SUDBURY NEUTRINO OBSERVATORY

SNO-STR-91-37

by
C. K. Hargrove, CRPP
D. Kessler, D. Paterson, Carleton University

Abstract

Monte Carlo studies have been made of various methods of encasing salt in acrylic tubes in order to detect Neutral Current (NC) neutrons in the SNO detector. We find that a practical alternative would involve 2.5 tonnes of salt in a saturated solution in 7.7 tonnes of the D2O. For a salt solution encased in acrylic tubes 2 mm thick and 5 cm in diameter, on a 50 cm lattice, 78% of NC neutrons will be captured on deuterons or chlorine. Further Monte Carlo studies have shown that such a method allows for implementation of a 'split-detector' in which separate halves of the detector display Charged Current (CC) only and CC+NC events respectively. While the rate for the NC measurements would be reduced, this method would result in simultaneous CC and NC observations, thus allowing separation of these data sets. Shut down periods for extraction of additives to the D2O, would also be eliminated, and ultimately no loss in statistical significance of the measurements would result.

INTRODUCTION

The measurement of the NC rate in SNO is critical to the solution of the Solar Neutrino Problem. The current or default method requires dissolving 2.5 tonnes of NaCl in the heavy water. The NC interaction with the D2O produces neutrons which are captured by the 35Cl of the salt, with subsequent detection of the Cerenkov light produced by the electromagnetic shower of the resulting capture gamma rays. Since the light from the capture gamma rays has the same intensity as the Cerenkov light from the CC events, the NC event rate can only be determined by subtraction of the sum of the CC and neutrino Elastic Scattering (ES) rates from the sum of the CC, ES, and NC rates. The measurement of these individual event rates must be made sequentially, taking many months each. The manipulation of additives to the D2O (Boron for neutron suppression during CC rate measurement, NaCl for neutron capture for NC rate measurement) will require effort and time to subsequently remove them. The detector will therefore be unable to discern short term variations in the NC rate versus the CC rate. The collaboration is therefore searching for a method of detection which will surmount the shortcomings of this method.

One of the methods previously suggested(1), partly in response to concerns regarding the corrosive effects of the salt water brine, was that the salt be encapsulated in tubes, with a geometry similar to that suggested for 3He proportional tube NC detectors(2). The dimensions of the tubes, following the 3He model of 2.0 cm radius tubes on a 75 cm. square lattice, would be such as to require nearly 4.5 tonnes of salt, compared with the 2.5 tonnes for the default method. Event detection efficiency would be reduced from the neutron capture efficiency by the limited detection efficiency for Cerenkov signals, which is taken(3) to be near 75% for 75% soft photocathode coverage for such chlorine capture gamma rays. Detection efficiency for this method has been estimated (1,3) at less than 50%. It was our opinion that such estimates for detection efficiency are too low and this has prompted us to check this opinion using our Monte Carlo program.

We find from our Monte Carlo that encasing the salt in tubes achieves somewhat better neutron capture efficiency than was estimated. Three illustrative cases were calculated, those being:

a) 4.5 tonnes of NaCl in 2.0 cm radius tubes on a 75 cm lattice.
b) 2.5 tonnes of NaCl in 1.5 cm radius tubes on a 75 cm lattice.

c) 2.5 tonnes of NaCl in 1.15 cm radius tubes on a 55 cm lattice.

We also find that a saturated salt solution with the brine encapsulated in tubes (also previously suggested(1)), achieves nearly the NC sensitivity of the default method, with little loss in light signal. In a variation on some recent suggestions(4) regarding a split detector, we propose a detector geometry which includes the salt solution in tubes in one half of the detector, and a boron loaded liquid in tubes in the other half of the detector, as a method for simultaneously and separately observing the CC and NC rates.

MONTE CARLO SIMULATIONS

SOLID SALT IN TUBES

The Carleton-CRPP NC Event Monte Carlo has been used to simulate the NaCl geometry mentioned above, as well as other similar geometries. The results are most encouraging. With the mean free path for neutrons in salt of density 2.165 g cm-3 being 1.36 cm, compared with the 2.33 cm mean free path for 3 Atm. 3He, both cases are nearly neutron black for 2 cm radius tubes. The neutron capture efficiency was studied via these Monte Carlo simulations for lattice constants in the range of 25 to 100 cm, and for tube radii of from 1.0 cm to 2.0 cm. We find the neutron capture efficiency for 2.0 cm radii tubes on a 75 cm lattice to be 63% for solid NaCl in such tubes. As well, deuterons are a neutron absorber, capturing 7% of NC neutrons. At 75% detection efficiency for such Cerenkov signals, 52% of NC events will be observed.

