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Characterisation of an ultra low-background point contact HPGe well-detector for an underground laboratory

Mikael Hult[a],[*], Gerd Marissens[a], Heiko Stroh[a], Guillaume Lutter[a], Faidra Tzika[a], Nikola Marković[b]

[a] *European Commission, Joint Research Centre, Directorate for nuclear safety and security, JRC-Geel, Retieseweg 111, 2440 Geel, Belgium*
[b] *Technical University of Denmark. Centre for Nuclear Technologies, Frederiksborgvej 399, 4000 Roskilde, Denmark*

HIGHLIGHTS

- The first ultra low background SAGe™ well detector was installed 225 m underground.
- It has an energy resolution superior to standard well Ge-detectors.
- The Ge mass is 2.57 kg corresponding to about 483 cm^3.
- After 19 months underground, the background count rate 40–2700 keV was 690 d^{-1}.
- With muon-suppression the background count rate 40–2700 keV was 601 d^{-1}.

ABSTRACT

Since a few years there are well-type HPGe-detectors with a small, point-like, anode contacts available commercially. This paper describes the characterisation of the first ultra low-background, so-called, SAGe™ well detector with regards to resolution and background performance. Inside a passive lead/copper shield in the underground laboratory HADES a background count rate of 690 ± 6 d^{-1} (268 ± 3 d^{-1} per kg Ge) was recorded 19 months after taking it underground.

1. Introduction

The workhorses of most radionuclide laboratories today are the HPGe-detectors. The technology to fabricate these high purity diodes has improved a lot since the first crystal was produced in the early 1960s (Hult et al., 2006; Hult, 2007). In recent years, the technology to produce thick planar detectors with a small point contact anode at the back has led to detectors with better resolution. The latest development is to transfer this technology to the production of well-crystals. Canberra's trade-name of these detectors is SAGe™ well detectors as an acronym for Small Anode Germanium. Traditional well-crystals are known to have the lowest (worst) resolution amongst different types of standard HPGe-detector, but with this new technology there is a significant improvement particularly at lower energies. This paper describes the first ultra-low-background SAGe well detector installed in an underground laboratory.

2. Materials and methods

2.1. The laboratory

The underground laboratory HADES is located at a depth of 225 m (500 m water equivalent) at the premises of the Belgian nuclear centre SCK•CEN (Andreotti et al., 2011) JRC-Geel has performed ultra-low background gamma-ray spectrometry (ULGS) there since 1992. For the moment there are 11 HPGe-detectors of different types in operation.

2.2. The SAGe™ well detector

The name given to this detector is Ge-14, which will be used throughout this article. The well's diameter available for samples is 16 mm and its depth 40 mm. The crystal height is 85 mm, its diameter 90.5 mm. The top of the crystal has a bevel to improve proper charge collection. The Ge mass is 2.57 kg (~483 cm^3). For the moment, this is the biggest crystal of this type offered by the producer. Manufacturing Ge-crystals of this size is difficult as it is very important to have a

perfect impurity distribution in the crystal to obtain an appropriate electric field. The endcap is made of ultrapure Al and has an outer diameter of 114.3 mm. The crystal holder is made of electrolytic copper. The deadlayer thickness in the well is about 50 μm and the corresponding thickness on the outer surface is about 0.5 mm. The detector has a typical ULB (Ultra Low-Background) design, i.e. it has a so-called U-style arm (365 mm) so that the pre-amplifier, which is an important source of natural radioactivity, is located outside the shield.

The shield is composed of (from inside to outside) 9 cm of electrolytic copper, 5 cm ULB lead (2 Bq kg^{-1} of ^{210}Pb), 15 cm "normal" lead (50 Bq kg^{-1} of ^{210}Pb). The detector and its shield were taken underground in July 2015.

Several of the electronic components were measured in HADES on other detectors before they were accepted for use in Ge-14. Of particular concern was the AC coupling capacitor, a component which is not required in standard coaxial detectors. In Ge-14, the detector signal is taken from the biased electrode and the outside of the crystal is on ground. The ideal AC coupling capacitor has an infinite resistance to DC currents, and a zero resistance to the charge pulse from the crystal. Selecting a capacitor with a high-quality dielectric material that withstands the high voltage and passes the signal without significantly contributing to noise or leakage current is cumbersome. A batch of 20 capacitors was measured in HADES, but of course only one of them was used in the front-end assembly. The massic activities of the selected (100 pF) capacitor are listed in Table 1. The relatively high massic activities for the capacitor, compared to e.g. those used by GERDA (O'Shaughnessy et al., 2013), forced us to introduce a piece of 30 mm electrolytic copper to be placed between the crystal and the front-end electronics (not seen in Fig. 2) as a radiation shield.

