Hindawi
Science and Technology of Nuclear Installations
Volume 2022, Article ID 5718920, 8 pages
https://doi.org/10.1155/2022/5718920

Research Article

Coincidence Summing Factor Calculation for Volumetric γ-ray Sources Using Geant4 Simulation

Dalal Abdullah Aloraini,[1] Mohamed Elsafi ,[2] Aljawhara H. Almuqrin,[1] and M.I. Sayyed[3]

[1]*Department of Physics, College of Science, Princess Nourah Bint Abdulrahman University, P.O.Box 84428, Riyadh 11671, Saudi Arabia*
[2]*Physics Department, Faculty of Science, Alexandria University, Alexandria 21511, Egypt*
[3]*Department of Physics, Faculty of Science, Isra University, Amman 11622, Jordan*

Correspondence should be addressed to Mohamed Elsafi; mohamedelsafi68@gmail.com

Received 11 April 2022; Revised 27 June 2022; Accepted 13 July 2022; Published 8 August 2022

Academic Editor: Hesham Zakaly

Geant4 simulation was applied to correct the coincidence summing (CS) effect in detecting a volumetric γ-ray sources, and this technique was applied to a^{152}Eu standard sources. The radioactive sources were a liquid cylindrical, rectangular, and Marinelli beaker shapes of different volume for each one. Radionuclide track (RT) including coincidence summing and monoenergetic track without coincidence summing. The results obtained from two approaches compared with the experimental data and the modified KORSUM code for cylindrical γ-ray source. The comparison showed that the adopted method in this investigation is useful for coincidence summing corrections for a voluminous γ-ray sources.Moreover, this technique requires far less computation time than the techniques that depend on the calculation of total efficiency.

1. Introduction

To measure and analyze radioactive materials we need a high-resolution detector which is HPG, but when it is used to detect photons, the possibility of detecting more than one photon at the same time is possible especially with a multi-energy source, thus the CS effect is involved. The effect of CS usually loses peak count, so, corrected counts are needed to correct due to the CS effect. This problem exists when the distance between the radioactive sample (a source or environmental sample or nuclear materials that emit multiline radiation) and the detector is small. Also, if the size of the detector is large, the absorption of photons will be higher and therefore the CS effect will be present. ICRM was the first to report this effect in the 1980s [1].

The correction factor (CF) of the CS depends on the calculation of peak-total efficiency or direct total efficiency and that is discussed by many authors by different methods and techniques such as total efficiency calculation using the Monte Carlo code [2], matrix form equations to calculate the total efficiency [3, 4], the GESPECOR code [5, 6], the code KORSUM and modifiedKORSUM code [7, 8], and the EFFTRAN code using the efficiency transfer technique or ETNA program [9, 10]. Total efficiency calculations sometimes become more difficult, especially for volumetric radioactive sources, where the changing of source or detector shape needed different complicated equations lead to less accuracy and long time for calculations, so the current technique determine the CS correction factor for different geometric sources using two options of GS without total efficiency calculation.

Kajimoto et al. calculated the CS correction for 24N point source in case of close detector-to-source geometry using EGS5 code Moto Carlo simulation [11]. Yucel et al. used a semiempirical formula to calculate the true CS corrections based on the total efficiency calculation and this method can be applied without any difficulty to Ge detectors for coincident nuclide [12]. Taibi et al. used the MCNP5 code

