Cosmogenic Activation of Germanium Detectors in EDELWEISS III

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Abstract. Activation of germanium crystals due to cosmic rays becomes a serious limitation for experiments searching for rare events with germanium detectors. Cosmic ray induced activation of the detector components and, even more importantly, of the germanium itself during production, transportation and storage at the Earth's surface, might result in the production of radioactive isotopes with long half-lives, with a possible impact on the expected background. We present a measurement of the cosmogenic activation in the cryogenic germanium detectors of the EDELWEISS III direct dark matter search experiment. The decay rates measured in detectors with different exposures to cosmic rays above ground are converted into production rates of different isotopes. They are compared to model predictions present in literature and to estimates calculated with the ACTIVIA code.

1. Introduction

Background understanding and reduction are two of the key issues for the current and next generation direct dark matter detection and double beta decay experiments.

As experiments are improving background control with passive and active shielding and background discrimination with new detector technologies, the intrinsic background from ^{222}Rn and long and medium-lived cosmogenic products of the target material become a serious threat for the signal discrimination. Notably, the contribution from tritium beta decays may have a significant impact on the sensitivity of the next generation of solid-state detectors.

The crystallization process can be assumed to remove all cosmogenically-produced radioactive atoms, with the exception of germanium isotopes like ^{68}Ge [1]. Their populations grow back again when the crystal is kept above ground. Short-lived isotopes decay rapidly as soon as the detectors are stored underground, provided the depth is sufficient to suppress the hadronic component of the cosmic rays [2]. However, it is preferable to reduce their initial intensities to the lowest possible level. Measurements of the production rates of decaying isotopes are helpful in designing a detector production procedure that limits these backgrounds to acceptable levels, and, more generally, to constrain models predicting the production rates of all isotopes, including those that may prove elusive to direct measurements.

In the following we present measurements of the cosmogenic activation of the germanium detector within the EDELWEISS-III experiment setup [3]. The complete analysis along with details and interpretation on these measurements have been recently published in [4].

[1] http://edelweiss.in2p3.fr/Collaboration/index.php

2. Data Analysis and Interpretation

The EDELWEISS experiment is dedicated to the direct detection of WIMPs. It is located in the Modane Underground Laboratory (LSM) in the Fréjus highway tunnel, where an overburden of about 1700 m of rock, equivalent to 4800 m of water, reduces the cosmic muon flux to 5 $\mu/\mathrm{m}^2/\mathrm{day}$. The experimental setup is installed in a class 10000 clean room, and the immediate vicinity of the cryostat is surrounded by a constant flow of deradonised air which reduces the radon level to $\sim$15 $\mathrm{mBq/m}^3$. The flux of gamma-rays is attenuated by a 20 cm thick lead shielding around the cryostat (18 cm of lead followed by an internal 2 cm of ancient lead). An active muon veto with a geometrical coverage of 97.7% tags muons that can interact in the lead shielding producing neutrons [5]. Radiogenic neutrons coming from the rock are attenuated by more than five orders of magnitude by a 50 cm thick polyethylene shielding. To reduce the flux of neutrons arising from (α,n) reaction and fission occurring in the materials close to the detectors, an additional 10 cm polyethylene shield has been installed between the detectors and the electronics, and the copper used in EDELWEISS-II has been replaced in large part by NOSV copper with better radiopurity ($<$ 0.02 mBq/kg 238U and 232Th [6]).

The active target of the EDELWEISS-III WIMP search experiment consists of twenty-four 800-g Fully-InterDigit (FID) germanium detectors, cooled down to an operating temperature of 18 mK. The detectors are cylindrical high-purity germanium crystals. Detector surfaces are entirely covered with interleaved Al electrodes, biased at alternate values of potentials [7]. The potentials applied to the electrodes are chosen to determine an axial electric field in the bulk of the detector [8], while in the volume within about 2 mm from the surfaces the electric field is parallel to them. As a consequence, electron-hole pairs created in the bulk volume are collected in the axial field by the electrodes with the highest bias on both sides of the detector, called fiducial electrodes, while surface events will be collected by adjacent electrodes. This scheme extends also to the cylindrical surfaces. Bulk events can be discriminated on the basis of the presence of signals of opposite signs on the fiducial electrodes on each side of the detector, and on the absence of signals on all other electrodes. The fiducial ionization (E_{fid}) is defined as the average of the signals on the two fiducial electrodes.

