRUM.      *
C *****
C
C TSCDIS=0.0
2000 RV=RAN(N)
ENUT=15000000*RV
IF (ENUT.LE.2223000.025) GOTO 2000
PROB=0.07467*EXP(-(RV-.3866667)**2)/0.08)
PROB=PROB-0.006+0.06727*EXP(-(RV-.4666667)**2)/0.1146868)
IF (PROB.LE.0.13594*RAN(N)) GOTO2000

C *****
C *      GENERATE HISTOGRAM OF INCIDENT NEUTRINO ENERGIES, SUM FOR MEAN.      *
C *****

KTR=( (ENUT/3E5)+1)
IENUTHST(KTR)=IENUTHST(KTR)+1
ENUMEAN=ENUMEAN+ENUT/1E6

C *****
C *      GENERATE FREE NEUTRONS WITHIN PRESCRIBED ENERGY SPECTRUM.      *
C *      FIRST, SUBTRACT DEUTERON BINDING ENERGY. THEN APPORTION ENERGY      *
C *      TO NEUTRON RANDOMLY (EN), AVERAGE ENERGY BEING 1/3 ENU-2223 keV      *
C *****

EN=(ENUT-222300)*2*RAN(N)/3

C *****
C *      GENERATE HISTOGRAM OF NEUTRON BIRTH ENERGIES, CALCULATE MEAN      *
C *****

KTR=( (EN/3E5)+1.0)
INENHIST(KTR)=INENHIST(KTR)+1
ENMEAN=ENMEAN+EN/1E6

C *****
C *      GENERATE BIRTH LOCATION (X1, Y1, Z1) AND DIRECTION (THET1,PHI1)      *
C *      FOR NEUTRON, AND THERMALIZATION DISTANCE AND POSITION.      *
C *      THERMALIZATION DISTANCE CALCULATION AS PER SEGRE, EQN12-4.2      *
C *      KEEP HISTOGRAM DATA OF BIRTH RADII FOR LATER OUTPUT.      *
C *****

1000 X1=599*(2.0*RAN(N)-1.0)
Y1=599*(2.0*RAN(N)-1.0)
Z1=599*(2.0*RAN(N)-1.0)
R1=SQRT(X1**2+Y1**2+Z1**2)
IF (R1.GT.599) GOTO 3000
KTR=(R1/12)+1
IR1HST(KTR)=IR1HST(KTR)+1
THET1=PI*RAN(N)
PHI1=PI*2.0*RAN(N)
DISTHERM=SQRT(((SCMFP**2)/0.725)*LOG(EN/0.025))

```

```

XNEW=X1+DISTHERM*SIN(THET1)*COS(PHI1)
YNEW=Y1+DISTHERM*SIN(THET1)*SIN(PHI1)
ZNEW=Z1+DISTHERM*COS(THET1)

*****
*   KEEP TOTAL OF THERMALIZATION DISTANCES FOR LATER AVERAGING   *
*****

TDISTHRM=TDISTHRM+DISTHERM

*****
*   DETERMINE IF NEUTRON THERMALIZES OUTSIDE D20. IF SO, COUNT     *
*   NEUTRON AND RETURN TO MAIN ROUTINE.                           *
*****

RN=SQRT(XNEW**2+YNEW**2+ZNEW**2)
IF (RN.GT.599) THEN
    NTHESCC=NTHESCC+1
    GOTO 90000
ENDIF

*****
*   DETERMINE NEAREST SCINTILLATOR AXES AND TEST FOR NEUTRON ENCOUNTER *
*   WITH SCINTILLATOR                                              *
*****

IF (DET.NE.'Y'.AND.DET.NE.'Y') GOTO 4000
500 IF (XNL.LT.ABS(XNEW)) THEN
    XNL=XNL+XGRID
    GOTO 3500
ELSE
    XNL=SIGN(XNL,XNEW)
    IF (XNL.LT.XNEW) THEN
        XNH=XNL+XGRID
    ELSE
        XNH=XNL
        XNL=XNL-XGRID
    ENDIF
ENDIF
3600 IF (YNL.LT.ABS(YNEW)) THEN
    YNL=YNL+YGRID
    GOTO 3600
ELSE
    YNL=SIGN(YNL,YNEW)
    IF (YNL.LT.YNEW) THEN
        YNH=YNL+YGRID
    ELSE
        YNH=YNL
        YNL=YNL-YGRID
    ENDIF
ENDIF
3700 IF (ZNL.LT.ABS(ZNEW)) THEN
    ZNL=ZNL+ZGRID
    GOTO 3700
ELSE
    ZNL=SIGN(ZNL,ZNEW)
    IF (ZNL.LT.ZNEW) THEN
        ZNH=ZNL+ZGRID
    ELSE
        ZNH=ZNL
        ZNL=ZNL-ZGRID
    ENDIF
ENDIF
IF (ABS(XNEW-XNL).LE.DX.OR.ABS(XNEW-XNH).LE.DX) THEN
    IF (ABS(YNEW-YNL).LE.DY.OR.ABS(YNEW-YNH).LE.DY) THEN
        IF (ABS(ZNEW-ZNL).LE.DZ.OR.ABS(ZNEW-ZNH).LE.DZ) THEN

```

