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Compton rejection for HPGe detectors via real-time pulse shape analysis[¥]

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Abstract:

A Lawrence Livermore National Laboratory-developed pulse shape analysis (PSA) technique which performs real-time Compton suppression in High Purity Germanium (HPGe) detectors without the use of anti-coincidence detectors is described. Some preliminary measurements of a variety of sources with a standard HPGe detector system and our prototype PSA algorithm have been made and indicate that a reduction in Compton continuum can be achieved via PSA. These measurements represent an initial assessment of the effectiveness of the prototype PSA system for the improvement of spectral quality and future improvements are expected. Additional work is progressing to optimize the effectiveness of the algorithm for Compton rejection in standard HPGe detectors. Work is also progressing to extend the methodology to segmented HPGe detectors which could potentially yield significantly better Compton rejection and gamma-ray imaging.

Introduction:

The suppression of Compton background in γ-ray spectra is important for a variety of reasons. These include the need for increased measurement sensitivity and/or speed. The increased speed is particularly important for applications that require high throughput or involve exposure of personnel to significant radiation dose.

The traditional approach to Compton rejection involves surrounding the primary detector (e.g. a Ge crystal) with a secondary detector (e.g. a bismuth germanate or sodium iodide annulus) which is operated in anti-coincidence mode. Unfortunately, the large size, weight, and cost of such a system can offset the expected benefits, especially for measurements performed in the field. For this reason, a Compton suppression technique based only on details of the charge pulse shape is attractive as it eliminates the dependence upon the anticoincidence detector.

Recent efforts to apply Ge detector pulse shape analysis (PSA) to Compton suppression[1,2,3,4] have focused on general characteristics of the charge pulse shape (e.g. rise-time, single-interaction-site vs. multiple-interaction-site shape, etc.). Recently, we presented a more fundamental approach based on a complete unfolding of the charge pulse shape into discrete components associated with individual γ-ray interactions.[5,6] Our more fundamental approach permits application of an algorithm which favorably rejects Compton escape events. The algorithm is chosen so as to allow for discrimination on both single-interaction-site and multiple-interaction-site escape events which differs from the algorithms of [1, 3] which were designed to reject only single-interaction-site events. Below is a brief description of the details of our algorithm along with experimental results from a series of real time measurements using a standard 5cm x 5cm HPGe detector and our prototype PSA system.

Description of the Compton rejection approach:

A more comprehensive description of the LLNL developed approach to Compton rejection via PSA is available [5, 6]. In summary, the novel aspect of our approach involves a complete unfolding of the charge pulse shape into discrete components associated with individual γ-ray interactions. The information thus acquired yields a measure of the position of the gamma-ray interactions within the HPGe crystal in terms of radial position and energy/interaction. This information is then used to favorably reject Compton escape events while keeping full energy deposition events. The advantage of the current approach, as compared with other recent approaches, is the potential to reject not only single-interaction-site escape events, but also multiple-interaction-site escape events.

For a given γ ray event, we seek the maximum energy, E_z, deposited in a single radial zone. The quantity of interest for the rejection criteria is the maximum fractional energy deposition, $E^*=E_z/E_{dep}$, where E_{dep} is the total energy deposited by the γ ray. Ideally, it is hoped that E^* will be equal to E_{max}/E_{dep}, where E_{max} is the maximum single-interaction energy deposition. This turns out to be true the majority of the time.

Our rejection algorithm operates as follows. All events with E^* less than a certain cutoff are accepted. All other events are rejected. The cutoff function is defined as follows:

$$f(E_{dep}) = \frac{2.0}{2.0 + \dfrac{511.0}{E_{dep}}}, \quad E_{dep} > 372 \text{ keV} \qquad (1)$$

$$f(E_{dep}) = \frac{\alpha}{E_{dep}}, \quad \alpha < E_{dep} < 372 \text{ keV} \qquad (2)$$

where E_{dep} is in keV, and α is a constant empirically determined (via Monte Carlo simulation) to be 220 keV. Below 220 keV, the rejection algorithm turns off (all events accepted) and no difference between the suppressed and unsuppressed spectrum will be produced for energies below 220 keV.

