Potential Use of the Braidwood Shields as a Highly Sensitive Supernova Detector

One of the proposed designs for the Braidwood veto shields involves the use of a modular, 2 meter-thick, active, liquid region viewed with photomultiplier tubes. This would constitute a sizable bulk of roughly 0.7 kilotons per detector. Should liquid scintillator be used, this would naturally lend itself to use as an excellent detector for supernovae. The combined mass of all 4 shields plus inner detectors would be equivalent to more than 3 KamLAND detectors for this purpose and, in the event of a supernova, would provide the best measurement of ν_e and ν_X components. Among other things, such measurements would be highly sensitive to both the neutrino mass heirarchy and also very small values of θ_{13}.

For the purposes of the following discussion, we will assume the "silo" shield configuration discussed in XXXX and that Gd-loaded scintillator is used in the shield to boost the neutron signal so that they could be well-detected by a "modest" ($\sim$few percent) coverage of PMTs distributed on the inner surfaces of the shield. For these purposes, the Gd concentration need only be large enough to compete favorably with the capture on hydrogen, so that even less than a 0.01% solution would suffice. The amount of scintillator also need not be very large, so that the liquid could be composed of more than 95% mineral oil, which would then dominate the cost.

1 Neutrino Interactions in Liquid Scintillator

Mineral oil/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 further study.

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

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

The threshold energy for this reaction 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 for this reaction 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 neutral current (NC) interaction, but does not have a well-defined signature and involves a low kinetic energy of the scattered proton (sub-MeV). Thus, we will not discuss this reaction further, although detection based on monitoring "noise rates" may still be possible.

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

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

This is another NC reaction with a threshold of 15.1 MeV which produces a distinctive 15.1 MeV high-energy gamma from the de-excitation of $^{12}C^*$, which should be easy to distinguish.

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

$\tan^2\theta_{13}$	$\bar{\nu}_e p \to e^+ n$		$\bar{\nu}_e^{12}C \to^{12} Be^+$		$\nu_e^{12}C \to^{12} Ne^-$	
	Normal	Inverted	Normal	Inverted	Normal	Inverted
10^{-6}	1441	1443	75	75	183	183
	(1386)	(1386)	(66)	(70)	(155)	(155)
$\geq 10^{-3}$	1441	2030	75	160	252	183
	(1381)	(2030)	(66)	160)	(252)	(151)
No osc.	1208		40		8	

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

Table 1: Computed rates in a 2 m liquid shield for a supernova at 10 kpc from Earth assuming no matter oscillations in the Earth (i.e. the supernova neutrinos arrive at a time when the bult of the Earth does not shield the detector.) Values in parenthesis refer to rates for which maximum matter oscillations in the Earth occur.

While certainly providing a more numerous signal in SuperK, this elastic scattering reaction ought to also yield a reasonable signal in scintillation detectors as well. 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 carries good directional information which might possibly be accessed if the prompt Cherenkov light could be identified in the shield.

2 Event Rates

The following is based on calculations from hep-ph/0312315 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 plus the four 65-tonne inner detectors. An estimate for $\bar{\nu}_e + e^-$ elastic scattering above 20 MeV has also been included by scaling from the observation of SN1987a.

3 Discussion and Conclusions

Referring to Table 1 several points are worthy of note: **1)** The signals are all 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. A supernova at 5kpc would likely make this more than a 3σ effect, however this needs to be studied in greater detail. **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)** While a detector such as SuperK would provide the best measurement of the $\bar{\nu_e}$ component of a SN signal along with the direction, a Braidwood shield-based detector, along the lines discussed here, would provide the best measurement of the flux, timing and energy spectra for the ν_e and ν_X components compared with any existing detector. **6)** With a coincident signal between all the Braidwood shields/detectors alone, there would be little question of SN signal validity. This raises the prospect of being able to send out an immediate alert to others with extremely high confidence.