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Gamma-ray imaging with a coaxial HPGe detector

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Abstract

We report on the first experimental demonstration of Compton imaging of gamma-rays with a single coaxial high-purity germanium (HPGe) detector. This imaging capability is realized by two-dimensional segmentation of the outside contact in combination with digital pulse-shape analysis, which enables to image gamma-rays in 4π without employing a collimator. We are able to demonstrate the ability to image the 662 keV gamma-ray from a ^{137}Cs source with preliminary event selection, with an angular resolution of 5° and a relative efficiency of 0.3%. This efficiency expresses the fraction of gamma-rays that can be imaged, out of the total gamma-ray flux which is emitted into the solid angle of the detector. In addition to the 4π imaging capability, such a system is characterized by its excellent energy resolution and can be implemented in any size possible for Ge detectors to achieve high efficiency.

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1. Introduction

The ability to image and characterize known as well as unknown gamma-ray sources is finding a variety of applications in biomedical research and nuclear medicine, astrophysics, national security, such as nuclear nonproliferation, stockpile stewardship, nuclear waste monitoring and, most recently, nuclear counterterrorism. While gamma-ray imaging is an established tool in nuclear medicine or astrophysics, only recently has the impact of gamma-ray imaging for nuclear security applications been recognized. Here, the goal is to provide improved capabilities to detect, localize, and characterize nuclear materials. One of the outstanding challenges in homeland security is the

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detection and identification of nuclear threats in the midst of a sea of non-threat objects, which consists of legitimate radioactive objects commonly found in commerce and environment. In addition to the detection of nuclear materials which can be achieved by simple counting instruments, it is crucial to obtain as much information from this material as possible to mitigate the primarily nuisance alarms. This can be achieved by identifying the radioisotope via its characteristic gamma-ray decay, and by imaging it, e.g. by measuring the location and the shape of sources. In addition to the ability to localize and image gamma-ray sources, gamma-ray imaging can potentially increase the sensitivity in finding such sources, particularly in complex and changing backgrounds, due to the ability to improve signal-to-background. In particular, collimator-less Compton imaging systems enable to measure signals and background simultaneously, and therefore potentially provide the biggest gain in signal-to-background. Gamma-ray imagers based on position-sensitive semiconductor detectors such as high-purity Ge (HPGe) provide excellent imaging and spectroscopic characteristics and therefore fulfill both important requirements in national security.

Well-established means of imaging consist of a mechanical and passive collimator such as parallel-hole or pinhole systems in front of a position-sensitive gamma-ray detectors [1]. These systems suffer from the trade-off between efficiency and resolution. More advanced collimator- or aperture-based instruments consist of modulated apertures either in space-coded aperture or time-rotation modulation aperture, which have limited capabilities in high-activity and complex backgrounds. The ideal gamma-ray imager, a gamma-ray lens, is very difficult to realize due to the small angle of total reflection. Multilayer, diffractive optics system that have been built are able to focus gamma-rays up to 160 keV; however, these systems are characterized by a large focal length and a small field of view [2]. An alternate way to image gamma-rays without the use of a collimator is Compton imaging. Recent advances in the two-dimensional segmentation of semiconductor detectors along with signal processing allow us now to build efficient and high-resolution Compton imaging systems.

We report on one possible implementation, which consists of a two-dimensionally segmented, coaxial HPGe detector. Other approaches consist of planar configurations made of a variety of materials such as Si, Ge, or CdZnTe, either in double-sided strip or pixelated geometry [3–5]. The advantage of a coaxial HPGe detector is the large volume of a single detector that can be manufactured, which translates into high efficiencies for gamma-ray energies up to several MeV. In addition, intrinsic properties of high-purity Ge enable excellent energy resolution and signal–noise ratios. The atomic number of $Z = 32$ represents an acceptable compromise between efficiency, which requires high-Z, and Compton imaging sensitivity which requires low Z. The latter is due to the fact that for Compton imaging at least one Compton scatter process is required before the gamma-ray is absorbed via the photoelectric effect, and the two first interactions have to be sufficiently far apart that one is able to separate them and is able to deduce the scattering angle with finite accuracy.

In the following, we will briefly introduce the concept of Compton imaging in Ge detectors. In Section 3, we will introduce the 40-fold segmented coaxial HPGe detector, which was built by ORTEC and used for our experiments. In Section 4 we discuss pulse-shape analysis procedures to deduce three-dimensional positions for individual gamma-ray interactions. Section 5 finally illustrates measurements, which demonstrate Compton imaging in such a detector and discusses the impact of improvements in the pulse-shape analysis of multiple interactions, which occur close to each other.

2. Compton imaging with a HPGe detector

As first published by Todd for nuclear medicine [6] and Schönfelder for astrophysics [7], the concept of Compton imaging relies on the Compton scattering process, and the relationship between the scattering angle θ, the energy of the incident gamma-ray E_γ, and the energy of the first