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GIOVE, a Shallow Laboratory Ge-Spectrometer with 100 µBq/kg Sensitivity

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Abstract. A new germanium gamma spectrometer called GIOVE (**G**ermanium spectrometer with **I**nner and **O**uter **Ve**to) has been set up at the underground/shallow laboratory (15 m w.e.) of MPI-K. Its double plastic scintillator veto system and neutron moderation interlayer lower the background by more than one order of magnitude compared to the other existing spectrometer at this facility. The integral (40-2700 keV) background rate of about 290 counts $(\text{day kg})^{-1}$ is just a factor 4 to 8 above that of the GeMPI spectrometers operated at LNGS (3800 m w.e.) and thus proves that even under shallow overburden sub mBq/kg sensitivities are achievable. Extended material screening and neutron attenuation studies preceded the final design of the spectrometer. The technical realization of the spectrometer is described in detail with special emphasis on the inner veto system. For its optimisation a simulation model was developed for light collection on small low activity PMT's under various geometrical conditions. Radon suppression is accomplished by employing a gas tight sample container and a nitrogen flushed glove-box system with an airlock. The active volume of the crystal was modelled by absorption scanning measurements and Monte Carlo simulations. The complete shield is implemented in a Geant4 based simulation framework.

Keywords: low background gamma ray spectroscopy, low radioactive background screening, plastic scintillator, cosmic veto, radon suppression, Monte Carlo simulation
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1. INTRODUCTION

GIOVE has been added to the screening facility at the MPI-K to meet the needs for the double beta and dark matter projects Gerda phase II [1] and XENON 1T [2]. It narrows the gap in sensitivity between the GeMPI spectrometers at LNGS [3, 4] and the older generation spectrometers at the Heidelberg underground low level laboratory [5]. A home based spectrometer is always desirable due to the immediate accessibility. The originally more than two orders of magnitude higher background at Heidelberg compared to the Gran Sasso based spectrometers is mainly due to muon-induced events which elude the veto, either due to its inefficiency or because radioisotopes/nuclear isomers are produced with lifetimes exceeding the veto interval. Interactions of muon induced neutrons add a comparable contribution. Examples are ^{71m}Ge, ^{73m}Ge and ^{75m}Ge with peak count rates of 10 to 20 counts per day (cpd) and kg detector crystal mass. Also their half-lives exceed the veto time of typically 20 µsec. For the activity concentration of the primordial chains of ^{238}U and ^{232}Th the GeMPI detector sensitivity ranges down to 10 µBq/kg [3], applying the full sample capacity of about 14 l, whereas at Heidelberg 1mBq/kg sensitivity was so far the standard. In addition to lower background, this difference is also due to larger crystal dimensions in case of the GeMPI's. The GIOVE crystal has a comparable mass of 2.11 kg.

2. BASIC DESIGN

The following design criteria of GIOVE led to these respective approaches:

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a) muon veto efficiency better than 99 % ↔ double veto layer made of plastic scintillators, one at the surface of the shield or close to it and the other near the germanium detector.

b) reduce the neutron induced background by moderation interlayers in the lead shield, but keep the shield as compact as possible↔use plastic scintillators in addition to borated polyethylene (PE) layers as neutron moderators.

c) line backgrounds of primordial radionuclides below 1 cpd↔screening of materials near the crystal at the GeMPI sensitivity level.

d) sensitivity at the range of 100 µBq/kg↔ in addition to low background, provide sample size exceeding 10 l.

e) Rn-equilibrium right from begin of each sample screening↔gas tight sample enclosure and a glove-box system including an air lock.

Concerning the last point, we wanted to improve the capability for radon suppression, not only by applying a nitrogen flushed glove-box as at LNGS, but also with gas tight sample containers. Depending on the texture of the sample and the radon isotope that has to decay or to grow in, the enclosure time may last several hours (^{222}Rn progenies), days (^{220}Rn progenies), or even weeks (^{222}Rn) before the sample is placed into the counting position.

