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Germanium detector test-stands at the Max Planck Institute for Physics and alpha interactions on passivated surfaces

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Abstract. The GeDet group at the Max Planck Institute for Physics in Munich, Germany, operates a number of test stands in order to conduct research on novel germanium detectors. The test stands are of a unique design and construction that provide the ability to probe the properties of new detector types. The GALATEA test stand was especially designed for surface scans, specifically α -induced surface events, a problem faced in low background experiments due to unavoidable surface contamination of detectors. A special 19-fold segmented coaxial prototype detector has already been investigated inside GALATEA with an α -source. A top surface scan provided insight into the physics underneath the passivation layer. Detector segmentation provides a direct path towards background identification and characterisation. With this in mind, a 4-fold segmentation scheme was implemented on a broad-energy point-contact detector and is being investigated inside the groups K1 test stand. A cryogenic test-stand where detectors can be submerged directly in liquid nitrogen or argon is also available. The goal is to establish segmentation as a viable option to reduce background in future large scale experiments.

1. Introduction

The Standard Model of particle physics has withstood the test of time, even though many high precision experiments have tried to find deviations from its predictions over the last two decades. But despite its success, the theory does have a number of shortcomings that require at least some extensions to the current framework. Inconsistency with general relativity, the strong CP problem, the evidence for dark matter (DM) and neutrino oscillations all hint at physics beyond the standard model.

The germanium detector group (GeDet) at the Max Planck Institute for Physics (MPP) develops germanium detectors suitable to search for some of this new physics, so far specifically focusing on neutrinoless double beta decay ($0\nu\beta\beta$). The observation of $0\nu\beta\beta$ would demonstrate Lepton Number Violation and establish the neutrino as a Majorana particle. The isotope ⁷⁶Ge decays via standard double beta $(2\nu\beta\beta)$ decay and is, thus, a candidate for $0\nu\beta\beta$. Detectors made of material enriched in ⁷⁶Ge are both source and detector.

Germanium detectors are also used for direct DM searches. Weakly interacting massive particles could interact in the germanium crystal, depending on their mass and the cross section. Neither DM or $0\nu\beta\beta$ have so far been directly observed. However, limits have been established in both cases. Although the requirements on the germanium detectors are quite different for the two searches, a goal is to develop a detector that could be used for both searches in a future large scale experiment.

For any such future experiment, the reduction and identification of background events is of utmost importance. Past experience [1] shows that in a well shielded detector the remaining background is caused by radioactivity in materials close to the detectors. The use of well-developed analysis tools and especially designed detectors is essential to suppress this background. Detector segmentation is a special feature used by the GeDet group as a method to identify background and understand detector physics. Detectors are developed in cooperation with Canberra France and are investigated in test-stands which are developed and operated at the MPP in Munich.

2. GALATEA test stand

The principle of the GALATEA [2] test stand is to be able to perform complete scans of the top and side of a germanium detector with no material between source and detector. This allows investigations with minimally penetrating alpha and beta particles. The stages to facilitate the scans are necessarily inside the same vacuum volume as the detector. The preamplifiers are also inside this volume. This in order to keep cable length, and therefore input capacitances to the preamplifiers, to a minimum. A schematic of the GALATEA setup is shown in figure 2.



Figure 1. Principle of the GALATEA test stand.



Figure 2. Schematic of the GALATEA setup [2].

Germanium detectors only function at cryogenic temperatures, therefore, the detector holder is connected to a cold finger which itself is connected to a tank filled with liquid nitrogen, also housed within the vacuum chamber. Two linear stages holding tungsten collimators are attached to a rotation stage. One linear stage moves its source radially across the top, the other moves up and down the side. Together with the rotation stage, the complete side and top of the detector can be scanned

3. SuperSiegfried test detector

SuperSiegfried (SuSie) is a cylindrical, true coaxial, n-type high purity germanium (HPGe) detector, which is 18 + 1 fold segmented. This means that the mantle is segmented 3-fold in z and 6-fold in ϕ plus a 19th segment on top which is unsegmented in ϕ , see figure 3. Each segment provides event by event energy (i.e. spectroscopy data) and pulse data. This data can then be crossed check with simulation to help build up a picture of the physics inside the detector. The segments are only partially metallised with each segment read out separately via a kapton cable with snap contacts [3]. The 19th segment is only metallised in a small sector, where the contact is placed.



