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Design of a two-dimensional pseudo coincidence Compton suppressor system for neutron activation analysis

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HIGHLIGHTS

- A new Compton suppressor system is designed using two face-to-face HPGe detectors.
- The algorithm for the identification of pseudo coincidence events from list data is presented.
- The double coincidence events are explained and removed using trigger hold-off technique.
- The developed system provides low-background high-resolution spectrometer for NAA.

ABSTRACT

Compton scattering events are the main source of error on the peak counting during the Neutron Activation Analysis (NAA). The Compton suppressor system in instrumental NAA reduces the detection limit of the technique and leads to a data with a higher degree of precision. In this paper, a two-dimensional coincidence Compton suppressor system is presented for the NAA technique. The system is established based on a CAEN digitizer which directly records the pre-amplifier output signals of the two HPGe detectors. The recorded events in the list mode file are analyzed offline by a Matlab code and the correlated photopeak events are realized. The performance of the system for Compton suppression is tested by measuring the gamma lines of Ba-133 and Cs-137 standard sources. The results show that the presented technique provides the peak to Compton ratio up to 10^4 and can be an alternative for conventional Compton suppressor systems.

KEYWORDS
Compton suppressor
Neutron Activation Analysis
List mode
Digitizer

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1 Introduction

Instrumental Neutron Activation Analysis is a well-established non-destructive technique for the determination of elements and their concentration in the bulk of the samples (Munita et al., 2019). The technique is based on the activation by neutron using neutron emitter radioisotope sources or research reactor facilities. After activation via (n,γ) reaction, the gamma-ray spectroscopy of the resulting compound nucleus performs using a high-resolution detector to determine the yield of gamma lines in the spectrum. Each gamma line is a specific signature of the elements and its yield determines the concentration of an element in the content. The quality of gamma-ray spectroscopy has a significant effect on the accuracy of the results. The conventional gamma-spectroscopy system in this method includes an HPGe detector, power supply, spectroscopy amplifier, and a computer equipped with suitable software for recording and data analysis. Since the investigated samples (soil, plant, milk, and alloys) contain a large number of elements, their related gamma spectrum includes many (10 to 100) peaks (Landsberger et al., 2002). The most important source of error during the analysis is the background spectrum caused by Compton scattering and its overlap with the other gamma lines. The Compton background leads to the disappearance of many peaks or even if observed, due to the predominance of the Compton, the value of the area under the peak is inaccurate. The Compton background in the recorded spectrum reduces the sensitivity and detection limits for the determination of some elements such as U, As, Th, and Ca. So the result of the analysis of that particulate elements will be reported with great inaccuracy in the presence of Compton events on the spectrum. To overcome the mentioned problem, in a typical gamma-ray spectroscopy system used for NAA, a Compton suppression system is used to increase the peak to Compton ratio (Stover and Lamaze, 2005). A perusal of the literature reveals that the use of the Compton suppression system improves the detection limit for As, Ca, Cd, Cr, Fe, Hg,

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Figure 1: The schematic of the designed Pseudo coincidence Compton suppressor system.

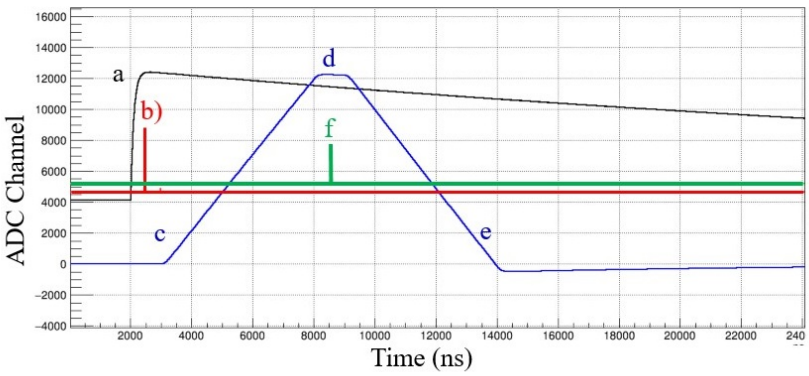

Figure 2: The signal inspector view: a) preamplifier signal, b) trigger, c) rise time of the trapezoidal energy filter, d) flat-top time, e) decay time of trapezoidal filter, f) Time tag.

K, Rb, Zn, Th, and U elements in geological, environmental, biological, archeological, and agricultural samples (dos Santos et al., 2012; Mauerhofer et al., 1996).

