Spectral Analysis for the High Efficiency Multimode Imager

Michelle Galloway, Andreas Zoglauer, Mark Amman, Steven E. Boggs, and Paul N. Luke

***Abstract*–The High Efficiency Multimode Imager, HEMI, is a combined Compton and coded aperture imager designed to detect, localize, and characterize gamma-ray sources within the energy range from tens of keV to a few MeV. HEMI consists of cubic centimeter CdZnTe detectors with good spectral resolution (~2% at 662 keV) that allow for the separation and identification of discrete gamma-ray energies. This paper describes the methods being developed to analyze spectra and identify radioisotopes using measurements from a 24-detector system, a 42-detector planar array, and simulations from a large-scale HEMI system.**

I. Introduction

THE High Efficiency Multimode Imager, HEMI [1], concept arose from a need for an instrument to detect and characterize radiological and nuclear materials. The HEMI detector utilizes both coded aperture and Compton scatter imaging techniques and therefore is ideally suited for the detection and localization of radioisotopes whose gamma-ray emissions are within the energy range of tens of keV to a few MeV. Fig. 1 shows one possible configuration for a prototype HEMI detection system: a modular array consisting of two 8 x 8 detector planes. Simultaneous multimode imaging is accomplished by using a partially populated front plane as an active mask combined with a fully populated back plane.

The HEMI coplanar-grid CdZnTe detectors are cubic centimeter modular elements with good spectral resolution (~2% FWHM at 662 keV). This energy resolution provides the basis for spectroscopic characterization and identification of radioisotopes, thereby making it possible for the HEMI system to discriminate between threat and non-threat radioactive sources. Additionally, the large area and modularity of the detectors allow for scalable and flexible instrument configurations in order to optimize the sensitivity and angular resolution of the system for specific applications.

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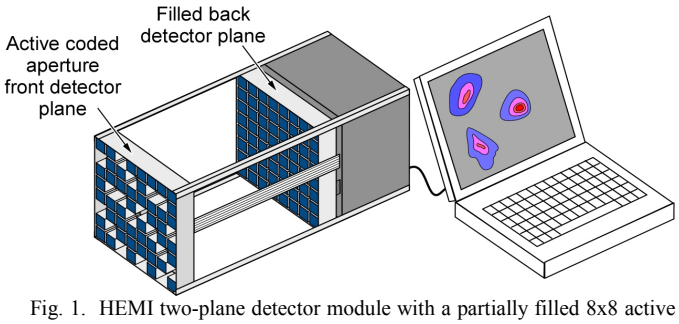

Fig. 1. HEMI two-plane detector module with a partially filled 8x8 active mask front plane and a filled backplane.

II. Spectral Analysis Method

The data-flow of the applied spectral analysis approach is shown in fig. 2. The background estimate and peak-based search algorithm are implemented using the class TSpectrum [2] of the ROOT [3] analysis package. ROOT has been used since it is freely available and allows for easy integration into MEGAlib [4], the data analysis package used for HEMI imaging reconstruction and simulations. The spectral analyzer is written in C++ and has an object-oriented design. As described in this paper, the algorithms incorporated in TSpectrum provide the basic functionality and accuracy required for the HEMI detection system.

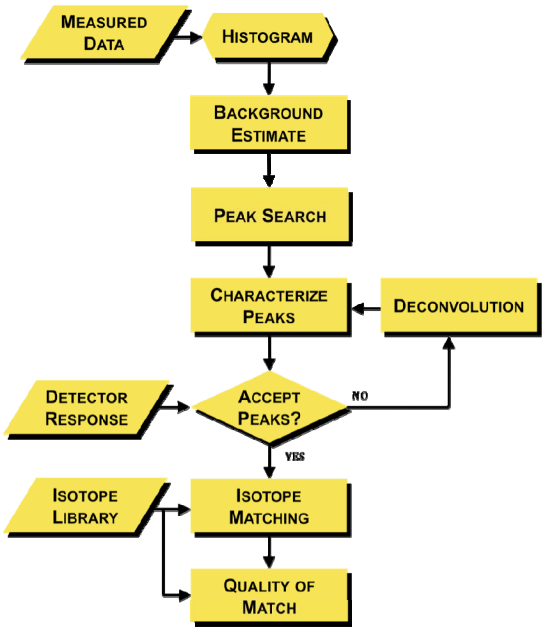

Fig. 2. Data-flow of the spectral analysis method.

