Compton Imaging with Coincidence Measurements for Treaty Verification Purposes

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Abstract—Nuclear arms control is a cooperative effort among many government agencies, requiring inspection processes and information sharing to be executed for verification purposes. Compton imaging is one technique used for gamma ray detection of special nuclear material (SNM). By using coincidence counting for measuring Compton scattering events, low-energy gamma background may be greatly reduced for improved detector sensitivity. A CAEN digitizer equipped with DPP firmware will be used to perform coincidence measurements of Compton scattering events through the use of multiple detectors and detector configurations, including NaI and LaBr scintillation detectors and HPGe semiconductor detectors. Future design considerations will be analyzed here to improve detector capabilities for treaty verification purposes where material discrimination is essential. A design is presented here that will be tested upon the arrival of the DPP firmware.

Index Terms—CAEN digitizer, coincidence counting, Compton imager, digital pulse processor, scintillation detector

I. INTRODUCTION

COMPTON scattering is a well-understood nuclear interaction event with many known applications in astronomy, medicine, and nuclear security [1-3]. It has been demonstrated that by using Compton scattering as a means of imaging special nuclear material (SNM), low-energy photons may be detected with excellent energy and spatial resolution [4]. Passive gamma-ray detection methods are limited by a detector’s sensitivity, especially in environments where low-energy gamma rays are self-attenuated in the presence of special nuclear material (SNM) and when the signal is relatively small compared to background gamma rays. By using a coincidence measurement in which only those events which occur within a certain time window are recorded, the detector’s signal-to-noise ratio may be greatly improved, thus allowing for the development of a highly sensitive and cost-effective gamma-ray detection device. Based on the known physics of Compton scattering, a simple device design has been realized (Fig. 1) in which an incident photon collides with a free electron at rest in the primary, scattering detector material and deposits its remaining energy into the secondary, absorbing detector material. Based on the amount of energy deposited in each detector, a cone may be constructed to define a certain region from which the source photon originated with the angle described in the Compton scatter formula,

\[ \cos \theta = 1 - \frac{m_e c^2 E_i}{E_0(E_0 - E_i)} \]

in which \( E_0 \) is the incident photon energy, \( E_i \) is the scattered photon energy, \( m_e c^2 \) is the electron rest mass energy of 511 keV, and \( \theta \) is the angle of scatter used to reconstruct the cone. By analyzing the intersection of multiple cones (Fig. 2), it is possible to accurately determine the source location of the incident gamma ray with an associated error in energy and spatial resolution due to the false assumption of free electron interaction.

While this technique has been previously studied for gamma spectroscopy, there have been recent efforts to improve this method for treaty verification purposes. As a result of improved imaging techniques, however, sensitive information related to the design of certain devices has been obtained, triggering an increased interest in research for methods which offer SNM verification without compromising the sensitive nature of specific devices. By developing a Compton imaging system based on coincidence measurements that exclusively validates declared SNM without obtaining information that would otherwise compromise national security, we hope to promote a practical means for the advancement of nuclear technologies. In this paper, several design considerations are presented for coincidence measurements for a Compton imaging system to be tested with CAEN digitizing instrumentation.

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II. MEASURING COINCIDENT EVENTS

Coincidence measurements are highly dependent upon the use of a delay to capture the same event with separate detectors. As in the case of particles emitted in cascade from the same nucleus, analyzing coincidences may significantly improve signal-to-noise sensitivity by greatly suppressing background. An analysis of several scintillation detectors has demonstrated the importance of a short resolving time for suppressing background, especially in situations where fast coincident measurements are desired [5]. CAEN digitizers equipped with Digital Pulse Processing (DPP) firmware will be used to analyze the resolving times of different detectors to evaluate the capabilities of taking meaningful coincident measurements.