```

                                IF (CAPTPROB * RAN(N)) THEN
                                    NUMDET=NUMDET+1
                                    GOTO 90000
                                ENDIF
                            ENDIF
                        ENDIF
                    ENDIF

*****
*   SCATTER NEUTRON A SCATTERING DISTANCE GIVEN BY AN EXPONENTIAL   *
*   DISTRIBUTION WITH A MEAN VALUE GIVEN BY SCMF.                   *
*****

4000  THETS=PI*RAN(N)
      PHIS=2.0*PI*RAN(N)
      SCDIS=-LOG(1.0-RAN(N))

*****
*   GENERATE HISTOGRAM OF SCATTERING DISTANCES AND TOTAL DISTANCE   *
*****

      KTR=5*SCDIS+1
      IF (KTR.GT.50) KTR=50
      ISCDSHST(KTR)=ISCDSHST(KTR)+1
      SCDIS=SCDIS*SCMF
      TSCDIS=TSCDIS+SCDIS

*****
*   REVISE OLD AND NEW NEUTRON LOCATIONS                             *
*****

      XOLD=XNEW
      YOLD=YNEW
      ZOLD=ZNEW
      XNEW=XNEW+(SCDIS*SIN(THETS)*COS(PHIS))
      YNEW=YNEW+(SCDIS*SIN(THETS)*SIN(PHIS))
      ZNEW=ZNEW+(SCDIS*COS(THETS))

*****
*   TEST FOR EXISTANCE OF NEUTRON DETECTING MODULES                 *
*****

      IF (DET.NE.'Y'.AND.DET.NE.'y') GOTO 12000

*****
*   SKIP THIS DETECTION ROUTINE IF NEUTRON HAD NOT CROSSED ONE EACH *
*   OF THE X, Y, AND Z BOUNDARY AXES. BOUNDARIES CROSSED = XXX, YYY *
*   ESTABLISH WHICH BOUNDARIES WERE CROSSED = XNEAR, YNEAR, ZNEAR) & *
*   OPPOSITE THREE FACES OF ELEMENT HAVING FACES XNEAR, YNEAR, ZNEAR. *
*****

0000  IFLAG=0
      IFLG2=0
      XNEAR=XNL+DX
      XXX=XNL
      XFAR=XNL-DX
      IF (XNEW.GT.(XNH-DX)) THEN
          XNEAR=XNH-DX
          XXX=XNH
          XFAR=XNH+DX
      ELSE IF (XNEW.GT.(XNL+DX)) THEN
          GOTO 11000
      ENDIF
      YNEAR=YNL+DY
      YYY=YNL
      YFAR=YNL-DY
      IF (YNEW.GT.(YNH-DY)) THEN

```

```

      YNEAR=YNH-DY
      YYY=YNH
      YFAR=YNH+DY
      ELSE IF (YNEW.GT.(YNL+DY)) THEN
        GOTO 11000
      ENDIF
      ZNEAR=ZNL+DZ
      ZZZ=ZNL
      ZFAR=ZNL-DZ
      IF (ZNEW.GT.(ZNH-DZ)) THEN
        ZNEAR=ZNH-DZ
        ZZZ=ZNH
        ZFAR=ZNH+DZ
      ELSE IF (ZNEW.GT.(ZNL+DZ)) THEN
        GOTO 11000
      ENDIF

```

```

*****
*                               FINAL DETECTION ROUTINE                               *
*   NOW EXAMINE EACH NEAR FACE IN SUCCESSION TO SEE IF NEUTRON ENTERED *
*   IT BETWEEN THE LIMITS OF THE ELEMENT EXTENT. IF DETECTORS ARE *
*   TUBULAR OR ROUND DISKS, SOLVE SIMULTANEOUSLY FOR NEUTRON PATH AND *
*   CIRCLE AROUND CENTRE OF ELEMENT. *
*****

```

```

IF (TUB.EQ.'Y'.OR.TUB.EQ.'y') GOTO 10400
SSCDIS=(ZNEAR-ZOLD)/COS(THETS)
XPR=XOLD+(SSCDIS*SIN(THETS)*COS(PHIS))
YPR=YOLD+(SSCDIS*SIN(THETS)*SIN(PHIS))
ZPR=ZNEAR
IF ((XPR.NE.MIN(XPR,XNEAR,XFAR).AND.XPR.NE.MAX(XPR,XNEAR,XFAR))
*.AND.(YPR.NE.MIN(YPR,YNEAR,YFAR).AND.YPR.NE.MAX(YPR,YNEAR,YFAR)))
* GOTO 10500
SSCDIS=(XNEAR-XOLD)/(SIN(THETS)*COS(PHIS))
XPR=XNEAR
YPR=YOLD+(SSCDIS*SIN(THETS)*SIN(PHIS))
ZPR=ZOLD+(SSCDIS*COS(THETS))
IF ((YPR.NE.MIN(YPR,YNEAR,YFAR).AND.YPR.NE.MAX(YPR,YNEAR,YFAR))
*.AND.(ZPR.NE.MIN(ZPR,ZNEAR,ZFAR).AND.ZPR.NE.MAX(ZPR,ZNEAR,ZFAR)))
* GOTO 10500
SSCDIS=(YNEAR-YOLD)/(SIN(THETS)*SIN(PHIS))
XPR=XOLD+(SSCDIS*SIN(THETS)*COS(PHIS))
YPR=YNEAR
ZPR=ZOLD+(SSCDIS*COS(THETS))
IF ((XPR.EQ.MIN(XPR,XNEAR,XFAR).OR.XPR.EQ.MAX(XPR,XNEAR,XFAR))
*.OR.(ZPR.EQ.MIN(ZPR,ZNEAR,ZFAR).OR.ZPR.EQ.MAX(ZPR,ZNEAR,ZFAR)))
* GOTO 10600
GOTO 10500

```