The general data flow of the spectral analysis method is as follows: After the background estimate and peak identification

processes are complete, the found peaks are then characterized and evaluated as legitimate peaks or as potential multiplets. This step utilizes the known detector response parameters that have previously been verified through simulation [5]. Potential multiplets are routed through a deconvolution process, currently the Gold algorithm contained in TSpectrum, and reevaluated. Peak energies that pass the selection criteria either initially or after deconvolution are then matched to a list of candidate radioisotopes and assigned a confidence factor to indicate the likelihood that each match is correct.

A. Background Estimation

An accurate background estimate is essential for reducing statistical fluctuations in measured spectra and for determining the peak area and the peak height. The background estimation method in class TSpectrum is based on an optimized version of the Statistics-sensitive Nonlinear Iterative Peak-clipping algorithm, SNIP [6]. A zero-area digital filter is used to approximate the background continuum underneath peak regions, simultaneously smoothing the spectrum. The filter operates as follows: A peak-clipping window of width w is chosen over a specified energy region so that w is approximately twice the expected full width at half maximum. Where $N(x)$ is the number of counts as a function of energy x, the background value is estimated as the lesser of $N(x)$ or the average over the clipping interval, (1).

$$[N(x-w)+N(x+w)]/2 \qquad (1)$$

Fig. 3 shows the effect of the clipping window width on the background estimate underneath a ^{137}Cs peak at 662 keV.

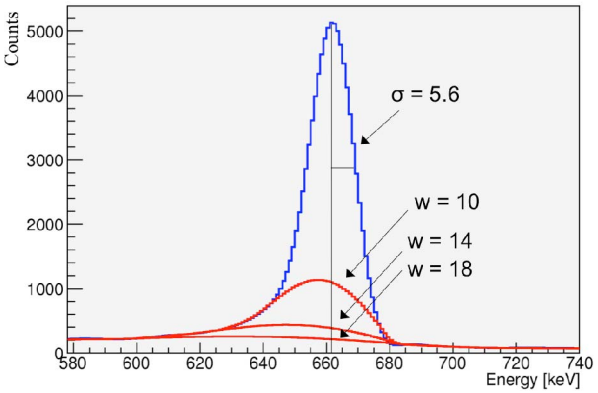

Fig. 3. Comparison of peak-clipping windows (w) under a measurement of a 662 keV ^{137}Cs peak (FWHM = 13) incident upon a 24-detector HEMI array.

In testing the parameters for the background estimate, it was found that a peak-clipping window equivalent to twice the full width at half maximum is an accurate localized approximation and is predominantly effective within the higher energy end of the spectrum (above ~500 keV). However, in measurements where the low energy background is significant, as seen in fig. 4, a narrower window is needed to accurately approximate the background.

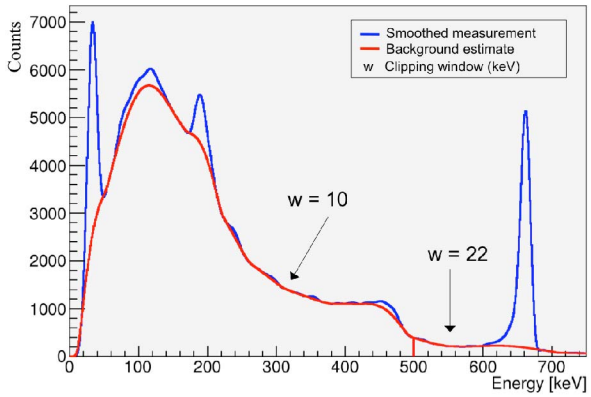

Fig. 4. Appropriate peak-clipping windows for a measurement of a ^{137}Cs source incident upon a 24-detector HEMI array.

