Physics Potential Of A Liquid Shield

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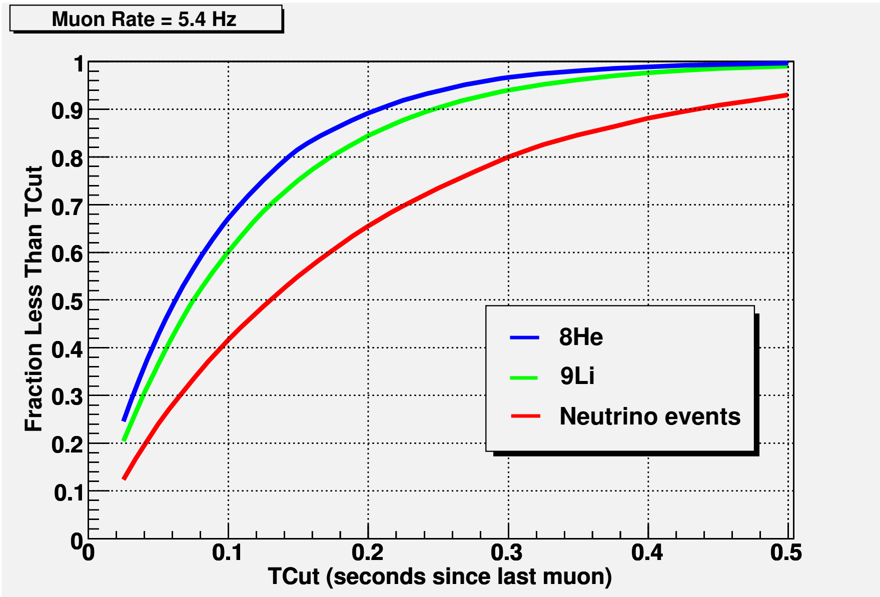
One of the proposed designs for the Braidwood veto shields involves the use of a modular, 1-2 meter-thick, water Cherenkov detector. This would constitute a sizeable bulk of between 0.3 and 0.7 kilotonnes of liquid per detector. The purpose of this note is to explore some of the physics which could be done with the shield itself were we to use a mineral oil + Gd + scint mixture for the liquid instead of water. Two of the prospects which stand out are: **1)** their use to help statistically determine the production rate of ^9Li and ^8He spallation products, and **2)** their use as a highly sensitive supernova detector which would surpass KamLAND and may provide a long-term future for the Braidwood facility beyond the reactor measurement itself.

1 Statistical Determination of ^9Li and ^8He Production

^9Li and ^8He can be produced via muon spallation in scintillator and yield a correlated background which can mimic the inverse β-decay signal. The expected production rate has large uncertainties and range from 0.016-0.07 per day per tonne for an overburden of 450mwe. Even a relatively small contribution from this could noticeably distort the apparent relative neutrino spectrum between the two sites as this contribution would be primarily seen at the far site where the actual neutrino signal is substantially smaller. The half-lives of ^9Li and ^8He are 0.12s and 0.18s, respectively. Given that the expected average muon rate in each 65-tonne volume at 450mwe is 5.4Hz, it is not practical to simply cut in time around each muon event. It is possible that a combination of timing and spatial cuts could be applied around each muon track, but this is predicated on a good track reconstruction and a well-understood vertex determination. Such an approach may well be pursued as a cross-check, but the complexities of this analysis are probably best avoided as a primary method if at all possible. It is also possible that the smaller number of showering muon events which might be responsible for isotope production might be identified so that timing cuts need only be applied to them, but it is yet to be demonstrated that these could be clearly picked out from the very high level of generated light due to the muon alone.