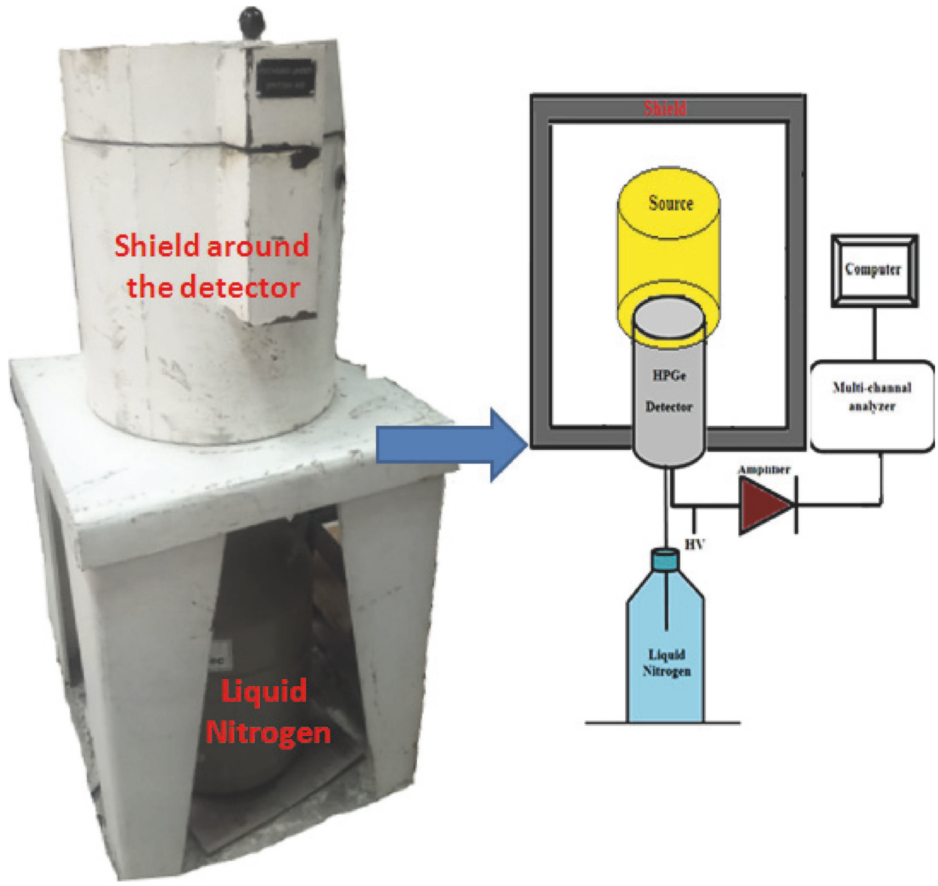

Figure 1: Illustration of the experimental setup.

Monto Carlo simulation to evaluate the true CS corrections for volumetric Eu-152 sources in gamma-ray spectroscopy, the results were confirmed with the TrueCoinc software, and a good agreement was obtained [13]. The problem of true CS correction for each of the point and volumetric sources was investigated through many previous works especially with the use of environmental sources or samples with low activity [14–25].

This work aims to utilize the Geant4 simulation (GS) to evaluate the correction factor for different volumetric ^{152}Eu sources (cylindrical and Marinelli beaker) using two options: monoenergetic and radionuclide tracks. In monoenergetic track (MT), the primary events have a monoenergetic energy while in a radionuclide track (RT), the complete decay scheme must be taken in the simulation and the primary events have multilines based on the decay scheme of radioactive sources.

2. Experimental Work

In this work, a coaxial HPGe spectrometry (Figure 1) has been used; its volume approximately was 110 cm^3 with a wide range of energy from 40 kV to 10 MeV for γ-ray detection. The detector dimensions are tabulated in Table 1. As mentioned in the radioactive sources used as shown in Figure 2, different volumetric sources with different shapes filled with radioactive liquid, the activity of them referred to 15 Sep 1989 are tabulated in Table 2. The detector efficiency and energy was calibrated by using radioactive two point sources (Cs-137, Co-60, and Eu-152) before the measurement.

Table 1: Main technical characteristics of HPGe detector provided by the company.

Crystal diameter	48 mm
Crystal length	54.5 mm
End cap distance	5 mm
Entrance window	1.5 mm
Dead layer	0.5 mm
The detector relative efficiency	24%
The resolution (FWHM) at 1.33 MeV	1.95 keV

The measured time was too long to obtain high and sufficient counts under each peak (see Figure 3). The analysis of the spectrum is performed by the region of interest (ROI) selecting. This is defined by ROI or the area of interest. The determination of ROI by choosing the start and end channels of the peak as required. The analysis using Genie-2000 software provides integrated count calculation as well

Figure 2: The radioactive volumetric sources used in the measurements.

Table 2: The characteristics of different volumetric sources used in practical measurements.