```

10400 AEE=1.0+(TAN(PHIS))**2
      BEE=2*(TAN(PHIS))*(YOLD-XOLD*(TAN(PHIS))-YYY)-2*XXX
      CEE=(YOLD-XOLD*(TAN(PHIS))-YYY)**2-DX**2+XXX**2
      IF (BEE**2.LT.4*AEE*CEE) GOTO 10600
      XPR=(-BEE+SQRT((BEE**2)-4*AEE*CEE))/(2*AEE)
      YPR=YOLD+(XPR-XOLD)*(TAN(PHIS))
      ZPR=ZOLD+(XPR-XOLD)/(TAN(THETS)*COS(PHIS))
      IF (XPR.GE.(XXX-DX).AND.XPR.LE.(XXX+DX).AND.YPR.GE.(YYY-DY).AND.
      *YPR.LE.(YYY+DY).AND.ZPR.GE.(ZZZ-DZ).AND.ZPR.LE.(ZZZ+DZ)) GOTO 10500
      XPR=(-BEE-SQRT((BEE**2)-4*AEE*CEE))/(2*AEE)
      YPR=YOLD+(XPR-XOLD)*(TAN(PHIS))
      ZPR=ZOLD+(XPR-XOLD)/(TAN(THETS)*COS(PHIS))
      IF (XPR.GE.(XXX-DX).AND.XPR.LE.(XXX+DX).AND.YPR.GE.(YYY-DY).AND.
      *YPR.LE.(YYY+DY).AND.ZPR.GE.(ZZZ-DZ).AND.ZPR.LE.(ZZZ+DZ)) GOTO 10500
      GOTO 10600

```

```

0500 IF ((599.0).LE.SQRT(XPR**2+YPR**2+ZPR**2)) GOTO 12001

```

```

10501 IF (CAPTPROB.GE.RAN(N)) THEN
      NUMDET=NUMDET+1
      TCAPDIS=TCAPDIS+TSCDIS
      TCAPDSPL=TCAPDSPL+SQRT((XPR-X1)**2+(YPR-Y1)**2+(ZPR-Z1)**2)
      CAPSPB=1.0-EXP(-TSCDIS/ABSMFP)
      CTAPRB=CTAPRB+CAPSPB
      GOTO 90000
ENDIF

*****
*           IT ESCAPED THIS ROW OF DETECTORS           *
*   SET FLAG TO GO AROUND AGAIN IF IT SCATTERED TO THE NEXT ELEMENT AXIS *
*****

10600 IF ((599.0).LE.SQRT(XPR**2+YPR**2+ZPR**2)) GOTO12001
      IFLAG=1

*****
*   UPDATE RECORD OF NEXT LOWER AND NEXT HIGHER AXES IF NEUTRON HAS   *
*   ENTERED A NEW BOX                                                 *
*****

11000 IF (XNEW.LT.XNL) THEN
      XNL=XNL-XGRID
      XNH=XNH-XGRID
ELSE IF (XNEW.GT.XNH) THEN
      XNL=XNL+XGRID
      XNH=XNH+XGRID
ELSE
      IFLG2=IFLG2+1
ENDIF
IF (YNEW.LT.YNL) THEN
      YNL=YNL-YGRID
      YNH=YNH-YGRID
ELSE IF (YNEW.GT.YNH) THEN
      YNL=YNL+YGRID
      YNH=YNH+YGRID
ELSE
      IFLG2=IFLG2+1
ENDIF
IF (ZNEW.LT.ZNL) THEN
      ZNL=ZNL-ZGRID
      ZNH=ZNH-ZGRID
ELSE IF (ZNEW.GT.ZNH) THEN
      ZNL=ZNL+ZGRID
      ZNH=ZNH+ZGRID
ELSE
      IFLG2=IFLG2+1
ENDIF
IF (IFLAG.GT.0.AND.IFLG2.LT.3) GOTO 10000

*****
*   DETERMINE IF NEUTRON HAS REACHED TANK EDGE. IF NOT, SCATTER AGAIN *
*****

12000 RN=SQRT(XNEW**2+YNEW**2+ZNEW**2)
      IF (RN.LE.599) GOTO 4000

*****
*   DETERMINE ABSORPTION PROBABILITIES FOR THIS NEUTRON           *
*****

12001 ABSPROB=1-EXP(-TSCDIS/ABSMFP)
      TABSPROB=ABSPROB+ABSPROB
      TESCDIS=TESCDIS+TSCDIS
      TESCDSP=TESCDSP+SQRT((XNEW-X1)**2+(YNEW-Y1)**2+(ZNEW-Z1)**2)

```

[illegible]