An attempt was made to reduce the amount of NaCl used from the 4.5 tonnes contained in such tubes, on the premise that tubes which were less 'neutron-black' would still achieve high neutron capture efficiency (because of multiple transits of the tubes by the neutrons). For absorbing elements having dimensions comparable to the neutrons' mean free path for scattering in the D2O, there is a high probability that a neutron will penetrate the absorber two or more times. The neutron capture probability would therefore be given by

Pcapt = 1-exp[-nd/lambda]

where lambda is the mean free path for neutron capture in the detecting material, d is the thickness of detecting material crossed averaged over entrance angle and position in the tube, and n is the number of times neutrons cross the detecting element. Since for 2 cm radius tubes, the mean neutron capture probability for single photon crossings is greater than 90%, virtual neutron blackness can be expected for n = 4. Then a reduction in detecting element diameter will not produce a corresponding reduction in capture efficiency. This was simulated for 1.5 cm radius tubes (2.5t of NaCl) and the results predict 57% neutron capture on chlorine and 8% on deuterons. Therefore a 44% reduction in the amount of salt produces only a 7% reduction in neutron capture efficiency. A further Monte Carlo simulation was done in which the tube radius was cut to 1.15 cm on a 55 cm lattice, achieving 66% neutron capture efficiency on 2.5 tonnes of NaCl, with 6% of neutrons capturing on deuterons. Such a geometry provides no more obstruction of the light signal than the 75 cm lattice, 2 cm radius tubes, with Monte Carlo simulations giving 23% photon losses for the 75 cm lattice, and 24% for the 55 cm lattice.

Table 1 lists the results of 10000 event Monte Carlo simulations for these solid salt in tubes cases in the first three rows. The first two columns specify the lattice constant and tube diameter simulated, and the third column indicates the amount of salt contained in each case shown. The neutron capture efficiency for the chlorine and that for the deuterons, as predicted by the Monte Carlo, are listed in the next two columns. The last column lists the Monte Carlo prediction of the percentage of light rays encountering at least one tube of the specified geometry. The last five rows of the table list the Monte Carlo results for various geometries of dissolved salt in tubes, which are discussed below.

DISSOLVED SALT IN TUBES

We have investigated the neutron capture efficiency of saturated salt solutions in tubes. Such detecting elements can be transparent, with only some slight loss in event position resolution due to scattering or reflection of photons. Salt saturates in water at 357 g/l. For salt in D2O, this results in a density of 1.38 g cm-3, and a chlorine density of 0.217 g cm-3. The mean free path for thermal neutron capture on chlorine is consequently 8.24 cm in such a solution, and the amount of D2O consumed in dissolving 2.5 tonnes of NaCl is 7.7 tonnes, or 0.77% of the D2O.

We find that to contain the 2.5 tonnes of salt in solution in tubes, a relationship exists between the tube diameter, d, and the lattice constant, L such that L = 10d. This relationship results from the fact that the total volume of such tubes is directly proportional to the square of the radius of the tubes, and inversely proportional to the square of the lattice constant. This latter relationship results from the fact that the number of tubes increases as the inverse square of the lattice constant. When the ratio of the tube radius and the lattice constant equals 10, the contained volume is 7 million litres (V = pi*Rtank*Atube*Ntubes/3). We have simulated various lattice constants and tube diameters, and we find good neutron capture efficiencies, approaching that for the default method. The tube sizes are such as to intercept much of the photon signal, but by selecting plastic tube materials so as to minimize the change in refractive indices at the boundaries, these intercepted photons will be scattered only a small amount, yielding little loss of signal.

TABLE 1: NEUTRON CAPTURE PROBABILITY FOR 'SALT-IN-TUBES'

NaCl Form	Lattice Constant cm	Tube Diameter cm	Mass of NaCl tonnes	Pcapt on Cl %	Pcapt on 2D %	Photon Interceptions %
SOLID						
	75	4.0	4.5	63	7	23
	75	3.0	2.5	57	8	17
	55	2.3	2.5	66	6	24
SOLUT'N						
	75	7.5	2.5	67	6	37
	60	6.0	2.5	71	5	43
	50	5.0	2.5	74	4	48
	40	4.0	2.5	76	3	55
	20	2.0	2.5	81	2	71

While a 20 cm lattice would be logistically unmanageable, it would result in virtually no loss in NC detection. Alternatively, a 50 cm lattice will capture 78% of NC neutrons, allowing observation of Cerenkov light from 59% of NC events compared to 64% for the default method.