Items	Source description			
	Cylindrical sources		Marinelli beaker sources	
Code	C1	C2	M1	M2
Volume (mL)	400	500	800	1000
Height (mm)	41.69	52.25	Of well = 40	
Radius (mm)	56.94		Maximum = 56.8 Minimum = 38.5	
Wall thickness (mm)	2.03		2.7	2.2
Jar material	Polypropylene			
Activity (kBq)at 19 Sep 1989	48.1 ± 6			

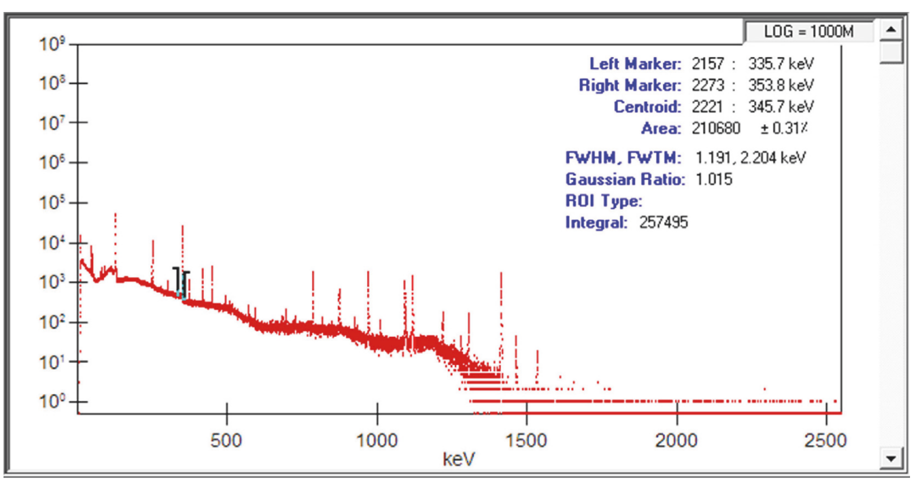

Figure 3: The experimental spectrum using ^{152} EU volumetric sources in log-scale measured by HPGe detector.

as the background count calculations depend on ROI. In addition, the Genie-2000 software has a big facility to carry out automatic search as well as peak area calculations using the changing in peak fitting using an interactive fit-peak.

The uncorrected measured photopeak efficiency of a certain energy (E) was evaluated by the following equation:

$$\varepsilon_e(E) = \frac{N_e(E)/t}{P_\gamma(E) A e^{-\lambda T}}, \quad (1)$$

where, N_e(E) is the net measured counts of full-energy peak after subtracted by the background at energy E, t is the actual time for experimental measurement, P_γ(E) is the probability of photon emission at a given energy E, A is the standard radionuclide activity in Bq, $e^{-\lambda T}$ represent the decay factor, where T is the production time and λ represent the decay constant. The uncertainty in the full-energy peak (FEP) efficiency is denoted by $\sigma\varepsilon$, and calculated by the following expression:

$$\sigma_\varepsilon = \varepsilon \cdot \sqrt{\left(\frac{\partial \varepsilon}{\partial A}\right)^2 \cdot \sigma_A^2 + \left(\frac{\partial \varepsilon}{\partial P}\right)^2 \cdot \sigma_P^2 + \left(\frac{\partial \varepsilon}{\partial N}\right)^2 \cdot \sigma_N^2}, \quad (2)$$

where, σ_N, σ_P, and σ_A, are the associated uncertainties with the net count rate N, emission probabilty P, and activity A, respectively. The corrected measured FEP efficiency is calculated by the following expression:

$$\varepsilon_t = \varepsilon_e \cdot CF, \quad (3)$$

where CF is the correction factor of the CS effect.

3. Geant4 Simulation (GS)

GS is a process of simulated radiation (photons, neutrons, protons, or electrons) and interact during materials. These simulations include multiple functions, including physical processes, geometry, analysis, and tracking. Physical processes contain multiple functions, including electromagnetic operations, interactions of radiation, and analyzes [17]. The simulation of the detector and the source is made in a large volume of the "world volume" as shown in Figure 4. Figure 4 represents the simulation of HPGe detector and cylindrical source and collimator. In this work, the simulated radiation was γ-ray photons with a radionuclide, including decay scheme (multiple energies) or using monoenergetic option (monoenergetic photons).