Figure 3. SuSie segmentation scheme [4].



Figure 4. SuSie detector with kapton cable [2] on transport ring.

Detectors with the 18-fold segmentation scheme were used to study the reduction of photon induced background in $0\nu\beta\beta$ experiments. The 5mm thick 19^{th} top segment was designed especially to study surface channel effects and charge trapping underneath the passivation layer on this top plate.

4. Top plate alpha scan

Alpha particles have little penetration power and are therefore used to study events close to the detector surface. An ²⁴¹Am source producing \approx 5.6 MeV alpha particles was used to irradiate the passivated top surface of the SuSie detector. These alpha particles have a nominal penetration depth of \approx 30µm in germanium and therefore are contained in the 19th segment. This can be seen clearly in the energy spectrum in figure 5 which shows the spectrum of a measurement at the marked position. The broad bump around 2.5 MeV is due to the alphas and can only be seen in the core (blue) and segment 19 (red) spectrum. The sum of the spectra recorded for segments 1 to 18 (green) show no alpha bump.



Figure 5. Energy spectra of the core (blue), segment 19 (red) and segments 1 to 18 (green) with a collimated ²⁴¹Am source aiming down at the top 19^{th} segment at position "X". The difference in the position of the alpha deposition energy peak between the core and 19^{th} segment is clearly visible. The holes and electrons are subject to different trapping effects in this region.

The detector has a dead layer on top consisting of the passivation layer and the area of low field underneath. In principle, only the energy deposited underneath that layer is recorded. In practice things are more complicated. The average energy deposited in the detector i.e. the bump position, is taken as the energy deposited underneath an "effective" dead layer. In the core, a shift of the average energy deposition to ~2.5 MeV from the initial ~5.6 MeV alpha particles is observed. However, figure 5 also shows that the peak position of the bump is different for the 19th segment, demonstrating that the classical picture of well-defined layers is oversimplified. The energy recorded in the core is dominated by electron drift while that of the segments by hole drift. The two different charge carriers are subject to different trapping effects, which is a typical feature of events close to the surface. This effect can also be seen by comparing the recorded pulses from the core and segment 19. Figure 6 shows a smaller pulse in segment 19 than in the core which is indicative of a more incomplete charge collection due to hole trapping than due to electron trapping. The pulse in segment 19 also has a longer rise time in comparison with the core pulse. The reduced speed of the holes could be due to a very low field gradient underneath the top surface at higher radii [5].



Figure 6. Example pulses from the core and segment 19 from the data sample used for figure 5. The comparatively smaller pulse seen in segment 19 is indicative of hole trapping.

A scan of the top surface was done with the collimated ²⁴¹Am source positioned at varying radii. The energy spectra of the core and segment 19 readouts for varying radii are shown in figure 7. The average alpha peak energies are clearly dependent on the radial position. The energy seen in the core lessens the further away from the core the source is positioned, meaning that the larger the radii the larger the probability of electrons being trapped. For holes the opposite is true. This radial effect is due to the path length of the charges inside the crystal and the field configuration. At smaller radii the holes have a longer path to the electrode and are more effectively trapped than the electrons and therefore the segment energy is less than the core. However, as the radii increases the electrons become trapped more effectively and the segment energy becomes more than the core. The energy spectra in figure 5 show a situation where the energy recorded in the core is higher than in segment 19 and, therefore, that at this position the holes are being trapped more effectively than the electrons.



Figure 7. Energy spectra for varying radii with respect to the core position for the core readout (left) and the segment 19 readout (right). The average alpha peak energies are clearly dependent on the radial position.

The different charge trapping effects can be interpreted as effective dead layers for holes and electrons. See figure 8. At small radii, i.e close to the core, no alpha bump can be seen. The effective dead layers are thus more than 30μ m, the penetration depth of the alphas, thick. Earlier investigations with photons [5] show dead layers of the order of millimetres. The detailed studies in the region of the tenth of micron layer thicknesses were only possible with alphas as probing particles.