A different approach would be to statistically determine (or limit) the contribution from these isotopes based on their time distribution relative to muons, as opposed to "cutting." This becomes possible in principle after recognising that, while 5.4Hz determines the average time separation between muons, the actual distribution is ∼Poissonian, containing muons which are clustered in time and muons which have larger time gaps between them. Therefore, the experiment livetime can be divided into pieces which are more likely or less likely to contain $^9Li/^8He$ events. To explore this, I will just consider the time difference, ΔT, between a given event and the last muon which passed through the detector. Note that ΔT is only being used as a convenient parameter here since the spallation event itself may well have been produced by a different muon, so the analytic calculation of the number of such events expected in this interval is quite not so straightforward. Accordingly, the fraction of events from each class with values of ΔT less than a given T_{cut} value were estimated using a Monte Carlo calculation and the results are shown in the accompanying figure. Note, for example, that the section of the data with $\Delta T < 0.14$ seconds would contain approximately half of the neutrino sample, but $\sim 75\%$ of $^9Li/^8He$ events. The rate of neutrino interactions expected at the far site is 1.8 per tonne per day. Thus, if we take the lower value of isotope production, in one year of livetime, one would expect to see $(1.8)(65)(365) = 42705$ neutrino events per detector and $(0.016)(65)(365) = 380$ $^9Li/^8He$ events. Therefore, the total number of correlated events expected with $\Delta T < 0.14$ seconds will be $(0.5)(42705) + (0.75)(380) = 21638$ and the total number with $\Delta T > 0.14$ will be $(0.5)(42705) + (0.25)(380) = 21448$. This amounts to a little less than a 1 standard deviation effect. Imposing an energy cut will help a bit since the neutrino signal peaks at around 4 MeV, whereas the isotope decay endpoints are above 10 MeV. But this gain is modest, increasing the significance to a bit more than 1 standard deviation. Combining both far detectors (the near ones are not useful here owing to the much higher neutrino flux) and integrating over 2 live years, one may therefore hope to achieve a bit more than a 2 standard deviation result if the lowest isotope production model turns out to be correct. This, alone, would be useful, but would clearly not provide a measurement to the accuracy one would want in order to subtract the contribution of these isotopes from the data.

Ideally, one would like to have a much larger data sample from which to extract the production rates. This is where the liquid shield may be very useful. The "silo" configuration, for example, would consist of 9 tanks which would each have a volume roughly equivalent to that of the inner



detector volume (i.e. 65 tonnes). Were this to be filled with liquid scintillator and doped with Gd to pick up the neutron signal, this would increase the statistics for determination of $^9Li/^8He$ by the method above by an order of magnitude. Thus, using both far shields, one would expect to see a ∼4.5 standard deviation effect after just 1 live year for the lowest assumed rate of isotope production.

2 Braidwood as a Supernova Detector

As a starting point, I take the paper by Bandyopadhyay *et al.* (hep-ph/0312315) which discusses the capabilities of KamLAND regarding supernova neutrinos (although several other papers have also been written relating to this subject). I will again assume the "silo" shield configuration and that Gd is used to boost the neutron signal relative to KamLAND so that they could be well-detected by a "modest" (∼few percent) coverage of PMTs which would be distributed in some fashion on the inner surfaces of the shield. The Gd concentration need not be as large as what we use in the main detector and Minfang from BNL has indicated to me that, for example, a 0.1% solution ought to be straightforward and have very good stability.

2.1 Basic Neutrino Interactions

Liquid scintillators have very nice properties which makes them very well suited for supernova neutrino detection. Here are the main reactions:

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

The threshold energy for $\bar{\nu}_e$ in this reaction is 1.8MeV. A supernova signal would result in positron energies in the region of tens of MeV, which would stand out well above any backgrounds. There is some modest directional sensitivity in this reaction which might be accessed from the relative reconstructed positions of the positron signal and neutron capture using high statistics, though this needs more study.

$$\bar{\nu}_e +^{12} C \rightarrow^{12} B + e^+$$

$$^{12}B \rightarrow^{12} C + e^- + \bar{\nu}_e$$

The threshold energy here is 14.4 MeV and the beta-decay of ^{12}B would follow with a half-life of 20.2ms and an endpoint energy of 13.4 MeV. Again, this should stand out well from the background, especially given the double-coincidence. It would be well distinguished from the double-concidence of the 1st reaction based on the time difference, since the neutron capture time will be more like ~1ms.

$$\nu_e +^{12} C \rightarrow^{12} N + e^-$$

$$^{12}N \rightarrow^{12} C + e^+ + \nu_e$$

The threshold here is 17.34 MeV and this would give a very similar signature as in the previous case, except that the ^{12}N endpoint is 16.3 MeV (plus the positron annihilation) and the half-life is 11.0ms, thus allowing a statistical separation based on the timescale of the double-coincidence.

$$\nu_X + p \rightarrow \nu_X + p$$

This is a NC interaction, but not a well-defined signature and low kinetic energy of the scattered proton (sub-MeV), so we probably give up on this. Although, detection based on monitoring “noise rates” may still be possible.

$$\nu_X +^{12} C \rightarrow^{12} C^* + \nu_X$$

$$^{12}C^* \rightarrow^{12} C + \gamma(15.1MeV)$$

Is another NC reaction with a threshold of 15.1 MeV which produces a distinctive 15.1MeV high-energy gamma from the de-excitation of ${}^{12}C^*$ which ought to be easy to pick out.

