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Position sensitivity of the proposed segmented germanium detectors for the DESPEC project

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ABSTRACT

The DESPEC HPGe array is a part of the NuSTAR project at FAIR, Germany. It is aimed at the spectroscopy of the stopped decaying exotic nuclei. Segmented γ-ray tracking detectors are proposed for this array in order to maximize detection efficiency and background suppression when searching for very rare events. Two types of detector modules—stacks of three 16-fold segmented planar crystals and 12- and 16-fold segmented clover detectors—have been investigated and compared from the point of view of the achievable position resolution using pulse shape analysis (PSA). To this end, detector signals from realistic γ-ray interactions have been calculated. These signals were treated by PSA in order to reconstruct the photon interaction locations. Comparing the initial interaction locations to the reconstructed ones, it was found that the double-sided strip planar detector yielded position reconstruction errors at least a factor 2 lower than the other detectors considered.

1. Germanium detectors for DESPEC

The DESPEC HPGe array is a part of the NuSTAR project at FAIR, Germany [1]. It is aimed at the spectroscopy of the decaying exotic nuclei stopped in the micro-strip silicon implantation detector, AIDA. Segmented germanium γ-ray tracking detectors are proposed for this array. In such detectors, the features of the output signal shapes generated during the charge collection time in the collecting segment (net charge signal) and in neighboring segments (transient signals) carry the information on the location of a γ-ray interaction within the bulk of the crystal. In this work, the achievable position resolutions of various proposed detectors are compared using pulse shape analysis (PSA). To this end, detector signals from realistic γ-ray interactions have been calculated. These signal were compared to a basis signal database by PSA in order to reconstruct the photon interaction locations. The comparison of the original interaction locations to the PSA-reconstructed ones yields a measure of position resolution for possible interaction location and energy combinations. This technique and the methods used are described in Ref. [2]. In the final array, the reconstructed interactions will be passed to γ-ray tracking and imaging algorithms. As the DESPEC array will be used to detect decay radiation from extremely rare isotopes or isomers, γ-ray tracking and imaging are essential for several reasons:

Compton background suppression: Energies of photons interacting in more than one crystals can be added back, while Compton-escape events can be identified and suppressed with no anti-coincidence shields required.

Recoil identification: In case of relatively long-lived nuclei or isomers, it is essential to correlate the γ-rays with an earlier implantation location in the silicon detector.

Background radiation suppression: Using γ-ray imaging, background photons and those originating in other parts of the experiment and in the environment, can be rejected.

These goals set a high requirement for the position sensitivity of the detectors, as well as for the resolving power of the multiple γ-ray interactions, necessitating the use of highly segmented germanium detectors, where PSA can be used to obtain a position resolution of a few mm [3,4].

2. Planar detectors

In order to efficiently utilize the space around the rectangular implantation detector, two types of detector modules have been proposed. The first scheme is a novel design featuring 16 or 24 modules of three $72\times72\times20$ mm planar crystal placed in a single cryostat. The triple modules would be placed around the implantation detector in two rings of 8 or 12. A number of stand-alone planar germanium detectors exist [5–7]. In order to achieve position sensitivity in a planar crystal, both sides may be segmented into orthogonal strips or one side may be pixelated. Detectors of both types with an equal number of output channels have been considered—a strip detector with eight strips on each face (resulting in 64 physically defined

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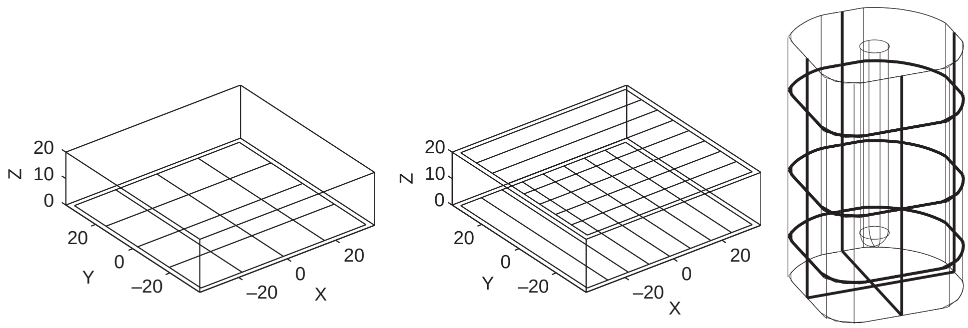

Fig. 1. The proposed crystal geometries. The pixel detector is shown on the left and the strip detector in the middle. A 16-fold segmented clover crystal is shown on the right. A single crystal from each array is shown—the three planar and the four coaxial crystals in a module are assumed to be identical.

voxels, 8.5×8.5 mm each) and a 4×4 pixel detector (resulting in 16 voxels, 17×17 mm). A 2-mm guard ring has been assumed in both cases. The geometries are shown on the left and middle of Fig. 1.