Figure 8. Effective dead-layer thickness for the core (green) and segment 19 (red) as a function of the radial position of the alpha source. The different charge trapping effects result in different effective dead layers for the holes and electrons.

An azimuthal scan was also carried out, i.e. at fixed radius with varying ϕ . The results demonstrated that the metallisation (as marked in figure 5) has a significant effect on the charge collection efficiency. In both the core and segment 19 spectra, the recorded energies shifted to larger energies as the source was moved closer to the metallisation. As the charge collection efficiency increases closer to the metallisation, it suggests increased electric field homogeneity in that region. This was observed earlier [5].

The use of alphas with the SuSie detector is a good way of studying detector surface effects in detail. The difference between the energy seen in the core and the segment provides a background rejection marker without the good bandwith needed for pulse shape analysis. In the future, a complete

characterisation of SuSie using alpha, beta and gamma sources will be carried out. GALATEA will also be used to characterise other detector types and further probe germanium detector properties.

5. K1 test stand and a first segmented n-type BeGe detector

The K1 test stand as depicted in figure 9 was built by Canberra France and modified by GeDet in Munich. It is used to study the detector response to photons and neutrons. The set up consists of a conventional cryostat containing one detector cooled via a cooling finger submerged in a LN2 dewar. Two copper "ears" on either side of the cryostat house the preamplifiers.



Figure 9. K1 test stand in Munich.



Figure 10. Conceptual design of the segmented BeGe.

In May 2014, the GeDet group received a segmented broad-energy (BeGe) point-contact n-type HPGe detector built by Canberra France. The segmentation scheme, as shown in figure 10, was designed as a compromise between having as few channels and as much capability of position reconstruction as possible. The segmentation is able to break ϕ degeneracy and pulse drift time degeneracy, thus allowing position reconstruction in 3D.

A top scan of the segmented BeGe in the K1 test stand has already been carried out with a ¹³³Ba source. Figure 11 shows averaged pulses for the 81keV line at varying radii of the source position. The averaging helps to demonstrate the features of these low amplitude pulses by eliminating the influence of electronic noise. At 81keV, the minimal variation of the depth of the interaction justifies averaging. The core signals do not change much for varying radii. The signal in the segment collecting the charge, segment 3, gets shorter as the radius decreases. The mantle and the two segments not collecting the charge show clear negative mirror pulses corresponding to the long drift of the electrons to the other end of the cylindrical detector. The mirror pulse in the mantle gets shorter as the radius decreases. However, the amplitude is constant. In the two non-collecting segments, the situation is more involved. At low radii, the amplitude is larger due to the proximity of the segments. However, these mirror pulses are shorter than for larger radii and they start later with respect to the core pulse.





Figure 11. Averaged pulses for the 81keV line of a ¹³³Ba top scan over varying radii of segment 3 of the segmented BeGe. The radial dependence of the pulse length can be seen in the signal in segment 3 and the mirror pulses in segments 1, 2 and mantle. The core signals change very little.

6. Gerdalinchen II

Gerdalinchen II is a cryogenic test facility designed to mimic the conditions in the GERDA experiment. The setup, as shown in figure 12, can hold up to 3 detectors in their holders in a string and submerge them directly into cryogenic liquid. The original goal was to verify that large segmented n-type crystals can be operated in cryogenic liquid over long periods of time.



Figure 12. Gerdalinchen II setup.



Figure 13. Results of a 140 day test of energy resolution stability of a detector in liquid nitrogen [6].

The results of a test as shown in figure 13 and detailed in [6] have shown that the energy resolution of bare germanium crystals operated over a long period of time is indeed stable. It also verified that the kapton cable snap contacts, as used also for SuSie, are suitable for usage in liquid nitrogen. The facility is available for further tests.

7. Summary and outlook

The GeDet group is concentrating on segmented detectors in order to better understand detector responses, surface effects, charge trapping and charge mobility. These results are used to derive implications for a future ton scale experiment and to establish segmentation as a viable option to reduce background in such an experiment. The group continues to design, build and operate test stands with which to carry out these studies. Alongside this, more general R&D for low background experiments is being carried out in the form of background rejection techniques, and pulse shape simulation and analysis.

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