B. Peak Search

The Mariscotti second differencing method in class TSpectrum is a peak search algorithm that is commonly used to identify statistically significant peak regions above a continuous background [7]. In principle, a region of the spectrum, where $N(x)$ is the number of counts as a function of energy x, can be described as (2).

$$N(x) = G(x) + Cx + B \qquad (2)$$

The peak regions, $G(x)$, are assumed to have a Gaussian shape and the background can be described as a linear approximation, $Cx + B$. For a continuous function, the second derivative of $N(x)$ disappears in regions containing only a linear background, however, in regions where a Gaussian peak region is present the second derivative does not go to zero. The peak energy occurs in the vicinity where the first derivative of $N(x)$ changes sign. Fig. 5 shows found peaks in a measured spectrum of ^{241}Am and ^{133}Ba sources incident upon a 42-detector planar array. The background is estimated using a window width equivalent to twice the FWHM over specified regions.

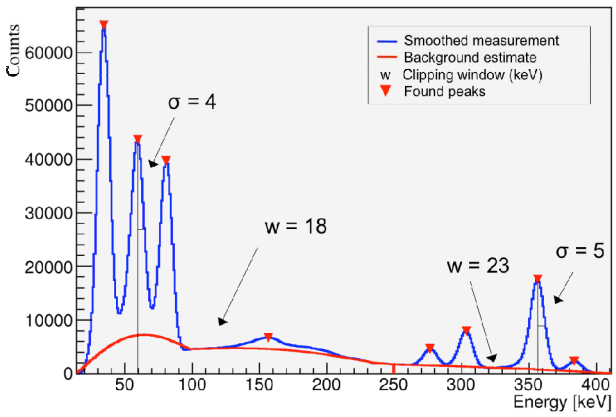

Fig. 5. Found peaks from measurements of ^{241}Am and ^{133}Ba sources incident upon a 42-detector HEMI array. Peak-clipping windows of width w = 2 × FWHM were used to estimate the background.

C. Peak Characterization and Selection

Once peaks have been identified in a spectrum, each peak shape is fit using a Gaussian approximation. The mean energy, total counts (less subtracted background), and energy resolution are then determined for each peak. The energy resolution from the Gaussian fit is compared to the expected energy resolution for a HEMI CdZnTe detector element at the peak energies. If the found peak width (σ) from the fit exceeds the expected width by a factor of 1.5, the peak is routed through a deconvolution process as a potential multiplet. Otherwise, the peak energies are matched to candidate isotopes.

D. Deconvolution

The Gold algorithm [8], one of the deconvolution algorithms available in class TSpectrum, is presently being used to deconvolve peaks in the HEMI spectra. Because it is an iterative method that positively constrains the solution, it allows for the generation of a stable solution that is appropriate for a physical system. Parameters specific to the HEMI system, such as detector energy resolution and thresholds, can be used to further constrain the solution and minimize the number of iterations needed for an accurate deconvolution.

Simulations of doublets centered around 662 keV were performed to test the effectiveness of this algorithm. Fig. 6 shows the limits of the deconvolution, i.e., the minimum separation between two convolved peaks that are able to be accurately resolved, as a function of detector energy resolution. In fig. 6, each of the single peak energies convolved in a doublet is resolved to within an accuracy of $\pm$1 keV after 100 iterations of the Gold deconvolution. At an energy resolution of 2% FWHM at 662 keV, a minimum energy spread of 14 keV between single peak energies is needed to resolve doublets, fig 7. This is approximately the FWHM at 662 keV. To resolve convolved peaks closer than the FWHM, model fitting approaches could be used.

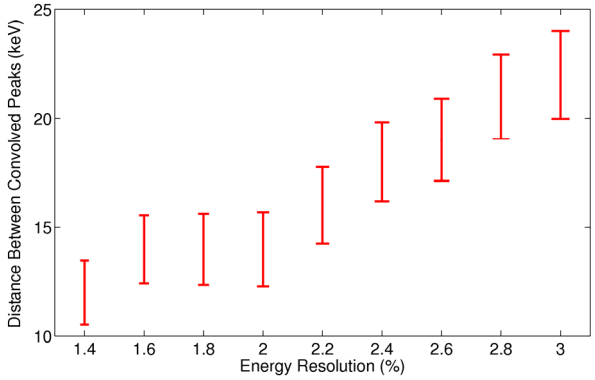

Fig. 6. Deconvolution limit of simulated doublets centered at 662 keV as a function of detector energy resolution, 100 iterations. Each single peak is deconvolved to within an accuracy of $\pm$1 keV.

