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Wavelength Shifter or Liquid Scintillator in SNO: First Pass

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1 Introduction

At the Vancouver workshop on neutral current detection Art MacDonald suggested that the addition of wavelength shifter or a water-based liquid scintillator to the D_2O might improve the overall performance of SNO, particularly for neutral current detection. Several difficulties were identified with such schemes which may render them unworkable, however the possible benefits are sufficient that it may be a good idea to consider them further. I am writing this note to bring those who were not present at the workshop up to date on this idea in the hope that they may identify either problems or advantages that we have missed up to now. I also hope that people in the collaboration who have experience with these materials, or know where information on them can be found in the literature, will send me a note and let me know.

The purpose of these additives is to increase the light output of electrons in the D_2O . In a previous D_2O CC experiment carried out at LAMPF [1] the addition of 1.0 mg/l of the wavelength shifter 4-methyl-umbelliferone was found to increase the light output of the D_2O by a factor of 3 (summed over their photocathode response function) by shifting light of wavelength too short to be detected by their PMT's ($\sim$360 nm) to a detectable wavelength ($\sim$450 nm). Another [2] group looked into the use of a water-based liquid scintillator consisting of 2% Triton X-100 (a commercial surfactant used to render scintillators water soluble for use in tritium assay), 0.25 g/l PPO (a primary scintillator) and 0.00625 g/l POPOP (a wavelength shifter matched to PPO) and found light yields which would correspond to an enhancement in the light yield in SNO of about a factor of ten. If this were the only effect it would be hard to argue against such a scheme, as this additional light has several beneficial effects in SNO. First, by increasing the light output of electrons in the D_2O relative to electrons created outside the acrylic vessel it should eliminate any backgrounds caused by light created outside the acrylic vessel (such as the PMT beta-gammas). Second, even a small admixture of isotropic light greatly improves the vertex resolution, in the absence of additional scattering we might get vertex resolution $\leq$10 cm. The added light would improve

the energy resolution of the detector. In the case of liquid scintillator the Cerenkov threshold is removed, which further improves the energy resolution for gamma rays. Hopefully this would make the NaCl gamma rays appear as a line in the energy spectrum, thereby allowing a direct extraction of the NC signal from the CC signal. For the light yields given above for scintillator it is even possible to imagine getting the threshold to a low enough energy to observe the sequential decays at the bottom of the uranium and thorium chains, thereby allowing us to measure our background directly and not rely on an external assay.

Unfortunately, there is no such thing as a free lunch. The added light comes at the price of a number of complications. Listed below are the problems which have been identified to date, roughly grouped according to their impact on the experiment.

2 Background and Triggering

The effect of wavelength shifter on the internal beta-gammas is currently unknown and will have to be investigated by MC, however it seems reasonable that the additional light would, if anything, improve our ability to discriminate against them. For the scintillator, however, the removal of the Cerenkov threshold would open the Pandora's Box of all the low energy background sources we have been able to largely ignore up to now. A serious problem comes from tritium. At the current best guess level of 0.05 μCi/l in the D_2O we would have $1.9x10:9$ decays/s. We are currently getting about 10 hits/MeV, so if the scintillator gives us a factor of ten more light we will get ~100 hits/MeV. The mean energy of an electron from tritium β-decay is 5.8 keV, so we will generate ~.6 hits/decay, or ~ $1.1x10:9$ hits/second, or ~90 hits in any 80 ns time window. This will obviously cause trouble for the fitter, which will be discussed below. It may also cause triggering problems, as this corresponds to a noise rate/PMT of ~110 kHz. Using the formula for randomly firing PMT's given in Bill Frati's report [3] I calculate that for 9800 PMT's at 110 kHz within an 80 ns window we would have a trigger rate of ~.7 Hz if we set the trigger threshold at 150 hits (taking the integral distribution roughly into account), which corresponds to a 600 keV threshold. This goes down quite rapidly with trigger level, for 155 hits (650 keV) it is ~.03 Hz.

If we left the trigger at roughly the same energy as it is now (20 hits, or ~2. MeV), we would put it at ~290 hits (200 real hits + 90 noise), and the trigger rate would be zero (my PC won't calculate anything over 171 hits, where the trigger rate from random coincidences is one every 19 days). However, this would eliminate one of the attractions of the scintillator idea, which is the ability to measure the Th and U contaminations directly. Assuming that the energy resolution at low energies will be too bad to see any of the decays directly in singles (although the 3.26 MeV β branch in the : 214Bi may be visible directly), the best bet is to see the time coincidence between the $\beta - \gamma$ decay of : 212Bi (: 214Bi) and the succeeding α-decay of the daughter : 212Po (: 214Po) which occurs with a 300 ns (160 μs)