```

WRITE (LUN2,97015) ' Y',YGRID
WRITE (LUN2,97016) ' Z',ZGRID
WRITE (LUN2,97017) ' X',2*DX
WRITE (LUN2,97017) ' Y',2*DY
IF(TUB.EQ.'Y'.OR.TUB.EQ.'y') THEN
  WRITE (LUN2,97024) ' TUBES OR ROUND DISKS'
ENDIF
WRITE (LUN2,97017) ' Z',2*DZ
WRITE (LUN2,97025) 'MFP (cm) IN DETECTOR = ', DETMFP
WRITE (LUN2,97025) 'CAPTURE PROBABILITY = ', CAPTPROB
WRITE (LUN2,95004) ' '
ENDIF

C
WRITE (LUN2,97015) ' DENSITY OF MEDIUM (g/cc)
* = ',ELEDENS
WRITE (LUN2,97015) ' MEAN INCIDENT NEUTRINO ENERGY (MeV)
* = ',ENUMEAN
WRITE (LUN2,97015) ' MEAN NEUTRON BIRTH ENERGY (MeV)
* = ',ENMEAN
WRITE (LUN2,97015) ' MEAN NEUTRON THERMALIZATION DISTANCE (cm)
* = ',DSTHRMM
WRITE (LUN2,97015) ' THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm
*) = ',SCMFP
WRITE (LUN2,97015) ' MEAN NUMBER OF SCATTERS PER NEUTRON
* = ',SCATIMS
WRITE (LUN2,97015) ' NEUTRON ABSORPTION MEAN FREE PATH
* = ',ABSMFP
WRITE (LUN2,95004) ' '
WRITE (LUN2,97020) ' MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH
* TANK EDGE (cm) = ',TESCDIS/(NNEUT-NUMDET-NTHESCC)
WRITE (LUN2,97020) ' MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER
* WITH TANK EDGE (cm) = ',TESCDSPL/(NNEUT-NUMDET-NTHESCC)
IF((DET.EQ.'Y'.OR.DET.EQ.'y') AND NUMDET.NE.0) THEN
  WRITE (LUN2,97020) ' MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH
* DETECTOR (cm) = ',TCAPDIS/NUMDET
WRITE (LUN2,97020) ' MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER
* WITH DETECTOR (cm) = ',TCAPDSPL/NUMDET
ENDIF
WRITE (LUN2,95004) ' '

WRITE (LUN2,95004) ' '
WRITE (LUN2,97019) ' ESCAPES, CAPTURES, AND ABSORPTIONS'
WRITE (LUN2,95004) ' '
WRITE (LUN2,95006) ' PRE-THERMAL ESCAPE PROBABILITY = ',PTEP
WRITE (LUN2,95006) ' POST-THERMAL ESCAPE PROBABILITY = ',PRESC
WRITE (LUN2,95006) ' TOTAL ESCAPE PROBABILITY = ',
*PTEP+PRESC
WRITE (LUN2,95004) ' '

IF(DET.EQ.'Y'.OR.DET.EQ.'y') THEN
  WRITE (LUN2,95006) ' PROBABILITY OF SCINTILLATOR CAPTURE = ',
* PRDET
ENDIF
WRITE (LUN2,95004) ' '

DO 90300, KTR=1,NCOMP
  WRITE (LUN2,95005) SYMBOL(KTR),PRELABS(KTR)
90300 CONTINUE
WRITE (LUN2,95006) ' TOTAL ABSORPTION PROBABILITY = ',PRABS

WRITE (LUN2,95000) ' 1 '
WRITE (LUN2,97003) ' HISTOGRAM OF INCIDENT NEUTRINO AND NEUTRON BI
RTH ENERGIES'
WRITE (LUN2,95004) ' '
ITEMPNEN=150
ITOT1=IENUTHST(1)

