NE 204: Advanced Concepts in Radiation Detection and Measurement

Experiment 8: Gamma-Ray Imaging with HPGe Strip Detectors

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Purpose

A double-sided strip detector (DSSD) made of high-purity germanium (HPGe) is used to study various different gamma-ray imaging concepts. The excellent energy resolution and 3D position sensitivity of the DSSD enables a systematic study of different imaging modalities. Collimator-based modalities; e.g. pinhole, parallel-hole, and coded-aperture imaging, can be investigated, as well as collimator-less modalities such as Compton imaging. Each modality can be evaluated for different source energies and configurations. Tomographic techniques can also be explored.

Approach

A high-resolution, 3D position sensitive HPGe DSSD system provides the opportunity to systematically compare a range of gamma-ray imaging modalities. Prerequisite is the ability to determine the number, energy, 3D position, and sequential ordering of individual gamma-ray interactions within the system. As such, this experiment is intended as an extension of Experiment 5 (position determination in HPGe DSSDs). Simple *event reconstruction* and *interaction sequencing* discussed in Experiment 5 must be implemented to explore the various imaging methods herein. Point sources of ^{137}Cs, ^{241}Am, ^{133}Ba, and ^{60}Co can be used to measure the point spread function (PSF) of the imager and evaluate imaging performance via metrics such as angular (or spatial) resolution, signal-to-noise ratio (SNR), constrast-to-noise ratio (CNR), and imaging efficiency/sensitivity.

Required Objectives for All Modalities

You may choose to evaluate one or multiple modalities depending on time and equipment constraints. Regardless of modality, the imaging performance should be quantified in terms of:

- Angular (or spatial) image resolution
- Contrast-to-noise ratio (CNR)
- Image sensitivity

Other metrics, such as uniformity of the imaging response, are also of interest. Depending on the modality, these analyses can be carried out at multiple energies to compare the imaging performance over relevant energy ranges. Comparitive analyses between modalities are of particular interest, if time permits.

Optional Objectives for All Modalities

Other imaging components you may wish to explore might include:

- **Source Detection** - The ability to detect a source based on simple counting, spectroscopy, and imaging can be compared. Imaging becomes an interesting component of the detection problem in high-background scenarios. For example, a ^{60}Co source can be placed near the DSSD to induce a significant gamma-ray background. The ability to detect other gamma-ray sources (e.g. ^{133}Ba or ^{241}Am) can be studied for simple counting, energy-specific counting (spectroscopic analysis), and imaging.
- **Tomographic Techniques** - A rotating source stage can be set up to investigate tomographic imaging techniques based on any of the listed imaging modalities and/or, in principle, radiography.
- **Extended Sources** - Most of the gamma-ray sources available for this lab are simple point sources; however, these can be combined with various motorized stages to produce more complex gamma-ray source distributions. For example, a rotating stage can be used in conjunction with a point source mounted on a radial extension to simulate a circular extended (i.e. non-point) source.

Imaging Modalities

Several gamma-ray imaging modalities can be investigated with the DSSD detector along with (in some cases) various collimators.

Pinhole Imaging

Pinhole aperture imaging represents the simplest means of image formation, defining a line-of-response from the interaction location in the imager (DSSD) and the pinhole aperture. Images can be formed by back-projecting the lines-of-response on to some imaging surface (or volume) on an event-by-event basis. In principle, the sensitivity and image resolution depend to a large degree on the aperture dimension, though other considerations such as the position resolution in the DSSD also affect the imaging performance. There are several optional objectives in addition to the required objectives detailed above:

- Compare the sensitivity and spatial resolution of the imager for different source-pinhole-detector configurations (i.e. magnifications).
- Compare the measured spatial resolution and image sensitivity with theoretical estimates for a given source-pinhole-detector configuration.
- Compare pinhole imaging with and without depth-of-interaction information from the DSSD.
- Evaluate the dependence of spatial resolution on the position resolution of the DSSD.