lifetime. Assuming a pulse-height defect for α's in these liquid scintillators of a factor of ten (Note: this has not been measured for this particular scintillator), then the α's will look like 880 (780) keV electrons, which would barely get above the 600 keV trigger mentioned above. If the numbers work out exactly like the case selected above the ideal solution would be a two-level trigger, where the first trigger was put at ~1 MeV where the accidental rate is negligible, and for a period of a few milliseconds after such a trigger the second trigger was set at ~500 keV (accidental rate ~46/s or one every 22 ms) to look for the following α's. These numbers vary greatly, however, on the exact amount of light we can get from the scintillator (for instance, if we only get a factor of 8 improvement in the light yield, the rate for a 600 keV trigger goes to ~25/s). We therefore need to consider this problem again when we have more realistic numbers, but for the moment it does not appear that this problem will kill the scintillator.

However, the above analysis ignores light produced by other low-energy natural radioactivity. : 40K, for instance, is a serious problem. If we put the trigger threshold below 1.4 MeV we will detect the γ's from : 40K decay. Taking the specific activity of : 40K as 2.6 x 10: 5 Bq/gm, assuming any potassium present contains the usual percentage of : 40K (.012%), and taking into account the 10.5% branching ratio to the γ, I calculate that the concentration of potassium needed to produce a 1 Hz rate in the detector is 3.1 x 10: -12 gm/gm in the D_2O ; 3.1 x 10: -10 gm/gm in the acrylic (assuming 20 tons of acrylic, half the γ's head inward), and 1.3 x 10: -9 gm/gm in the NaCl. A cursory search of the SNO literature produced no numbers against which to check the first two of these, although certainly the number for the acrylic looks daunting. Averaging the values for Salt 1 and Salt 2 found in the Guelph handout [4], potassium looks to be ~6 x 10: -5 gm/gm in NaCl, at this level we would have a 46 kHz event rate from : 40K γ's. Inclusion of other low-energy decays like : 60Co will only make things worse. Obviously this trashes the above scheme for measuring Th or U levels in the D_2O if we put NaCl in, unless we are able to reduce the potassium content of the NaCl considerably (John Barton tells me that NaI manufacturers have achieved ~0.01 ppm potassium, but whether the techniques used could be applied to NaCl at the ton level is not known). If we can reach something within a few orders of magnitude of the above levels in the D_2O and acrylic we may still be able to measure the U and Th in the water (by using the vertex reconstruction one can look for two decays within the specified time and within, say, 1m of each other and thereby live with a higher trigger rate from : 40K), or we may be able to use the scintillator to improve the NaCl signature (by turning the trigger up to ~2 MeV), but we can't do both at the same time with the current levels of potassium in the NaCl. This conclusion does not apply, however, if we use gadolinium to detect the neutrons, so we should think about that angle.

3 Event Reconstruction

In addition to the salutory effects on the reconstruction mentioned in the Introduction, these additives would have several less helpful consequences. The first comes from the 90 hits caused by tritium within a 80 ns window. Taken by itself I think this would be a nuisance rather than a real problem (a solar neutrino event now has >500 hits), we are working on ideas to exclude these bad hits from the event and will report progress when there is some. A potentially more serious problem comes from scattering and attenuation. The wavelength shifter mentioned above was measured to have an attenuation length for its own light of 250 cm at a concentration of .5 mg/l, so it is obviously useless for SNO. The scintillator was measured to have an attenuation length of 5.2 m, which is better but still maybe not good enough. This second measurement was made in such a way that some scattered light would have been counted as not attenuated, so the scattering length may be even shorter. Monte Carlo calculations will have to be done to determine what level of scattering and attenuation we would find tolerable (this conclusion will depend to some extent on the fitter used, we are working on this question), but I would guess that we will need attenuation and scattering lengths longer than 6m to do a good job. For the wavelength shifter there is the added requirement that the higher-frequency light must be adsorbed within a distance of the order of the hoped for vertex resolution, this sets a lower limit on the concentration of the shifter (which may be higher than the upper limit set by the attenuation). In both cases the light must be re-emitted within at most a few ns, otherwise the improved vertex resolution is lost (preliminary results with Peter's MC show that when the ratio of added light/Cerenkov light is 1:1 the improved vertex resolution is largely lost when the mean life for re-emission is ~3 ns). So all the above discussion is academic until we identify at least one substance that simultaneously satisfies all of these requirements (and a few more given below). This is where I could really use some help, anyone out there who knows of any candidate materials please pass them along (along with references).

