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Pulse shape discrimination performance of inverted coaxial Ge detectors

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ABSTRACT

We report on the characterization of two inverted coaxial Ge detectors in the context of being employed in future ^{76}Ge neutrinoless double beta ($0\nu\beta\beta$) decay experiments. It is an advantage that such detectors can be produced with bigger Ge mass as compared to the planar Broad Energy Ge (BEGe) or p-type Point Contact (PPC) detectors that are currently used in the GERDA and MAJORANA DEMONSTRATOR $0\nu\beta\beta$ decay experiments respectively. This will result in a lower background for the search of $0\nu\beta\beta$ decay due to a reduction of detector surface to volume ratio, cables, electronics and holders which are dominating nearby radioactive sources. The measured resolution near the ^{76}Ge Q-value at 2039 keV is 2.3 keV FWHM and their pulse-shape discrimination of background events are similar to BEGe and PPC detectors. It is concluded that this type of Ge-detector is suitable for usage in ^{76}Ge $0\nu\beta\beta$ decay experiments.

1. Introduction

Germanium detectors are best suited to measure precisely the energy of MeV scale γ rays. In the past, large high purity Ge detectors with high detection efficiency had a semi-coaxial geometry and a mass of several kg [1,2]. Point contact detectors, like Broad Energy Germanium (BEGe) [3] or p-type Point Contact (PPC) [4] detectors have a lower mass (~0.7 kg) for operational voltage below 5 kV but exhibit a smaller capacitance and hence better energy resolution. In addition, the analysis of the time profile of the detector signals, called pulse shape analysis [5], allows a powerful discrimination between single or multiple energy depositions inside the crystal or from surface events. This feature is used in the search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039.061 ± 0.007 keV [6]) to reject background events with a high efficiency.

The lower limit of the ^{76}Ge $0\nu\beta\beta$ half life has recently been established by the GERDA collaboration at $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 5.3 \times 10^{25}$ years (90% C.L.) [7]. In order to further improve this limit, reduction of the background, dominated by nearby sources [8,9], can be achieved by lowering the radioactive material surrounding the detector (like cables and holders). The recently designed inverted coaxial detectors [10] combine the advantages of point contact detectors with larger mass and lower surface to volume ratio by featuring a well on the opposite side of the contact. In this paper the pulse shape performance of two such commercially available detectors from MIRION, called Small Anode Germanium (SAGe) well detector [11], are characterized with the aim to study their compatibility with $0\nu\beta\beta$ decay experiment requirements, in particular if the pulse shape discrimination (PSD) is similar BEGe and PPC detectors.

2. Experimental setup

The characterization measurements of two similar inverted coax detectors took place in the HADES underground laboratory in Mol, Belgium [12] and in the Niederniveau-Messlabor-Felsenkeller underground laboratory [13] in Dresden, Germany. With an active mass of 2.6 kg and a volume of 425 cm^3, the former detector, referred to as "Ge-14" detector in the following, is the heaviest detector currently available from the manufacturer (cf. [14] for detailed dimension) while "Det-X" has an active mass of 1.4 kg and a volume of 200 cm^3. Each crystal was installed inside a vacuum cryostat (cf. Fig. 1) located in the center of a lead castle with an inner copper shell for shielding from external radiation. Similarly to BEGe or PPC detectors deployed in GERDA and MJD, these crystals are made of p-type high purity Ge. A high negative potential of −4000 V is applied to the small p+ contact while the rest of the outer surface, covered with a Li-drifted n+ contact, is grounded. The electric field modulus, which results from the contribution of both

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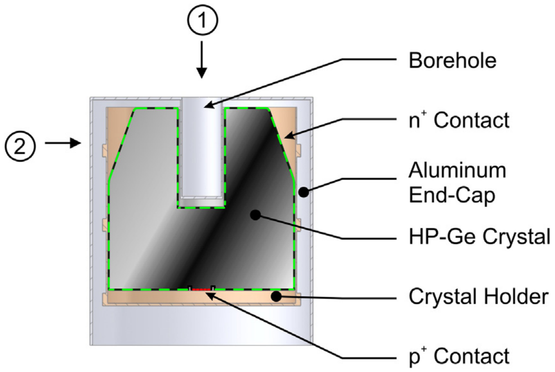

Fig. 1. Sketch of both Ge-14 and Det-X detectors environment including the crystal holder and the aluminum end-cap. The numbers refer to the two source positions used to characterize the HPGe detectors.

the applied high voltage and the intrinsic space charge distribution, is shown in Fig. 2 together with the weighting potential [15]. As a consequence of the E-field profile, holes always drift along the same path near the p+ contact ("funnel effect"). Also, the weighting potential features a very low gradient everywhere in the detector except in the vicinity of the p+ contact. The p+ electrode is AC coupled to a charge sensitive amplifier, delivered by MIRION, for signal readout. The signal is then digitized with a Flash ADC at a sampling frequency of 100 MHz. For each triggered signal we record 4000 samples at full FADC resolution around the rising edge of the signal for PSD. We also save 4000 samples at 25 MHz by adding 4 samples of the high frequency signal for energy calculation.

