RESEARCHING ALGORITHMS FOR PROCESSING GAMMA SPECTRUM OF PVT DETECTOR

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Abstract

The study investigated algorithms for processing the gamma spectrum of PVT detectors. Various commonly used algorithms and algorithms were examined for handling the gamma spectrum of PVT detectors. During the research, the Energy Weighted Counts (EWC) algorithm was selected and implemented to process the gamma spectrum using simulated data of gamma scattering spectra on PVT detectors. Specifically, the energy-weighted algorithm was applied to effectively differentiate between the gamma spectra of three important isotopes Cs^{137}, Co^{60}, and I^{131}. The results of the study demonstrated the success in meeting the specified requirements, especially in selecting the optimal algorithm for identifying the three isotopes on the PVT detector, all achieved through the utilization of the GEANT4 simulation software. This research not only provided a detailed insight into gamma spectrum processing but also proposed an effective algorithm using simulation software to explore and evaluate algorithms on PVT detectors. This marked a significant step in the research and development within this field..

Keywords: gamma spectrum, PVT detectors, EWC algorithm, GEANT4 simulation, isotope Identification.

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1. Introduction

The optimization and enhancement of Radiation Portal Monitors (RPMs) employing Polyvinyl Toluene (PVT) scintillators for detecting ionizing radiation from radioactive sources in transported goods are crucial for improving their efficiency and reliability. The PVT detectors are utilized in these applications because of their cost-effectiveness and efficient detection capabilities. However, their performance is often hampered by inherent limitations such as low charge density, which leads to reduced photoelectric effects and suboptimal energy resolution (ITDB, 2020). This study aimed to address these limitations by proposing the implementation of the Energy Weighted Counting (EWC) algorithm, which is designed to improve the resolution and discrimination of radioactive isotopes in the gamma spectrum detected by PVT detectors (Siciliano et al., 2020). The EWC algorithm works by weighting the counts in each energy bin by the energy of that specific bin, thereby enhancing the clarity of gamma spectra and facilitating the identification of different isotopes. This method is particularly effective in transforming broad Compton edges into narrow, sharp peaks, thus improving isotope discrimination. The research employed Monte Carlo simulations, specifically using the Geant4 toolkit, to accurately model the radiation detection processes within RPMs. An extended Gaussian peak formula was utilized to closely replicate the actual spectrum shape observed in experimental data. This simulated spectrum then served as the basis for applying the EWC algorithm. In this study, Geant4 simulations were employed to describe the radiation detection process of the PVT detector. The elements composing the detector materials, such as Polyvinyl Toluene, Teflon, and air, were meticulously defined in the simulation. The PVT detector was encapsulated in a Teflon layer to prevent external light interference, and the surrounding environment was modeled to ensure simulation accuracy.

The simulation results showed that the gamma spectrum obtained from PVT simulations closely matched empirical observations, validating the accuracy of the simulation models. The application of the EWC algorithm significantly enhanced the system's capability to distinguish between different radioactive isotopes, such as Cs-137, Co-60, and I-131, as illustrated by the sharp peaks in the processed gamma spectra. This improvement reduced the incidence of false alarms and improved the overall filtering performance of the RPM (Lee et al., 2020). In addition to the EWC algorithm, other advanced algorithms such as the Neural Network (NN) algorithm and the Spectral Deconvolution (SD) algorithm were investigated for their potential to enhance the capabilities of PVT detectors. The NN algorithm involves training a computer system to differentiate between various radioactive isotopes based on previously analyzed spectral libraries, offering fast processing times but requiring extensive sample libraries for reliable operation. The SD algorithm aims to reverse the effects of performance degradation due to instrument errors, significantly enhancing the resolution of scintillation crystals like NaI(Tl) and CsI(Tl) (Connolly & Martin, 2021).