Epoxy-glue is another important source of natural radioactivity and its use is minimised in ULB detectors. During design phase it was not clear if epoxy could be avoided in the cryostat arm so it was tested for radiopurity (Table 1). In the final realisation, it was possible to produce the arm from one single piece without having to use any glue.

The complete endcap is made of high purity aluminium. It is 184.2 mm high and has a mass of 306 g. It was measured on the so-called Pacman detector (Lutter et al., 2013), where it was placed over the endcap of the lower detector.

Due to the AC-coupling, as described, above, there is only one contact needed. The phosphor bronze spring (wire) used for pushing the high purity copper high voltage contact towards the anode was also measured in HADES. Its position in Fig. 2 is just below the crystal and above the HDPE insulator.

3. Characterisation of the detector

3.1. Energy resolution

The manufacturer (Canberra, 2017) claims a resolution almost similar to the so-called BEGe-detectors and significantly better than standard coaxial or well detectors. This was also confirmed by Britton and Davies (2015), when testing a SAGe well detector of 275 cm^3. Fig. 1
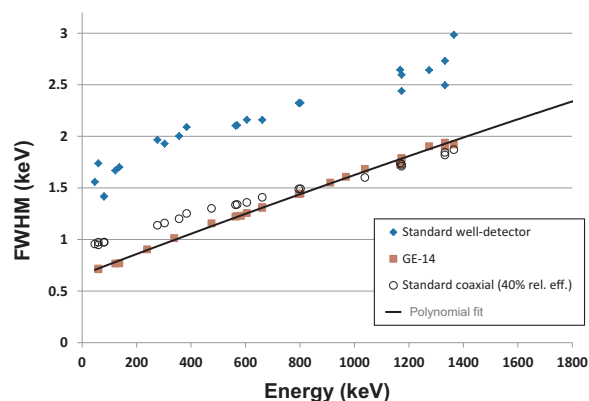

Fig. 1. The energy resolution of Ge-14 compared to some other detectors. The solid line is a fit with a second order polynomial going through a data-point at 2614 keV.

shows the measured resolution of Ge-14 (483 cm^3) in comparison with two other HADES detectors. It may be observed that the resolution of Ge-14 is significantly better than a standard well detector of similar size (Ge-12) and similar well diameter and also better than a standard (190 cm^3) coaxial detector (Ge-T5) at energies below ~800 keV.

3.2. Computer model based on efficiency calibration

Since 1998, computer models of the HPGe-detectors in HADES have been built using the EGS Monte Carlo simulation package (Kawrakow and Rogers, 2006). At first EGS4 was used but since 2010, the EGSnrc version is used (Lutter et al., 2017). Fig. 2 shows the model of Ge-14 used in the EGSnrc computer simulations. The main use of the computer model is to calculate coincidence summing corrections which can be quite significant for a well-detector. In addition, the efficiency transfer calculations are performed using this computer model.

Table 1
Massic activities in mBq g^{-1} (Bq kg^{-1}) of the materials selected for Ge-14. The reference date is at measurement time in May 2015. Decision thresholds according to ISO 11929-2010.

Radionuclide[a]	Capacitor	Al-endcap	contacts	Epoxy glue
^{238}U	2.88 ± 0.63	< 0.021	19 ± 9	1.89 ± 0.17
^{226}Ra	24.5 ± 1.0	< 0.012	< 0.4	1.26 ± 0.06
^{210}Pb	22 ± 4	< 0.03	< 0.14	1.5 ± 0.3
^{228}Ra	6.9 ± 0.5	< 0.005	0.18 ± 0.03	0.16 ± 0.02
^{228}Th	4.0 ± 0.3	< 0.007	0.24 ± 0.03	0.17 ± 0.02
^{40}K	1.4 ± 0.4	< 0.022	0.38 ± 0.14	2.7 ± 0.2