A typical Compton suppressor system includes a central HPGe detector surrounded by either NaI (Tl) or BGO detectors. The Compton scattering events will be detected by both detectors and the photo peaks will be detected by the HPGe detector. The acquisition system measures the gamma-rays in anti-coincidence mode. The mentioned Compton suppressor systems are expensive (about 150 k$) and are not easy to access. In this paper, a 2D pseudo coincidence Compton suppressor system is designed using two conventional HPGe detectors.

2 Materials and methods

The presented spectrometer at Nuclear Science and Technology Institute (NSTRI) is established based on a 14-bit CAEN waveform digitizer (CAEN DT5730) that samples directly from the preamplifier output of the two face-to-face HPGe detectors (ORTEC-GEM 20200, Canberra3001c). Figure 1 shows the schematic of the designed system. In this configuration, all the nuclear electronic modules are omitted and the system is loaded with firmware. Figure 2 shows the signal inspector view of the digitizer (Caen, 2022). The algorithm that transforms the sampled raw waveforms (Fig. 2-a) to a trapezoidal signal is based on the Jordanov energy filter and is called Pulse Height Analyzer (PHA) (Jordanov and Knoll, 1994). The trapezoid filter plays the role of a Gaussian filter of shaping amplifier in analog nuclear electronics. The advantages of the trapezoidal filter compared to Gaussian filter for high-resolution low-level background gamma-ray spectroscopy have been clarified by Jordanov et al.(Jordanov et al., 1994). The height of the trapezoid flat-top (Fig. 2-d) at the time tag (Fig. 2-f) is proportional to the energy of radiation. The procedure for optimum selection of energy filter parameters (rise time, flat-top time, decay time, baseline mean, etc.) can be found in our previous paper (Biganeh et al., 2019). After the correct configuration of the setting for each channel of the digitizer, the MC2 software records the energy and the timestamp of the all detected events in two detectors and stores them in a text file (Caen, 2018). The procedure for recognizing the pseudo coincidence events is described in the next section.

3 Experimental Details

To test the performance of the system, the detected gamma-rays of Ba-133 (276.4, 302.9, 356, 383.8 keV) and Cs-137 (662 keV) in the two detectors are recorded in a list file (a file contains the energy and time of each event). The experiment lasted 4 hours to record enough photopeak events on the list. The size of the list file is 2 GB for each channel of the digitizer. The algorithm for the identification of pseudo coincidence events and conversion of list-mode data to the 2D spectrum is shown in Fig. 3.

