THE GIOVE DETECTOR: HIGH SENSITIVITY GERMANIUM SPECTROSCOPY AT SHALLOW DEPTH

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High purity germanium crystals can be manufactured into gamma ray detectors with excellent energy resolution, and are therefore very well-suited to measuring trace amounts of radioactivity in materials. Germanium spectroscopy has become a vital tool to screen materials for radioactivity for use in rare-event particle physics experiments, such as dark matter, neutrinoless double beta decay, and solar neutrino searches.

Experiments using this technology to reach their background reduction targets include the GERDA search for neutrinoless double beta decay and the XENON dark matter project operating at Gran Sasso National Laboratory (LNGS) in Italy [1,2]. Typically these experiments require a very low background from Uranium and Thorium chains, therefore germanium detectors performing material screening must be able to detect concentrations of radio-impurities in construction materials at the μBq/kg level. This is usually achieved by operating screening facilities deep underground where there is substantial overburden to shield from cosmic rays and their secondary particles.

Currently the most sensitive germanium detectors in operation are the GeMPI detectors at LNGS, developed by the Max-Planck-Institut für Kernphysik (MPIK) in Heidelberg, Germany. With approximately a 3800 m of water equivalent (m w.e.) overburden, the GeMPI detectors have been shown to achieve sensitivities in the 10 $\mu Bqkg^{-1}$ range for U and Th isotopes. However it can be inconvenient and time-consuming for experiments to rely on these detectors. Experiments must ship all their materials to LNGS for measurements, which can take up to 100 days of counting time to collect sufficient statistics. The scarceness of adequate material screening facilities makes it difficult to serve the needs of many experiments simultaneously [3].

SUMMARY

The GIOVE detector is a highly sensitive germanium detector used for material screening in rare-event particle physics experiments. Design principles of the shield and the results of preliminary material screening tests are discussed.

For this reason, effort has been put into developing germanium spectrometers that can reach similar sensitivities as the GeMPI detectors, but which operate at shallow depths where there is minimal shielding from cosmic ray particles. The Germanium-Inner-Outer-Veto (GIOVE) detector, located in the low-level laboratory at MPIK, is at the forefront of these efforts. With a mere 15 m w.e. overburden, GIOVE has been shown to achieve sensitivities in the 100 $\mu Bqkg^{-1}$ range from U and Th in typical γ-ray sample screening measurements [3]. The sensitivity levels demonstrated by GIOVE mark a breakthrough in shallow depth germanium spectroscopy, indicating that it may be possible in the near future for such detectors to reach the sensitivities available at deep underground counting facilities.

THE GIOVE SHIELD

Background Sources in GIOVE

The GIOVE shield has been developed to reduce all major sources of background in the detector. There are four major contributions to background in GIOVE: cosmic ray muons, environmental radiation (from the walls and shield materials), neutrons from (α, n) reactions or spontaneous fission of natural U and Th isotopes, and neutrons from cosmic rays - the first two components being the most dominant background sources.

Muons, produced by cosmic rays interacting with the atmosphere, contribute to background in GIOVE by a number of different mechanisms. First, they produce bremsstrahlung photons and electrons when they interact with high density materials such as the lab walls or detector materials. Muons can also produce neutrons by muon capture (dominant at lower muon energies), photonuclear interactions, and spallation (high muon energies); the former being the most dominant source of muonic neutron production in the shallow depth lab. Furthermore, these neutrons can produce photons and electrons which can be captured by germanium atoms. Following capture, the germanium ions may become excited and lines will be seen in the energy spectrum of the detector. The de-excitation lines of ^{71m}Ge, ^{73m}Ge, and ^{75m}Ge due to neutron capture on the crystal are the most problematic neutron-induced background component seen in the detector [3].

Environmental radiation is a second major background source, caused by radio-impurities in the lab surroundings and the shield layers themselves. The shield layers have been carefully selected for high levels of radio-purity, however even trace concentrations of some radioisotopes in the materials can pose a problem as the lines can be seen directly in the detector. Radioactivity in the lab walls, in particular the 2.6 MeV γ-line due to decays of the ^{232}Th daughter nuclide ^{208}Tl, can also be seen directly in the detector.

