Coincidence Backgrounds from Natural Radioactivity in Braidwood

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1 Introduction

The ability to tag neutrino events using the combination of a positron signal followed by a well-defined neutron capture has historically been a very powerful tool to achieve a nearly background-free measurement. However, given the precision of the next generation of reactor experiments, care must be taken to ensure that previously-ignored backgrounds to not play a significant role in new experiments. The purpose of this document is to access whether the contamination of backgrounds from uranium and thorium play any particular role in the background budget of the Braidwood experiment (or experiments of its kind).

The main contribution of backgrounds emerging from the decay of ^{238}U and ^{232}Th comes in the form of uncorrelated single rates. The combination of the coincidence requirements and a fast neutron capture time help mitigate this background to negligible levels. However, any *correlated* backgrounds arising from the uranium and thorium chains could be an issue. Such backgrounds can emerge from (α,n) reactions initiated by the U and Th decay chains. We consider the following (α,n) reactions that could take place on elements present within or in close proximity of the fiducial volume:

^{2}H(α, α n)^{1}H (Q = -2.223 MeV);
^{13}C(α,n)^{16}O* (Q = +2.215 MeV);
^{17}O(α,n)^{20}Ne (Q = +0.5871 MeV);
^{18}O(α,n)^{21}Ne (Q = -0.6890 MeV).

Any potential carbon and/or oxygen target could therefore be a source of backgrounds. Examples of this include the acrylic vessel $(C_5H_8O_2)_n$, and, of course, the scintillator oil with a composition of $(CH_2)_n$, with minor Gd-doping.

The main background from such (α,n) reactions comes from the reaction on ^{13}C, producing an excited state of ^{16}O*. The excited oxygen state will decay emitting a high energy

(6.13 MeV) gamma ray, which will be in coincidence with a neutron. Such a background is similar enough to the neutrino signal ^{1}H($\bar{\nu}_e, e^+$)n to be a concern if these rates are too high. Such a background source has been previously reported by the KamLAND collaboration [1]

We examine the contamination levels necessary to keep the background due to ^{13}C(α,n)^{16}O* below 0.01 events/ton/day. This study will make a number of simplifying, conservative assumptions in order to determine the expected background rates and it is not meant to be the final word on this particular background. A follow-up Monte Carlo study should provide a more accurate prediction of the background rate.

2 Calculating (α,n) Backgrounds

The primary background arising from (α,n) reactions stems from the creation of the excited 0^+ state of ^{16}O. The de-excitation of ^{16}O creates a high energy gamma ray that could be mis-identified as a positron coincident with a neutron. To a lesser extent, ^{17}O(α,n)^{20}Ne and ^{18}O(α,n)^{21}Ne can also contribute to background, since they emit gammas with 2-3 MeV energies. However, such reactions are confined to the acrylic vessel and are greatly reduced, as is shown below.

There are two source locations that one must consider. First, there is a contribution due to ^{238}U and ^{232}Th in the bulk of the scintillator oil. In this case, one can scale the activation as a function of the level of contamination present in the detector. The expected background rate due to bulk activity is then given by the following expression:

$$R^{\lambda,i} = Y_{c,i} \cdot \sum_j BR_j \cdot \epsilon_{j,i} \cdot D^{\lambda} \tag{1}$$

where $R^{\lambda,i}$ is the rate of correlated backgrounds (in units of events/ton/day) for a given decay chain λ (uranium or thorium), $Y_{c,i}$ is the neutron yield for element i in compound c, BR_j is the branching ratio for a given isotope j in an equilibrium chain to produce an α particle, $\epsilon_{j,i}$ is the efficiency for the j-th alpha particle and reaction on element i to be detected, and D_j is the decay rate for a given decay chain λ.

In the case of bulk activity, the number of decays D^{λ} can be expressed as a function of contamination level:

$$D^{\lambda} = \text{DecayRate} \ \times \ \text{Mass} \ \times \ \text{Contamination} \tag{2}$$

The contamination is expressed in terms of g/g. For example, ^{238}U yields 3.92×10^5 decays/μg/year. Therefore:

$$D^{238U} = 1.073 \times 10^{15} \cdot C(g/g) \text{ events d}^{-1} \text{ t}^{-1} \tag{3}$$

Similarly, ^{232}Th in equilibrium results in 1.28×10^5 decays/μg/year, or:

$$D^{232Th} = 3.504 \times 10^{14} \cdot C(g/g) \text{ events d}^{-1} \text{ t}^{-1} \tag{4}$$

It should be noted that the above assumes the chain is in secular equilibrium. However, certain elements of the chain (such as ^{222}Rn, ^{224}Rn, and ^{226}Rn) will *not* be in equilibrium. It is possible, however, to always express the influx of radon in terms of an equivalent secular equilibrium activity.

In the second case, one can consider (α,n) reactions on the acrylic vessel. Typically, one needs to worry about both carbon and oxygen activation. Furthermore, the activity present on the vessel tends to be much higher than that found in the bulk scintillator oil. It is more convienient to express the decay activity in terms of activity at the surface.

$$D^{surface} = 9.77 \times 10^{10} \cdot S(Bq/cm^2) \cdot P(r) \text{ events d}^{-1} \text{ t}^{-1} \tag{5}$$

where S(Bq/cm^2) is the surface activity of the acrylic. The above equation is listed for a 3-meter acrylic sphere. Note that for the acrylic sphere there exists also a reduction factor $P(r)$, which accounts for the probability of reconstructing an acrylic event inside the fiducial volume. Because of the high neutron capture, this suppression factor is very large.

