Looking at ^{12}B at Braidwood in Light of KamLAND

Janet Conrad, December 20, 2004

This memo shows that the KamLAND ^{12}B rates agree with back-of-envelope calculations for neutron production of ^{12}B. The calculations are then applied to Braidwood to obtain the rate. Two separate methods to reduce the systematic and statistical error from these events to a negligible level for the $\sin^2\theta_w$ analysis are discussed.

1 The Question

Jon Link pointed out that KamLAND sees about 60 ^{12}B decays per day (they quote 80/kton/day [1]). Only about 1.2 of these events are due to stopping muons because the stopping rate is so low. Therefore, nearly 100% of the KamLAND rate is due to $n+^{12}\mathrm{C}\rightarrow p+^{12}\mathrm{B}$. So the question is: What will the rate be at Braidwood from neutron production of ^{12}B? This has not been included in our error budget for $\sin^2\theta_W$.

2 The Process: $n+^{12}\mathbf{C}\rightarrow p+^{12}\mathbf{B}$

Neutron production of ^{12}B has been studied in the lab[2]. The threshold for this interaction is 13 MeV. The cross section reaches its maximum for neutrons above about 90 MeV. After reaching threshold, the cross section, integrated over scattering angle, is about 30 mbarns (where I did this integration – most papers quote $d\sigma/d\Omega$ as a function of the angle).

A few points to notice, which are all related to the fact that neutron production of ^{12}B requires a high energy neutron:

- This requirement greatly reduces the neutron candidates which can contribute. For the calculations below, assume that $E_n > 20$ MeV will contribute. The fraction of events in this range is parameterized in reference [3].
- This requirement means that the muon which produced the event suffered a high energy loss (Deep Inelastic Scattering or DIS). This is

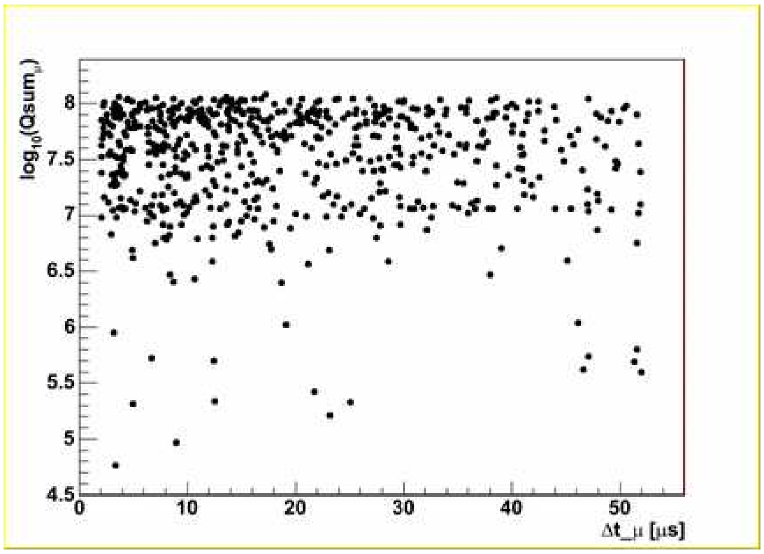

Figure 1: MIPS vs. time for the muons associated with ^{12}B events in KamLAND

shown in Figure 1, which, for the KamLAND ^{12}B events shows the energy in the detector as a function of time for the muon which preceded the ^{12}B decay. Log$_{10}$(QSUM) of about 7 is a muon which traverse the detector at the midpoint, and 6.5 is about the average pathlength [4]. The fact that the points are not evenly distributed about 6.5, but are instead far above 7 indicates that the ^{12}B are coming from high energy events. This is reiterated in a KamLAND thesis by DongMing Mei [5] points out that the multiplicity formula of reference [3] needs to be adjusted because "nuclear cascades ... dominate neutron production at large depths."

In fact, these neutrons are not the target fragment in the event, as one can see from reference [6]. This paper shows that for 500 GeV muons, with energy transfers from 40 to 400 GeV, a C target will fragment to, on average, 2 neutrons and the energy is $< 10MeV$.

- It isn't immediately obvious how to scale the high energy component of neutron production. While we have a general parameterization for the scaling of mean neutron multiplicity, production of high energy neutrons may decrease much more rapidly because of threshold effects. This can be studied using GEANT and should go on the list of "Things to do." For now, we will assume that the high energy tail scales as the mean multiplicity, as described in reference [5].

- These events will produce a lot of light in the detector associated with the incoming muon. First, there is the energy released when the neutrons are produced. Second, in the $n+^{12}\mathrm{C}\rightarrow p+^{12}\mathrm{B}$, can typically carry away many MeV of energy. In other words, these events should be easy to veto, with no changes to the proposed muon-neutron veto [7].