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ITOT2=INENHIST(1)
WRITE (LUN2,97000) ' E(keV) = ',ITEMPNEN,' +/- 150 KEV. #
*Neutrinos = ',IENUTHST(1), ' # Neutrons = ',INENHIST(1)
ITEMPNEN=ITEMPNEN+300
DO 90510, KTR=2,50
    WRITE (LUN2,97001) ' ',ITEMPNEN,IENUTHST(KTR),INENHIST(KTR)
    ITEMPNEN=ITEMPNEN+300
    ITOT1=ITOT1+IENUTHST(KTR)
    ITOT2=ITOT2+INENHIST(KTR)
C
90510 CONTINUE
C
    WRITE (LUN2,97002) ' ', 'TOTAL = ',ITOT1,ITOT2
C
    WRITE (LUN2,95000) '1 '
    WRITE (LUN2,97004) ' HISTOGRAM OF NEUTRON BIRTH RADII '
    WRITE (LUN2,95004) ' '
    ITEMPNEN=6
    ITEMPTOT=IR1HST(1)
    WRITE (LUN2,97005) ' RADIUS (cm) = ',ITEMPNEN,' +/- 6 cm. Number of
* Neutron Births = ',IR1HST(1)
    ITEMPNEN=ITEMPNEN+12
    DO 90520, KTR=2,50
        WRITE (LUN2,97006) ' ',ITEMPNEN,IR1HST(KTR)
        ITEMPNEN=ITEMPNEN+12
        ITEMPTOT=ITEMPTOT+IR1HST(KTR)
C
90520 CONTINUE
C
    WRITE (LUN2,97007) ' ', 'TOTAL = ', ITEMPTOT
C
    WRITE (LUN2,95000) '1 '
    WRITE (LUN2,97008) ' HISTOGRAM OF NEUTRON SCATTERING DISTANCES '
    WRITE (LUN2,95004) ' '
    TMPN=0.1*SCMFP
    ITEMPTOT=ISCDSHST(1)
    WRITE (LUN2,97009) ' Scattering Distance (cm) = ',TMPN,' Number of
* Scatters = ',ISCDSHST(1)
    TMPN=TMPN+0.2*SCMFP
    DO 90530, KT=2,50
        WRITE (LUN2,97010) ' ',TMPN,ISCDSHST(KT)
        TMPN=TMPN+0.2*SCMFP
        ITEMPTOT=ITEMPTOT+ISCDSHST(KT)
C
90530 CONTINUE
C
    WRITE (LUN2,97007) ' ', 'TOTAL = ', ITEMPTOT
C
    *****
    * FORMATS
    *****
95000 FORMAT(A2)
95001 FORMAT(2X,A5,3X,F9.5,4X,F9.7,4X,F7.3,2X,F12.6)
95004 FORMAT(A1)
95005 FORMAT(1X,' ABSORPTION PROBABILITY FOR',3X,A5,' = ',2X,F7.5)
95006 FORMAT(1X,A41,2X,F7.5)
96002 FORMAT(1X,A5)
96003 FORMAT(1X,A1)
97000 FORMAT(1X,A10,1X,I5,2X,A28,1X,I6,2X,A14,1X,I6)
97001 FORMAT(A1,11X,I5,31X,I6,17X,I6)
97002 FORMAT(A1,39X,A8,I6,17X,I6)
97003 FORMAT(A58)
97004 FORMAT(A34)
97005 FORMAT(1X,A15,1X,I3,2X,A37,5X,I6)
97006 FORMAT(A1,16X,I3,44X,I6)

```