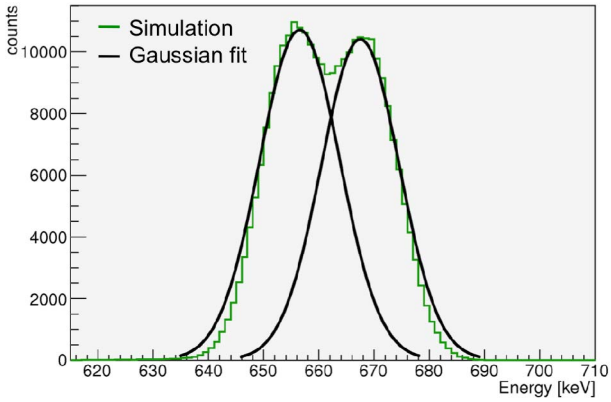

Fig. 7. Simulation of two convolved peaks, 14 keV apart. The Gaussian fit shows the single peaks deconvolved to a separation of 13 keV using the Gold algorithm.

E. Isotope Matching and Assessment

The peak energies resulting from the characterization and deconvolution of found peak regions are then matched to gamma-ray energies from a library consisting of expected background radioisotopes (naturally occurring radioactive materials and daughter isotopes), medical and industrial isotopes, special nuclear materials, and their respective branching ratios [9]-[12]. Isotopes that emit gamma-ray energies within $\pm$1 keV of the found energy are selected as candidates. Once a list of candidate radioisotopes is generated, a quality factor can be assigned to each isotope to indicate the probability that it is a correct match. Several factors contribute to the confidence of the match, i.e., the presence of correlated gamma rays in the spectrum for each candidate, the relative intensities of these gamma-ray energies as compared to the expected branching ratios, and the presence of expected backscatter peaks in the spectrum. An assessment of the relative intensities of correlated gamma-ray energies must include a correction for detector efficiency as a function of energy. In addition to these factors, the statistical significance of the identified peak energy as well as the likelihood that the candidate isotope is present within the detection environment can also aid in assessing the quality of the match.

III. Results

To test the background estimation and peak search method, a simulation was performed using a multitude of typical background sources [13] incident upon an 8x8 two planar HEMI array. Using 100 iterations of the deconvolution algorithm, the peak finder located sixteen actual peaks, four false peaks, and two peaks that fell below the noise threshold, fig. 8. One of the four false peaks (near 300 keV) is a low energy tail mistakenly identified as a separate peak. This particular misidentification may be corrected by applying a closer fit to the peak shape. For example, a Landau fit on the low energy tail of the peak in addition to a Gaussian fit on the main peak region yields a closer approximation to the irregular peak shape that is a result of imperfect charge collection in the

CdZnTe detectors. A closer approximation also allows for a more accurate determination of the peak area. The remaining three false peaks may be eliminated either by crosschecking the presence and relative intensities of correlated gamma-ray emissions from the candidate isotopes, or by eliminating these peaks as statistically insignificant. In general, increasing the threshold for peak detection will minimize the detection of false peaks.

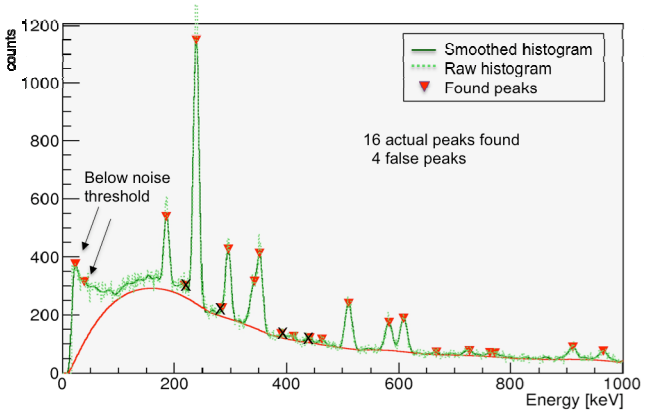

Fig. 8. Simulation of background isotopes incident upon an 8x8 HEMI two-plane array. Shown is the raw histogram (dashed line), the histogram after the smoothing algorithm is applied (solid line), and the resulting background estimate (red line). The Mariscotti method is then used to find the peaks (red triangles).