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

While certainly providing a more numerous signal in SuperK, this "classic" elastic scattering reaction ought to also yield a sizeable signal in scintillation detectors as well (though this appears to be overlooked in most discussions I've read). While not having the double-coincidence to eliminate backgrounds, a large fraction of the signal would be above 20 MeV, which should be distinctive enough to be identified within the ~10s burst. This component clearly carries good directional information which might possibly be accessed if the prompt Cherenkov light could be identified in the shield.

2.2 Event Rates

The following is taken from the previously mentioned reference for the number of events expected for various classes, for a supernova at 10kpc, scaled to the volume of 3.15 kilotonnes, which would correspond to 4 silo shields with 2m of liquid between inner and outer walls in addition to the four 65-tonne inner detectors. I've also included an estimate for $\bar{\nu}_e + e^-$ elastic scattering above 20 MeV by scaling from the observation of SN1987a.

$tan^2\theta_{13}$	$\bar{\nu}_e + p \rightarrow e^+ + n$		$\bar{\nu}_e +^{12} C \rightarrow^{12} B + e^+$		$\nu_e +^{12} C \rightarrow^{12} N + e^-$	
	nominal	+ earth effect	nominal	+ earth effect	nominal	+ earth effect
10^{-6}	1441 (1443)	1386 (1386)	75 (75)	66 (70)	183 (183)	155 (155)
$\geq 10^{-3}$	1441 (2030)	1381 (2030)	75 (160)	66 (160)	252 (183)	252 (151)
no osc.	1208		40		8	

$\nu_X +^{12} C \rightarrow^{12} C^* + \nu_X$	$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ (scaled from SN1987a)
138	196

where the numbers in parentheses correspond to an inverted mass heirarchy.

Several points are worthy of note: **1)** The signal is very large as well as being very distinct! **2)** There is a sensitity to very small values of θ_{13} and the specific value can be constrained to a reasonable extent by the ν_e reaction on ${}^{12}C$ for normal heirarchy or by the $\bar{\nu}_e$ on ${}^{12}C$ for inverted heirarchy. **3)** There is some sensitivity to earth matter effects, though this is difficult. For the case of normal mass heirarchy and $tan^2\theta_{13} > 10^{-3}$, this amounts to about a 1.6σ effect for the $\bar{\nu_e}+p$ reaction. Some additional sensitivity could be gained by looking at higher energy events, but not a substantial improvement (it looks like I can get about 1.8σ by selecting events between 40 and 60 MeV). Of course, a supernova at 5kpc would make this more than a 3σ effect... however, all this really needs to be studied in greater detail. The numbers look interesting enough to follow this further - it might even give us a very good excuse for being on the other side of the earth compared to Japan! **4)** The distinction between inverted and normal mass heirarchy ought to be very clear so long as $tan^2\theta_{13}$ is larger than about 10^{-5}. **5)** Should a supernova occur near the edge of the galaxy, *i.e.* ~20kpc, the factor of ~4 reduction would still leave us with a reasonable signal in each catagory. On the other hand, with only 1 kilotonne, KamLAND would find it much more difficult to extract pertinent information. For instance, even the distinction between the oscillated and non-oscillated $\bar{\nu_e}+p$ would be difficult for the case of normal mass heirarchy and the statistics on the other signals would be borderline. **6)** With a coincident signal between all the Braidwood shields/detectors alone, there would be no question of SN signal validity as we would instantly confirm ourselves. This raises the prospect of being able to send out an alert to others on a very short timescale (*i.e.* instantly) with extremely high confidence.

3 Reactor II+ at Higher Energies???

This falls into the catagory of more speculative, but perhaps not entirely crazy. With more than a kilotonne at near and far positions, **IF** we could pull the same trick of using the neutron peak itself to establish and identical relative energy threshold (say, above ~5MeV-ish) and **IF** the fast neutron background could be eliminated (say, using a Cherenkov signal), perhaps one could even go beyond the Reactor II scenario for θ_{13} at these higher energies. There is clearly much that would have to be demonstrated to even think about this and I would not advocate advertising this possibility to the funding agencies right now. But, if you had all this Gd-loaded scintillator anyway, you'd at least give it a go, right?!