The data analysis is dedicated to the low WIMP mass search [9] and [10]. The energy region of interest is from 2 to 50 keV; the background at energies below 20 keV in such a detector is thus of particular interest.

The cosmogenic products that contribute to the low-energy spectrum are those that decay via electron capture. The capture is often followed by the emission of a K-shell X-ray with characteristic energy between 4 and 11 keV. L-shell captures will produce weaker lines at lower energies. The energy of the relevant lines above 1 keV are listed in [4]. The K:L intensity ratios are known and can be used to test the energy dependence of the efficiency of the detector.

An additional contribution comes from the beta decay of tritium (^{3}H) originating from nuclear reactions induced by the interaction of the hadronic component of cosmic ray showers with atoms in the material [11]. It has an end point Q_β of only 18.6 keV described by [12], and a particularly long lifetime ($\tau = 17.79$ y), so that the tritium activity can be expected to be constant throughout the life of the detector.

Data collected over 160 days devoted to WIMP searches from July 2014 to April 2015 have been considered for this analysis. The average heat trigger threshold and baseline resolutions were monitored hour by hour. For this analysis, only hours when this trigger threshold is below 2 keV were selected. The hourly fiducial baseline resolution on the fiducial ionization measurement was also required to be less than 400 eV.

Of the twenty-four detectors used to define coincidences between detectors, thirteen detectors with an individual exposure greater than 60 days have been considered for this analysis. It corresponds to 87.0% of the total exposure of 1853 detector·day. A sub-sample of events with an online threshold below 0.8 keV is also defined, for precision tests of the efficiency correction

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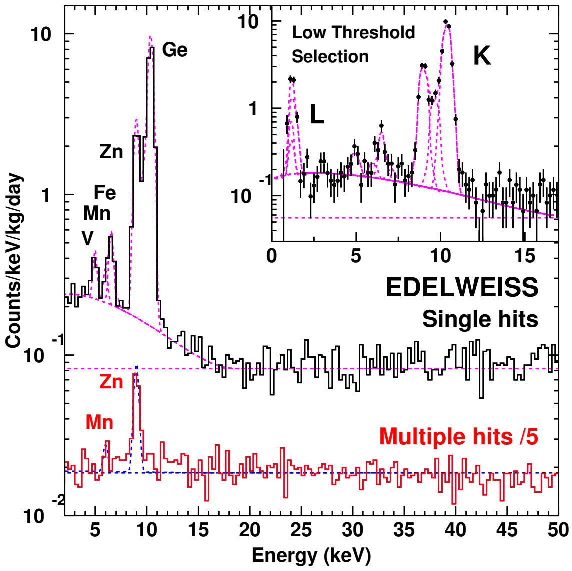

Figure 1. Efficiency-corrected spectrum for the 1853 detector·day sample, together with the fit to the data described in the text. The distribution for single events is in black, and the red spectrum representing multiple-hit events has been scaled down by a factor of 5 for clarity. The inset shows the efficiency-corrected spectrum for the 0.8 keV selection (499 detector·day), used to test down to 1 keV the efficiency model.

model and of the sample purity at energies lower than used in the final analysis. This sample corresponds to 499 detector·day, to which 10 detectors contribute.

An event is included in the analysis if it is a single event passing the fiducial cut. An event is considered as a single if the sum of the ionization energies of all other detectors that may have triggered in an interval of 10 ms is less than 1 keV.

The resulting efficiency-corrected spectrum for the 1853 detector·day sample is shown in Fig. 1. The inset shows the efficiency-corrected spectrum for the data set with an online trigger threshold below 0.8 keV (499 detector·day), used to test the efficiency model. The electron capture and the tritium beta-decay intensities described below are taken from the fit of the sample of events with the 2 keV threshold cut.

The decay rates of the different cosmogenically-produced isotopes are obtained from simultaneous fits of the energy spectra of single and multiple hit events. The fit model has three components: *i)* the tritium spectrum, *ii)* a Compton background and *iii)* K- and L- spectral lines.

The fit of the entire 2 keV threshold data set results in an observed tritium activity of 0.94 ± 0.06 (stat.) ± 0.10 (syst.) events per day and per detector, extrapolated down to 0 keV considering the Fermi correction to the beta decay spectral shape [4]. However, the rate can be expected to vary from detector to detector. Therefore, the same fit is performed for each detector individually. The tritium rate is obtained from the fit with the flat Compton background which consists of 0.089 ±0.002 cts/kg/day/keV for the single selection.