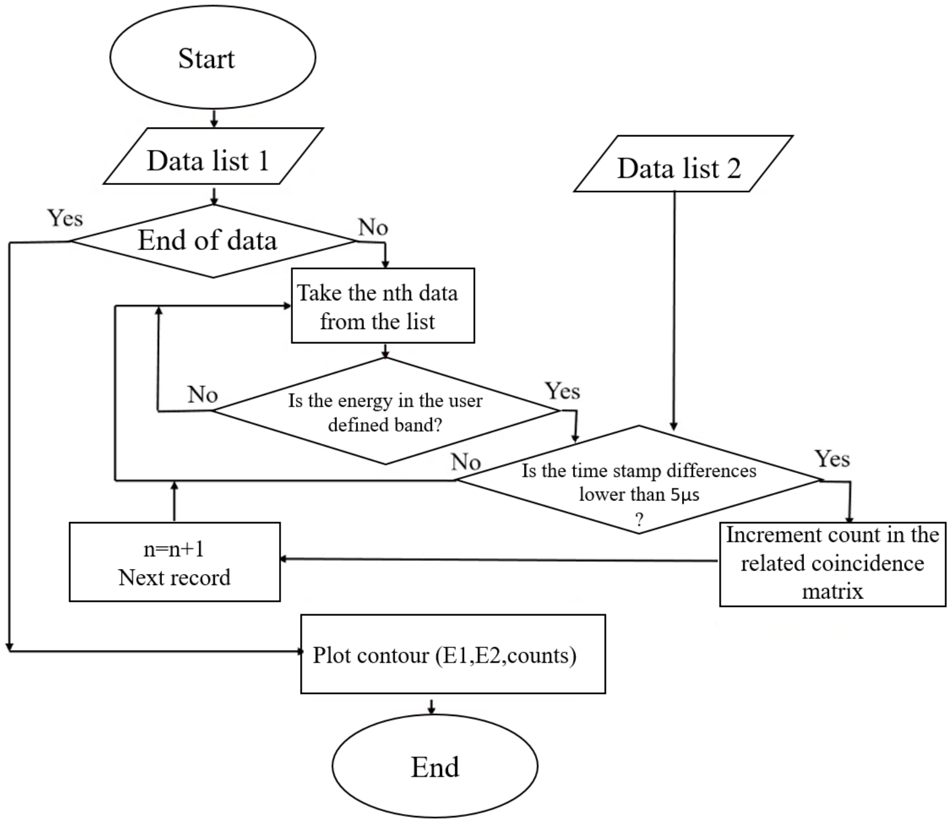

Figure 3: The algorithm for conversion of list-mode data to the 2D spectrum.

Using this algorithm, the offline analysis of the list mode data is done to extract the pseudo coincidence correlated counts.

The problem that appears during data analysis using the mentioned algorithm is the record of double coincidence events on the list data due to the large coincidence time window in pseudo coincidence mode. Figure 4 well describes the condition where the double coincidence occurs. As shown in Fig. 4, in the case of coincidence between channels #1 and #2, for each valid trigger, a trigger validation gate propagates with a bandwidth of TST. In the case of double coincidence, two events of channel #1 (shown as a and b) are in coincidence with a single event (shown as c) of the other channel. So, when the trigger validation gates of the two channels overlap each other, the first overlap enables the first signal of channels #1 and #2 and the second overlap records the signal of channel #1 but there is no valid signal in channel #2 (case. 1 in Fig. 4). During the data acquisition, the double coincidence event is an interrupting factor in recognizing correlated events. To avoid this phenomenon, the trigger hold-off parameter of the energy filter is set greater than twice the pseudo coincidence time window. The trigger hold-off prevents the re-triggering of the signal at channel 1 and the recorded events in list mode one by one correlate with one another (case. 2 in Fig. 4).

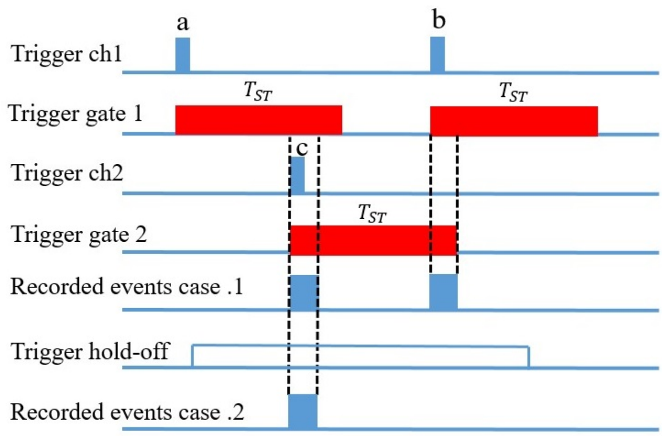

Figure 4: The description of the double coincidence event in channel #1.

4 Results and discussion

In the offline analysis of the list-mode data, the optimum value of 5s is selected for the pseudo coincidence time window to obtain the maximum peak to Compton ratio and to efficiently detect the chance coincidence gamma-rays of Ba-133 (0.11 μCi) and Cs-137 (0.08 μCi). The pseudo coincidence time window just confirms that the detected events are virtually correlated and allows the record of events in a matrix. However, the issue that needs to be addressed is that the efficiency of the coincidence acquisition

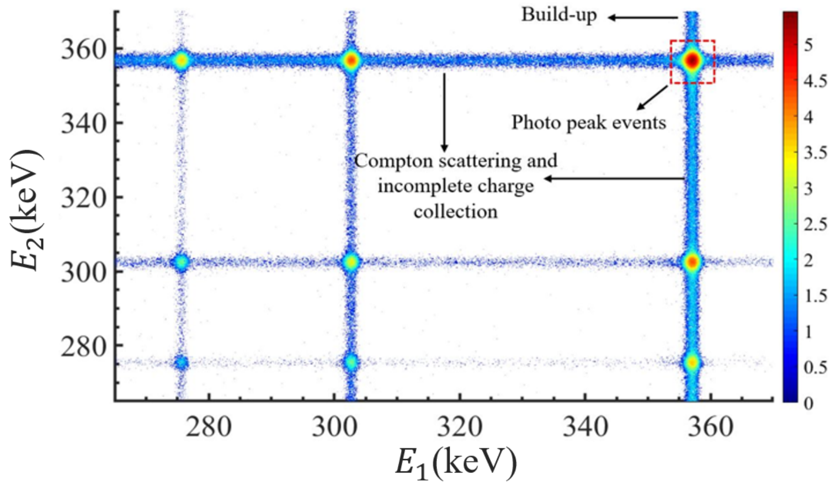

Figure 5: The 2D pseudo coincidence spectrum of Ba-133 radioisotope. The gamma-region of 256, 302, and 356 keV of Ba-133.