MECHANICAL DESIGN CONSIDERATIONS

A geometry similar to that proposed for 3He proportional tubes would be suitable for the case of a saturated salt solution in tubes. A lattice constant of 50 cm would insure 78% of NC neutrons capture on salt and deuterons. Using the same acrylic as in the spherical vessel, tubes of 5 cm diameter, and 1 metre in length, could be strung together to hang from hooks in the SNO vessel.

The strength of this acrylic will be such as to withstand a pressure of 580 psi (270 psi for unannealed bond joints)(5) on 2.5 cm thick panels. The salt solution in each tube will contribute 550g in negative buoyancy, resulting in a pressure of a fraction of a psi. The acrylic in each tube, then, may be much less than 2 mm thick. (In fact, bladders become a viable option, but we will continue our discussion here based on a tube geometry.) The longest string of tubes would exert a force of 61 N on the suspension system. The total acrylic added would be less than 0.3 tonnes. Since the acrylic vessel will weigh of the order of 11 tonnes, the increase in photodisintegration background resulting from the addition of the tubes will be less than 3% of that contributed by the spherical vessel itself. This contribution will, however, be distributed throughout the D2O, resulting in a slight increase in the photodisintegration background near the centre of the vessel. (The acrylic thickness may be up to an order of magnitude less than what is proposed here, depending upon 'out-of-detector' handling methods. It has been inflated here only to permit continued discussion below, without dwelling upon this logistics matter.)

LIGHT SCATTERING FROM TRANSPARENT SALT TUBES

The refractive index for D2O is 1.334. Optical tests were done(6) on the candidate acrylics for use in the spherical vessel and the refractive index for these materials was found to be in the range of 1.46 to 1.49. The refractive index for saturated salt solutions is in the range of 1.40. This near matching of refractive indices at the cylindrical boundaries results in only a small amount of reflection and scattering of the optical signals, without substantial loss in intensity. We have modelled the D2O/Acrylic and Acrylic/Brine boundaries for horizontal rays of various angles of incidence on the tubes (assuming tubes aligned vertically), and for the refractive indices quoted above. We find the path of these rays to be shifted horizontally on exiting the tubes, normal to the direction of the ray, by a mean value of less than 1 mm in the direction of the centres of the tubes encountered. We also find the direction of the rays, averaged over all (horizontal) angles of incidence, to be bent by encountered tubes, towards the centres of such tubes, by a mean angle of 6 degrees. The angular width of the Cerenkov annular ring due to multiple scattering will be near 6 degrees, and so we may anticipate that the horizontal effect of the tubes will be to broaden the scatter of the Cerenkov photons in the horizontal plane by a factor near sqrt(2). Given the case of a 50 cm lattice constant and 5 cm diameter tubes, some 48% of light rays will experience horizontal bending at each tube encountered. The impact of this scattering on event reconstruction has not been evaluated, but it is apparent that rays travelling 8.5 metres from origin to the photomultiplier tubes will be deflected a mean distance of 90 cm (which is approximately equal to the width of the annular ring of the Cerenkov light due to multiple scattering), compared to the 560 cm radius of the Cerenkov light annulus. As well, this deflection will be towards the centres of tubes encountered, so that taking all angles of incidence, the mean deflection will approach zero, and the result will be a broadening of the Cerenkov ring in the horizontal plane.

We have also considered the transmittance of light through the acrylic, and reflectance of light at the acrylic/water boundaries. We have taken the mean absorption coefficient for the acrylic to be 0.03 cm-1, as measured for a wavelength of lambda=400 nm(6). For those rays encountering tubes, we find through simulation that the bulk transmittance is 0.98. This leads us to predict that the transmittance of light through each encountered tube will be of the order of 91%, with approximately 7% of the light reflected and 2% absorbed in the acrylic. We have not considered absorption of light in the brine, since the amount of salt will not be increased beyond the originally planned 2.5 tonnes. We have also ignored the reflectance of light at the acrylic/brine boundary since the similarity in refractive indices on both sides of the boundary will result in substantially less reflectance than at the acrylic/water boundary. We therefore conclude, since only half the light will encounter tubes for the lattice under discussion, that 95% of the light generated by events in the D2O will survive the array of tubes, though half the light beams will be broadened by a mean angle of up to 6 degrees.