For completeness I will mention a couple of other effects on the reconstruction. At scintillation/Cerenkov light ratios of 4:1 it has been experimentally verified by LSND that the initial electron direction can still be extracted from the data. Very preliminary work modifying Peter's code verifies this at a level of 3:1, however when the ratio has reached 10:1 the directional information becomes degraded (the mean value of angle between the true direction and the reconstructed direction for a 7 MeV electron goes from ~29: o for pure Cerenkov light to ~44: o for 10:1). This is done with the current fitter, which may not be optimized for extracting the direction from a large amount of isotropic light, so we may be able to improve on this. If we achieve 10:1 we will also have to take multiple hits into account. At this level a 10 MeV event will hit ~10% of the tubes, thus ~1% of the tubes (or ~10% of the hit tubes) will be doubles. This will bias the energy scale if not accounted for, but I see no problem in doing so.

4 Other Effects

4.1 Neutron Losses

The scintillation light production discussed above assumed a scintillator concentration in the D_2O of 2% by volume. This is almost all Triton X-100, or iso-octyl phenoxy polyethoxy ethanol, which works out to $C_{34}O_{11}H_{62}$ [?], or 9.6% H by weight with a density of 1.08. So 2% by volume contributes the same amount of hydrogen as adding 1.9% light water. Jerry Wilhelmy stated at the Vancouver meeting that adding 2% light water at the same time as adding the NaCl would reduce the capture rate on the NaCl by 40%, so if we go with the scintillator option we will reduce our efficiency accordingly. I am assuming that it would be prohibitively expensive to deuterate the scintillator to prevent this. The wavelength shifter discussed above would not affect the efficiency in this way, as we would only need to add ~1 kg.

4.2 Chemistry

Any additives must be evaluated for their long-term effects on the acrylic. The scintillator mentioned above has been measured in an acrylic box, so it must not vigorously attack it, however the long-term effects are unknown. The wavelength shifters were kept in resin containers for ~year periods without degrading, but the effect on acrylic is also unknown. The effects of the additives on the water system are another obvious problem. The Triton X-100 is a polar molecule and would probably be removed by the current water system. As it is present at the percent level, this would cause massive problems and is certainly not on. We would either have to modify the water system to allow the scintillator to pass, or go to a surfactant that would pass through the system (which I think is an inherent contradiction). The wavelength shifter would also probably not pass through the system, but as it is present at the ~mg/l level it may be possible to continually add it to the return water stream.

4.3 Cost

Assuming a way can be found to make a scintillator pass through the water system, for the materials discussed above cost would probably not be a serious problem. The Triton X-100 is available from Aldrich in 0.5 l quantities at a cost of £260,000 for 20 tons, the price would presumably drop greatly for these large quantities. If we continually resupplied the wavelength shifter we would need ~78 kg/year, which should also not be a cost problem.

5 Conclusion

If we succeed in identifying an actual substance there would be other things to consider such as mine safety (for ton quantities of scintillator), what the opinion of Candu-Ops would be, etc., but I think the above is enough for now. It looks like we would be entering a swamp, and even from out here I can see a lot of alligators. The physics goal of an independent measurement of the U and Th concentrations is very appealing but also looks very difficult. We must try to quantify the physics advantages of achieving smaller light gains. This will take a lot of MC work, however I would advocate delaying this until we have identified substances which meet the other (possibly fatal) requirements outlined above. The first of these is that the level of noise hits, scattering, attenuation, and time and distance delay to the re-emission of the light be consistent with acceptable reconstruction. These will depend upon the fitter, and we are working on this problem in the hope of applying what is learned to SNO in general. The second is that the effects on the water system and acrylic are acceptable. I currently need input on what substances to consider and where to find information. The interfaces which must be considered on a short time scale are:

1. Can the current electronics/DAQ handle 100 kHz noise rates in the tubes, trigger levels at ~200 hits, and ~1500 hits/event? Can a two-level trigger be implemented, and do the electronics recover fast enough to see the 300 ns delayed α from : 211Po decay?
2. What modifications are required to the water system to accomodate these substances, and do they change the footprint significantly?
3. One idea that was put forth in Vancouver is to use scintillator in a light water fill to measure the U and Th levels directly in the discrete NC detectors that have been proposed. This would require these counters to be mounted in the acrylic vessel while the light water is removed and the D_2O added, which is not in the current plan. What changes to the acrylic vessel would be required for this to be feasible?

If we are unable to get a more concrete idea of what we would be actually be adding by the time the above 3 items are frozen we will just have to assume that we will not be adding anything and design accordingly, we will then try to retrofit if a promising option is identified.

References

[1] P.Nemethy et al., NIM 173, 251, (1980)

[2] C.R. Winn and D. Raftery, IEEE Trans. in Nucl. Sci., NS-32, 727 (1985)

[3] W.Frati, SNO_STR-90-36

[4] "Tables of Primordial Radioactivity in a Variety of Materials", J.J. Simpson and P. Jagam and a cast of dozens, May 7, 1990.

Knox, unsubstantiated rumor based on the Aldrich catalog.