Cosmogenic Production as a Background in Searching for Rare Physics Processes

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Abstract

We revisit calculations of the cosmogenic production rates for several long-lived isotopes that are potential sources of background in searching for rare physics processes such as the detection of dark matter and neutrinoless double-beta decay. Using updated cosmic-ray neutron flux measurements, we use TALYS 1.0 to investigate the cosmogenic activation of stable isotopes of several detector targets and find that the cosmogenic isotopes produced inside the target materials and cryostat can result in large backgrounds for dark matter searches and neutrinoless double-beta decay. We use previously published low-background HPGe data to constrain the production of $^3\text{H}$ on the surface and the upper limit is consistent with our calculation. We note that cosmogenic production of several isotopes in various targets can generate potential backgrounds for dark matter detection and neutrinoless double-beta decay with a massive detector, thus great care should be taken to limit and/or deal with the cosmogenic activation of the targets.

Key words: Cosmogenic activation, Dark matter detection, Double-beta decay
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1 Introduction

The direct detection of weakly interacting massive particles (WIMP) and the search for neutrinoless double-beta (0νββ) decay are fundamentally important for physics beyond the standard model of particle physics. The direct detection of WIMPs would help to determine the mass and cross section of a WIMP, while any observation of neutrinoless double-beta decay would clearly show that the neutrino is a Majorana particle and that the lepton number is not conserved. Both types of experiments are searches for extremely rare signals and thus require large mass exposures of sensitive detectors with small internal backgrounds and sufficient shielding against external backgrounds at a deep underground site.

The physics goals of upcoming double-beta decay experiments are to probe the quasi-degenerate neutrino mass region as low as 100 meV and demonstrate that backgrounds can be achieved at or below 1 count/ton/year in the 0νββ decay peak region of interest (ROI). To realize these goals, these experiments must construct detectors in an ultra-low background structure. Although these experiments are foremost neutrino mass experiments, they may potentially contribute to dark matter searches. In contrast, dark matter experiments will not necessarily be built of a material composed of 0νββ isotope. In any case, cosmic-ray produced long-lived isotopes are potential sources of background for either type of experiment.

In this paper, we revisit old calculations of the production rates for critical cosmic-ray produced isotopes. The need for this revisit arises, because of recent improvements in the understanding of the cosmic-ray neutron flux and, in the case of 3H, the availability of reaction codes that fully identify all the reaction products in the final state. In Section 2, we evaluate, several long-lived isotopes that are produced in germanium by cosmic ray neutrons while the material resides on the Earth’s surface. We then validate our calculation by comparing them to the measured production rates in Section 3. We discuss the effect of cosmogenic activation of natural xenon and various other targets on dark matter detection in Section 4. Finally, we give our conclusions in Section 5.

2 Cosmogenic production in germanium

2.1 Cosmogenic production of radioactive isotopes

The early work of Avignone et al. showed that isotopes produced in Ge by fast cosmic-ray neutrons could create background in double beta decay
and dark matter experiments. Both the Heidelberg-Moscow [6] and IGEX [7] experiments observed $\gamma$-rays from such isotopes (e.g. $^{68}\text{Ge}$, $^{60}\text{Co}$). Thus, motivated the need to limit the cosmogenic activation, a better understanding of the production rate of cosmogenic isotopes is required. The production rate, $R_i$, of the radioactive isotope $i$ can be calculated according to

$$R_i = \sum_j N_j \int \phi(E) \sigma_{ij}(E) dE,$$

(1)

where $N_j$ is the number of target nuclear isotope $j$, $\sigma_{ij}$ is the neutron excitation function for the product $i$ from target $j$, and $\phi$ is the cosmic neutron flux. We ignore the contribution of cosmic protons because the flux is much smaller. Ziegler carried out a comprehensive study on neutron cosmic ray flux [8] and pointed out that some of the data from early measurements [9,10] is incorrect or of marginal quality [11]. Several cosmic neutron fluxes [9,12] were used in the evaluation of cosmogenic production in both natural germanium and enriched $^{76}\text{Ge}$ conducted by Avignone et al. [13] while significant differences emerged in the production rate of $^{68}\text{Ge}$ and $^{60}\text{Co}$ due to the varying values for the cosmic neutron flux. The quality of the neutron flux data has significantly improved due to new measurements [14]. Improved recent measurements by Gordon et al. [15] show that the flux density spectrum at sea level can be parametrized as

$$\phi(E) = 1.006 \times 10^{-6} e^{-0.35 \ln^2 E + 2.1451 \ln E} + 1.011 \times 10^{-3} e^{-0.4106 \ln^2 E - 0.667 \ln E}$$