Other minor sources of neutrons include those from (α, n) reactions and spontaneous fission of natural U and Th isotopes, however this effect is almost negligible at shallow depths. Neutrons from the hadronic component of cosmic rays also contribute a small amount of background, but this effect can largely be shielded by the 5.3 m rock and soil overburden in the lab.

Shield Design Principles

In order to address the various background sources outlined above, the shield has been designed with both active and passive shield components to achieve the necessary background suppression targets. The main purpose of GIOVE is to achieve exceptional sensitivity in the 100 μBqkg^{-1} range at its shallow-depth location. With the 15 m w.e. overburden, the muon flux in the low-level lab is reduced merely by a factor of 2 to 3, the integral flux being approximately 90 m^{-2} s^{-1} [4]. This is a small reduction in comparison to deep underground locations such as LNGS, where the muon flux is reduced by a factor of 10^6. Therefore a cosmic ray muon veto efficiency of $\geq$99% is necessary in order to avoid observation of bremsstrahlung radiation resulting from muons incident on high density materials. This is dealt with by the active component of the shield known as the inner and outer muon veto system, which is described in greater detail below.

The second background suppression target requires attenuation of the neutron-induced background component, mainly delayed de-excitation γ-lines of meta-stable Ge isomers, to the greatest possible extent. The three meta-stable Ge isotopes mentioned previously have lifetimes longer than the muon veto, and therefore this source of background must be addressed by neutron absorption rather than active shielding methods [3]. In order to prevent neutrons from reaching the Ge diode, neutron-absorbing layers make up part of the passive shield. The remainder of the passive shield is dedicated to suppressing radiation from the lab environment and radio-impurities in the shield layers.

Figure 1 depicts the side-view of GIOVE, which consists of four types of shield layers surrounding the Ge diode inside the copper sample chamber. The plastic scintillator layers make up the active component of the shield, known as the inner and outer muon veto system to which GIOVE can attribute its name. Highly sensitive PMTs installed in both scintillator layers detect charged particles passing through the setup, and data collection is stopped for about 300 μs when a muon event is registered. This ensures that the resulting bremsstrahlung photons and electrons are not seen in the detector. Plastic scintillator (type EJ-200) was chosen because of its high photon yield and fast signal response. These characteristics are especially important because it ensures good discrimination between muon signals and environmental gamma events, which minimizes the amount of dead time in the detector due to accidental gamma triggers.

The two-layer structure of the muon veto system is advantageous because muons passing undetected through the outer plates, through the outer edges and corners or depositing energy just below the sensitive threshold, still have a chance of being detected by the inner plates. The result of the inner-outer veto system is a $\geq$99% muon tagging efficiency with an acceptable dead time fraction of $\sim$2%, greatly minimizing much of the muon-induced background component in the setup.

The passive shield layers consist of three 5 cm layers of low-activity lead, three 5cm layers of boron-loaded polyethylene and a 7 cm layer of high purity copper surrounding the sample chamber. The Pb layers are dedicated to suppressing environmental radiation due to lead's high mass density, relatively high radiopurity, and low cost. A total of 15 cm of Pb shielding ensures that the shield is compact enough to keep muonic neutron production in these layers low, but large enough to ensure sufficient attenuation of the 2.6 MeV γ-line emitted by the lab walls. High purity copper surrounds the sample chamber, providing a final layer to suppress any radio-impurities in Pb or B. The Cu layer has been stored with minimal sea-level exposure following manufacture to limit cosmogenic activation.

The remainder of the passive shield consists of three layers of 3-10% boron-loaded polyethylene (PE), which are dedicated to attenuating neutrons produced by muons interacting with the lead or other sources. Polyethylene is a neutron moderator, and therefore slows neutrons down to thermal energies so that they can be absorbed by a neutron capture target. The capture target must be a material with a large thermal neutron capture cross-section, in this case boron was deemed most suitable because of its relatively high radiopurity and a large thermal neutron capture cross section of 767 b [5]. As shown in Fig. 1, the higher boron-loaded polyethylene plates are positioned on the outer layers of the detector due to potential radio-impurities in B. It was found that greater than 3% boron loading in polyethylene provides only a small improvement in neutron absorption [3]. As a result of the neutron attenuating layers, the neutron flux in the detector has been reduced by $\sim$70%. This in combination with the inner-outer muon veto system allows GIOVE to reach integral count rates that are typically obtained at moderately deep underground sites of several 100 m w.e.