Two sources, ^{241}Am, and ^{228}Th, were used for the characterization. The first source allowed localized energy deposition at the detector surface for checking the detector isotropy since 95% of 59 keV gammas are absorbed when crossing 3 mm of ^{76}Ge. The ^{241}Am source was encapsulated in a Cu collimator of 16 mm thickness with a 2 mm hole and then placed at different positions around the detectors. In the following, we show measurements at position 2 for four angles (0°, 90°, 180° and 270°) and position 1 (cf Fig. 1). The latter source (^{228}Th), located at position 1, 10 cm above the crystal, produces a broad energy spectrum up to 2.6 MeV with specific event topologies, used for studying pulse shape discrimination.

3. Detector characterization

In the following, we report on the energy resolution of both inverted coaxial detectors and compare it to BEGe and PPC detectors. We require to achieve similar values for integrating these new detectors in a $0\nu\beta\beta$ experiment.

3.1. Energy resolution

For detector Ge-14, the energy is corrected for charge trapping following the same procedure as in [17]. This correction improves the energy resolution at 2.6 MeV by 16%. A gaussian fit to the 59.5 keV ^{241}Am line has been performed on top of the Compton background as for the ^{208}Tl double escape peak (DEP) at 1592 keV and in the full energy peak (FEP) of the 1621 keV line from ^{212}Bi and at 2615 keV from ^{208}Tl. We find an energy FWHM resolution of 1.1% and 1.5% at 59.5 keV for Ge-14 and Det-X respectively. At 1.6 MeV, it reaches 2.04(2.07) keV, i.e. 0.13% for the Ge-14(Det-X) detector which is slightly better than the value of 0.16% at 1.332 MeV reported by MIRION. The energy dependence of the resolution FWHM is plotted for both detectors in Fig. 3. From these measurements, we find similar energy resolution at the ^{208}Tl FEP for both detectors as compared to GERDA BEGe detectors in vacuum [3] and MJD PPC detectors [18].

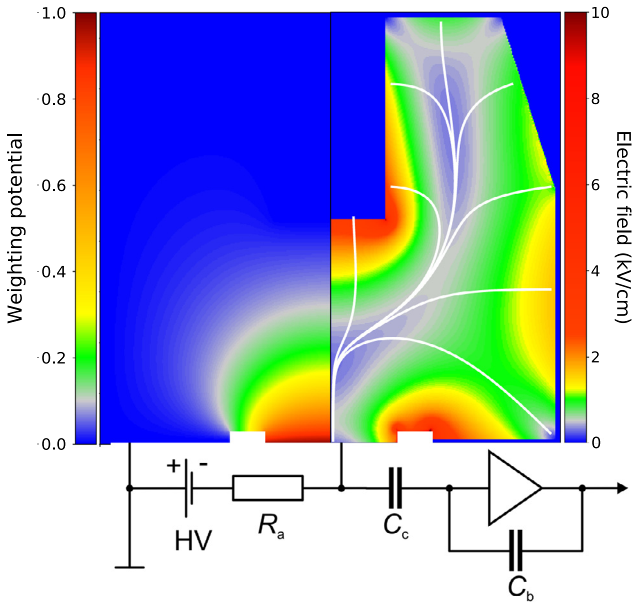

Fig. 2. Weighting potential (left) and simulated electrical field modulus distribution (right) of the p-type Ge-14 detector for an impurity concentration of 1.0 to 0.7 $\times 10^{10}$ cm^{-3} from the bottom to the top. The white lines show some simulated charge carrier paths using the ADL software [16].

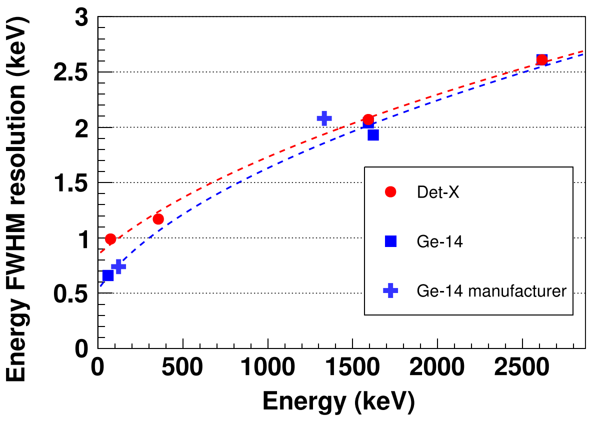

Fig. 3. Energy FWHM resolution as a function of energy for both detectors. Manufacturer's data are taken with a ^{57}Co (122 keV) and a ^{60}Co (1332 keV line) sources.

3.2. Signal rise time

The rise time is an interesting observable for probing the weighting and electric potential homogeneity of a Ge detector close to the p-contact with combining ^{241}Am source measurements at different positions. This parameter is defined as the time interval needed for the charge signal to reach from 5% to 95% of its maximum amplitude.

In Fig. 4, we show a comparison of ^{241}Am rise time distributions and typical pulses are displayed in Fig. 5. No angular dependence is found for the Ge-14 detector. For pulses located on the side of the 2.6 kg detector, we find an averaged rise time of 750 ns. Also, due to the non-spherical shape of the weighting potential (cf. Fig. 2), events arising from the well of the detector, (^{241}Am top), feature an expected lower rise time of about 630 ns. Due to its smaller dimensions, Det-X traces exhibit a much lower averaged rise time of about 420 ns. It must be noticed that an angular dependence is found for this detector, leading to a significant 20 ns rise time difference in between 0° and 180°.