(2)

where $E$ is neutron kinetic energy in MeV and $\phi$ in units of cm$^{-2}$s$^{-1}$MeV$^{-1}$. This parametrization function agrees with the data within $\sim 2\%$ accuracy as shown in Fig. 1.

Note that the variation of the cosmic ray muon and neutron fluxes at various locations around world have been reported by Ziegler [8] and Gordon et al. [15]. Cosmic ray muon and neutron fluxes depend strongly on the altitude and the variation is described as a function of altitude in Ziegler’s paper [8]. In addition, the variation from different locations at the sea level caused by geomagnetic rigidity is also substantial [8,15]. In the northern hemisphere, this variation is within 10% [15]. This work applies the measured cosmic ray neutron flux in the northern hemisphere described in Eq. (2).

We use the TALYS code 1.0 [16] to generate the excitation functions of isotopes produced by neutrons on stable isotopes of germanium and copper. TALYS is a nuclear reaction program which simulates nuclear reactions that involve neutrons, photons, protons, deuterons, tritons, $^3\text{He}$- and alpha-particles, for target nuclides of mass 12 and heavier. In the TALYS code 1.0, a suite of nuclear-reaction models has been implemented into a single code system which enables
to evaluate nuclear reactions from the unresolved-resonance region up to intermediate energies. We show, for example, the excitation functions of $^{60}Co$ and $^3H$ by neutrons on germanium isotopes in Fig. 2 and 3 respectively. Based on Eq. (1), the production rates of cosmogenic isotopes in natural and enriched (nominally 86% $^{76}Ge$ and 14% $^{74}Ge$) germanium are estimated and tabulated in Table 1. Isotopes with half-lives above 10,000 years are not listed because their contribution to the backgrounds are expected to be negligible due to their low decay rate. The production rates of $^{60}Co$ and $^{68}Ge$ in germanium agree within a factor of 2 with Ref. [17,18], while the rate of $^3H$ is a factor of 7 smaller than the estimates in Ref. [13,19], where the old cosmic neutron flux from Ref. [9,12] or [20] is used. Compared to the old neutron-flux measurements, the recently measured flux is smaller at energies below 50 MeV, but larger between 50 MeV and 1 GeV. $^3H$ can produce background for dark
Fig. 3. $^3H$ production cross section as a function of neutron kinetic energy.

matter detection via $\beta$-decay with an end point at 18.6 keV.

Table 1
The calculated production rates (per day per kg) of cosmogenic isotopes in natural and enriched (86% $^{76}Ge$ and 14% $^{74}Ge$) germanium using TAYLS and the neutron flux model described in the text. Very long and short lived isotopes are not listed because their contribution to the backgrounds are expected to be negligible. Also shown are isotopes which are produced by cosmogenic activation of copper.

| Cosmogenic Isotope | Production Rate (/kg day) | $t_{1/2}$ |
|-------------------|---------------------------|-----------|
|                   | Natural Ge | Enriched Ge | Natural Cu |           |
| $^{68}Ge$         | 41.3       | 7.2         |            | 270.8 d   |
| $^{60}Co$         | 2.0        | 1.6         | 46.4       | 5.2714 y  |
| $^{57}Co$         | 13.5       | 6.7         | 56.2       | 271.79 d  |
| $^{55}Fe$         | 8.6        | 3.4         | 30.7       | 2.73 y    |
| $^{54}Mn$         | 2.7        | 0.87        | 16.2       | 312.3 d   |
| $^{65}Zn$         | 37.1       | 20.0        |            | 244.26 d  |
| $^{63}Ni$         | 1.9        | 1.8         |            | 100.1 y   |
| $^3H$             | 27.7       | 24.0        |            | 12.33 y   |