Simulated γ-ray interactions were used to test the position sensitivity of these two detectors types. The small size of the voxels of the strip detector generally greatly aids in position reconstruction. The small width of the strips results in transient signals that are larger than those in the pixel detector since adjacent strips are on average closer to the interaction point; and in fact, the transient signals from the next-to-adjacent strips provide transient pulses of useful amplitude. Nevertheless, some drawbacks for the strip detector also exist. Since the 64 voxels are readout through only 16 channels, for some events with 3 or more interaction points in a crystal, the correct voxels cannot be identified [2] resulting in position errors that are larger than the voxel size. Furthermore the sensitivity to the prompt flash is increased due to the larger size of the contacts compared to the pixel detector. Another advantage of the pixel detector is that only one side of the crystal needs to be readout (the non-segmented contact may or may not be used) possibly simplifying the design of the compact cryostat.

3. Clover segmentations

The second proposed alternative consists of six clover detector modules where each module contains four coaxial crystals 90 mm in length and initially 60 mm in diameter. The sides are cut flat for an efficient packing, resulting in a maximum width of 53.5 mm. These crystals are similar to those of the EXOGAM [8] and TIGRESS [9] detectors, however, here 12- and 16-fold segmentations are considered. Unlike the existing clover detectors, no tapering of the crystals is required on the front end. A schematic of a detector crystal is shown on the right in Fig. 1. In contrast to the two natural segmentations of a planar detector, each with 16 segments, a coaxial detector for a clover module may be segmented in a variety of ways. Typically, a crystal is segmented into four angular parts (see Fig. 1) in such a way that the segmentation lines cross at right angles on the front face and run on the flat sides of the cylinder. Of the currently existing detectors, the TIGRESS array has an additional segmentation in the depth of the detector, where there is a front and back segment, 20 and 70 mm deep, respectively. While such segmentation is sufficient for Doppler correction, a finer segmentation will be required in the DESPEC array. A number of triple and quadruple depth segmentations have been considered from the point of view of the attainable position resolution in all segments. The segmentations that have been considered are summarized in Table 1. The notation 25–25–40 represents a segmentation where there is triple depth segmentation with segment depths of 25, 25 and 40 mm from front to back of the crystal.[1]

Table 1
Segmentations of clover detectors tested in this work and the obtained position resolutions for single randomly distributed 600 keV interactions.

Number of Segments	Depth Segmentation (mm)	Mean position Sensitivity (mm)
12	25–25–40	3.43
12	20–40–30	2.71
16	20–25–25–20	2.08
16	15–25–30–20	2.09
16	15–25–25–25	2.19

In order to efficiently visualize the differences between the segmentations, a set of 16 000 random interaction locations were reconstructed by PSA for each clover detector. While this approach is useful to compare the position sensitivities of the detectors, one must keep in mind that in real events the distribution of the interaction locations between segments as well as the frequency of multiple interactions in the same segment will also play a role. The mean position errors are summarized in Table 1. Since here the energies of all interactions were set to 600 keV, the resolutions obtained are somewhat better than would be expected from the more common lower-energy interactions due to the difference in the signal-to-noise ratio. The three-dimensional position resolutions can be seen in Fig. 2 for the worst case and for one of the best cases. Considering the position reconstruction errors for the 25–25–40 segmentation shown on the left, two problematic areas are immediately apparent. The resolution is rather poor in all coordinates in the front segments. In the coaxial part of the crystal the resolution is considerably better with the exception of the depth coordinate (z) in the back segment. This can be understood considering that the information on the depth of an interaction is primarily given by the transient signals in segments in front of and behind the target segment. For the back segment there is only one such signal available, and the sensitivity is greatly reduced, especially when the interaction is far away from the forward segment. Expanding the middle segments at the expense of the front and back segments somewhat improves the situation (see the 20–40–30 detector in Table 1). A further improvement can be achieved using a quadruple depth segmentation. In this case it is possible to use small segments in the front and back parts of the detector while maintaining a reasonably small segment size of the middle segments. Table 1 shows three such segmentations. The overall position resolutions are significantly better for these

[1] Note that the sizes of the segment volumes may differ from the segmentation of the surface due to the curvature of the electric field lines, particularly in the front part of the detector.