The forms of (1) and (2) are based on the energy deposition characteristics of γ-rays which fully absorb in the HPGe. At higher energies (E_γ>372 keV) a Compton backscatter will typically provide the highest energy interaction point, and thus we accept only events whereby E^* is less than $f(E_{dep})=E_c(E_{dep})/E_{dep}$, where E_c is the Compton edge as calculated assuming that $E_{dep}=E_\gamma$. At lower energies (E_γ<372 keV), the photoabsorption event at the end of the path becomes the dominant interaction point, and thus we only accept events whereby E^* is less than $f(E_{dep})=\alpha/E_{dep}$, where α is the energy deposited by a typical photoabsorption interaction.

Experimental measurements utilizing prototype PSA system:

Sources (^{60}Co, ^{137}Cs, ^{152}Eu, ^{232}Th, and ^{239}Pu) were each measured alone and in combination using the prototype PSA system. The single and combination sources were measured to permit an initial assessment of the change in spectral quality between the suppressed and unsuppressed spectra as generated by the prototype PSA system. The two spectra, suppressed and unsuppressed, for each source and source combination were collected simultaneously with source-to-detector distances adjusted such that the count rate from each source was approximately 1 kHz. The HPGe detector system used has been described previously [6] and a description of the system will not be repeated here.

Results and assessment of performance:

A typical measure of the performance of a Compton suppressed gamma-ray detection system is the peak-to-Compton ratio as measured with a single gamma-ray emitting source or a source which emits a limited number of gamma-rays. The peak maximum is calculated via fitting. The Compton continuum contribution is calculated as the average height over an energy range which is selected to minimize the contribution from other gamma-rays. To assess the change in the peak to Compton ratio between the prototype PSA system and the unsuppressed system, ^{137}Cs and ^{60}Co sources were each measured and the spectra analyzed. Figure 1 and Figure 2 show the measured suppressed and unsuppressed spectra for the ^{137}Cs and ^{60}Co sources, respectively.