3.1. Radionuclide Track (RT). The decay scheme of radionuclides represents the primary events, where the decay scheme of Eu-152 source was simulated in details, including all energies emitted from this source. These energies were interacted with the HPGe crystal and the results of all interaction types (photoelectric, compton, and pair production) registered in a histogram file. After simulating the program, the run occurred with a number of events at least 10^7 events and the generated spectrum as shown in Figure 5 was obtained using root software. Gaussian distribution was used to fit each peak in the spectrum to calculate the area under this peak. The simulated FEP efficiency using the radionuclide track at certain energy, denoted by ε_1 and its equation is as follows:

$$\varepsilon_1 = \frac{\text{Area under the peak}}{\text{Primary events}^* I_\gamma}. \quad (4)$$

3.2. Track 2: Monoenergetic Track (MT). Monoenergetic gamma rays represent the primary events, where a single energy from Eu-152 source was simulated in details. These events with the sample energy were interacted with the HPGe crystal and the results of all interaction types (photoelectric, compton, and pair production) registered in a histogram file. After simulating the program, the run occurred with a number of events at least 10^7 events and the generated spectrum as shown in Figure 6 was obtained using root software. Gaussian distribution was used to fit each peak in the spectrum to calculate the area under this peak. To limit the error within 1%, a number of particles (primary events) 10^7 are used in each simulation, otherwise the error has well gotten higher as the number goes less [15, 16]. The simulated FEP efficiency using the monoenergetic track at certain energy, denoted by ε_2 and its equation is as follows:

$$\varepsilon_2 = \frac{\text{Area under the peak}}{\text{Primary events}}. \quad (5)$$

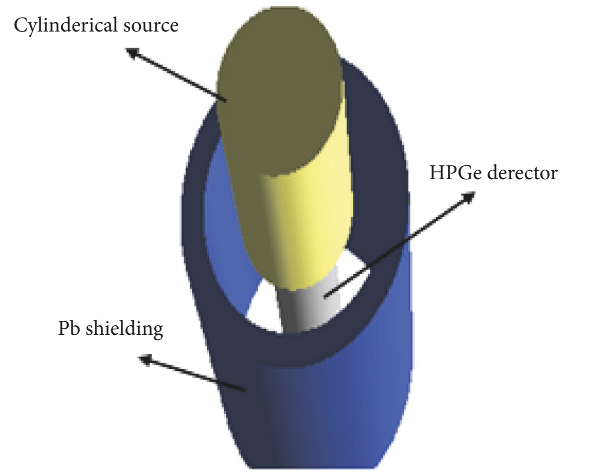

Figure 4: A model of radioactive cylindrical source and HPGe detector shielded by lead.

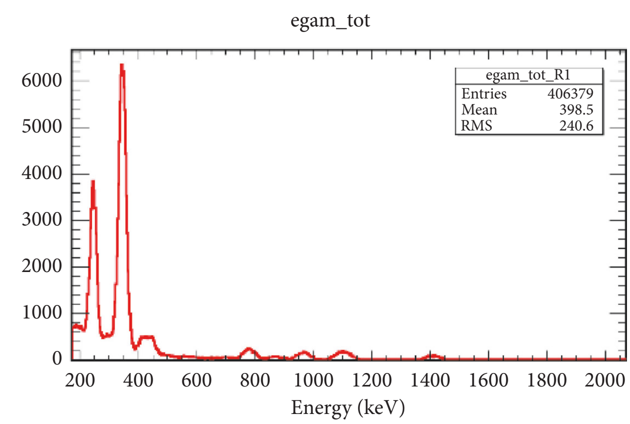

Figure 5: The simulated spectrum in using radionuclide decay shows the number of counts at different γ-ray energies.

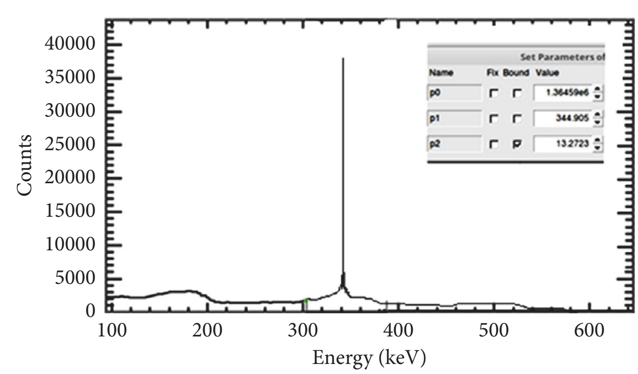

Figure 6: The simulated spectrum at 344 keV using Gaussian distribution in monoenergetic track.