The study concluded that the EWC algorithm is an effective approach for processing the gamma spectrum in RPMs utilizing PVT detectors. By enhancing isotope discrimination capabilities, increasing sensitivity, and reducing false alarms, the EWC algorithm improves the operational efficiency and reliability of RPM systems in real-world applications. Future research could focus on further optimizing these algorithms and exploring their integration with advanced detection technologies to enhance security measures (Leroy & Rancoit, 2009; Ely et al., 2006).

2. Theoretical basis and methodology

2.1. Algorithm for Energy Windows

In some typical spectroscopy measurement devices, the energy range is divided into multiple channels, for example, 512 channels or 1024 channels. Due to the inherent characteristics of plastic scintillators and the poor energy resolution of plastic scintillation material, only a limited number of energy windows can effectively assess energy information. The optimal number of windows depends on the size and purity of the plastic material (such as light attenuation and light reflection effects), as well as the specific objectives of the measurement device. When determining a particular isotope, two windows are used one window immediately adjacent to the Compton scatter edge and another window for all other values. However, in practical applications, most radioactive sources emit various energy levels, and many applications require the identification of multiple isotopes. Therefore, measurement systems are designed with more windows. Statistical data from measurements are valuable, and since measurements for transportation means are typically brief, the limits the number of windows allowed for practical measurements are not yet perfected.

The pulses from Photomultiplier Tubes (PMT) are directed to the corresponding discriminative circuits for each window and sorted by pulse height. Commercial systems currently offer from two to eight energy windows. Window division for the narrow energy range of plastic scintillation detectors is more complex compared to NaI(Tl) detectors. Currently, the Energy Windows (EW) is a fundamental function of the RPM alert device, which signals an alert when a vehicle passes a certain threshold compared to the background signal (National Urban Security Technology Laboratory for the U.S. Department of HomelandSecurity, 2015). The EW utilizes information in the Compton scatter energy spectrum corresponding to different gamma energies. The energy spectrum is divided into multiple regions (windows), and the relative ratio between the regions caused by Compton edges can provide a preliminary estimate of the energy region of the incident gamma rays. However, the limitation of the EW algorithm is the difficulty in distinguishing isotopes with equivalent energies, such as Co^{60} (1.17/1.33 MeV) and K^{40} (1.461 MeV) (Euan L. Connolly et al, 2021).

2.2 Neural Network Algorithm

The Neural Network (NN) algorithm was investigated for its application in the detection of radiation sources using PVT technology. This technique involves training a computer system to accurately differentiate between various radioactive isotopes based on previously analyzed spectral libraries. The system learns from data (sample libraries) of the energy spectra of isotopes that need to be distinguished from other isotopes in the library. Ultimately, the system can analyze the energy spectrum of a detected source with the sample energy spectrum to produce results. The advantage of the NN algorithm is its fast processing time. The drawback is the requirement for a large number of sample libraries to build a reliable database during the learning period for the algorithm to operate effectively. Spectra not present in the sample library may not be accurately detected, and the isotope discrimination capability of the system is limited by the resolution of PVT. Additionally, the accuracy of the NN algorithm depends heavily on the accuracy of the simulation model during the learning phase and various shielding factors. The application of the NN algorithm to PVT systems is still a relatively new field, requiring further in-depth research in the future.