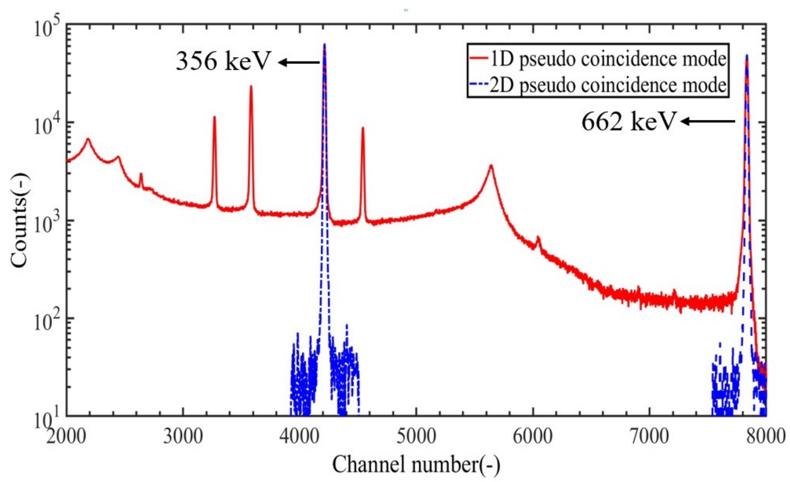

Figure 6: The projection of the 2D spectrum with a bandwidth of 10 keV is also shown.

system must be constant for NAA samples with different activities for the preset pseudo coincidence time window. The expected activities of a sample in NAA are as follows:

- 0.01 to 0.1 μCi for long half-life elements.
- 1 to several μCi for medium half-life elements.
- 10-20 μCi for short half-life elements.

We consider the upper case and assume that the activity is 20 μCi. This activity is equivalent to 7.4×10^5 d.s^{-1} (7.4×10^{-1} d.μs^{-1}). So, the coincidence time window (5 μs) is large enough to record the events without any loss if seen by a detector.

Assume that E_1 and E_2 are the recorded energy by detectors #1 and #2, respectively. A 5500×5500 matrix array of E_1 and E_2 events is built-up. Figure 5 shows the 2D pseudo coincidence spectrum of the gamma-rays. Due to limitations in the RAM of our computer, we plot the data in the 270 to 370 keV region. The circles shown on the matrix diameter represent the background-free photopeak events. This region carries the most valuable information about the NAA experiment. The ridges parallel to the axis are Compton scattered (low energy sides) or pile-up events (high energy sides). To obtain the photopeak events a diagonal cut of the matrix with a bandwidth of 10 keV is selected. Figure 6 shows the projection of the 2D spectrum to the conventional 1D spectrum for gamma lines of 356 and 662 keV. As shown in Fig. 6, by separation of unwanted events such as Compton scattering, background, and pile-up, the peak to Compton ratio increased up to 10^4 in the 2D pseudo coincidence mode. Moreover, the energy resolution of the 2D spectrometer (RT) can be predicted by the resolution of each HPGe detector using Eq. (1) (Čížek et al., 2010):

$$R_T = \frac{1}{2}\sqrt{R_1 + R_2} \tag{1}$$

5 Conclusions

In the past decade, many efforts have been devoted to using Compton suppression systems for NAA. These systems are often very expensive and include complex nuclear electronics. In this paper, we switched from analog to digital gamma-ray spectroscopy to design a Compton suppressor system using conventional HPGe detectors. The results of our experiment confirm that the 2D gamma-ray spectroscopy using a list mode file can increase the peak to Compton ratio up to 10^4 and improves the spectrometer energy resolution. Moreover, due to the use of Pseudo coincidence data acquisition, no lead shielding is needed in the presented technique. Although significant improvements have been achieved using the 2D Compton suppresser system, this technique needs a long time of data acquisition (4 hours) to obtain enough data of photopeak events to project the 2D spectrum to a conventional histogram. Further to this work, we are going to initiate a series of NAA experiments using the presented technique to investigate the possible improvement of the detection limit in the NAA technique.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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