1 Question 1

1) It seems that the ^{9}Li background is one of the most difficult ones. KamLAND experience suggests that the probability of ^{9}Li formation (as well as high multiplicity neutron production) is much larger for the relatively rare "showering muons" (more than 10^6 photo-electrons in KamLAND) than for the "standard muons." Thus, if one can separate the two classes of muon events, one can (as in KamLAND) veto the showering ones much longer, thus reducing the ^{9}Li background substantially. Can this be done in your detector?

Measuring backgrounds. Since the expected production rates for spallation-produced ^{9}Li and ^{8}He at Braidwood are uncertain by at least a factor of two, it will be important to measure these rates *in situ*. Our goal is to keep the uncertainty in background rates below 0.3% of the real IBD rate, which will be about 200 d^{-1} in each 70-ton far detector. The uncertainty in the background rates should thus be $\leq 0.6\ \mathrm{d}^{-1}$.

What KamLAND did. KamLAND measured [1] the ^{9}Li background *in situ* by extracting a signal having the charcteristic exponential decay ($T_{1/2}$ = 178 ms, mean life = 257 ms) after the passage of a tagged muon through their 12 m detector. (Although they were unable to separate ^{9}Li and ^{8}He with the decay-time distribution, the distribution of e-like energy was consistent with all ^{9}Li.) This ^{9}Li signal sits on a quasi-flat background of accidental coincidences of real IBD events with the tagging muon.

This accidental rate can be reduced by raising the threshold on deposited muon energy, thereby lowering the tagged muon singles rate. If, as expected, the ^{9}Li events come mostly from interacting muons producing large showers of hadrons, raising this threshold should have little effect. The distribution of ionization loss of muons uniformly illuminating a sphere is approximately an upward linear ramp, with a rounded cutoff at the energy loss along a diameter ($\sim$ 3.5 GeV for KamLAND, $\sim$ 1.3 GeV for Braidwood, see Fig. 1). KamLAND got a clean ^{9}Li signal with a 3.0 GeV cut on muon energy deposit. They then extrapolated to zero threshold by fitting signal and background contributions at progressively lower muon thresholds. It was found that the 3.0 GeV cut lost only 14% of ^{9}Li events, and that *essentially no loss of ^{9}Li events occurred as the threshold was raised to 4.0 GeV, well beyond the ionization cutoff [1].*

Measuring ^{9}Li at Braidwood. A similar measurement can be done at Braidwood despite the higher muon flux. The expected muon rate through the central 5.2 m detector is 4.5 Hz. These muons can be identified and localized with the detector itself, and the rate of tagged muons can be reduced by raising the cut on deposited energy as done by KamLAND. From the simulation in Fig. 1, a Braidwood muon threshold of 1.4 GeV would give a 1/20 reduction in tagged muon rate, while a threshold of 1.5 GeV would give a 1/200 reduction. Based on the KamLAND experience, we would expect negligible change in ^{9}Li rate for this small threshold change.

Let us take a simple numerical example. Suppose that the time distribution of IBD-like events following a tagged muon is binned in 50 ms bins (as was done by KamLAND), and let us choose a threshold that gives a 1/20 reduction in muon rate. Muons in this sample will have a mean time separation of 20/(4.5 Hz) = 4.4 s; with a small reduction in sample size, we can require at least

Figure 1: Monte Carlo simulation of muon energy loss by ionization in the Braidwood sensitive volume, 5.2 m in diameter. The rounded cutoff occurs at the mean energy loss of muons crossing a diameter, 1.3 GeV. A similar plot for the KamLAND detector would have a turnover at 3.5 GeV.

2.0 s between tagging muons, giving $\sim$ 30 bins beyond the ^{9}Li decay to measure the accidental background. Then with a real IBD rate of 200 d^{-1}, each bin will have an accidental background of

$$(1/20)(4.5\ \mathrm{Hz})(50 \times 10^{-3}\ \mathrm{s})(200\ \mathrm{d}^{-1}) = 2.25\ \mathrm{d}^{-1}.$$

(With a threshold only slightly higher, this background rate will be 10 times smaller).

Next, assume that the ^{9}Li rate in the detector is 10 d^{-1}, which is on the high side of estimates. We would like to know this rate to 0.6 d^{-1}, or 6% of itself. Again for a specific numerical example, look at the first four 50 ms bins, which contain about half of the ^{9}Li signal, or 5.0 event/d. With 1000 days ($\approx$ 3 years) of running, these 4 bins will have 5000 events over a background of $(4)(2.25\ \mathrm{d}^{-1})(1000\ \mathrm{d}) =$ 9,000 events. The sum of ^{9}Li signal and accidental background in these bins will thus be known to $(14,000)^{-1/2} = 118$ events. The background in these 4 bins can be measured from a total of 30 bins, or $30 \times 2250 = 67,500$ events, so it is known to $(4/30)(67,500)^{-1/2} = 35$ events. The uncertainty in the ^{9}Li signal is thus $(118^2 + 35^2)^{-1/2}/5000 = 2.5\%$ of itself, much better than needed. Clearly this estimate could be improved with a fit, and clearly an arbitrarily clean signal could be obtained with slightly higher threshold.

It remains to extrapolate the ^{9}Li signal to zero threshold, a problem currently under investigation. To do this, one needs to reduce the tagged muon rate by means other than threshold. Two possibilities: 1) exploit the distance correlation between the muon and the IBD-like event; 2) require a fixed minimum time between tagging muons, e.g. 2.0 s, as the threshold is lowered. Poisson statistics will rapidly reduce the sample size, but the number of events available before the selection is very large.

References

[1] K.S. McKinny, KamLAND thesis, University of Alabama (2003).