A. CAEN Digitizers

CAEN digitizers rely on a specified time window between two events to determine coincidence if measured within the established time trigger limited by the resolving time. Three mechanisms have been examined for generating a logic pulse with a time trigger. The first mechanism, leading edge, suffers from inconsistencies associated with amplitude walk and detector non-uniformities, resulting in statistical uncertainties and random coincidences to be counted. The second uses a crossover timing to reduce the amplitude walk issue, but is only applicable for bipolar pulses. The third is called the constant fraction timing method (Fig. 3) is used with the CAEN instrumentation to diminish these irregularities.

By using this timing method to introduce a delay in recording the same event from two separate detectors, coincidence measurements can be made with the schematic shown in Fig. 4. The time-to-amplitude converter (TAC) shown uses the arrival of the two triggers to produce a pulse with amplitude proportional to the trigger arrival time difference. The pulse is then sent to a multi-channel analyzer (MCA), where the time spectrum for the source is created and coincidence may be determined by introducing a threshold to the TAC. Random coincidences are suppressed with a y-offset in the time spectrum so that only true coincidences contribute to the pulse height. The coincidence peak location corresponds to the fixed delay, which was set as described earlier. For ideal detectors, the transition region corresponding to the coincidence peak is sharp. It will be seen after setting a time trigger with the CAEN equipment that real detectors will transition smoothly to the accidental coincidence region.

B. DPP Firmware

DPP firmware significantly simplifies the process of generating logic pulses for the user in making coincidence measurements with CAEN digitizers by analyzing separate events digitally with an analog-to-digital converter (ADC). The instrumentation is capable of running in both “normal” and “coincidence” acquisition modes to offer the option of collecting all events or only coincident events, which may prove useful in comparing the system’s overall efficiency with different detectors and configurations. By using the DPP firmware operating in coincidence acquisition mode it will be possible to compare the resolving times of different detectors with varying distances to the source. These measurements could motivate further investigation of detector sensitivity using coincidence measurements to determine what environments may be more suitable for assorted Compton imaging applications. The resolving time of different detectors may be experimentally determined under changing conditions by using the equation for resolving time given as:

\[
\tau = \frac{\tau_1 + \tau_2 - \tau_{12} - \tau_0}{2(\tau_1 - \tau_0)(\tau_2 - \tau_0)},
\]

(2)
where $r_1$ is the count rate for split source 1, $r_2$ is the count rate for split source 2, $r_{12}$ is the count rate with both split sources 1 and 2, and $r_3$ is the background count rate.

The detectors to be analyzed in this study will be a Canberra NaI 2” x 2” scintillation detector, a Canberra LaBr 1.5” x 1.5” scintillation detector, and a Canberra Falcon-5000 HPGe semiconductor detector. An analysis of detector capabilities has been performed (Table 1) using data given from Canberra, where the detectors were obtained [6]. The rise time of the detectors will be important to consider so that a sufficiently small window may be used for measuring coincident events without allowing a significant amount of random coincidences to be recorded. The resolution will also be important to consider to determine the capabilities of the imaging system with various source technologies for different detectors. The resolution for a cesium-137 source has been included because of the availability of the source in the Nuclear Security Laboratory. It would also be meaningful to use the DPP firmware with coincidence capabilities with varying source distances and shielding properties to better understand the impact on detector sensitivity and spatial resolution.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Rise time (ns)</th>
<th>Resolution at 667 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI</td>
<td>500</td>
<td>7 %</td>
</tr>
<tr>
<td>LaBr</td>
<td>60</td>
<td>3 %</td>
</tr>
<tr>
<td>HPGe</td>
<td>20</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>

The obvious tradeoffs for using a specific detector include cost, timing resolution, and energy resolution, but little research has been done to investigate the threshold of using combinations of multiple NaI or LaBr scintillation detectors to elucidate the wide gap in detector performance between these and semiconductor detectors. CAEN digitizers equipped with DPP firmware allow for up to eight channels for coincidence measurements. The effects of using unique combinations and configurations of detectors will be analyzed in further detail.

### III. Design for Material Discrimination

There is great interest in developing nuclear imaging techniques for nuclear security purposes. Current techniques of gamma spectroscopy have presented problems for treaty verification because they can reveal too much sensitive information about the cargo under interrogation. Research is now focused on developing a gamma ray imaging device that validates declared SNM but does not intrude on sensitive information that may compromise national security.

