A FLUKA Study of $\beta$-delayed Neutron Emission for the Ton-sized DarkSide Dark Matter Detector

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Abstract. In the published cosmogenic background study for a ton-sized DarkSide dark matter search, only prompt neutron backgrounds coincident with cosmogenic muons or muon induced showers were considered, although observation of the initiating particle(s) was not required. The present paper now reports an initial investigation of the magnitude of cosmogenic background from $\beta$-delayed neutron emission produced by cosmogenic activity in DarkSide. The study finds a background rate for $\beta$-delayed neutrons in the fiducial volume of the detector on the order of $< 0.1$ event/year. However, detailed studies are required to obtain more precise estimates. The result should be compared to a radiogenic background event rate from the PMTs inside the DarkSide liquid scintillator veto of 0.2 events/year.

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\textbf{β-decay delayed neutrons}

Most neutrons emitted by nuclear de-excitation after cosmogenic activation were included in our original investigation [1]. Such emission is governed by strong interactions and hence they occur in time coincidence with the initiating muon or muon induced shower, although the simulation did not required the initiating particle to be observed. This study reported the response of the DarkSide (DS) water (CTF) and scintillator (LSV) vetoes to the number of all such neutrons.

However it is also possible that radioactive nuclear isotopes produced by cosmogenic activation undergo β-decay to a daughter nucleus which itself may then promptly emit a neutron. Such decays are not in time coincidence with an incident muon or muon induced shower and would not have been included in our original study. The study did include neutrons produced in materials (including the cavern walls) with or without a charged particle incident in the vetoes. However the number of these neutrons is severely attenuated by shielding before entering the active volume of the DS dark matter detector. This is opposed to neutron emission from delayed β-activity produced in or near the active detector volume.

The topic of delayed neutrons has been studied extensively, for example in the context of nuclear reactors and the R-process in astronomy. The graph shown in Figure 1 was taken from a report on an ongoing effort to prepare an evaluated database for delayed neutron emission [2]. The possible precursor nuclei which can result in delayed neutron emission are indicated by the red (measured) and orange (model predicted) boxes in the figure as a function of proton and neutron numbers.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Potential Precursors in the A ≤ 72 Region [2].}
\end{figure}

Further, one can find experimental information on nuclear levels for some precursor nuclei, their excited daughter isotopes and the resulting isotope after neutron emission [3]. As an example, the level diagram for the $^9\text{Li}$ precursor which can lead to $^8\text{Be} + n$ is shown on the left in Figure 2.
Figure 2.  left) Level scheme for $^9$Li precursor isotope leading sometimes to delayed neutron emission by the creation of $^8$Be.  right) Measured neutron kinetic energy spectrum for delayed neutrons from the $^9$Li precursor.  The visible small peak corresponds to the most likely transition at dE= 0.682 MeV (= 0.764 MeV in Table 2).

Table 2 gives the decays and probabilities for delayed neutron emission from different levels in the $^8$He, $^9$Li, $^{13}$B and $^{17}$N precursor nuclei. Only transitions with at least 0.1% probability and no additional emitted charged particles are included. These four isotopes comprise 95% of the produced precursor nuclei obtained from a FLUKA simulation for the DS detectors.

| $^8$He $\rightarrow$ $^7$Li+n | levels (MeV) | $dE_n$ (MeV) | fraction (%) |
|-----------------------------|--------------|---------------|--------------|
| 5.40 - 0.4776               | 4.82         | ~ 8           |
| 3.21 - 0.4776               | 7.32         | ~ 8           |

| $^9$Li $\rightarrow$ $^8$Be+n | levels (MeV) | $dE_n$ (MeV) | fraction (%) |
|-------------------------------|--------------|---------------|--------------|
| 11.81 - 3.03                  | 8.78         | 3             |
| 11.283 - 3.03                 | 8.253        | 1             |
| 2.78 - 1.6654                 | 1.114        | 16            |
| 2.4294 - 1.6654               | 0.764        | 30            |