Decay rate of a radioactive isotope depends on the time of material exposure to the source of radiation (t_{exp}) and on the time the isotopes were allowed to decay without being exposed to cosmic rays (t_{dec}), following the relationship $\frac{dN_i}{dt} = P_i \times (1 - e^{\frac{-t_{exp}}{\tau}})(e^{\frac{-t_{dec}}{\tau}})$ per each period of exposure and storage in shallow sites. The production rate, P_i, of a radioactive isotope i can be calculated as follows: $P_i = \sum_j N_j \int \phi(E)\sigma_{ij}(E)dE$ where N_j is the number of target nuclear isotope j, σ_{ij} is the excitation function of isotope i produced by neutrons on stable isotopes of material j, and ϕ is the cosmic neutron flux.

Different input cosmic-ray neutron spectra can lead to a variation in production rates of about 20-30%, whereas the excitation functions may account for up to a factor of 2 difference

Table 1. Rates of production (expressed in $kg^{-1} \cdot day^{-1}$) of isotopes induced in natural germanium as measured in EDELWEISS-III germanium detectors, compared with previous estimates and measurements in Refs. [13], [17], [15], [16], [14] and [11]. Errors on the production rate include statistical and for ^{3}H and ^{65}Zn systematic uncertainties, too. Systematic uncertainty is based on the minimization of the reduced χ^2. Estimate in this work refers to ACTIVIA calculation, considering semi-empirical [18] (a) and MENDL-2P database [19] (b) cross sections. For ^{49}V, both calculations give the same result. An upper limit for ^{3}H from IGEX data (E) is shown together with calculations [15] for all isotopes. (I) and (II) refer to GEANT4 and ACTIVIA calculations from [16]. The lower limit for ^{68}Ge at saturation value is listed. It is derived from the fit value of 81 $\pm$ 6 at a 90% C.L. ACTIVIA calculations for ^{68}Ge are also given including a potential 10-h flight of Ge powder (a* and b*). The last two columns refer to estimates from model [20] and experimental data (Exp.) from Ref. [11].

	This work		Cebrian [13]		Barabanov	Mei	Zhang	Klapdor	Avignone [11]	
	Exp.	Calc.	(Ziegler)	(Gordon)	[17]	[15]	[16]	[14]	[20]	Exp.
^{3}**H**	82±21	46(a) 43.5(b)				27.7 $<$21(E)	48.3 (I) 52.4 (II)		210	
^{49}**V**	2.8±0.6	1.9 (a,b)								
^{65}**Zn**	106±13	38.7(a) 65.8(b)	77	63		37.1		79	34.4	38±6
^{55}**Fe**	4.6±0.7	3.5(a) 4.0(b)	8.0	6.0		8.6		8.4		
^{68}**Ge**	$>$71	23.1(a) 36.2(a*) 45.0(b) 97.6(b*)	89	60	81.6	41.3		58.4	29.6	30±7

in the production rate of ^{68}Ge. The difference increases with the atomic number of the isotope produced.

The EDELWEISS-III data and the best fit to these data are compared to the ACTIVIA calculations [4] and previous studies from Cebrian et al. [13], Klapdor-Kleingrothaus et al. [14], Mei et al. [15] and the update of this work from Zhang et al. [16] and the estimates from Avignone et al. [11]. All these calculated rates are also listed in Table 1.

3. Conclusion

Cosmogenic activation of materials can compromise the sensitivity of ultra-low background experiments via the production of long-lived isotopes at Earth's surface due to nucleons. The tritium contribution can be very dangerous due to the continuum beta decay shape and the lifetime of 17.79 year. The first measurement of the ^{3}H decay rate in germanium detectors is presented. It has been interpreted in terms of production rate of 82 $\pm$ 21 nuclei/kg/day with statistical and systematic uncertainties combined.

The measured production rates on ^{49}V, ^{55}Fe and ^{65}Zn of 2.8 $\pm$ 0.6 nuclei/kg/day, 4.6 $\pm$ 0.7 nuclei/kg/day and 106 $\pm$ 13 nuclei/kg/day, respectively, presented here are the most accurate to-date. A lower limit of 71 nuclei/kg/day at 90% C.L. on the production rate of ^{68}Ge is discussed.

The tritium production due to cosmic-ray neutrons is thus important and the present measurement provides valuable information needed to evaluate the reduction of the exposure to cosmic rays necessary for germanium detector arrays used for dark matter searches. It can be foreseen that the precision of the present measurements will help constrain and further improve the models.

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