Radiogenic neutron background predictions in DEAP-3600 and in situ measurements

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Abstract. Neutron-induced backgrounds are among the dominant backgrounds in many low-background experiments. One of the main processes that produce these neutrons is the \((\alpha,n)\) reaction occurring in detector components. We present NeuCBOT, a new tool for calculating \((\alpha,n)\) yields and neutron energy spectra in arbitrary materials. By combining NeuCBOT calculations with \textit{ex situ} measurements of the radioactive contamination of detector components, we predict the neutron backgrounds in the DEAP-3600 WIMP detector.

1. Introduction

A key component of rare event searches is minimizing backgrounds that may imitate the sought after signal. For experiments seeking to directly detect Weakly Interacting Massive Particles (WIMPs), this is largely done by differentiating between nuclear recoil (NR) signals expected from WIMP-nucleus scattering interactions and electron recoil (ER) signals produced by \(\beta\) and \(\gamma\)-ray interactions. However, NR backgrounds remain a risk.

One important class of NR background comes from neutrons, which have two primary origins. Cosmogenic neutrons result from atmospheric muons interacting with the detector environment; they are generally reduced by building detectors deep underground and are vetoed with water Cherenkov detectors. Radiogenic neutrons are produced by nuclear reactions in the detector environment; due to the close proximity of the target and their 1–10 MeV energy scale, these neutrons may produce WIMP-like signals in a detector.

In these proceedings, we quantify the neutron backgrounds in the DEAP-3600 WIMP detector, focusing on methods used to predict them and an \textit{in-situ} test of this prediction.

DEAP-3600 [1] is located at SNOLAB, at a depth equivalent to 6 km of water. It consists of \(\sim\)3.3 tonnes of liquid argon (LAr) contained in a 5 cm-thick acrylic vessel, viewed by an array of 255 Hamamatsu R5912 HQE PMTs. The PMTs are separated from the LAr by 45 cm-long acrylic light guides, making for a total of 50 cm of acrylic separating the PMTs from the LAr.

The area between the light guides is filled with alternating layers of high density polyethylene and polystyrene foam that serve as thermal insulation and additional neutron shielding. The detector sits inside a water tank that shields it from external backgrounds and acts as muon veto to tag potential cosmogenic events.

LAr scintillates with a \(\sim\)6 ns fast component and a \(\sim\)1300 ns slow component. ERs produce signals dominated by the slow component, while NRs produce mostly fast light. As a result, the technique of pulse shape discrimination very efficiently removes ER backgrounds. However, a full assessment of the NR backgrounds, including those induced by neutrons, is needed.
2. Material assays
Each component of DEAP-3600 was subjected to a material assay campaign, meant to measure the radioactive contamination of each material in the detector.

The assays were performed by γ-ray spectroscopy with the SNOLAB PGT and germanium well detectors. Ashen samples of acrylic were also α-counted to measure \(^{210}\text{Pb}\) contamination.

Table 1. Approximate assay results from the PMT glass. Measurements assume secular equilibrium within each decay chain, except for \(^{238}\text{U}\), which has been split into an upper and lower chain. The \(^{238}\text{U}_{\text{lower}}\) chain begins at \(^{226}\text{Ra}\).

| Isotope     | \(^{238}\text{U}_{\text{upper}}\) | \(^{238}\text{U}_{\text{lower}}\) | \(^{235}\text{U}\) | \(^{232}\text{Th}\) |
|-------------|----------------------------------|----------------------------------|-----------------|-----------------|
| Activity [mBq/kg] | 225                              | 920                              | 25              | 140             |

The dominant source of radiogenic neutrons is expected to be the borosilicate glass in the PMTs, due to their comparatively high concentration of \(^{238}\text{U}\), their relatively high \((\alpha, n)\) yield, and their proximity to the LAr. The assay results for the borosilicate glass are summarized in table 1, which shows the measured activities of uranium and thorium chains. In these measurements, we assume secular equilibrium in the \(^{235}\text{U}\) and \(^{232}\text{Th}\) chains, and we split the \(^{238}\text{U}\) chain before \(^{226}\text{Ra}\) into an upper and lower decay chain.

3. Radiogenic neutron background predictions
These assay results can be used to predict the flux of neutrons coming from each component. In the uranium and thorium decay chains, there are three processes that produce neutrons: spontaneous fission, direct neutron emission, and the \((\alpha, n)\) reaction.

