SNO-STR-90-99

BEADS -- AN OPTION FOR NEUTRAL CURRENT DETECTION IN SNO?

R. G. H. Robertson
August 27, 1990

ABSTRACT

Spherical beads in the size range 10-100 μm can be suspended in liquids for long periods, as their sedimentation rates are modest. However, they can easily be removed by macroscopic filtration when desired. This raises possibilities for simplified methods of neutral current detection in SNO. The beads may be made of a ^{10}B-loaded scintillator or of some material such as NaCl (coated with an insoluble film) to allow neutron detection via, respectively, scintillation light or Cerenkov light. While there are some significant advantages, there are sufficiently serious problems that the method is of doubtful value.

INTRODUCTION

The present plan for detecting neutral-current interactions in SNO calls for capturing the free neutrons produced in such interactions. The most suitable capture nuclide is Cl because NaCl can be dissolved in the heavy water, is available in very high purity, is compatible with the construction materials of the containment vessel, and leads to a high-energy gamma ray that produces Cerenkov light in the heavy water.

However, because this Cerenkov light would be indistinguishable from that produced by charged-current interactions of solar neutrinos, a subtraction would have to be made. Various means have therefore been explored to make the neutron capture distinctive enough to permit event-by-event separation of neutral and charged-current processes. Proportional counters or solid or gaseous scintillators containing a high-cross-section nuclide that produces charged particles on neutron capture are promising in principle but difficult in practice. All materials need to have very high purities, and installing macroscopic devices in the heavy-water vessel complicates its construction significantly.

Monte Carlo simulations have shown that scintillation light can be distinguished on the basis of its isotropy from Cerenkov light event-by-event.

The schemes considered up to now have involved either dissolution of an additive in the heavy water, or installation of macroscopic devices. A "mesoscale" alternative is considered here that might be applicable either to scintillation or to Cerenkov light production, but that would avoid either dissolution of an additive or installation of devices. The question is whether micron-sized beads containing the appropriate material(s) could be suspended in the heavy water for neutron detection.

Scintillating beads are of interest, because they would meet the objective of event-by-event identification of neutron captures. However, it may be noted in passing that materials such as NaCl, Cd, or Gd could in principle also be incorporated into beads to implement the Cerenkov method without the need to dissolve anything in the heavy water.

1. Minimum bead size

As has been discussed elsewhere,[1,2] only ^{3}He, ^{6}Li, and ^{10}B appear suitable as the target nuclei of scintillators. Of these only the last two would be suitable in small solid scintillator beads, and ^{10}B has the advantage that the secondary particles (^{4}He and ^{7}Li; total energy 2.79 MeV) have a small range. The total range in a hydrogenous scintillator material is 10 microns, which sets a minimum size for the beads. This is not a sharply defined quantity, because smaller sizes would simply reduce the light output, and even with larger sizes, some fraction of the particle energy will be released outside the bead. But qualitatively, the larger the bead, the better the spectroscopic quality of the information. When the energy is fully contained, an energy resolution of about 25 to 30% can be expected in a B-doped scintillator (BC-454). While not outstanding, it would provide some discrimination against (and measurement of) the 5-8 MeV alphas characteristic of the U and Th chains.

2. Quantity of Material.

If an additive is uniformly dispersed in the heavy water at the molecular level, then one can calculate the probability of neutron capture on each element after the method of Earle and Wong.[3] The water is 99.85% D_2O and the additive is B with an enrichment of 90% ^{10}B (σ = 3420 b). The goal is 50% capture on B, neglecting neutron escape from the acrylic vessel.

Element	σ/atom	elem. frac. f	σ x f	cap. frac.
H	0.278	0.0010	2.8×10^{-4}	22%
D	4.56×10^{-4}	0.666	3.0×10^{-4}	24%
O	1.49×10^{-4}	0.333	0.5×10^{-4}	4%
B	3420.	1.8×10^{-7}	6.3×10^{-4}	50%

This elemental fraction of B corresponds to a mass of 270 g. For a scintillator material that is 5% boron by weight (Bicron BC-454), the total mass of scintillator is 5.4 kg.

When the additive is not dissolved in the water but is in the form of macroscopic beads, this relationship will no longer hold exactly. Consider the effect of agglomerating a certain fixed amount of additive from a molecular solution into larger and larger droplets (beads) of a distinct phase. The capture fractions given above remain valid as long as a neutron has the same probability of encountering any given atom as it did in the solution limit.

There are, in fact, two droplet size scales whose onset will cause departures from the solution limit. One is the occurrence of self-shielding, in which boron atoms on the inside of a droplet are less likely to be exposed to a neutron because the droplet is becoming "black" to neutrons. The second is the droplet-separation limit, in which droplets become so widely separated that, depending on whether a neutron is born near one or far from one, it has a greater or smaller chance of encountering a droplet. This second limit sets in roughly when the average droplet separation becomes comparable to the mean distance between scatterings of a thermal neutron.