| $^{13}$B $\rightarrow$ $^{12}$C+n | levels (MeV) | $dE_n$ (MeV) | fraction (%) |
|----------------------------------|--------------|---------------|--------------|
| 8.860 - 4.9463                   | 3.914        | 0.2           |

| $^{17}$N $\rightarrow$ $^{16}$O+n | levels (MeV) | $dE_n$ (MeV) | fraction (%) |
|----------------------------------|--------------|---------------|--------------|
| 5.939 - 4.143                    | 1.796        | 7.4           |
| 5.379 - 4.143                    | 1.236        | 50            |
| 5.085 - 4.143                    | 0.942        | 0.6           |
| 4.554 - 4.143                    | 0.441        | 38            |

Table 1. Level schemes for delayed neutron emission of the most copiously produced precursor nuclei. Only the sum fraction of 16% is available for $^8$He.

In the case of delayed neutron production from the $^9$Li precursor, an experimental measurement of the emitted neutron kinetic energy spectrum is also available [4]. This is shown on the right in Figure 2. The peak near 680 keV corresponds to the most frequent
neutron energy from the decay of the lowest excited states of $^{9}$Be to $^{8}$Be + n, but the experimental value does not quite match the expected $dE$ = 764 keV. This emission is expected in 30% of the $^{9}$Li decays.

**Precursor production in FLUKA**

Good agreement is obtained between the experimental results of Borexino [9] and a FLUKA simulation of cosmogenic isotope production in light target materials, i.e., liquid scintillator. For example, the predicted and measured yield for the $^{9}$Li precursor are $3.1\pm0.4$ and $2.9\pm0.3 \times 10^{-7}$ ($\mu$ g/cm$^2$)$^{-1}$ respectively. Even though FLUKA [6, 7] does include the treatment of the decays of radioactive nuclei, it does not correctly treat the subsequent delayed emission of neutrons [8]. Thus a list of precursor nuclei and their production properties, location, energy, and time, were recorded in a FLUKA simulation for the DS ton-sized experiment. The number of simulated events corresponds to a lifetime of approximately 34 years. Statistical uncertainties of the simulated results are small ($<10\%$) when compared to systematics which are not reported.

On the left in Figure 3 the positions of all precursor nuclei are shown for distances $\leq$ 500 cm from the center of the sensitive volume. The blue and red symbols indicate production within the LSV and inner sensitive volume respectively, while the black symbols correspond to locations fully contained inside the CTF. It is assumed that delayed neutrons produced in the CTF do not result in background due to their distance from the sensitive volume and moderation in the water and scintillator vetoes. Delayed neutrons created inside the liquid

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**Figure 3.** left) Location of precursor production in the DarkSide setup given as a function of radial distance versus height; red - sensitive volume, blue - LSV and black - CTF ($R<500$ cm, yellow symbols correspond to the CTF steel floor support). right) Precursor production as function of radial distance from center of sensitive volume; red - sensitive volume, blue - LSV and green - $^{9}$Li precursors inside LSV. Precursor nuclei created at and inside the Dewar are shown by the black hatched region and the spike at 200 cm indicates production in the LSV vessel material.
argon sensitive volume are also rejected since the coincident $\beta$-decay electron and possible charged particle emissions would be detected with very high probability.

The raw rate of precursor nuclei production as a function of distance from the center of the sensitive volume is given on the right in Figure 3. The blue solid histogram corresponds to the per year production rate in the LSV while the green solid histogram shows the production fraction from the $^9$Li precursor. More critical precursor nuclei created in the passive material inside the Dewar close to the sensitive volume are indicated by the hatched black region. Their total predicted rate of 1.8 events per year can be compared to the expected rate of radiogenic neutrons with comparable energies produced by the DS photomultipliers on the inner detector which is $56\ (= 556 \times 0.1)$ neutrons per year [10].