Table 2. The rate of neutron emission per Becquerel of isotopes in the \(^{238}\text{U}\), \(^{235}\text{U}\), and \(^{232}\text{Th}\) decay chains. Fission yields were calculated using SOURCES-4C [2], and direct neutron emission rates were calculated from branching ratios given in [3].

| Chain | Isotope | Reaction | Yield [n/s/Bq] |
|-------|---------|----------|----------------|
| \(^{238}\text{U}\) | \(^{238}\text{U}\) | Fission | \(1.1 \times 10^{-6}\) |
| \(^{238}\text{U}\) | \(^{234}\text{U}\) | Fission | \(3.0 \times 10^{-11}\) |
| \(^{230}\text{Th}\) | \(^{230}\text{Th}\) | Fission | \(8.1 \times 10^{-14}\) |
| \(^{210}\text{Tl}\) | \(^{210}\text{Tl}\) | Direct | \(1.5 \times 10^{-8}\) |
| \(^{235}\text{U}\) | \(^{235}\text{U}\) | Fission | \(3.1 \times 10^{-9}\) |
| \(^{231}\text{Pa}\) | \(^{231}\text{Pa}\) | Fission | \(1.3 \times 10^{-10}\) |
| \(^{232}\text{Th}\) | \(^{232}\text{Th}\) | Fission | \(3.9 \times 10^{-11}\) |

These first two processes depend only on the amount of radioactivity present. Their rates are given in table 2. As is evident from this table, the dominant fission neutron emitter is \(^{238}\text{U}\).

The \((\alpha, n)\) reaction depends on the activity and energy of each α-emitter present in a material, as well as its isotopic composition. It is therefore necessary to compute the neutron yield of each decay chain in each material under consideration. We compute neutron yields in DEAP-3600 in two ways: using SOURCES-4C [2] and using NeuCBOT [4].
3.1. NeuCBOT
The Neutron Calculator Based on TALYS (NeuCBOT) is an \((\alpha, n)\) calculator that allows the user to specify a material composition and a list of \(\alpha\) energies or a list of \(\alpha\)-emitting isotopes and their relative abundances [4]. NeuCBOT then uses a library generated by the TALYS nuclear reaction simulation code [5] and a table of stopping powers produced by SRIM [6] to calculate \((\alpha, n)\) yields and outgoing neutron spectra. If the user specifies a list of \(\alpha\)-emitting isotopes, NeuCBOT looks up nuclear data from the ENSDF database [7]. NeuCBOT is available for download at https://github.com/shawest/neucbot. Validation of the neutron yield and energy spectrum calculations is shown in [4, 8].

Table 3. \((\alpha, n)\) yields computed by NeuCBOT for materials relevant to DEAP-3600, assuming secular equilibrium in the \(^{235}\text{U}\) and \(^{232}\text{Th}\) decay chains. The \(^{238}\text{U}\) chain is divided into upper and lower chains, with the lower \(^{238}\text{U}\) chain beginning at \(^{226}\text{Ra}\).

| Material          | \(^{238}\text{U}_{\text{upper}}\) [n/s/Bq] | \(^{238}\text{U}_{\text{lower}}\) [n/s/Bq] | \(^{235}\text{U}\) [n/s/Bq] | \(^{232}\text{Th}\) [n/s/Bq] |
|-------------------|------------------------------------------|------------------------------------------|--------------------------|--------------------------|
| Acryllic          | 2.19\times 10^{-7}                      | 9.72\times 10^{-7}                      | 1.42\times 10^{-6}       | 1.33\times 10^{-6}       |
| Alumina           | 5.14\times 10^{-7}                      | 1.38\times 10^{-5}                      | 2.01\times 10^{-5}       | 2.21\times 10^{-5}       |
| Borosilicate Glass| 3.93\times 10^{-6}                      | 1.76\times 10^{-5}                      | 2.56\times 10^{-5}       | 2.43\times 10^{-5}       |
| Polyethylene      | 2.52\times 10^{-7}                      | 1.09\times 10^{-6}                      | 1.58\times 10^{-6}       | 1.49\times 10^{-6}       |
| Polystyrene       | 3.01\times 10^{-7}                      | 1.29\times 10^{-6}                      | 1.88\times 10^{-6}       | 1.77\times 10^{-6}       |
| Stainless Steel   | 1.31\times 10^{-9}                      | 5.52\times 10^{-7}                      | 4.42\times 10^{-7}       | 1.96\times 10^{-6}       |

Table 3 lists the \((\alpha, n)\) yields computed by NeuCBOT for several materials relevant to DEAP-3600. For these calculations, we assumed the material compositions specified in [4].