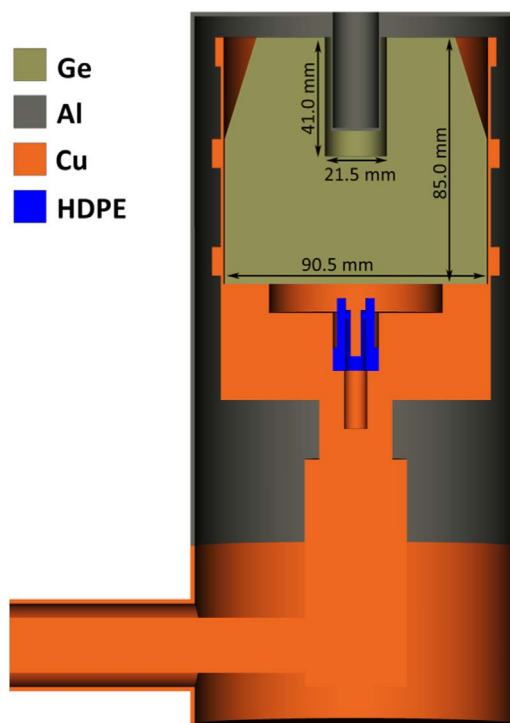[a] Long-lived mother in case of decay series.

Fig. 2. Schematic representation of the EGSnrc model of detector Ge-14 used in the Monte Carlo simulations. Note that the model is not an exact representation of the reality.
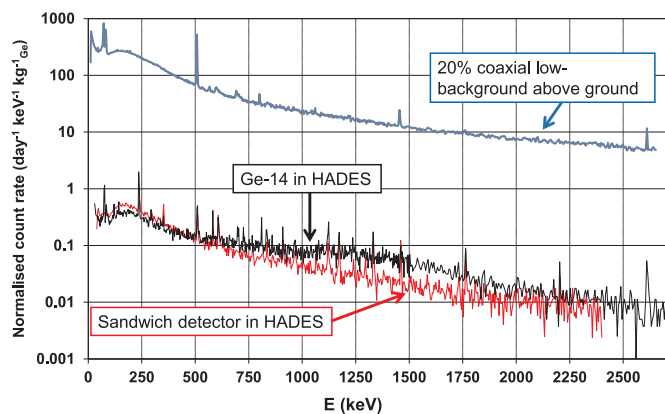
Fig. 3. The background spectrum of Ge-14, 16 months after taking it to HADES compared to the sandwich detector (in HADES since 2006) and Ge-T2 (above ground).

3.3. Background characterisation

Fig. 3 shows the background of Ge-14 measured in HADES starting 16 months after taking it underground. It is compared to a low-background 20% rel. eff. coaxial detector located above ground and the sandwich detector (Wieslander et al., 2009) in HADES. Note that the background counting rate has been divided with each of the detectors' mass (in case of the sandwich detector; 2 masses). The count-rates of individual peaks and certain energy intervals are given in Table 2. In addition to "normal" background measurements, data was taken with a muon shield placed on top of the lead shield. It was composed of two 2 cm thick plastic scintillators 76 × 76 cm electronically connected in coincidence and separated by 5 mm of Pb, similar to the muon shield described by Wieslander et al. (2009). The muon shield reduced the overall (40–2700 keV) count rate by 13% to $601 \pm 6 \, \mathrm{d^{-1}}$ ($237 \pm 3 \, \mathrm{d^{-1}}$ per kg Ge).

The time a Ge-detector has spent underground is important. In deep

(> 1000 m w.e., water equivalent) and semi-deep (100–1000 m w.e.) underground laboratories, the background count-rate continue to decrease significantly during the life-span of a detector due to the decay of activation and spallation products such as ^{57,58,60}Co, ^{68,77}Ge and ^{65}Zn in Ge and Cu and also (like above ground) of possible impurities like ^{134,137}Cs and ^{210}Pb.

An attempt to characterise the background components was performed in a similar manner as described by Hult et al. (2013) for the detector Ge-5. The contribution from activation products in germanium was estimated from determination of (summation) peak areas at 143 keV (^{57}Co), 818 keV (^{58}Co), 1123 keV (^{65}Zn) and calculations based on estimates of ^{68,77}Ge, ^{60}Co and ^{54}Mn. The contribution from radon from the laboratory air (average concentration in the lab is 7 Bq m^{-3}) was estimated by measuring the count rate in the 609 peak as a function of the radon concentration measured using an Alphaguard™. By extrapolating to zero radon concentration, the contribution from ^{226}Ra in the detector and shield can be determined. A measurement with ultra-pure tantalum plates that were stored more than 10 years underground, was performed to distinguish background signals from the shield and from inside the detector. Furthermore, by knowing the activity concentration in certain construction material, their contribution to the background could be calculated using Monte Carlo simulations. Fig. 4 shows the estimated contribution of different sources today and in 8 years from now after decay of some activation products and impurities. A peculiarity was the relatively high count-rate in the peak at 238.6 keV, presumably from the decay of ^{212}Pb. The count–rate of peaks associated with other Th-232 daughters showed count-rates an order of magnitude lower. Interference from ^{214}Pb or other radionuclides were investigated but excluded. All the tested materials (Table 1) have higher massic activities of ^{226}Ra than that of ^{228}Ra or ^{228}Th so they are not likely to contribute to this peak. A possible explanation that will need further investigation is that thoron may emanate from a component and drift towards the point contact. Simulations with a point source located at the point contact show good agreement of the relative count-rates of the peaks at 239 keV, 583 keV and 2614 keV and the sum of the latter two peaks following the decay of ^{208}Tl.