3.3. CF Calculation. The correction factor of the CS can be estimated from the two options, where the radionuclide track contains multiple lines and is detected at the same time, so the possibility of coincidence summing exists, and in the second track (MT), just a monoenergetic line was detected or simulated so there is no coincidence summing.

Table 3: The calculated photopeak area and its uncertainty for two different tracks as well as the full-energy peak efficiency for both the options.

Energy (keV)	RT		MT		ε_1	ε_2
	Area	Uncertainty	Area	Uncertainty		
121.78	366907	5.98E + 02	412000	7.17E + 02	0.014676	0.01648
244.7	248693	4.24E + 02	290250	6.76E + 02	0.009948	0.01161
344.28	225366	3.91E + 02	233750	5.98E + 02	0.009015	0.00935
411.12	182760	3.51E + 02	200250	4.24E + 02	0.00731	0.00801
443.97	167838	3.17E + 02	191000	3.91E + 02	0.006714	0.00764
778.91	128199	3.01E + 02	135250	3.51E + 02	0.005128	0.00541
867.38	105589	2.89E + 02	123750	3.17E + 02	0.004224	0.00495
964.082	101021	6.71E + 02	112750	3.01E + 02	0.004041	0.00451
1085.84	100618	7.07E + 02	104250	2.89E + 02	0.004025	0.00417
1112.08	91091	7.17E + 02	100000	6.71E + 02	0.003644	0.004
1212.95	87196	6.76E + 02	92000	7.07E + 02	0.003488	0.00368
1299.15	80188	5.98E + 02	86250	7.17E + 02	0.003208	0.00345
1408.01	67732	4.24E + 02	75250	7.17E + 02	0.002709	0.00301

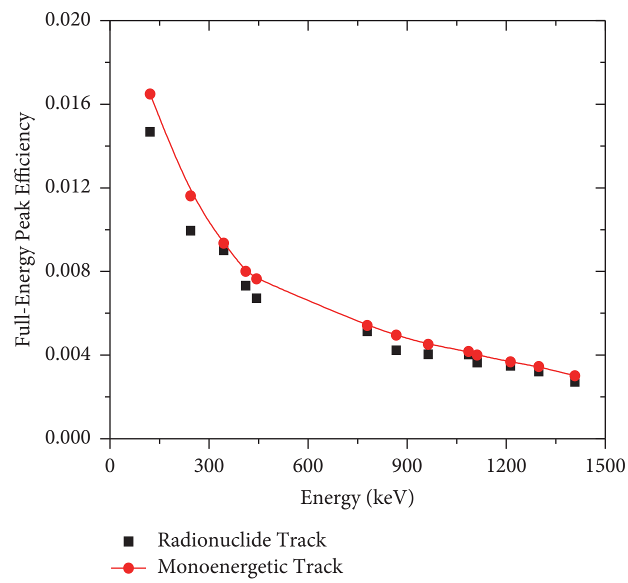

Figure 7: Comparison of ^{152}Eu full-energy peak efficiency calibration curve using two different tracks using cylindrical source of 1000 mL put at the top of the detector.

The correction factor calculated by the following equation is as follows:

$$CF = \frac{\varepsilon_2}{\varepsilon_1}. \quad (6)$$

4. Results and Discussion

First, the detector geometry and the radioactive source in [8] are modeled using the Geant4 code, where the detector crystal dimensions were 58.2 mm diameter and 79 mm length. The cylindrical source activity was 86.2 ± 1.5 kBq (date: 2013 May 1). The source is distributed uniformly inside a cylinder (100 mmφ, 149 mmH) filled with 0.1 M HCl and has an active volume of 1000 ml. The FEP efficiency was calculated by radionuclide and monoenergetic tracks, the net area under the peak was calculated and tabulated in Table 3, from this area and the number of primary events, the simulated FEP efficiency was calculated as shown in Figure 7. The FEP efficiency by using MT higher than the FEP efficiency by RT et al. discussed energies, where at 244.7 keV from 1000 ml cylindrical source, the FEP efficiency in by using MT was 0.01161, and the FEP efficiency by using RT was 0.009948, while at 1408.1 keV, the FEP efficiencies were 0.00301and 0.00271, respectively.