```
97007 FORMAT (A1, 50X, A8, 1X, I10)
97008 FORMAT (A45)
97009 FORMAT (1X, A28, 1X, F7.3, 1X, A21, 3X, I8)
97010 FORMAT (A1, 29X, F7.3, 25X, I8)
97011 FORMAT (15X, A50)
97012 FORMAT (26X, A20, I7)
97013 FORMAT (37X, A19)
97014 FORMAT (A58)
97015 FORMAT (A50, F11.5)
97016 FORMAT (A2, ' LATTICE SPACING          = ', F9.3, ' cm')
97017 FORMAT (A2, ' AXIS ELEMENT THICKNESS = ', F9.3, ' cm')
97018 FORMAT (6X, A45)
97019 FORMAT (1X, A35)
97020 FORMAT (1X, A66, 1X, F11.4)
97021 FORMAT (26X, A30, F5.2)
97022 FORMAT (1X, A31, F10.6)
97024 FORMAT (25X, A21)
97025 FORMAT (1X, A23, 1X, F11.7)
      END
```

APPENDIX 3

MONTE CARLO OUTPUT REPORTS

APPENDIX 3, REPORT 1

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER			CROSS SECTIONS (b)	
ELEMENT	MASS (amu)	FRACTION	SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.87306
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.21119
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.02818
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 9124.28125
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26243.5430
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 307.4923

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01790
 POST-THERMAL ESCAPE PROBABILITY = 0.46601
 TOTAL ESCAPE PROBABILITY = 0.48391

ABSORPTION PROBABILITY FOR 2D = 0.24835
 ABSORPTION PROBABILITY FOR 1H = 0.22710
 ABSORPTION PROBABILITY FOR O = 0.04064
 TOTAL ABSORPTION PROBABILITY = 0.51609

APPENDIX 3, REPORT 2

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6652878	7.600	0.000456
1H	1.00800	0.0009979	81.500	0.278000
O	15.99500	0.3331428	4.240	0.000149
Na	22.99000	0.0002857	3.400	0.530000
Cl	35.45300	0.0002857	15.000	33.259998

TOTAL MASS OF ADDITIVES (t) = 2.500000

DENSITY OF MEDIUM (g/cc) = 1.11214
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.90361
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.22065
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03587
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82470
 MEAN NUMBER OF SCATTERS PER NEUTRON = 9104.37695
 NEUTRON ABSORPTION MEAN FREE PATH = 970.85193

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26195.0625
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 308.3970

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01840
 POST-THERMAL ESCAPE PROBABILITY = 0.12232
 TOTAL ESCAPE PROBABILITY = 0.14072

ABSORPTION PROBABILITY FOR 2D = 0.02535
 ABSORPTION PROBABILITY FOR 1H = 0.02318
 ABSORPTION PROBABILITY FOR O = 0.00415
 ABSORPTION PROBABILITY FOR Na = 0.01265
 ABSORPTION PROBABILITY FOR Cl = 0.79394
 TOTAL ABSORPTION PROBABILITY = 0.85928

APPENDIX 3, REPORT 3

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER			CROSS SECTIONS (b)	
ELEMENT	MASS (amu)	FRACTION	SCATTERING	ABSORPTION
2D	2.01410	0.6656680	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149
Gd	157.30000	0.0000002	27.000	47000.000000

TOTAL MASS OF ADDITIVES (t) = 0.004600

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.90012
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.22663
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03288
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 9104.13574
 NEUTRON ABSORPTION MEAN FREE PATH = 1017.68402

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26165.1582
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 306.9803

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01720
 POST-THERMAL ESCAPE PROBABILITY = 0.12598
 TOTAL ESCAPE PROBABILITY = 0.14318

ABSORPTION PROBABILITY FOR 2D = 0.02653
 ABSORPTION PROBABILITY FOR 1H = 0.02426
 ABSORPTION PROBABILITY FOR O = 0.00434
 ABSORPTION PROBABILITY FOR Gd = 0.80168
 TOTAL ABSORPTION PROBABILITY = 0.85682

APPENDIX 3, REPORT 4

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 100.000 cm
 Y LATTICE SPACING = 100.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.000 cm
 Y AXIS ELEMENT THICKNESS = 2.000 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 7.0093699 (3 He at 1 Atm.)
 CAPTURE PROBABILITY = 0.2716143

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.94328
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.25240
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.04380
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 3810.41089
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 8556.6143
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 191.3396
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 13904.0488
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 208.2675

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01530
 POST-THERMAL ESCAPE PROBABILITY = 0.37698
 TOTAL ESCAPE PROBABILITY = 0.39228

PROBABILITY OF SCINTILLATOR CAPTURE = 0.23619

ABSORPTION PROBABILITY FOR 2D = 0.17879
 ABSORPTION PROBABILITY FOR 1H = 0.16349
 ABSORPTION PROBABILITY FOR O = 0.02925
 TOTAL ABSORPTION PROBABILITY = 0.37154

APPENDIX 3, REPORT 5

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.000 cm
 Y AXIS ELEMENT THICKNESS = 2.000 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 7.0093699 (3He at 1 Atm.)
 CAPTURE PROBABILITY = 0.2716143

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.85254
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.21426
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03605
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 399.06290
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 720.6028
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 60.1246
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 1225.1149
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 68.3468

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01640
 POST-THERMAL ESCAPE PROBABILITY = 0.14864
 TOTAL ESCAPE PROBABILITY = 0.16504
 PROBABILITY OF SCINTILLATOR CAPTURE = 0.76880
 ABSORPTION PROBABILITY FOR 2D = 0.03184
 ABSORPTION PROBABILITY FOR 1H = 0.02911
 ABSORPTION PROBABILITY FOR O = 0.00521
 TOTAL ABSORPTION PROBABILITY = 0.06616

APPENDIX J, REPORT 6

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 100.000 cm
 Y LATTICE SPACING = 100.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.000 cm
 Y AXIS ELEMENT THICKNESS = 2.000 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 2.3364570 (3He at 3 Atm.)
 CAPTURE PROBABILITY = 0.6135581