4. Conclusions

The data show that the resolution of the SAGe well detector is indeed superior to standard well detectors. Furthermore, the ULB version of the detector has equally good background performance as ULB versions of other types of HPGe-detectors. The enhanced possibilities (compared to standard well-detectors) of performing pulse-shape analysis further adds to the usefulness of this detector.

JRC-Geel performs reference measurements in all fields where radioactivity measurements are needed. The detector is expected to
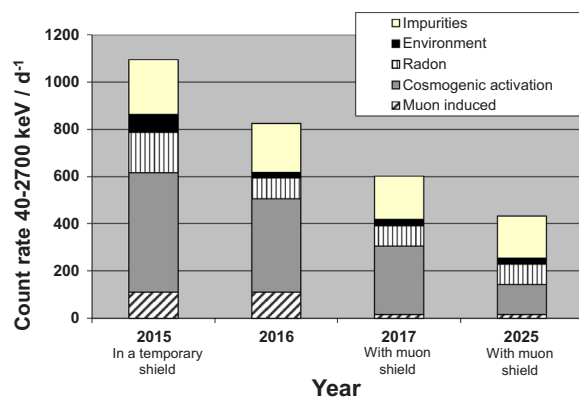
Table 2
The background count rate (in counts per day) of Ge-14 compared to other detectors (with much longer time spent underground) in HADES, measured end of 2016 and beginning of 2017. Note that none of the numbers are obtained using a muon shield and that the uncertainty only reflects counting statistics. The variation over time has not been possible to address yet (for Ge-14) and therefore not included in the uncertainty.

Peak/interval (keV)	Ge-14 Installed 2015 (d^{-1})	Ge-3 60% rel. eff coaxial Installed 1997 (d^{-1})	Ge-7[a] 90% rel. eff. Coaxial (XtRa) Installed 2006 (d^{-1})
46.5	0.45 ± 0.20	1.28 ± 0.25	1.3 ± 0.2
186	< 0.6	< 0.40	1.11 ± 0.19
239	17.5 ± 1.3	0.90 ± 0.20	2.9 ± 0.3
295	0.8 ± 0.3	0.43 ± 0.15	0.99 ± 0.19
352	1.2 ± 0.3	0.72 ± 0.15	2.2 ± 0.2
511	5.3 ± 0.5	2.8 ± 0.2	4.5 ± 0.3
609	2.5 ± 0.3	0.69 ± 0.12	1.6 ± 0.2
911	1.03 ± 0.23	0.45 ± 0.10	0.83 ± 0.12
969	0.45 ± 0.22	< 0.14	0.49 ± 0.10
1020	0.77 ± 0.24	0.19 ± 0.07	0.48 ± 0.09
1332	1.34 ± 0.25	< 0.05	0.60 ± 0.10
1460	0.54 ± 0.21	0.62 ± 0.09	1.13 ± 0.12
1764	1.04 ± 0.20	< 0.07	0.67 ± 0.09
2204	0.55 ± 0.14	< 0.05	0.22 ± 0.06
2614	1.20 ± 0.17	< 0.05	0.78 ± 0.09
100–2000	585 ± 6	267 ± 2	388 ± 2
40–1500	603 ± 6	325 ± 2	410 ± 2
1500–2700	91 ± 3	11 ± 0.4	32 ± 0.5
40–2700	690 ± 6	336 ± 2	442 ± 2
40–2700 divided by Ge-mass in kg	268 ± 3	250 ± 2	245 ± 1

[a] Ge-7 is the upper detector in the sandwich system (Wieslander et al., 2009).

Fig. 4. Estimation of the contribution of different background sources to the background count-rate (40–2700 keV) for Ge-14 immediately after installation, today (2017) and 8 years from now.

contribute significantly to projects where measurements of mono-energetic gamma-ray emitting radionuclides in small samples are required. Examples of such projects are ^{137}Cs and [228]Ra in sea water samples, [241]Am in reference materials and ^{210}Pb in environmental samples.

Acknowledgements

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