3 Alpha Thresholds

Table 1 lists the alpha particles emitted in the decay chains of ^{232}Th and ^{238}U, along with their kinetic energies. If we concentrate solely on the ^{13}C(α,n)^{16}O* excited state, there exists a threshold of 6.05 MeV to enable the reaction. Translating this threshold to an equivalent threshold for the alpha particle, with a Q-value of +2.215 MeV, we find:

$$T_\alpha = \frac{17}{13}(6.05 - 2.215) = 5.015 MeV \tag{6}$$

Assuming that the cross-section and efficiencies for each energy is the same above threshold, we can find the number of alphas that can participate in the carbon activation reaction from the two chains. Those sums are shown in Table 1.

4 Target Yields

Thick target yields for alphas on a variety of materials currently exist and have been studied extensively [2]. When an element is part of a compound (c) or mixture, the yield from a given by the following expression:

$$Y_{i,c} = \frac{S_i}{S_c} Y_i \tag{7}$$

where S_i is the stopping power for the component i, and S_c is the stopping power for the material. Table 2 shows the stopping powers for a number of common materials. To find the stopping power of a given material, one simply takes the mass average of each element in the compound. For example, for CH_2:

Table 1: Alphas emitted by the uranium and thorium decay chains. The number of alphas that are above $^{13}C(\alpha,n)^{16}O^*$ threshold is shown. The number is weighed by the branching ratio. Secular equilibrium has been assumed. Only daughter events below radon are considered in the case of the thorium decay chain.

	Parent	α K.E. (MeV)	Below Rn in Chain?	Above 5.035 MeV?	Weight
^{238}U					
	^{238}U	4.196	No	No	0.
	^{234}U	4.777	No	No	0.
	^{230}Th	4.688	No	No	0.
	^{226}Rn	4.784	Yes	No	0.
	^{222}Rn	5.490	Yes	Yes	1.
	^{218}Po	6.002	Yes	Yes	1.
	^{214}Po	7.687	Yes	Yes	0.999
	^{210}Po	5.305	Yes	Yes	1.
	^{214}Bi	4.564	Yes	No	0.
Total Weight					4.
^{232}Th					
	^{232}Th	4.011	No	No	0.
	^{228}Th	5.423	No	Yes	0.
	^{224}Ra	5.686	No	Yes	0.
	^{220}Rn	6.288	Yes	Yes	1.
	^{216}Po	6.778	Yes	Yes	1.
	^{212}Po	8.785	Yes	Yes	1.
	^{212}Bi	6.090	Yes	Yes	0.6406
Total Weight					3.641

Table 2: Stopping powers for 5 MeV alpha particles.

Element	Stopping Power (MeV mg^{-1} cm^2)
H	2.971
C	0.830
O	0.756
CH_2	1.137
H_2O	1.003

$$S_{oil} = \frac{12}{14} \cdot 0.830 + \frac{2}{14} \cdot 2.971 \equiv 1.136 \ \text{MeV mg}^{-1} \text{ cm}^2 \tag{8}$$

Assuming the acrylic vessel in Braidwood is composed of the same material as in SNO, one can calculate the yield equations for the most common materials in the Braidwood detectors.

$$Y_{\text{oil}} = 0.975 Y_C \tag{9}$$

$$Y_{\text{acrylic}} = 0.512 Y_C + 0.249 Y_O \tag{10}$$

The neutron yields on carbon and oxygen for a 5.3 MeV alpha on the natural elements of carbon and oxygen are listed below:

$$Y_C = 1.0 \times 10^{-7} \tag{11}$$

$$Y_O = 6.0 \times 10^{-8} \tag{12}$$

With the above equations, it is now possible to estimate the rate of (α,n) activation. Assuming each an every event that is detected, with no suppression from the acrylic, we find:

$$R^{232Th,oil} = 1.24 \times 10^8 \cdot C(g/g) \text{ events d}^{-1} \text{ t}^{-1} \tag{13}$$

$$R^{238U,oil} = 4.18 \times 10^8 \cdot C(g/g) \text{ events d}^{-1} \text{ t}^{-1} \tag{14}$$

$$R^{232Th,acrylic} = 2.35 \times 10^4 \cdot S(Bq/cm^2) \text{ events d}^{-1} \text{ t}^{-1} \tag{15}$$

$$R^{238U,acrylic} = 2.58 \times 10^4 \cdot S(Bq/cm^2) \text{ events d}^{-1} \text{ t}^{-1} \tag{16}$$

If we assume we only want 0.01 events per ton per day, it places the following restrictions on the contamination levels:

Bulk Contamination: 8×10^{-11} g/g ^{232}Th; 2×10^{-11} g/g ^{238}U
Surface Activity : 0.42 μBq/cm^2

The above cleanliness requirements are extremely conservative. Currently, limits have been placed on the contamination levels for U and Th based on activity measurements made on gadolinium which have yielded a upper limit of 10^{-12}g/g activity on uranium and thorium. Note that this background level applies both to U/Th concentrations as well as radon equivalents.

In comparison with KamLAND, their experiment sees approximately 70 events above 1 MeV for 766 ton-years of data [1]. This contamination is equivalent to ≈ 0.09 events/ton/day in their fiducial volume. KamLAND also reports a ^{210}Po activity yielding $(1.47\pm0.20)\times10^9$ α, which is equivalent to 5.5×10^{-11}g/g of ^{238}U [1] Taking the above rates, our production yield for ^{13}C excitation is within a factor of 3 from the KamLAND measurement.

5 Acknowledgments

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References

[1] T. Araki *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **94**, 081801 (2005)

[2] Heaton *et al*, "The Red Book", SNO internal document.

[3] R. G. H. Robertson *et al*, SNO internal document.

[1] Presumably this comes mainly from Rn ingress. Needs to be verified.