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.90668
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.18593
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.02779
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 3019.50317
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 6387.2954
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 166.0817
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 10707.5283
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 182.2187

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01340
 POST-THERMAL ESCAPE PROBABILITY = 0.34938
 TOTAL ESCAPE PROBABILITY = 0.36278
 PROBABILITY OF SCINTILLATOR CAPTURE = 0.31200
 ABSORPTION PROBABILITY FOR 2D = 0.15650
 ABSORPTION PROBABILITY FOR 1H = 0.14311
 ABSORPTION PROBABILITY FOR O = 0.02561
 TOTAL ABSORPTION PROBABILITY = 0.32522

APPENDIX 3, REFORK 1

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER			CROSS SECTIONS (b)	
ELEMENT	MASS (amu)	FRACTION	SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.000 cm
 Y AXIS ELEMENT THICKNESS = 2.000 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 2.3364570 (3He at 3 Atm.)
 CAPTURE PROBABILITY = 0.6135581

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.89718
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.22759
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03445
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 257.97360
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 512.1498
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 51.2777
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 771.5570
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 54.7919

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01720
 POST-THERMAL ESCAPE PROBABILITY = 0.11076
 TOTAL ESCAPE PROBABILITY = 0.12796
 PROBABILITY OF SCINTILLATOR CAPTURE = 0.82816
 ABSORPTION PROBABILITY FOR 2D = 0.02111
 ABSORPTION PROBABILITY FOR 1H = 0.01931
 ABSORPTION PROBABILITY FOR O = 0.00345
 TOTAL ABSORPTION PROBABILITY = 0.04388

APPENDIX 3, REPORT 8

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 100.000 cm
 Y LATTICE SPACING = 100.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.100 cm
 Y AXIS ELEMENT THICKNESS = 2.100 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 7.0093699 (3He at 1 Atm.)
 CAPTURE PROBABILITY = 0.2830654

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.91383
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.21322
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03176
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 3630.10571
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 8286.5947
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 186.3368
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 13076.6504
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 198.6816

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01680
 POST-THERMAL ESCAPE PROBABILITY = 0.37952
 TOTAL ESCAPE PROBABILITY = 0.39632
 PROBABILITY OF SCINTILLATOR CAPTURE = 0.24548
 ABSORPTION PROBABILITY FOR 2D = 0.17237
 ABSORPTION PROBABILITY FOR 1H = 0.15762
 ABSORPTION PROBABILITY FOR O = 0.02820
 TOTAL ABSORPTION PROBABILITY = 0.35819

APPENDIX 3, REPORT 9

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER				
ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149
3He	3.01603	0.0000001	1.100	5327.000000

TOTAL MASS OF ADDITIVES (t) = 0.000035

DENSITY OF MEDIUM (g/cc) = 1.11046
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.84939
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.22515
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03819
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82585
 MEAN NUMBER OF SCATTERS PER NEUTRON = 9059.85938
 NEUTRON ABSORPTION MEAN FREE PATH = 9531.44141

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26083.9609
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 308.2007

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01860
 POST-THERMAL ESCAPE PROBABILITY = 0.37743
 TOTAL ESCAPE PROBABILITY = 0.39603

ABSORPTION PROBABILITY FOR 2D = 0.17510
 ABSORPTION PROBABILITY FOR 1H = 0.16013
 ABSORPTION PROBABILITY FOR O = 0.02865
 ABSORPTION PROBABILITY FOR He = 0.24009
 TOTAL ABSORPTION PROBABILITY = 0.60397

APPENDIX J, REPORT 10

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 25.000 cm
 X AXIS ELEMENT THICKNESS = 0.006 cm
 Y AXIS ELEMENT THICKNESS = 2.900 cm
 Z AXIS ELEMENT THICKNESS = 2.900 cm
 MFP (cm) IN DETECTOR = 0.0373450 (1:2 wt. 6LiF:ZnS plates)
 CAPTURE PROBABILITY = 0.2748148

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.87566
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.18415
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.02339
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 3454.72632
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 7696.1646
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 178.3368
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 12657.0137
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 196.6181

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01830
 POST-THERMAL ESCAPE PROBABILITY = 0.38388
 TOTAL ESCAPE PROBABILITY = 0.40218

PROBABILITY OF SCINTILLATOR CAPTURE = 0.25166

ABSORPTION PROBABILITY FOR 2D = 0.16657
 ABSORPTION PROBABILITY FOR 1H = 0.15232
 ABSORPTION PROBABILITY FOR O = 0.02726
 TOTAL ABSORPTION PROBABILITY = 0.34615

APPENDIX J, REPORT 11

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000

% D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656667	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333326	4.240	0.000149
6Li	6.01512	0.0000005	0.400	940.000000
F	18.99840	0.0000005	4.000	0.010000
Zn	65.37000	0.0000005	4.200	1.100000
S	32.06400	0.0000005	1.200	0.510000

TOTAL MASS OF ADDITIVES (t) = 0.009710

DENSITY OF MEDIUM (g/cc) = 1.11080

MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.91287

MEAN NEUTRON BIRTH ENERGY (MeV) = 2.23291

MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.03403

THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503

MEAN NUMBER OF SCATTERS PER NEUTRON = 9085.00391

NEUTRON ABSORPTION MEAN FREE PATH = 8835.74707

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26104.5996

MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 306.8575