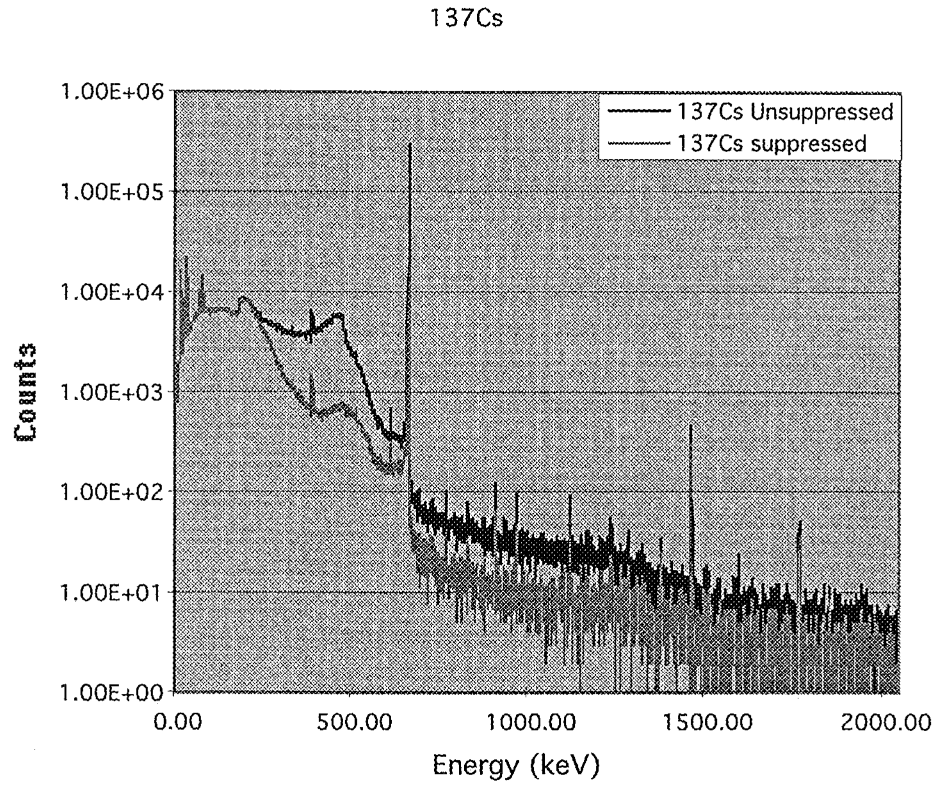

Figure 1. Cesium-137 as measured with the LLNL-developed prototype PSA system. The Compton edge from the 661-keV gamma-ray is significantly reduced as compared to the total peak height.

For the ^{60}Co measurement, the average Compton continuum was calculated for the region spanning 1.04 – 1.096 MeV For the ^{137}Cs measurement, the average Compton continuum was calculated in the energy region between 0.40 – 0.46 MeV. A net suppression of the continuum in the energy regions mentioned compared to the maximum peak height is on the order of 3 – 4 times. Table 1 shows the preliminary assessment of the relative change in the Compton continuum for the sources mentioned. It should be noted that the results indicated are based upon single measurements and the peak/Compton and relative improvement values reported represent only gross estimates.

Another useful figure of merit (FOM) for spectral quality is the peak height as compared with the fluctuation of the local background for a background-dominated environment. Because most background in a gamma-ray spectrum is a result of Compton escapes from higher-energy gamma-rays emitted from the sample[7] and not external sources (Cosmic, etc.), this FOM is useful for many cases. To approximate a background-dominated situation, a ^{152}Eu source was