3 First Principles Calculation of the KamLAND Rate

KamLAND sees about 60 events per day, which can be attributed entirely to neutron production. Using this number, the idea is to calculate the production cross section and show that it agrees with the lab measurements discussed above. The purpose of the exercise is to make sure that we understand all of the factors that apply so that this can then be extrapolated to Braidwood.

According to DongMing's Thesis[5], 2% of the throughgoing muons at KamLAND produce neutrons. The through-going rate is 0.3 Hz in the fiducial region. That means there are 490 events with neutrons per day. The average neutron multiplicity per event-with-neutron is 8 n/event. Based on the parameterization from [3], 5% of the 8 neutrons will have $E_n > 20$ MeV and thus be candidates to produce ^{12}B. The result is 200 $n_{high\ E}$/day that can produce ^{12}B. There are 60 ^{12}B events per day. Thus there are 0.3 $^{12}\mathrm{B}/n_{high\ E}$.

The rate $^{12}\mathrm{B}/n_{high\ E}$ can be used to calculate the cross section. For this, we assume that the KamLAND oil density is 0.75 g/cm^3, the average pathlength in the detector is 740 cm, and use $M = 12$, since only the Carbon contributes. The result is about 15 mbarns.

This is not in precise agreement with the expected cross section. But KamLAND is not actually trying to measure a ^{12}B production cross section and therefore may not have taken all of the steps needed for a precise measurement. For example, when they quote 60 events per day, they may not have worried about correcting for efficiency for the trigger or reconstruction. So, given the level of approximation used here and the fact that efficiencies are unknown, we take this extracted cross section to be in good agreement with the 30 mbarn estimate from the lab measurements.

Based on this, it looks like the contributions to the calculation of the KamLAND rate are understood to within a factor of 2.

4 Scaling to Braidwood

The rate of neutron production in a 900 day run is based on a 7 Hz through-going rate. Starting with the KamLAND calculation procedure, this is corrected for 2% production of events with neutrons per through-going moun, multiplied by 8 neutrons/muon-event-with-neutron and multiplied by 0.05% for the number of neutrons above 20 MeV. This gives 0.056 Hz. The following scale extra factors are needed:

- Correction for path-length. The neutron production by through-going muons depends on the number of ^{12}C targets. Kamland has a radius of 5.0 m and our study used a radius of 1.5 m so this factor is 3.33.
- Correction for neutron yield per muon. The neutron yield per event goes down at higher depths because the muon energy decreases. One can read a scaling factor of 2.5 off of plots from references [3] and [5].

In 900 days of running, this results in 43k neutrons that could potentially produce ^{12}B.

To calculate the rate of ^{12}B production, one can either scale from the KamLAND ^{12}B/n rate or use the following: the density of oil at is 0.85 g/cm^3, the average path length is 210 cm and the cross section is 30 mbarns. Either way, you get about 120k events.

The lower window for the analysis will be either 3 or 3.5 MeV and the upper will be 5 MeV. The fraction of ^{12}B that produce a β in the 3 to 5 MeV window is 20%. Thus the number of background events will be 24,000 events. If we did not have a muon-neutron veto, this would be a problem for the analysis.

However, the systematic error will be well constrained. The number of events to be subtracted will be well measured in two ways because they are easily tagged by the incoming parent muon (unlike the longer lived spallation products). First, the two far detectors will measure the rate in the window. Second the two near detectors can measure the rate to either side of the energy window. As a result, we expect the statistical error to be about 0.2%. This results in an error on the subtracted background of 48 events, which is negligible compared to the other background errors in this analysis.

5 Using the Muon-Neutron Veto

The muon-neutron veto proposed in reference [7] removes these events. This veto looked for a penetrating muon followed by a neutron signal (or more) within 600 ms. It induces a deadtime of 6.4% which is already considered in our calculations.

The veto was estimated to be 97% efficient for removing events where at least one neutron captures on the Gd. In fact, the ^{12}B events are likely to have many neutrons, as was discussed above. So the veto is likely to be much more efficient. It should be noted that the probability of producing ^{12}B increases with the number of neutrons, thus events with ^{12}B are more likely to have extra neutrons to trigger the veto. Nevertheless, events with only 1 neutron which produces the ^{12}B, leaving none to trigger the veto must be studied. The ^{12}B decay itself can produce enough light to produce a veto. Or, alternatively, it may be necessary to use an energy veto also.

Accepting this 97% efficiency gives a rate of 720 unvetoed-by-neutron ^{12}B events. Again, this is a well-understood number because the vetoed events can be used to constrain the rate of unvetoed events. Therefore, the muon-neutron veto provides a second method of reducing the error from the n-produced ^{12}B to a negligible level.

References

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[6] M. R. Adams *et al.* [E665 Collaboration], "Nuclear decay following deep inelastic scattering of 470-GeV muons," Phys. Rev. Lett. **74**, 5198 (1995) [Erratum-ibid. **80**, 2020 (1998)].

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