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?*

The answer is yes; a method similar to that of KamLAND may be used to reduce the background from ^{9}Li. at Braidwood. A study from KamLAND [1] shows that 85% of all muons which produce ^{9}Li deposit more energy than expected for a minimum ionizing particle crossing the detector diameter (3.7 GeV at KamLAND). The corresponding energy deposition for Braidwood is 1.5 GeV and 97% of all muons which enter the 5.2 m Braidwood inner vessel would leave less than this energy. The half-life of ^{9}Li is 175 ms, so rejecting all neutrino like events occurring within 500 ms of a muon which deposits more than 1.5 GeV in the inner vessel would reject 72% of all ^{9}Li events while introducing an acceptable 7% dead-time (which would be by far the dominant contribution to the total dead time). Based on our estimate of ^{9}Li production (see the answers to Questions 2 and 4), we expect 2.5/day neutrino-like decays from ^{9}Li of which 0.7/day would be untagged. This is an acceptable background. Clearly the use of tracking from the tagging and shield system leads a more accurate prediction of the minimum ionizing energy expected from a muon entering the inner vessel. This would allow a lower energy deposition cut, which would exclude a larger fraction of the ^{9}Li background.

Currently, we assign a 100% uncertainty to the ^{9}Li production rate (see the answer to Question 4). Over the course of the experiment, a sample of 2,500 tagged ^{9}Li decays will accumulate and an analysis of time interval between muon passage and ^{9}Li decay will allow the determination of the total production rate (tagged and untagged) with a precision of about 0.5/day and the estimation of the number of untagged neutrino like ^{9}Li decays with a precision of 0.4/day.

2 Question 2

Expand on the background expected form ^{9}Li. *KamLAND has a number but how does it extrapolate with depth (muon energy)?*

Our estimate of the ^{9}Li production rate at 450 MWE (see Table 1) uses the cross sections for spallation isotopes measured using muon beams in Ref. [2]. In that experiment, the cross section for ^{9}Li production was measured at E_μ=190 GeV and the energy scaling of the cross section of other isotopes (^{8}Li, ^{6}He) measured at E_μ=100 and 190 GeV is applied to the ^{9}Li cross section. This scaling contributes the primary uncertainty of 50%. The muon energy spectrum as a function of depth comes from Ref. [4], which gives a detailed comparison between simulation and data from underground experiments and agrees with our calculation [3] at the 10% level. Convolution of the muon energy spectrum with the scaled cross section for ^{9}Li production from muons gives the rates shown in Table 1. This calculation agrees with the observed at at KamLAND [5] within a factor of two and we use this difference in assigning the uncertainty to our calculations.

Depth (MWE) and topography	Muon flux (m^{-2}-s^{-1})	Avenge muon energy (GeV)	Neutron production rate (ton^{-1}-d^{-1})	^{9}Li production rate (ton^{-1}-d^{-1})
450, flat (Braidwood)	0.21	84	178	0.078
450, hemispherical (Braidwood)	0.56	68	404	0.18
900, flat (2 × Braidwood)	0.029	134	35	0.015
900, hemispherical	0.090	114	97	0.042
2700, hemisphere (KamLAND, this calculation)	0.0021	214	3.6	0.0015
2700, hemisphere (KamLAND, measured)	0.0026[7]			0.003[5]

Table 1: Muon, neutron and ^{9}Li rates for various depths and topographies. "flat" refers to a flat overburden, "hemispherical" refers to the approximation of a mountainous overburden with a hemisphere. All values come from the calculation described in the answer to Question 2 except the last line, with is the measured value from KamLAND. **Note: I have removed the CHOOZ lines from Jon's tables. There is measurement of the "vertical muon flux" which is 0.4/m2-s which needs to be explained if we want to include the CHOOZ lines.**

3 Question 4

As an exercise and to understand the importance of various overburden patterns, please provide a calculation of the background for twice as much overburden over the far detector as was assumed so far. (This is NOT a suggestion to go deeper!).

The answer is given in Table 1. All the rates come from the calculation described in the answer to Question 2 except for the line labelled "KamLAND, measured" with is the observed value from Ref. [5]. For a given overburden, a flat topography gives a factor of 2-3 lower background rates than a hemispherical topography.

As is apparent from Table 2 of the Project Description [6], we expec the dominant uncertainties in our measurement of $\sin^2\theta_{13}$ will come from relative normalization between the near and far detectors (0.3%) which will contribute twiae as much to the overall systematic error than the background (0.15%). Therefore, there is little gain in moving to depths greater than 450 MWE.

References

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