The addition of neutron moderation layers makes the shield as bulky that a direct access of the sample chamber from the outside is no longer possible and therefore sample container are needed anyhow. Other constructional constraints resulted from the screening outcome. For instance, we did not succeed in finding boron compounds suitable as admixture in the PE polymerisation process at acceptable ^{40}K concentration for near detector placement. As a consequence the innermost PE layer had to be shielded by at least 5 cm of lead. Fig.1 shows the resulting shielding arrangement. Along horizontal direction it consists of 5 cm lead, 5 cm plastic-scintillator (outer veto), 5 cm lead, 10 cm borated (3%) polyethylene, 5 cm lead, 2 cm steel frame holding the inner plastic scintillator plates (5 cm), 6 cm high purity copper and finally the sample chamber with 11 mm copper wall thickness. On top, the first lead layer is below the outer veto-plates, followed by an extra layer of borated (10%) PE. At the bottom a further 10% B PE plate completes the moderation layer given by the outer plastic-scintillators at the sides. The sample chamber is lowered into the counting position together with the upper shielding block.

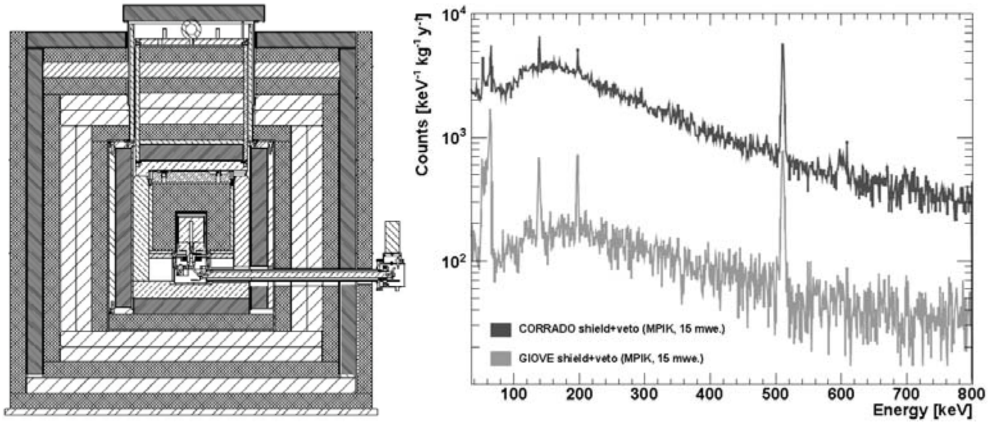

FIGURE 1. (a) Cut drawing of GIOVE. For details see text. (b) Low energy spectra of CORRADO and GIOVE

3. Inner veto

As depicted in Fig. 1 the inner veto encloses the inner shield on all sides. In order to obtain a dense packaging and to keep uncovered spots as small as possible we decided to place the PMT into a cut out recess at one edge of each scintillator plate. Thus, only the cables had to fit through the contact area of the plates. Likewise, the outer much larger veto plates have been equipped by the company Scionix with PMT type "ELT 9900" mounted in a sufficiently deep blind hole. Inspired by the screening results from the XENON100 experiment [6] that the PMT type R8520 provided by Hamamatsu is rather radio-pure, we used for the inner veto a modified version suited for the emission wavelength of plastic scintillator type EJ-200. This type of scintillator was selected by screening measurements with the GeMPI spectrometer performed at LNGS [7].

The special mounting of the small 1"x1" cubic shaped PMT's (R 8520-106 MOD) was guided by extended light collection simulations [8] in order to find the optimal arrangement. The simulation calculation followed the complete traveling path of a light photon from its emission at randomly chosen locations through the scintillator with interactions by absorption and reflection until reaching the PMT surface. As entry parameters, the absorption length of 380 cm and the refraction index of 1.58 were chosen. These parameters were iteratively tuned and the entire simulation validated on various measurements performed with collimated gamma sources across a test plate and later with a muon telescope defining a certain spot of muon interaction. The latter consisted of two 50 mm diameter plastic scintillation detectors operated on coincidence mode. These two spatially confined detectors were located positioned above and below the tested scintillation plate along a common axis. More than 6 configurations including various PMT positions, with one or two PMT, mounted at the corners, on flat opposite sides or on one side were simulated and compared by their light yield and homogeneity of spatial resolution. The best solution was found for corner mounting with the viewing axis pointing to the center of the plate. Since the difference between one and two PMT's (on opposite sides) was not strongly evident, the less costly and less complex solution with just one PMT for each plate was finally chosen. Before the orders were placed, a plastic scintillator plate with the final dimension and PMT mounting was carefully measured with sources and the muon telescope. The measurements agreed well with the calculations of the simulation model [8].

A Pertinax based circuitry with the voltage divider and sockets for the PMT pins has been constructed from selected low activity components. The PMT was glued onto the bottom surface of the cutout recess of the plastic scintillator at a central position by applying optical cement.