A design has been proposed by Brookhaven National Laboratory under a grant from Defense Threat Reduction Agency (DTRA) that uses coincidence measurements with Compton imaging to detect hot spots of SNM [3]. By using a 24-layered concept of double-sided silicon strip detectors in a 3 x 3 array, energy resolution of 4 keV FWHM at 356 keV has been achieved. While the design is still being improved upon to exhibit increased sensitivity at room temperature, researchers are quite optimistic of the success of the project.

The concept hinges on the idea of increasing the probability that a gamma ray scattering event is captured by essentially trapping the photon between many layers of detectors until coincidence measurements can be made, such that background levels are significantly reduced. Similarly, by setting a signal output threshold or systematically programming characteristic isotopic energies to be rejected, certain materials may be discriminated for detection and sensitive information may not be revealed. The idea of developing a detector which only images hot spot locations allows for detection of the presence of SNM along with cause for secondary, more intrusive detection methods. Various experiments will be performed with multiple detector configurations focused on maximizing the probability that a gamma ray scattering event is captured.

In an effort to understand the effect of scattering angle on detector efficiency, a lead collimator will be used to concentrate incident photons onto the detector at different angles and with different sources (Fig. 5). It can be expected that for smaller incident angles, the signal will greatly decrease and the imaging system will require the use of a shortened resolving time to block random coincidences from being captured. This may only be achieved with the more efficient detectors, and multiple NaI detectors may need to be introduced to produce multiple angles for capturing gamma ray interactions.

![Fig. 5. Schematic of using a lead collimator to understand the effect of incident angle on detector efficiency](image-url)
with random coincidences to be ignored. By using the total energy of every recorded event measured in coincidence as the incident energy just prior to the final interaction event as shown in Fig. 6 and described as:

$$E_0 = \sum_{i=1}^{j} E_i, \ i=1,2,\ldots,j$$ (3)

it may be possible to reduce the statistical error associated with cone reconstruction and develop a way to selectively discriminate materials which emit characteristic gamma-ray energies. In doing so, materials that are commonly used for the construction of nuclear technologies would not be imaged unless secondary, more intrusive methods, may be required in the presence of illicit material that was not declared. This configuration would effectively function as an array of detectors as previously demonstrated to maximize the probability of capturing scattering events in coincidence that interact more than once before photoelectric absorption. In the previous configuration with two parallel detectors, there exist multiple parameters that would need to be optimized for efficiency. Changing the distance between the detectors may generate a cone with less uncertainties for directional resolution because the scattered photon travelled a greater distance, but it would also require a longer coincidence time dependence and may open a larger window for random coincidences. By using an array-like configuration for Compton imaging, it would ensure full energy deposition for characteristic gamma-ray peaks if coincident events are recorded and may offer the ability to discriminate against select materials if treaty verification purposes require it for maintaining national security.

IV. CONCLUSION

CAEN digitizers have the capability of performing coincidence measurements for Compton imaging applications of gamma ray sources. It has been mentioned that coincidence measurements are important in many applications where background suppression is desirable. By using common method to generate a logic pulse as a time trigger to record coincidence, Compton imaging may be performed with the construction and intersection of multiple cones from the Compton scatter formula. Low-Z materials are sought after for the scattering material to ensure a Compton scatter event occurs, and high-Z materials are used for the absorbing materials to ensure photoelectric absorption captures all of the scattered photon’s energy.

The use of modern gamma spectroscopy techniques for treaty verification purposes has elicited sensitive information that may compromise national security, and alternative, less-intrusive methods for the detection of SNM are sought after. The use of layered silicon wafers allows for a higher probability of gamma ray interactions to be recorded in coincidence, especially with a surrounding NaI calorimeter to capture multi-dimensional scatter events that 2-D detectors would otherwise miss. This design will be incorporated with the CAEN digitizing equipment available in the nuclear security lab to produce a Compton imaging system based on coincidence measurements that will address the issues discussed in this paper.

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REFERENCES

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