THE 'SALT-IN-TUBES' SPLIT DETECTOR

We have simulated the case where the tubes distributed throughout the detector are loaded with the salt solution on one side of the detector, or a boron loaded liquid for neutron suppression on the other side of the detector. With the isotopic abundance of 10B being 19.8%, and the neutron cross section for 10B being 3837b, boric acid would be neutron black in 5 cm diameter tubes. This would have the effect of suppressing NC event signals on the borated side of the detector, thus causing the borated side of the detector to display CC events, while the salted side would display the combined CC+NC rate. (3% of NC neutrons would be captured by deuterons, adding to the CC background on the borated side of the detector. This can be subtracted out after the NC rate has been determined from the salted side of the detector.) While this would reduce the NC event rate by approximately half as a result of the dividing of the D2O volume, it would eliminate the need for time to be taken to extract additives from the D2O and thereby permit simultaneous CC and NC data taking to begin immediately subsequent to the light water ES measurement. With extended running time, and simultaneous rather then consecutive CC and NC observation, the timewise integrated neutrino cross section of the detector will be increased for both CC and NC interactions. As well, the CC and NC rates would be statistically separable.

The results of the simulation indicate that 37% of NC neutrons will be capture on the salt solution, 41% will capture on boric acid resulting in no signal, and the balance will escape or be absorbed in the water. This will result in Cerenkov light being received from 56% of the NC neutrons born in the 500 ktonnes of D2O on the salted side of the detector (plus the CC signals), while the other side of the detector simultaneously displays only CC events. (This relative weighting of the signals from the two halves of the detector can be adjusted somewhat through the mean free path for neutrons crossing the borated tubes, and through the relative numbers of salted and borated tubes.) The mean free path for the chlorine capture gamma rays is near 40 cm in the D2O, so little signal will cross the salt/boron boundary, and that which does will exhibit a directionality enabling projection back into the salted side of the detector. There will remain an uncertainty in locating the salt/boron boundary, due to detector position resolution, which may lead to discarding of events within the central 5% of the detector. However, the CC and NC rates will be simultaneously and separately observable.

It is, in fact, not clear that the advantages of using boron outweigh the resulting difficulties. It may be more practical to dispense with any neutron capture agent in one half of the detector. The result of such a method would be a small increase in the NC signal in the opposite half of the detector due to longer neutron random walks, offset by a small increase in the CC background in the unsalted half of the detector due to increased neutron captures on deuterons.

Assuming that such a method will result in the elimination of at least a four month detector shut down (boron or salt extraction) during the first two years of operation, the increased operating time will offset the loss in sensitivity, so that no increase in statistical uncertainty will result.

CONCLUSIONS

We have shown that the method of encasing the planned 2.5 tonnes of NaCl in acrylic tubes achieves 66% NC neutron capture probability on chlorine, plus 6% NC neutron capture probability on 2D, as compared to 82% NC neutron capture probability in the diffused salt (default) method. This method suffers only a small (12%) reduction of NC event detection efficiency, but will result in obstruction of 24% of photons by the salt tubes. The advantage of the method is that most of the D2O is not loaded with salt, and therefore requires no special apparatus or subsequent purification. This in turn results in increased detector operating time.

We have also shown that a saturated solution of 2.5 tonnes of salt enclosed in acrylic tubes can be implemented to achieve 78% NC neutron capture probability. While 48% of photons will encounter tubes in this method, 91% of these will be transmitted with some horizontal bending, resulting in a horizontal broadening of the Cerenkov annular pattern by an average of 6 degrees for each encounter. The effect of non-zero vertical incidence angles has yet to be included in this analysis, but will worsen the situation somewhat. This will affect the SNO detector's position resolution.

We have also proposed that this method of the saturated salt solution in tubes, in combination with a boron loaded liquid in tubes, can be implemented in a way which will permit simultaneous and separate observation of both the CC and NC rates, with no loss in CC or NC event detection.

These methods do not overcome the difficulty of the increased measurement uncertainty which results from the subtraction of the CC rate as a background to the NC rate.

REFERENCES

1 Earle, E.D.; Bitnet Message; 11-sep-90
2 Bowles et al.; Neutral Current Neutrino Interactions in the Sudbury Neutrino Onservatory.
3 Robertson, R.G.H.; NC Detector Envelope
4 Simpson, J.; Bitnet Message (third-time-lucky); 24-oct-90
5 The SNO Collaboration; The Mark II SNO Detector.
6 Davidson et al.; Red Book Annex-2