3.2. Predicted rates
Given the results from the material assays and the \((\alpha, n)\) yields in table 3, we estimate that \(~143,000\) neutrons will be produced per year in total. About 70% of these neutrons are expected to come from the borosilicate glass in the PMTs.

By using these neutron spectra as input to a Geant4 simulation, we estimate the rate of them producing an identifiable signal. For these simulations, we assumed a NR threshold of 80 photoelectrons (equivalent to \(~11\text{ keV}_{ee}\)) and made no fiducial cuts.

Table 4. Expected number of radiogenic neutrons with >80 photoelectron signals in DEAP-3600, using \((\alpha, n)\) yield calculations from NeuCBOT and SOURCES-4C for the three dominant sources.

| Component | Material         | NeuCBOT [n/year] | SOURCES-4C [n/year] |
|-----------|------------------|------------------|---------------------|
| PMTs      | Borosilicate glass | 15               | 13                  |
| PMTs      | Ceramic          | 1                | 2                   |
| Filler foam | Polystyrene   | 3                | 2                   |
| Total     |                  | 19               | 17                  |

The results of these simulations are shown in table 4. The predictions from NeuCBOT and SOURCES-4C are close to each other, though NeuCBOT predicts slightly higher rates. This difference is within the \(~30\%\) systematic offset between NeuCBOT and SOURCES-4C as reported in [4].
Additional analysis cuts such as energy and fiducial cuts are expected to greatly reduce the number of these neutrons that present a background to the DEAP-3600 WIMP search.

4. In-situ validation

After a neutron scatters in the LAr, it will travel until it thermalizes and then captures. Once a neutron enters the LAr, it is unlikely to penetrate the thick acrylic buffer surrounding it. Therefore, the neutron will most likely either thermalize and capture in either the LAr or the acrylic. The $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ reaction has a Q-value of 6.1 MeV and releases its energy through a cascade of $\gamma$-rays, and the $^1\text{H}(n,\gamma)^2\text{H}$ reaction produces a single 2.2 MeV $\gamma$-ray.

We expect the neutron capture reaction to follow the initial argon recoil by a few hundred microseconds. By looking for a delayed coincidence between an event with a NR-like pulse shape and an energy above $\sim 11$ keV$_{ee}$ and a multi-MeV ER signal, we can tag neutrons and estimate the neutron-induced event rate in the detector.

4.1. AmBe neutron source calibration

To determine the efficiency of such a delayed tagging technique, we deployed an $^{241}\text{AmBe}$ source into a calibration tube outside the detector, inside the muon veto.

The results of this calibration are shown in figure 1. The ER peaks from the $^1\text{H}(n,\gamma)^2\text{H}$ and $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ reactions are labeled. Captures on other isotopes and partial $\gamma$-ray energy depositions populate most of the remaining distribution. The low energy tail of the $^1\text{H}(n,\gamma)^2\text{H}$ peak is due to 2.2 MeV $\gamma$-rays that lose some of their energy in the acrylic rather than the LAr.

To identify delayed coincidences, NRs above $\sim 11$ keV$_{ee}$ were tagged if they were followed by an ER signal above $\sim 1.9$ MeV. NRs followed by an ER within 1 ms were tagged as true coincidences; those followed by an ER 1–10 ms afterwards were counted as random coincidence events that provide a background to the search.

As can be seen in figure 1, little variation in tagging efficiency is seen with the NR energy. After subtracting out random coincidences, we expect to see a neutron capture signal within 1 ms of a neutron recoil with a $\sim 19.3\%$ efficiency.
4.2. Limits on the neutron background rate
Applying a similar analysis to \sim 5 days of data, no such NR-ER pairs were observed. This is consistent with the expected neutron event rate. Preliminary projections to a 109 day dataset indicate that the lack of any observed coincidences will allow for a 90% confidence upper limit of <26 neutron interactions >80 photoelectrons per year.

5. Conclusions
We predict a rate of 17 (19) neutrons producing detectable signals per year in DEAP-3600, using NeuCBOT (SOURCES-4C). Preliminary estimates of the neutron event rate in the data are consistent with these predictions. Additional cuts on position and energy will further reduce the rate of these events producing backgrounds to the WIMP search.

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