2.2 *Self-Shielding Limit.* The treatment is kept very schematic in order to obtain a simple estimate. The neutron cross-section for a macroscopic sphere may be written

$$\sigma_m = \pi r^2 f,$$

where r is the sphere radius and f is blackness fraction that represents the neutron absorption probability for a neutron passing through the sphere. (The analysis becomes less accurate as f approaches 1.)

$$f = \frac{N_0 \rho_B 4 \pi r^3 \rho \sigma_B}{10 \rho 3 \sigma_{geom}}$$

where ρ_B/ρ = fraction of ^{10}B by weight
ρ = density of material (BC-454 = 1.025 g/cm^3)
$\sigma_B = 3420 \times 10^{-24}$ cm^2

$$\sigma_{geom} = \pi r^2.$$

If neutron blackness sets in when f is about 0.1, then

$$r = 0.75 \ (N_0 \ \sigma_B \ \rho \ \rho_B/\rho)^{-1}$$

$$= 60 \ \mu m.$$

2.3 *Bead Separation Limit.* If the total mass of beads is M, then the number present in the vessel is

$$N = 3 \ M \ / \ (4 \ \pi \ r^3 \ \rho).$$

The average volume occupied by each bead is

$$V = 0.9 \times 10^9 \ / \ N \ cm^3$$

and the average separation between beads is

$$d = 10^3 \ N^{-1/3}.$$

The mean free path between scatters for a neutron is 2.7 cm. Equating this to d, one finds a bead radius of 300 μm. For the parameters chosen here, the blackness limit sets in somewhat before the separation limit. More generally, the blackness-limit radius scales linearly with ρ/ρ_B, while the separation-limit radius scales as the cube root of this ratio.

It should be noted that these "limits" are not true limits in any sense, but mark the points beyond which extra absorbing material (boron) will be needed in order to maintain the same neutron capture efficiency as in a true molecular solution.

3. Optical Scattering and Absorption.

There is a strong motivation for making the bead radius as large as possible, consistent with the limits given above. The beads present their geometric cross section for scattering Cerenkov photons generated within the D_2O by charged-current processes. Scattering from beads (or, for that matter, from macroscopic detectors in the heavy water) causes problems in the reconstruction of events by giving a few PMT hits the wrong relative time.

The probability that a Cerenkov photon will strike a bead is given by,

$$P_S = \pi r^2 \ R/V,$$

where R is a characteristic length of order the radius of the vessel, about 600 cm.

$$P_S = R\ M\ /\ (1.2 \times 10^9\ r\ \rho).$$

For the parameters chosen, M = 5400 g and r = 60×10^{-4} cm, one finds an average scattering probability of 45%. This is much too high, and it would be essential to find ways to reduce this about an order of magnitude. A larger bead radius is the most immediate hope, although the dependence is only linear. More detailed calculations of the blackness-radius limit would be needed. Note that increasing (or decreasing) the boron concentration does nothing as long as the blackness-radius limit is adhered to, because both M and r scale linearly with the inverse of boron concentration.

4. Sedimentation Rate.

Beads that are not exactly neutrally buoyant must be kept suspended by constant mixing of the D_2O. The tendency for heavier beads to settle out at the bottom or for lighter beads to float to the surface must be counteracted by a mass flow rate of D_2O up or down at velocities that exceed the terminal sedimentation velocity.

The viscous force on a sphere moving at velocity v through a medium of viscosity η is

$$F_V = 6\ \pi\ \eta\ r\ v.$$

Equating this to the net force due to gravity,

$$F_g = (4/3)\ \pi\ r^3\ (\rho - \rho_W)\ g,$$

where ρ_W is the density of D_2O (1.10 at 20 C), one finds the terminal sedimentation velocity,

$$v = (2/9)\ r^2 (\rho - \rho_W)\ g/\eta.$$

If the viscosity of D_2O is the same as H_2O, 0.013 poise at 10 C, and the density of the scintillator is 1.025, then

$$v = -\ 1.3 \times 10^3\ r^2\ \text{cm/s}.$$

For example, if r = 60×10^{-4} cm, v = $-\ 4.5 \times 10^{-2}$ cm/s.

The lowest flow rate in the vessel is likely to occur at the equator, where the cross sectional area is 10^6 cm^2. If the flow is perfectly uniform across this diameter, then a flow rate of 45 l/s (downward in this case) is required. This is high, but not inaccessible. However, the previous section made it clear that larger values of r are desirable, and the

flow rate is proportional to r^2. Careful matching of the density of the scintillator to that of the heavy water would mitigate the problem.

The inevitable development of plumes and other flow instabilities make the flow question much more complicated. It is not obvious that such instabilities hinder the objective of a uniform distribution of beads in the vessel. For example, a relatively fast-flowing plume in the center of the vessel might serve to carry beads toward the bottom from where they would spread out and gradually float upwards. In this way a homogeneous distribution might be achieved at lower flow rates than that given above.

5. Time to Equilibrium

The time to reach a homogeneous distribution can be expected to be about 10 times the time to recirculate a volume of water equal to the vessel volume. This time, at the flow rate of 45 l/s, is about 6 hours, so some 60 hours would be needed for homogenization after a perturbation.