The pulse height distribution of the assembled scintillator signals has been measured in a lead shielded compartment to set the threshold for the veto signal at a well-defined position in the minimum between the falling slope of natural gamma-ray spectrum and the high energy Gaussian shape distribution from muons. In all plates this "valley" is strongly pronounced and demonstrates the good light collection of the assembly.

4. Monte Carlo simulation

Beside the capability to reach low detection limits the new gamma spectrometer GIOVE should be able to determine activities with high accuracy below 10%. Reaching such a low uncertainty budget depends on the precise knowledge of the characteristic energy-dependent detector efficiency, and thus on the inactive surface dead layer (DL) and on the active bulk volume (AV) fraction. These not-well known geometrical parameters were fixed according to the approach described in [9], which includes calibrations of the detector with point-like sources at different positions and then compared to the results with Monte-Carlo (MC) simulations of the full detector-source setup, here generated with the Geant4-based toolkit MaGe [10]. In a first step a fine-grained scan with a collimated 5 MBq ^{241}Am source [11] was performed in order to check the diode position inside the vacuum cryostat. Indeed, a small asymmetry has been found and taken into consideration.

In a second step, the average DL was determined by irradiating the detector with a ^{241}Am and ^{133}Ba source on the top and from the side. The ratios of low-energy gamma-rays from both sources were computed and compared with MC simulated ratios with varying dead-layer values. For both the top and the lateral site of the diode the data and the MC converged for an average DL of (1.50+-0.1) mm. This is by ~1 mm thicker than the nominal value. However, considering a storage time of the diode at room temperature for about 8 years the observed DL growth is in agreement with 0.1 mm/yr observed also for other detectors [12].

In a final step, the remaining AV fraction of the detector model was optimized by changing the dimensions of the bore hole dimensions for fixed DL values. The detector was irradiated with long-ranged 1.1 MeV and 1.3 MeV gamma-rays from a ^{60}Co source and the experimental efficiencies were compared with the simulated ones varying the bore hole parameters. The resulting AV fraction is (339+-23) cm^{3,} which corresponds to 86% of the total volume.

The obtained results are very satisfactory. Further improvements can be achieved by intercomparing expanded calibration sources and by introducing variable DL thicknesses as presented in the second publication in [12].

5. Background performance

A 25 day background run under almost final conditions resulted in the integral (40 – 2700 keV) preliminary background rate of (293.5 ± 2.1) (day kg)$^{-1}$. The veto suppression factor corresponds to 95, i.e. the direct count rate is 28008 ± 3.4 (day kg)$^{-1}$. This has to be compared with the older spectrometers at Heidelberg: Dario = 4160 (d kg)$^{-1}$; veto factor 14 and Corrado = 3720 (d kg)$^{-1}$, veto factor 11. The rate of the Gran Sasso based GeMPI's range from 35 to 70 (d kg)$^{-1}$ [7] and thus only 4 to 8 times lower than for GIOVE. In Fig. 2 the improvement in the low energy range against Corrado is clearly demonstrated. In Table 1 preliminary rates of detected background lines are listed. The most prominent lines at low energy are induced by neutrons produced by cosmic muon interactions in the shield. Their rate is comparable or lower as in case of Dario or Corrado (see Fig. 2) which have less than half of the mass of GIOVE. Also the annihilation line has a 6 times lower specific rate than in Corrado. The rates of the cosmogenic radionuclides suggest that we see here the *in situ* production rate. For ^{60}Co the derived activity concentration by simulating a homogeneous distribution in the 230 kg Cu next to the crystal corresponds to about 50 μBq/kg. This is about 20 times lower than the production rate at sea level [13]. Unfortunately the background rate of the ^{40}K line is slightly above the design level.

As a conclusion, the overall achieved background level of GIOVE is unique so far for shallow lab spectrometers, and will allow spectroscopy at the 100 μBq/kg range for primordial and other activity concentrations.

TABLE 1. Preliminary line background counting rates.

Energy [keV]	Isotope	Counting rate [d^{-1}]
53	^{73m}Ge	8 ± 2
65	^{73m}Ge	30 ± 3
139	^{75m}Ge	9 ± 1
198	^{71m}Ge	10 ± 1
352	^{212}Pb	1.3 ± 0.6
511	e^+e^-	18 ± 1
835	^{54}Mn	0.8 ± 0.5
1173	^{60}Co	1.1 ± 0.4
1332	^{60}Co	0.9 ± 0.3
1461	^{40}K	1.6 ± 0.3
2615	^{208}Tl	0.4 ± 0.2

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