Naturally, all materials used to construct the shield were selected to ensure the highest possible levels of radiopurity throughout the setup. The target for line background rates caused by primordial radionuclides is less than 1 d^{-1} in the Ge detector, which has been achieved in the current GIOVE

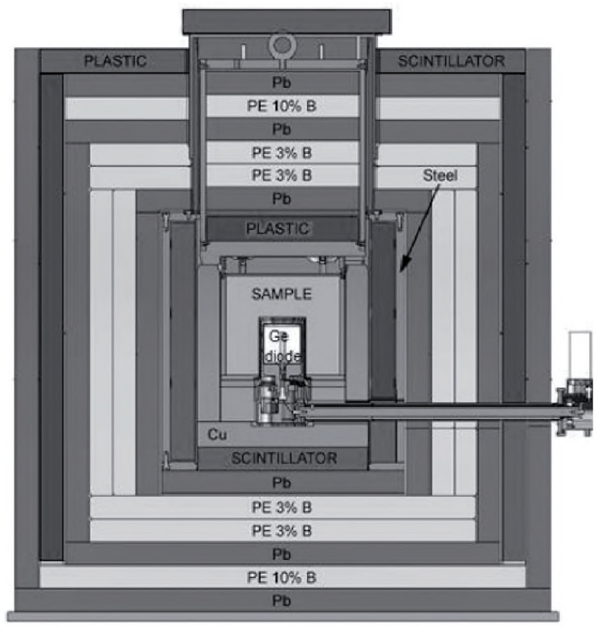

Fig. 1 Cross-section of the GIOVE shield.

set-up. Electron-beam welding and electropolishing has been applied wherever possible during construction to ensure clean surface finishes, and final assembly of the shield took place in the clean room conditions of the low level lab. However despite all efforts to minimize radio-impurities during material selection, it may be possible to improve the sensitivity of the detector if materials with higher radio-purity can be found to replace the current shield layers. This is an area of ongoing investigation. In particular, we are exploring alternatives to borated polyethylene as a neutron capture target and Pb as a shield against environmental radiation due to potential radio-impurities in both materials.

CONCLUDING REMARKS AND FUTURE WORK

GIOVE is a promising development in shallow-depth germanium spectroscopy as it has been shown to attain material screening sensitivities formerly only possible at moderately deep underground sites. The unique shield design of GIOVE, combining passive and active shielding techniques allow the detector to achieve sensitivities in the 100 μBqkg^{-1} range for primordial U and Th traces in γ-ray screening measurements. This is just one order of magnitude greater than what is achieved by the GeMPI detectors at LNGS, where a 3800 m w.e. overburden suppresses the muon flux by a factor of 10^6.

The inner and outer muon veto system makes up the active component of the shield, consisting of two plastic scintillator plates positioned on the inner and outer layers of the shield. At its shallow depth location, GIOVE requires a muon veto efficiency of $\geq$99%, which has been achieved in part due to the unique two-layer structure of the scintillator plates.

The passive shield layers include 15 cm Pb and 7 cm Cu of low intrinsic radioactivity, which are dedicated to shielding from radiation in the lab environment and from radio-impurities in the shield layers. Three 5 cm layers of borated polyethylene serve as a neutron moderator (PE) and capture target (B). These neutron attenuating layers have been shown to reduce the neutron flux in the detector by approximately 70%.

In order to further optimize the shield design, alternative shield materials are currently being investigated to improve the radio-purity and neutron attenuating properties of the current GIOVE setup. In particular, materials with high mass density and radio-purity are being considered as alternatives to Pb, and alternate neutron moderators and absorbers are being explored to further minimize radio-impurities and increase neutron absorption. In addition to new materials, new configurations of the existing shield layers are also being tested in simulations. Preliminary results suggest that it may be possible to further improve the sensitivity of GIOVE in the future.

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