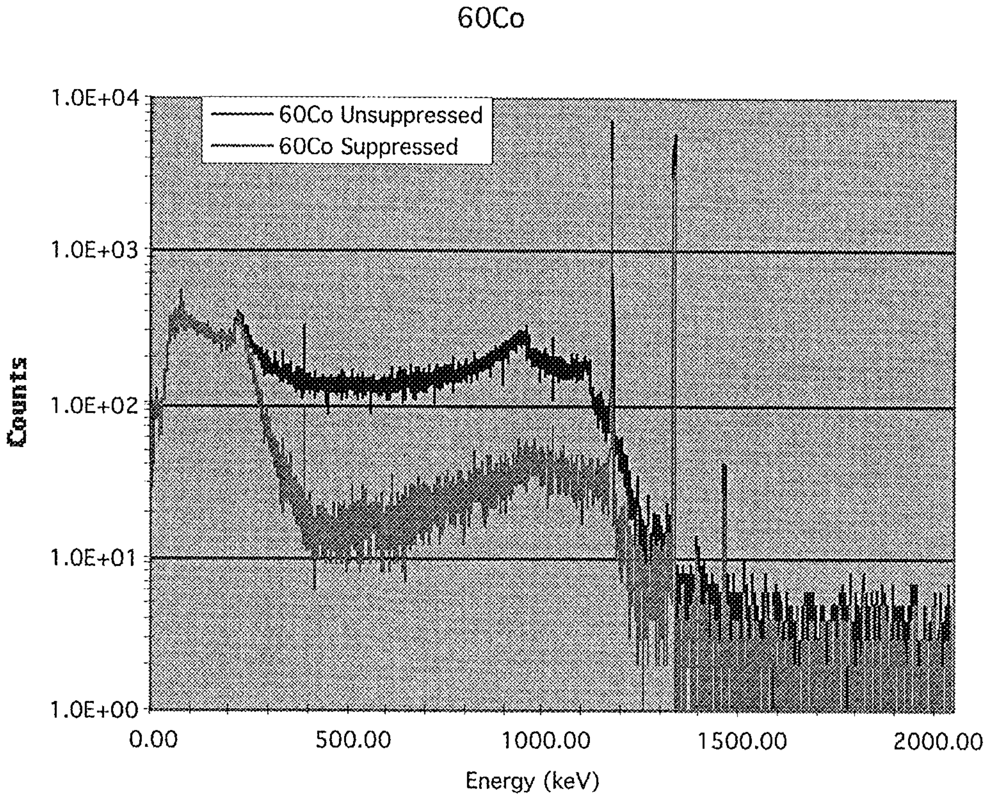

Figure 2. Cobalt-60 as measured with the LLNL-developed prototype PSA system.

Table 1. Preliminary assessment of the relative change in the Compton continuum for the sources mentioned. It should be noted that the results indicated are based upon single measurements and the values reported represent only gross estimates with large uncertainty.

Nuclide	Peak Height (counts)	Ave. Compton (counts)	Peak/Compton
^{60}Co, unsuppressed	5952 (1332 keV)	173 (1.04 – 1.1 MeV)	34
^{60}Co, suppressed	3596 (1332 keV)	34 (1.04 – 1.1 MeV)	105
		Relative improvement	105/34 = 3.1
^{137}Cs, unsuppressed	3.16E5 (661.6 keV)	5.18E3 (400 – 460 keV)	61
^{137}Cs, suppressed	1.55E5 (661.6 keV)	6.70E2	231
		Relative improvement	231/61 = 3.8

measured simultaneously with ^{137}Cs and ^{60}Co sources. The Co and Cs were added to produce additional Compton interference and increase the background for energies below 1332 and 661 keV, respectively. The measured spectrum is shown in Figure 3.

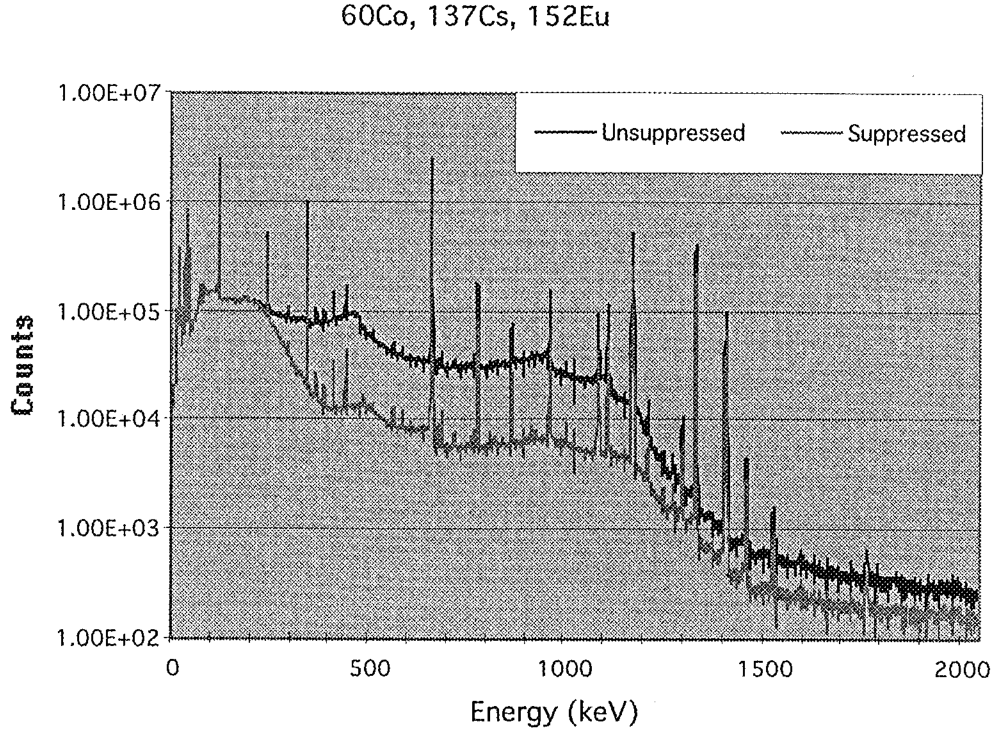

Figure 3. Cobalt-60, ^{137}Cs and ^{152}Eu sources as measured with the LLNL-developed prototype PSA system. The presence of the ^{137}Cs and ^{60}Co were added to increase the background in the regions of the ^{152}Eu 411, 867 and 1112 keV peaks.