The peak finder and isotope identification methods were tested using measurements of a 9.5 μCi ^{241}Am source and a 0.5 μCi ^{133}Ba source incident upon a 42-detector planar array. Fig. 9 and fig. 10 compare the accuracy of peak identification as a function of accumulated counts.

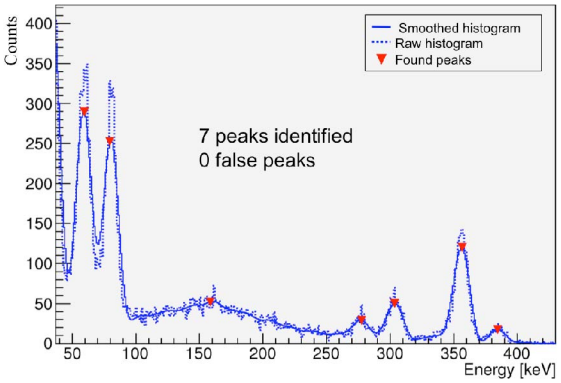

Fig. 9. Measurement of ^{241}Am and ^{133}Ba sources incident upon a 42-detector HEMI planar array, 2.5×10^4 total counts.

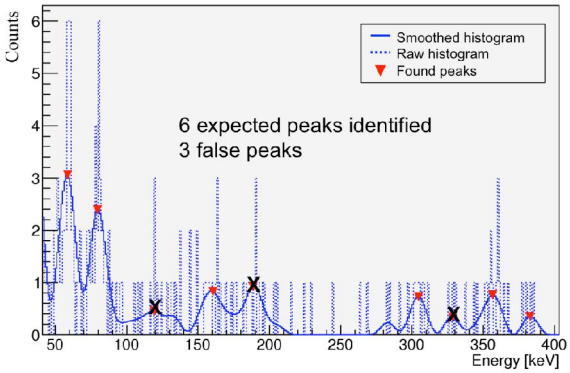

Fig. 10. Measurement of ^{241}Am and ^{133}Ba sources incident upon a 42-detector HEMI planar array, 2.5×10^2 total counts.

The isotope identification method and radioisotope library were used to match the found peaks in the measurement from fig. 9. As seen in Table I., the isotope identifier yielded the correct match for all of the peak energies from the 25,000-count spectrum with the exception of the 80.1 keV gamma ray that is a doublet consisting of two ^{133}Ba energies. The candidate isotope for this energy, ^{131}I, can be ruled out when assessing the quality of match, as several prominent gamma-ray energies from this isotope are missing in the spectrum. Although the isotope identifier found several overlapping energies for ^{133}Ba and ^{133}Xe, the presence of the 276 keV and 356 keV gamma-ray lines clearly indicate the presence of ^{133}Ba in the spectrum. An assessment of relative intensities in the spectrum based on the expected branching ratios confirms ^{133}Ba as the correct isotope.

TABLE I. FOUND ISOTOPES FROM FIG. 9

Peak Energy (keV)	Closest Isotope Match	Isotope γ-ray (keV)	Correct Match
59.2	^{241}Am	59.54	^{241}Am
80.1	^{131}I	80.19	^{133}Ba *
159.5	^{133}Ba, ^{133}Xe	160.61	^{133}Ba
276.5	^{133}Ba	276.40	^{133}Ba
303.3	^{133}Ba, ^{133}Xe	302.85	^{133}Ba
355.9	^{133}Ba	356.02	^{133}Ba
384.5	^{133}Ba, ^{133}Xe	383.85	^{133}Ba

*The two ^{133}Ba gamma-ray lines contributing to this peak have energies 80.9 keV and 79.6 keV with a relative intensity of 13:1, respectively.

IV. CONCLUSIONS

The spectral analysis methods being developed for the HEMI detection system have been shown to be effective for estimating spectral background, finding peaks above a background continuum, and identifying candidate isotopes in both simulations and measurements of the HEMI detection system. Further modifications to the existing spectral analysis methods will be investigated, e.g., matching of spectral templates to find peaks, and forward folding and model fitting approaches to resolve multiplets.

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