2.2 An Upper Limit on the Tritium Production Rate in Enriched Ge

For the low-energy data analysis of Ge-detector double-beta decay experiments, the question of the tritium content is an important issue. The Heidelberg-
Moscow [21] and IGEX [22] experiments have both published low-background, low-energy spectra from Ge detectors operated deep underground. The Heidelberg-Moscow data has a low-energy threshold of 9 keV, whereas the IGEX data reaches lower to 4 keV. Figure 4 shows the IGEX spectrum. Overlaid on that spectrum is the tritium $\beta$-decay spectrum normalized to 250 counts with a constant background level of 2.5 counts/keV added. The data is 80 kg-d of exposure. The "fit" was done by eye: that is the normalization of the tritium curve was determined by adjusting it until it passed approximately through the measured data points.

![IGEX spectrum with fit](image)

Fig. 4. The low-energy IGEX spectrum (80 kg-d) [22] with the fit-by-eye to a tritium spectrum.

If one assumes that the normalized curve accurately represents the data, then the assigned 250 counts represents the maximum number of tritium events that can be contained within the data. Since it is likely that other sources of a signal (noise, low energy x-rays, etc.) are present, we consider the 250 counts to be an upper limit on the spectral contribution due to tritium.

Tritium will be produced within the Ge by high-energy neutron-induced interactions while it is stored above ground. The Ge detector was underground for about 1 year prior to this data being obtained and the enriched Ge was above ground 3-5 years after enrichment and prior to going underground [23]. Therefore the tritium was produced for 3-5 years and then decayed away for a year before counting.

To convert the 250 counts to an upper limit on the tritium production we use 3 years for the exposure time as this gives the largest production rate. The tritium production rate ($k$) depends on the number of counts ($dN$) observed during the counting time ($dt$), the exposure time to cosmic rays ($t_{exp}$) and the cool-off time before counting starts ($t_{dec}$). The production rate is then given by:

$$k = \frac{dN}{dt}$$
\[ k = \frac{dN}{dt} \left( \frac{1}{1 - \exp\left(-\frac{t}{17.79y}\right)} \exp\left(-\frac{t}{17.79y}\right) \right) \tag{3} \]

\[ k < \frac{250}{80 \text{ kg-d}} \cdot \frac{1}{1 - \exp\left(-\frac{3y}{17.79y}\right) \exp\left(-\frac{1y}{17.79y}\right)} \tag{4} \]

\[ k < 21 \text{ tritium atoms/kg-d} \tag{5} \]

where the mean life of tritium is 17.79 y. This resulting upper limit on the tritium production rate in Ge due to cosmic rays (21 tritium atoms/kg-d) is consistent with our TALYS code calculation of 24 tritium atoms/kg-d. The rate is much lower than a previous calculation \[13\] of 110-140 tritium atoms/kg-d, which couldn’t discern the fraction of events of \(^{72}\text{Ge(n,x)}^{70}\text{Ge}\) that led to tritium production.

3 Comparison between this work and the previous measured rates

Avignone et al. have measured and calculated cosmogenic production rates for some isotopes utilizing natural germanium detectors \[13\]. Their results are compared to this work in Table 2. A reasonable agreement can be found for several isotopes except for \(^3\text{H}\). The differences in the rates of \(^3\text{H}\) production is due to the difference in the cosmic neutron energy spectra applied in two calculations.

Table 2
The production rate of isotopes in natural germanium.

| Cosmogenic Isotope | Measured Rate (Hess Model \[9\]) | Calculated Rate (Lal Model \[12\]) | Calculated Rate (This work) | Calculate Rate (kg day) |
|-------------------|---------------------------------|-----------------------------------|-----------------------------|------------------------|
| \(^3\text{H}\)    | -                               | ~210                              | ~178                        | 27.7                   |
| \(^{54}\text{Mn}\) | 3.3±0.8                         | 2.7                               | 0.93                        | 2.7                    |
| \(^{65}\text{Zn}\) | 38.0±6.0                        | 34.4                              | 24.6                        | 37.1                   |
| \(^{68}\text{Ge}\) | 30±7                            | 29.6                              | 22.9                        | 41.3                   |