As described in a previous reference [5], another useful figure of merit for spectral quality is the peak height as compared with the fluctuation of the local background. The sensitivity (S) for a particular gamma-ray peak, in a background dominated environment, can be approximated as $S=(P-B)B^{-1/2}$. Where P is the on peak sum; and B is the average intensity of the Compton continuum in the regions immediately adjacent to the peak of interest (usually determined as a smoothed step function between the low energy and high energy side of the peak). The effectiveness can then be defined as the ratio of S for the Compton suppressed case (S_{sup}) to the unsuppressed case (S_{unsup}). An improvement in spectral quality for the gamma-ray of interest can then be defined as a $\varepsilon = S_{sup}/S_{unsup}>1$. Table 2 shows the calculated effectiveness for several lower-intensity ^{152}Eu gamma-rays in a mixed ^{60}Co, ^{137}Cs, ^{152}Eu measurement. The ^{60}Co and ^{137}Cs were introduced to make the measurement of the 411, 867 and 1112 lines of ^{152}Eu more difficult by increasing the Compton continuum in the energy region.

Future directions, potential improvement through segmentation:

As discussed in [5], the primary cause of performance degradation in this technique results when the distance between gamma-ray interactions in the HPGe detector is small compared to

Table 2 Effectiveness, ε, of the suppression system spectra for low-intensity gamma-rays at the energies indicated. Values greater than 1 indicate a relative improvement. It should be noted that the results indicated are based upon single measurements and the values reported represent only gross estimates with large uncertainty.

Gamma (keV)	unsup P	unsup B	sup P	sup B	Effectiveness, ε
411	1.49E+05	8.45E+04	3.58E+04	1.28E+04	0.91
867	7.84E+04	3.52E+04	2.83E+04	6.40E+03	1.19
1112	1.14E+05	2.57E+04	5.46E+04	5.44E+03	1.21

the spacial resolution achieved via the analysis. This can result, for example, if multiple interactions occur in the same virtual detector zone. One way to address this issue is to try and compensate for the increased maximum deposition energy (E*, [5]) by increasing the value of the cutoff function. This is being studied. Alternatively, one can seek to eliminate the problem altogether by highly segmenting the outer contact of the HPGe. This would make possible spatial resolution in 3-dimensions, and thus would better separate out the interaction points, even those which occur in the same radial zone. By analyzing the pulse shapes produced on each segment, a position resolution smaller than the segment size could be realized. Assuming a ~1 mm^3 position resolution (in cylindrical coordinates, Δr=1mm, $\Delta\phi$=.066 rad, Δz=1mm), simulations show that the current algorithm would improve in effectiveness by 20% for the 964-keV line in ^{152}Eu. Furthermore, with this degree of position resolution, a new algorithm based on Compton tracking could also be applied. In this algorithm, all possible ordering sequences of the interaction points are examined to find a path which is consistent with the Compton scattering formula. If such a sequence is found, the γ ray is accepted, otherwise it is rejected. The improved technique could increase the effectiveness by 30% over the current value for the 964-keV line in ^{152}Eu.[5]

Conclusion:

The potential for PSA to provide real-time Compton rejection is significant. Initial indications are that the Compton continuum can be reduced and that peak sensitivities can be improved versus unsuppressed HPGe detector systems. Significant improvements over the results reported for the LLNL-prototype system are expected, though much more work is required to optimize the Compton rejection algorithms for use with standard HPGe detectors. Work is also in progress to extend the methodology to segmented HPGe detector systems.

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