2.3 Spectral Deconvolution Algorithm

The Spectral Deconvolution (SD) algorithm is designed to reverse the effects of performance degradation due to errors in the instrument system and compensate for them appropriately. Applying this technique to scintillation crystals like NaI(Tl) and CsI(Tl) has proven successful in significantly enhancing the resolution of the measuring device. This technique has contributed to improving the Full Width at Half Maximum (FWHM) from 12% at 662 keV in the raw spectrum of a 3”x3” NaI(Tl) detector to 3% (Meng and Ramsden, 2000). The advantages of the SD algorithm for PVT have been studied, markedly increasing the capabilities of PVT for spectral analysis. Isotope identification techniques have also been developed to utilize these enhanced capabilities, as well as systems for classifying isotopes. Uncertain isotopes can be categorized based on their similarities in their spectra. The total energy spectrum generated from a gamma radiation source is a component of the gamma ray spectrum combined with the feedback function of the gamma ray detection device. By calculating the response function of the detection device, the gamma ray spectrum can be inversely engineered from the energy spectrum. To achieve this, the response function must be calculated for each individual detection device since each device has unique characteristics. The gamma spectrum decoding process is an advanced data processing technique that can be implemented through standalone software or with the support of dedicated hardware. A dedicated computer is required to perform the necessary iterative process of raw energy spectrum deconvolution.

2.4 Energy Weighted Counts Algorithm

The EWC is an approach in which the count in each energy bin is multiplied by the energy of that specific bin. The formula for the EWC is expressed as follows:

$$C_K = C_i \times E_i \tag{1}$$

Here, C_i represents the count in the energy bin E_i initially, and C_K is the count afterward. This aids in distinguishing the gamma spectra of radioactive isotopes such as Cs^{137}, Co^{60}, and I^{131}.

To precisely determine the gamma energy with PVT, the research team proposed an isotope discrimination algorithm using EWC in their previous study. The objective of this research was to evaluate the principle through Monte Carlo simulations and experiments, demonstrating that gamma-emitting nuclei with similar Compton edge energies could be differentiated by transforming broad Compton edges into narrow, sharp peaks using EWC. However, in this study, the EWC was applied. It is a relatively effective and accessible that meets the requirements for classifying isotopes. The research team approached this through GEANT4 simulations, yielding some promising results.

3. Results

3.1. The Monte Carlo simulation was employed to model the configuration of the simulation detector system

The Monte Carlo is widely employed in nuclear applications such as shielding, radiation transport, and neutron physics analysis. The Monte Carlo refers to a statistical approach where the expected characteristics of particles (such as particle fluence) are estimated by sampling a large number of histories for each particle, with their trajectories simulated by a computer. In this study, the Geant4 software, utilizing the Monte Carlo simulation , was employed to describe the radiation detection process of the detector.

Firstly, the elements composing the material were declared in the Geant4 simulation. Subsequently, the material constituting the PVT detector, Polyvinyl Toluene, was specified from the Geant4 NIST material library (GEANT4 Simulaton Toolkit, 2022). The density of Polyvinyl Toluene declared in the simulation was 1.032 g/cm^3 (primarily composed of C and H). Additionally, a layer of Teflon was used to encapsulate the Polyvinyl Toluene crystal, preventing external light from entering the detector. Moreover, the material surrounding the PVT detector, representing air, was declared to ensure the accuracy of the simulation (Figure 1 describes the simulation configuration of the PVT detector).

The materials polyvinyl toluene, Teflon, and air were declared as follows:

```
G4Element* C = NISTManager->FindOrBuildElement("C");
G4Element* N = NISTManager->FindOrBuildElement("N");
G4Element* Ar = NISTManager->FindOrBuildElement("Ar");
G4Element* O = NISTManager->FindOrBuildElement("O");
G4Element* F = NISTManager->FindOrBuildElement("F");
// Dry Air
Air = new G4Material("Air", 0.001205*g/cm3, 4, kStateGas);
Air->AddElement(C, 0.000124);
Air->AddElement(N, 0.755268);
Air->AddElement(O, 0.231781);
 Air->AddElement(Ar, 0.012827);
// Polyvinyl Toluene
PVT = NISTManager -> FindOrBuildMaterial ("G4_PLASTIC_SC_ VINYLTOLUENE");
// Teflon
Teflon = new G4Material("TeflonTape", 2.25*g/cm3, 2, kStateSolid);
Teflon->AddElement(C, 0.2402);
Teflon->AddElement(F, 0.7598);
```