6. Alpha Backgrounds.

The allowable concentration of U and Th in the material of the beads depends on the fraction of the alpha events that lie underneath the neutron-capture peak at 2.8 MeV, b, the total mass of material (M) and the acceptable S/N ratio.

$$C_U = S\ e\ /\ (S/N\ b\ 4 \times 10^{11}\ m\ M),$$

where S is the expected neutron production rate (5000 per year), e the capture efficiency (50%), m the alpha multiplicity for each U decay (8), and the constant is the specific activity of U. Inserting M = 5400 g and S/N = 10,

$$C_U = 5.8 \times 10^{-14}.$$

We have assumed that b is about 0.25, a result of the poor resolution of scintillators. This purity is obviously very difficult to reach. The corresponding purity for Th is about 2.4×10^{-13}.

7. Photodisintegration Backgrounds.

The number of neutrons produced by photodisintegration is approximately 4000 times smaller than the number of alpha decays. Purity levels in the 10^{-10} to 10^{-11} range are needed to match the alpha background rates.

8. Electron Backgrounds.

A well-known characteristic of solid scintillators is the pulse-height defect that causes the light output from a heavily ionizing event to be a factor 10 to 20 smaller than the light from an electron event of the same energy. Thus 150 to 300 keV deposited by an electron will give the same photon yield as the 2.8-MeV neutron capture event.

Electron energy loss falls from 0.4 keV per micron at 100 keV down to 0.2 at minimum ionizing in CH_2. The small size of beads is helpful in reducing electron backgrounds -- a bead 60×10^{-4} cm in radius cannot develop more than 50 keV of mean energy loss. Multiple scattering and the Landau tail for electron energy loss will still permit larger losses, however. Increasing the bead size to 500 micron radius (desirable for other reasons) would cause every minimum-ionizing electron to produce about the same amount of light as a neutron capture.

Even so, there is substantial rejection of electron backgrounds owing to the low probability of an electron moving in the heavy water striking a bead. A 2-MeV electron has a range of about $r_e = 1$ cm in water. The volume swept out is

$$V_e = r_e \pi r^2$$

and the probability of a bead center lying within that volume is then

$$P_e = r_e \pi r^2/V = M / (1.2 \times 10^9 \, r \, \rho)$$

$$= 7.3 \times 10^{-4}$$

for 60-micron radius beads.

There is, in addition, the standard method of pulse-shape discrimination which can be applied to reduce electron backgrounds still further.

Electron backgrounds from the U and Th chains in the D_2O should be at the level of about 10^3 times the neutron backgrounds produced by photodisintegration. Hence the electron backgrounds in scintillating beads should be smaller than the neutron backgrounds. (We have not yet considered the limits that would have to be placed on K in the heavy water and the scintillator.)

Tritium causes a different sort of background if beads are not protected from direct contact with the heavy water. The total surface area of the beads is

$$A = N\ 4\ \pi\ r^2$$

$$= 3\ M\ /\ r\ \rho.$$

The range of a 10-keV electron is about 3 microns, and for about 1/3 of all decays taking place within this range of the surface an electron will enter the scintillator. The maximum specified tritium concentration[4] is C_t = 10 nCi/g. The corresponding scintillator rate is

$$C_t\ 37\ M\ 3 \times 10^{-4}\ 1.1\ /\ r\ \rho$$

$$= 10^5\ s^{-1}$$

for 60 micron radius beads. If each event produces 20 photons, the quantum efficiency of the 10000 PMTs is 20%, and the geometrical efficiency is 70%, then the dark rate in each tube is increased by 30 s^{-1}. This increase can be neglected per se. The mean value of N_{HIT} is 2.8, and more detailed calculation would be needed to determine the shape of the tail of this distribution.

SUMMARY

The use of scintillating beads in the heavy water confers the advantages of mechanical simplicity, very straightforward measurement of backgrounds associated with the beads (by changing their number), easy removal by filtration and good light output.

There are very significant disadvantages, however, which may be insurmountable. As with any scintillator, extremely low levels of U and Th are required. Keeping the beads suspended homogeneously appears to call for very high flow rates. Making sure there are no eddies or traps where concentrations of beads could accumulate might be difficult. Scattering of Cerenkov light by the beads is excessive, at least in the simplified model used, and would need to be reduced an order of magnitude if simultaneous charged-current and neutral-current operation is to be achieved.

REFERENCES

1. "Solar Neutrino Neutral Current Detection Methods in the Sudbury Neutrino Observatory", C. K. Hargrove and D. J. Paterson, preprint June 1989.

2. "Detection of Neutral Current Neutrino Interactions in the Sudbury Neutrino Observatory", Los Alamos SNO Collaboration, LA-UR-90-546.

3. "Calculations of Neutron Transport in the SNO Vessel", E. D. Earle and P. Y. Wong, SNO-87-12 (Annex-1).

4. "Photons from and Safety of Tritiated D_2O", E. D. Earle.