It is worthwhile to mention that our results agree within a factor of two with a recent calculation by Barabanov et al. \[24\]. Table 3 shows the comparison. The difference between two calculations are mainly due to the use of different cosmic ray flux values.
Table 3
The production rate of isotopes in germanium

| Cosmogenic Isotope | Natural Ge (/kg day)) | Enriched Ge (/kg day)) |
|--------------------|-----------------------|------------------------|
|                    | Ref. [24]             | This work              | Ref. [24] | This work |
| $^60\text{Co}$     | 2.86                  | 2.0                    | 3.31      | 1.6       |
| $^68\text{Ge}$     | 82.7                  | 41.3                   | 4.32      | 7.2       |

4 Cosmogenic production in natural Xe and other targets

Liquid noble gases, such as liquid xenon (LXe) [25,26,27] and liquid argon (LAr) [28,29,30], have shown excellent pulse shape discrimination capabilities. Liquid cryogens offer the possibility to construct ton-scale target mass detectors [31,32,33] at a reasonable cost. We list in Table 4 the cosmogenic production rates of isotopes which can produce potential backgrounds for xenon-based dark matter detection experiments. Because the interaction rate of WIMPs in xenon decreases dramatically with the nuclear recoil energy, the sensitive energy region for xenon-based dark matter experiments is the very low energy region. Thus, $^3\text{H}$ β-decay with the end-point energy of 18.6 keV can result in large backgrounds for xenon-based dark matter experiments. The demonstrated background discrimination power of 1000 [25] via pulse shape analysis is not sufficient to discriminate against electronic recoil events induced by $^3\text{H}$ β-decay. However, it is likely that tritium will be reduced by a large factor during purification of the xenon.

In Table 5 we tabulate the cosmogenic production rate of $^3\text{H}$ in various targets of dark matter detection experiments. These numbers can be used to guide the requirements for electron-recoil rejection and cryogenic purification to prevent $^3\text{H}$ background.

It is worthwhile to mention that it has been demonstrated that liquid argon can achieve a pulse shape discrimination power of $1.3 \times 10^6$ against electronic recoil events at energy of 15 keV [34]. Thus, at such a high energy threshold, the cosmogenic $^3\text{H}$ will not be a problem for LAr-based dark matter detection and the dominant background source will be $^{39}\text{Ar}$ contained in natural argon.

5 Conclusions

We have investigated the cosmogenic production of various isotopes in several target or source materials pertinent for dark matter and double-beta decay experiments. The tritium production in these materials due to cosmic-ray neutrons is substantial and steps must be taken to either reduce exposure
Table 4
The production rate (per day per kg) of some long lived cosmogenic isotopes in natural xenon. Also shown is the half-life. Isotopes with very long half-lives or very small production rates are not listed because their contributions to the background are expected to be negligible.

| Cosmogenic Isotope | Production Rate (/kg day) | $t_{1/2}$ |
|--------------------|---------------------------|-----------|
| $^{3}H$            | 16.0                      | 12.33 y   |
| $^{121m1}Te$       | 11.7                      | 154 d     |
| $^{123m1}Te$       | 12.1                      | 119.7 d   |
| $^{127m1}Te$       | 5.0                       | 109 d     |
| $^{101Rh}$         | 0.04                      | 3.3 y     |
| $^{125Sb}$         | 0.04                      | 2.7582 y  |
| $^{119m1}Sn$       | 0.02                      | 293.1 d   |
| $^{123Sn}$         | 0.004                     | 129.2 d   |
| $^{109Cd}$         | 3.2                       | 462.6 d   |
| $^{113m1}Cd$       | 0.002                     | 14.1 y    |

Table 5
The cosmogenic production rate (per day per kg) of $^{3}H$ in various targets.

| Target | Ar | Xe | NaI | CsI | TeO$_2$ | CaWO$_4$ |
|--------|----|----|-----|-----|---------|-----------|
| Rate (/kg/day) | 44.4 | 16.0 | 31.1 | 19.7 | 43.7 | 45.5 |

of the target to cosmic rays, reduce the resultant $^{3}H$ within the target after exposure, or develop an event-by-event analysis to remove $^{3}H$ decay events from the data stream.

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