The total rate of precursor production inside the full LSV is approximately 14.3 per year. Table 2 lists the yearly production rates for the four most frequent precursor nuclei. The expected rate of delayed neutron production from these precursor nuclei is estimated by applying the transition probabilities as given by the level schemes. $^9$Li is by far the most frequently produced precursor nucleus in the DS experiment. In 50% of the $^9$Li decays a delayed neutron will be produced and of those 60% originate from the transition between the lowest excited level in $^9$Be to $^8$Be + n with a rather small energy difference of $dE=764$ keV.

| precursor nuclei | $^8$He | $^9$Li | $^{13}$B | $^{17}$N | of total |
|------------------|--------|--------|--------|--------|---------|
| fraction (%)     | 8      | 63     | 19     | 7      | 95/100  |
| events (y$^{-1}$) | 1.15   | 8.9    | 2.6    | 1.0    | 13.6/14.3 |
| delayed neutrons (y$^{-1}$) | 0.18   | 4.5    | 0.054  | 0.95   |

Table 2. FLUKA prediction for the production of the four most frequently found precursor nuclei in the DS experiment.

**Backgrounds from $\beta$-delayed neutrons in DarkSide**

To complete the simulation, neutrons found from the four most frequently produced precursor nuclei were then injected in the FLUKA simulation at their respective positions, energies, and rates as described above. FLUKA then provided an estimate of the number of these neutrons which reach the sensitive volume along with the energy deposited into both the sensitive region and the LSV.

Events with raw energy deposition between $10$ keV $< dE < 1$ MeV in the sensitive volume are conservatively considered potential background to DS [1]. The rate of background events from $\beta$-delayed neutrons is given in Table 3 for the four most copiously produced precursor nuclei. Neutrons from other FLUKA predicted precursor nuclei would add no more than 10% to this result. A total of approximately 2.3 raw background events per year are predicted. Note that 97% of these events originate from precursor nuclei created in the Dewar. Only a fraction of these events should give rise to a WIMP like signature for the DS dual phase liquid argon time projection chamber. Thus a study with detailed detector response is required to address a more realistic rate prediction.
| precursor nuclei  | \(^8\text{He}\) | \(^9\text{Li}\) | \(^{13}\text{B}\) | \(^{17}\text{N}\) |
|------------------|----------------|----------------|----------------|----------------|
| events (y\(^{-1}\)) | 0.003 | 1.83 | 0.02 | 0.42 |
| with no LSV signal (y\(^{-1}\)) | \(4 \times 10^{-5}\) | 0.07 | \(5 \times 10^{-4}\) | 0.01 |

Table 3. FLUKA predicted rate of delayed cosmogenic background events for the DS experiment. See text for the definition of signals for the inner sensitive detector volume and the LSV.

Most of these events will not be vetoed by the DS outer detectors since the \(\beta\)-decay delayed neutrons occur well after the originating cosmogenic muon or shower. However, decay signals in the LSV and CTF are recorded and are available for offline analysis where events can be removed using a conservative lower limit of \(dE_{\text{LSV}} > 1\) MeV for the raw energy deposited in the LSV. This is shown in Table 3 where a total rate of < 0.1 background events per year to the DS experiment from \(\beta\)-delayed cosmogenic neutrons is found.

Conclusion

The impact of cosmogenic \(\beta\)-decay delayed neutron background in the DarkSide ton-sized experiment was studied. Even with very conservative assumptions a rate of < 0.1 events per year is found. Fluka predicts approximately 97% of the delayed neutron background originates from precursor nuclei created in the DS Dewar. According to the simulation, the production rate of these precursor nuclei inside the Dewar is 1.8 per year. This should be compared to expected 56 neutrons per year from DS inner detector PMTs. Thus the background contribution from cosmogenic \(\beta\)-decay delayed neutrons is small, but to improve the prediction, a careful simulation of the detailed detector response is required.

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**Appendix**

Level scheme for daughter nuclei after $\beta$-decay from three precursor, $^8$He, $^{13}$B and $^{17}$N, and resulting isotopes after neutron emission (from reference [3]).