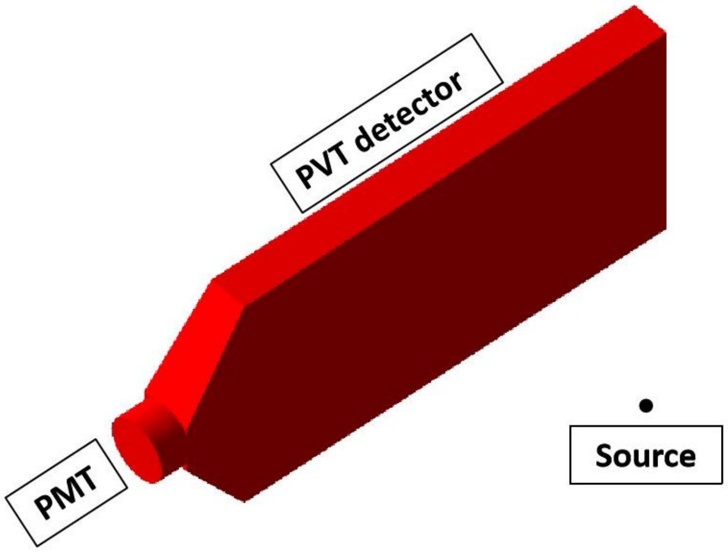

Figure 1. The simulation configuration of the PVT detector

After the materials of the detector and the outer Teflon layer were specified, a PVT detector with dimensions of 800 × 300 × 50 mm and a 1.5 mm thick Teflon layer, along with their positions in the air, were defined as follows:

```
G4VSolid* WorldSolid = new G4Box("WorldSolid",box_world_x , box_world_y, box_world_z);
G4LogicalVolume* WorldLog = new G4LogicalVolume(WorldSolid, Air, "WorldLogical");
WorldPhys = new G4PVPlacement (0,G4ThreeVector(0,0,0), WorldLog, "WorldPhys", 0, false, 0, true);
G4Box* PVTCrystalBox = new G4Box("PVTBox", x_crystal/2, y_crystal/2, z_crystal/2);
PVTCrystalLog = new G4LogicalVolume(PVTCrystalBox, PVT, "PVTLog");
PVTCrystalPhys = new G4PVPlacement(0, G4ThreeVector(0,0,0), PVTCrystalLog,
"PVTPhys",WorldLogical,false,0,true);
G4Box* TeflonWrapping = new G4Box("Tepflon", x_crystal/2 + teflon_tape_thickness, y_crystal/2 +
teflon_tape_thickness , z_crystal/2 + teflon_tape_thickness);
G4SubtractionSolid* TeflonWrappingSolid = new G4SubtractionSolid("TeflonWrappingTape", TeflonWrapping,
PVTCrystalBox);
G4LogicalVolume* TeflonWrappingLog = new G4LogicalVolume ( TeflonWrappingSolid, Teflon,
"TeflonWrappingLog");
TeflonWrappingPhys = new G4PVPlacement(0, G4ThreeVector(0,0,0), TeflonWrappingLog,
"TeflonWrappingPhys", WorldLogical, false, 0, true);
```

The list of physics processes used in Geant4 for describing the internal processes within the PVT detector and the gamma decay processes of radioactive nuclei includes:

G4EmLivermorePhysics: Used to describe electromagnetic interactions of gamma with the material.

G4Decay: Employed to model the decay process of radioactive nuclei.

G4RadioActiveDecay: Utilized for modeling the decay process and emission of gamma rays from radioactive nuclei.