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01700
 POST-THERMAL ESCAPE PROBABILITY = 0.36796
 TOTAL ESCAPE PROBABILITY = 0.38496

ABSORPTION PROBABILITY FOR 2D = 0.16535
 ABSORPTION PROBABILITY FOR 1H = 0.15120
 ABSORPTION PROBABILITY FOR O = 0.02705
 ABSORPTION PROBABILITY FOR 6Li = 0.27097
 ABSORPTION PROBABILITY FOR F = 0.00000
 ABSORPTION PROBABILITY FOR Zn = 0.00032
 ABSORPTION PROBABILITY FOR S = 0.00015
 TOTAL ABSORPTION PROBABILITY = 0.61504

APPENDIX 3, REPORT 12

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 25.000 cm
 X AXIS ELEMENT THICKNESS = 0.100 cm
 Y AXIS ELEMENT THICKNESS = 0.100 cm
 TUBES OR ROUND DISKS
 Z AXIS ELEMENT THICKNESS = 23.500 cm
 MFP (cm) IN DETECTOR = 0.0578547 (6LiI straws)
 CAPTURE PROBABILITY = 0.8533704

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.89004
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.20007
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.02840
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82503
 MEAN NUMBER OF SCATTERS PER NEUTRON = 3581.72510
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 8237.8652
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 185.3449
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 12745.7363
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 200.1420

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.02020
 POST-THERMAL ESCAPE PROBABILITY = 0.36708
 TOTAL ESCAPE PROBABILITY = 0.38728

PROBABILITY OF SCINTILLATOR CAPTURE = 0.25572

ABSORPTION PROBABILITY FOR 2D = 0.17179
 ABSORPTION PROBABILITY FOR 1H = 0.15710
 ABSORPTION PROBABILITY FOR O = 0.02811
 TOTAL ABSORPTION PROBABILITY = 0.35700

APPENDIX 3, REPORT 13

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656656	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333320	4.240	0.000149
6Li	6.01512	0.0000019	0.400	940.000000
I	126.90440	0.0000019	3.800	6.200000

TOTAL MASS OF ADDITIVES (t) = 0.038700

DENSITY OF MEDIUM (g/cc) = 1.11082
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 6.88969
 MEAN NEUTRON BIRTH ENERGY (MeV) = 2.21410
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 14.02793
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 2.82505
 MEAN NUMBER OF SCATTERS PER NEUTRON = 9071.81836
 NEUTRON ABSORPTION MEAN FREE PATH = 4040.26196

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 26062.7246
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 306.9318

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.01680
 POST-THERMAL ESCAPE PROBABILITY = 0.25571
 TOTAL ESCAPE PROBABILITY = 0.27251

ABSORPTION PROBABILITY FOR 2D = 0.08943
 ABSORPTION PROBABILITY FOR 1H = 0.08178
 ABSORPTION PROBABILITY FOR O = 0.01463
 ABSORPTION PROBABILITY FOR 6Li = 0.53810
 ABSORPTION PROBABILITY FOR I = 0.00355
 TOTAL ABSORPTION PROBABILITY = 0.72749

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 100.000 cm
 Y LATTICE SPACING = 100.000 cm
 Z LATTICE SPACING = 1200.000 cm
 X AXIS ELEMENT THICKNESS = 2.000 cm
 Y AXIS ELEMENT THICKNESS = 2.000 cm
 Z AXIS ELEMENT THICKNESS = 1200.000 cm
 MFP (cm) IN DETECTOR = 0.0000100
 CAPTURE PROBABILITY = 1.0000000

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 0.00000
 MEAN NEUTRON BIRTH ENERGY (MeV) = 0.00000
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 0.00000
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 10000.00000
 MEAN NUMBER OF SCATTERS PER NEUTRON = 0.00000
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.00000
 POST-THERMAL ESCAPE PROBABILITY = 0.95280
 TOTAL ESCAPE PROBABILITY = 0.95280

PROBABILITY OF SCINTILLATOR CAPTURE = 0.04720

ABSORPTION PROBABILITY FOR 2D = 90.67622
 ABSORPTION PROBABILITY FOR 1H = 1.24387
 ABSORPTION PROBABILITY FOR O = 0.09527
 TOTAL ABSORPTION PROBABILITY = 0.00000

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER				
ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 25.000 cm
 X AXIS ELEMENT THICKNESS = 0.006 cm
 Y AXIS ELEMENT THICKNESS = 2.900 cm
 Z AXIS ELEMENT THICKNESS = 2.900 cm
 MFP (cm) IN DETECTOR = 0.0000100
 CAPTURE PROBABILITY = 1.0000000

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 0.00000
 MEAN NEUTRON BIRTH ENERGY (MeV) = 0.00000
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 0.00000
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 10000.00000
 MEAN NUMBER OF SCATTERS PER NEUTRON = 0.00000
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.00000
 POST-THERMAL ESCAPE PROBABILITY = 0.93300
 TOTAL ESCAPE PROBABILITY = 0.93300
 PROBABILITY OF SCINTILLATOR CAPTURE = 0.06700
 ABSORPTION PROBABILITY FOR 2D = 20.73159
 ABSORPTION PROBABILITY FOR 1H = 1.73327
 ABSORPTION PROBABILITY FOR O = 0.09329
 TOTAL ABSORPTION PROBABILITY = 0.00000

SNO NEUTRAL CURRENT DETECTION MONTE CARLO RESULTS

NUMBER OF EVENTS = 10000
 % D2O (molecular fraction) = 99.85

COMPOSITION & CONTENTS OF THE DETECTOR WATER

ELEMENT	MASS (amu)	FRACTION	CROSS SECTIONS (b)	
			SCATTERING	ABSORPTION
2D	2.01410	0.6656681	7.600	0.000456
1H	1.00800	0.0009985	81.500	0.278000
O	15.99500	0.3333333	4.240	0.000149

DISCRETE DETECTING ELEMENT LAYOUT

X LATTICE SPACING = 25.000 cm
 Y LATTICE SPACING = 25.000 cm
 Z LATTICE SPACING = 25.000 cm
 X AXIS ELEMENT THICKNESS = 0.100 cm
 Y AXIS ELEMENT THICKNESS = 0.100 cm
 Z AXIS ELEMENT THICKNESS = 23.500 cm
 MFP (cm) IN DETECTOR = 0.0000100
 CAPTURE PROBABILITY = 1.0000000

DENSITY OF MEDIUM (g/cc) = 1.11079
 MEAN INCIDENT NEUTRINO ENERGY (MeV) = 0.00000
 MEAN NEUTRON BIRTH ENERGY (MeV) = 0.00000
 MEAN NEUTRON THERMALIZATION DISTANCE (cm) = 0.00000
 THERMAL NEUTRON SCATTERING MEAN FREE PATH (cm) = 10000.00000
 MEAN NUMBER OF SCATTERS PER NEUTRON = 0.00000
 NEUTRON ABSORPTION MEAN FREE PATH = 15815.62988

MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH TANK EDGE (cm) = 0.0000
 MEAN DISTANCE FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000
 MEAN DISPLACEMENT FROM BIRTH TO ENCOUNTER WITH DETECTOR (cm) = 0.0000

ESCAPES, CAPTURES, AND ABSORPTIONS

PRE-THERMAL ESCAPE PROBABILITY = 0.00000
 POST-THERMAL ESCAPE PROBABILITY = 0.96350
 TOTAL ESCAPE PROBABILITY = 0.96350

PROBABILITY OF SCINTILLATOR CAPTURE = 0.03650

ABSORPTION PROBABILITY FOR 2D = 20.25125
 ABSORPTION PROBABILITY FOR 1H = 1.74104
 ABSORPTION PROBABILITY FOR O = 0.09634
 TOTAL ABSORPTION PROBABILITY = 0.00000

END

19/09/90

FIN