Parallel-Hole Collimated Imaging

Parallel-hole (and other multi-aperture) imaging modalities are widely used in nuclear medicine. A parallel-hole collimator consists of parallel holes of various shape separated by attenuating septa designed to prevent photons from crossing from one line-of-response (defined by the parallel holes) to another. Image sensitivity and resolution scales differently than for the pinhole aperture case for various source distances. Addititional optional objectives include:

- Compare the measure spatial resolution and image sensitivity with those predicted from theory for a given source-collimator-detector setup.
- Evaluate the impact of DSSD position resolution on the imaging performance.

Coded-Aperture Imaging

A coded-aperture is often described as an extension of a pinhole imager to provide multiple, unique projection patterns for each potential source location in the field of view. The theoretical sensitivity is improved from the pinhole case due to the increased amount of unattenuated gamma-ray flux incident on the detector, though more complex image reconstruction techniques must be used to recover the image. Both uniformly redundant array (URA) and random-type masks are available for use.

Required

- Develop an image reconstruction technique to deconvolve the multi-aperture response and recover the 2D gamma-ray source distribution. For example, consider an approach based on cross-correlation with the mask pattern or back-projection.

Optional

- Compare image sensitivity and spatial resolution for different source-mask-detector configurations.
- Evaluate the effect of DSSD position resolution on imaging performance.

Compton Imaging

Compton imaging, as the name implies, is based on the kinematics of Compton scattering. This approach requires full gamma-ray *event reconstruction*; i.e. the determination of the interaction positions and energies depositied in gamma-ray events consisting of multiple gamma-ray interactions. In addition, the sequence of the interactions must be known in order to select the correct scatter direction and opening angle of the Compton cone. In principle, Compton imaging in HPGe DSSDs is capable of omni-directional (4π) imaging with high sensitivity at energies above 500 keV (collimator-based modalities become less efficient at higher gamma-ray energies). Like coded-aperture imaging, Compton imaging requires the use of image reconstruction techniques.

Required

- Develop a Compton image reconstruction technique e.g. a cone a cone back-projection method. Use this algorithm to create images of gamma-ray point sources at various energies.

Optional

- Evaluate the impact of position and energy resolution of the DSSD on the imaging performance.
- Evaluate the effect of gamma-ray event sequencing on the imaging performance.

Addendum - Discussion of Image Evaluation Metrics

- **Sensitivity/Efficiency** reflects the capability to detect features in the image. It is important to keep in mind the distinction between **dection efficiency** (the ability to detect and potentially identify an isotope based on count-rate/spectroscopy measurements) and **imaging efficiency** or **sensitivity** (a measure of the amount of input signal required in order to detect/localize a specific feature in the image). Imaging efficiency expresses the fraction of detected events that end up at the "correct" location in the resultant image, where the "correct" location implies that the location in the image can be associated with the location of the original object in the imaging space. More rigorously, **sensitivity** represents the *true-positive fraction*, $\frac{TP}{TP+FN}$, which can relate to imaging either in terms of binary classification (whether a source is identified to be present in the image) or, for quantitative imaging techniques, the fraction of true signal (e.g. activity) that is recovered in the image. Keep these definitions in mind when formulating an experimental procedure to evaluate sensitivity.

- **Image Resolution** reflects the ability to measure shapes of objects and differentiate between separate objects in the image. Image resolution is often measured in terms of point, line, or edge-spread functions (representing the imagers response to a point, line, or edge input). The blurring of the image can be described by convolution of the input image and these response functions (typically the PSF). A canonical way to measure image resolution is to experimentally determine the minimum spatial distance at which two point sources can be resolved. The Rayleigh criterion is commonly used to define the successful resolution of two points.

- **Image Contrast** reflects the ability to measure relative differences in intensities of features measured in the image. Contrast is often quantitatively expressed in terms of the *contrast-to-noise ratio*: $CNR = \frac{S_a - S_b}{\sigma}$ where S_a and S_b represent the signal intensity of two regions of interest in the image, and σ represents the RMS of the image noise. Note that the CNR is related to the signal-to-noise ratio (SNR) of the image, which compares the mean image intensity value to the RMS of the image noise.