The list of physics libraries used in Geant4 is declared as follows:

```
RegisterPhysics(new G4EmStandardPhysics_option4(verboselvl));
RegisterPhysics(new G4DecayPhysics(verboselvl));
RegisterPhysics(new G4RadioactiveDecayPhysics(verboselvl));
```

In addition to declaring the physics lists, specifying the gamma range within the material is crucial. This helps reduce the processing time of Geant4 with possible secondary processes occurring inside Geant4. The gamma, electron, and positron ranges are declared in the simulation as follows:

```
SetCutValue(2.0 * cm, "e-");
SetCutValue(2.0 * cm, "e+");
SetCutValue(2.0 * cm, "gamma");
```

Source of Gamma Emission in Simulation: The gamma emission source used in Geant4 simulation includes the sources Cs^{137} (A = 137, Z = 55), Co^{60} (A = 60, Z = 27), and I^{131} (A = 131, Z = 53). The variation between gamma emission sources is achieved by modifying the Z and A values in the Geant4 simulation. These sources are declared as point sources with isotropic emission angles and are placed approximately 30 cm away from the detector. The number of events of interest for each simulation is around 10^9 events, ensuring statistical significance. The gamma emission sources are declared as follows:

```
if(ParticleGun -> GetParticleDefinition() == G4Geantino::Geantino())
{G4int Z = 53;
G4int A = 131;
G4double ionCharge = 0.*eplus;
G4double excitEnergy = 0.*keV;
G4ParticleDefinition* ion = G4IonTable :: GetIonTable() -> GetIon (Z, A, excitEnergy);
ParticleGun -> SetParticleDefinition(ion);
ParticleGun -> SetParticleCharge(ionCharge);}
```

```
G4double phi = G4RandFlat::shoot(0.,2.*3.1415926);
G4double theta = G4RandFlat::shoot(0.,0.5*3.1415926);
G4double ypos = 0;
G4double zpos = detector->GetSampleDistance();
G4double xpos = 0;
G4ThreeVector position_source(xpos,ypos,zpos);
G4double x_momentum = sin(theta) * cos(phi);
G4double y_momentum = sin(theta) * sin(theta);
G4double z_momentum = cos(theta);
G4ThreeVector momentum_source (x_momentum, y_momentum, z_momentum ) ;
ParticleGun -> SetParticleMomentumDirection(momentum_source);
ParticleGun -> SetParticlePosition(position_source);
ParticleGun -> GeneratePrimaryVertex(anEvent);
```

The width of the energy peak To ensure that the obtained energy spectrum of the PVT detector matches those observed in experiments, the extended Gaussian peak formula is applied, similar to the formula used in MCNP:

$$\mathrm{FWHM}(E) = a + b\sqrt{E + cE^2} \quad (2)$$

Here, FWHM is the full width at half maximum of the energy peak, and the parameters a, b, c are tuning parameters used in the simulation, with E representing the energy at the peak (MeV). The parameters (a, b, c) employed in this simulation are (0, 0.05086, 0.30486).

3.2 Simulation Results of Spectrum Processing Using the Energy Weighted Counts Algorithm

After simulating 10^9 events for each radioactive source, namely Cs^{137}, Co^{60}, and I^{131} placed at a distance of 30 cm, the gamma spectra obtained from these sources at the PVT detector are illustrated in Figures 2, 3, and 4. It can be observed that the gamma spectra obtained from the three sources Cs^{137}, Co^{60}, and I^{13} perfectly match the typical spectrum shapes observed in experiments. Subsequently, the energy-weighted counts algorithm was applied to the obtained spectra, as shown in Figure 5.

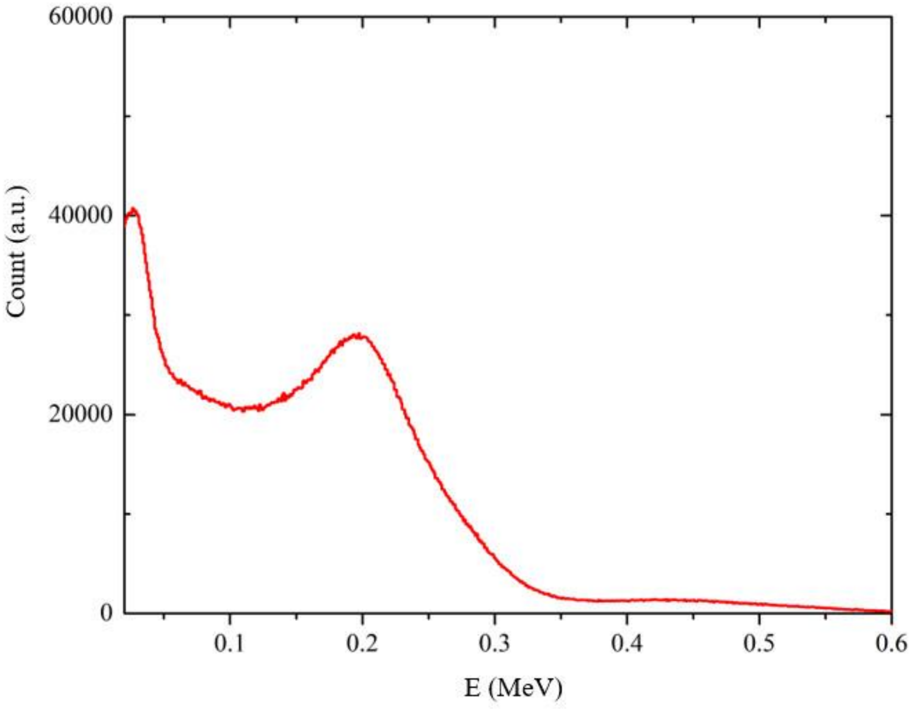

Figure 2. Gamma spectrum of I^{131} obtained from PVT simulation

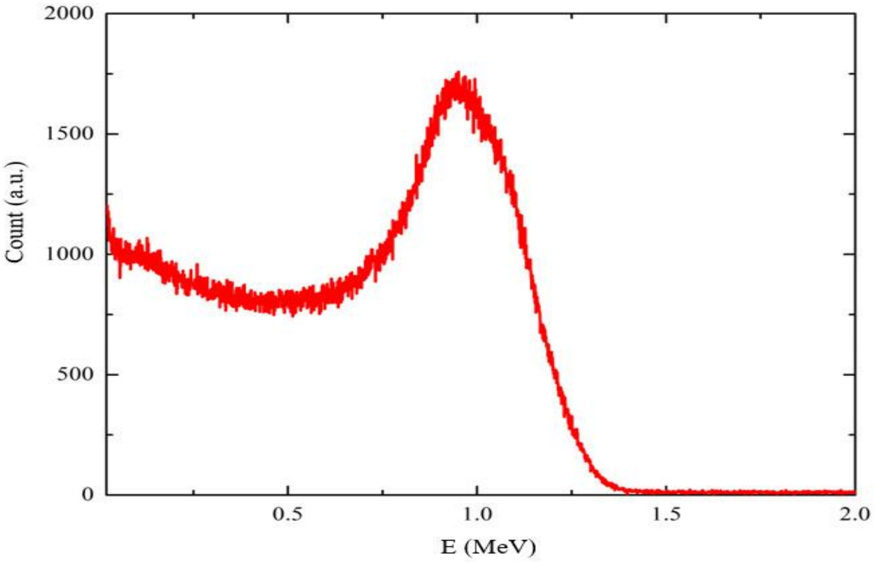

Figure 3. Gamma spectrum of Co^{60} obtained from PVT simulation

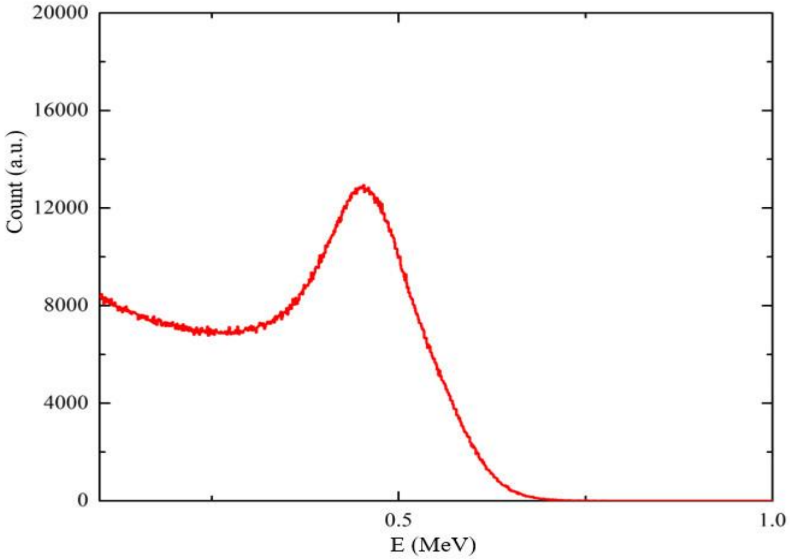

Figure 4. Gamma spectrum of Cs^{137} obtained from PVT simulation

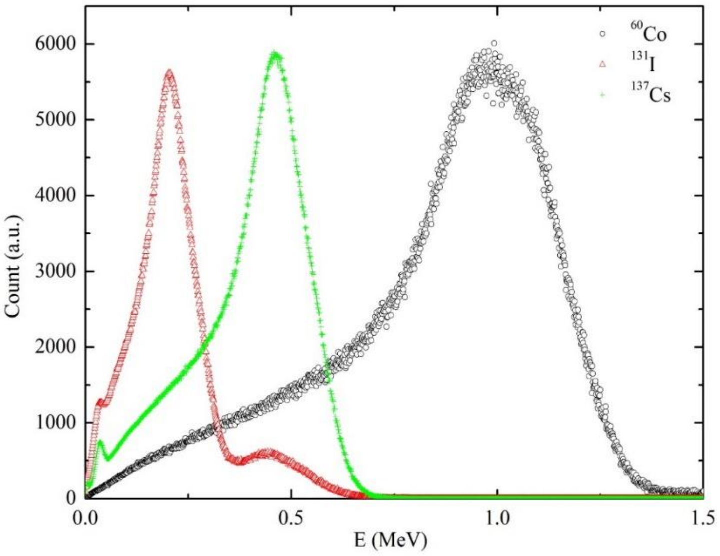

Figure 5. Successive gamma spectra of the sources Cs^{137}, Co^{60}, and I^{131} after applying the EWC algorithm

After the application of the EWC, the gamma spectrum configurations are depicted in Figure 5. As depicted in the figure, it is discernible that the gamma spectra corresponding to the three isotopes Cs^{137}, Co^{60}, and I^{131} exhibit complete separation and are distinctly identifiable. Hence, the EWC facilitates the discernment of gamma spectrum configurations for the three isotopes Cs^{137}, Co^{60}, and I^{131}.

4. Conclusion

Throughout the course of our research, significant strides have been made in the following areas gamma spectra processing. To achieve this systematically explored various widely and algorithms designed for the nuanced processing of gamma spectra originating from PVT detectors. The strategic choice was made to employ the EWC algorithm for the processing of gamma spectra, leveraging simulated data derived from gamma scattering spectra on the PVT detector. The application of the Energy Weighted Counting, in conjunction with its algorithm, yielded successful differentiation among the gamma spectrum shapes associated with the three isotopes Cs^{137}, Co^{60}, and I^{131}. This notable achievement not only fulfilled the project's requirements but also underscored the optimal selection of algorithms for the precise identification of these three isotopes. In conclusion, our research has substantially contributed valuable insights to the realm of gamma spectra processing from PVT detectors. The judicious application of the EWC algorithm has proven to be highly effective, aligning seamlessly with the specific objectives of our study, particularly in the discrimination between Cs^{137}, Co^{60}, and I^{131} gamma spectrum shapes.

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