The CFwas calculated using equation 6 at different energies of the cylindrical ^{152}Eu radioactive source. The calculation of CF in the present simulated technique was

Table 4: Comparison between the present work and the modified KORSUM code and the deviation error between them.

Decay mode	Energy (keV)	Correction factor (CF)		Δ%
		Modified KORSUM [8]	Present work Geant4	
$EC(\beta^{+})$	121.78	1.1235	1.1229	−0.05
	244.7	1.1674	1.1671	−0.03
	443.97	1.1375	1.138	0.04
	867.38	1.17	1.172	0.17
	964.082	1.1154	1.1161	0.06
	1085.84	1.036	1.0361	0.01
	1112.08	1.0977	1.0978	0.01
	1212.95	1.0553	1.0551	−0.02
	1408.01	1.101	1.111	0.90
β^{-}	344.28	1.0377	1.0372	−0.05
	411.12	1.0961	1.0957	−0.04
	778.91	1.0551	1.055	−0.01
	1299.15	1.0756	1.0757	0.01

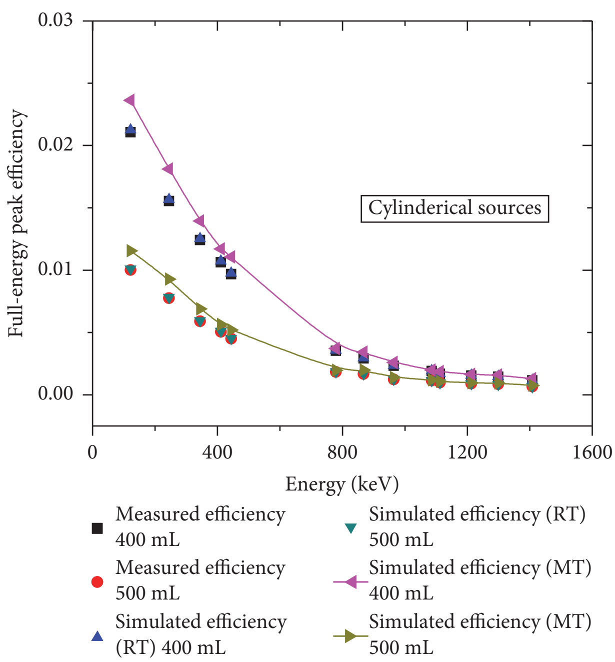

Figure 8: The experimental, simulated RT, and simulated MT full-energy peak efficiency for different cylindrical volumetric 152Eu sources as a function of different γ-ray energies as a function of different γ-ray energies.

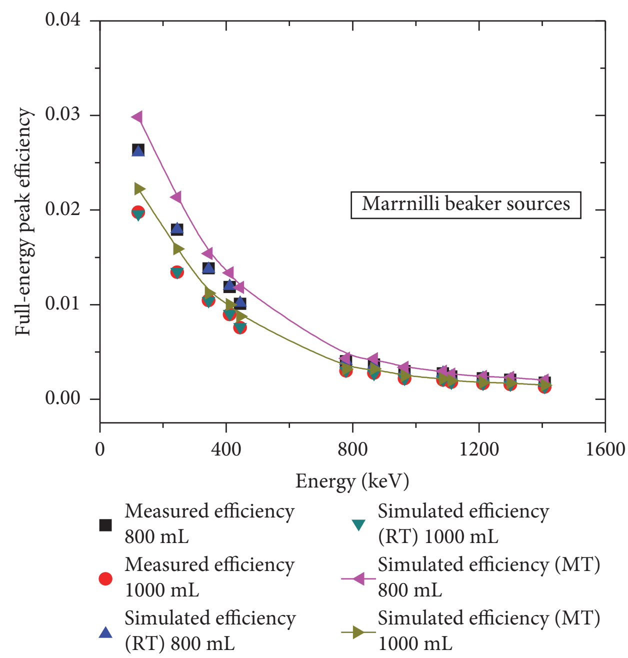

Figure 9: The experimental, simulated RT, and simulated MT full-energy peak efficiency for different Marinelli beaker volumetric ^{152}Eu sources as a function of different γ-ray energies.

compared with the modified KORSUM code [8], and the relative deviation (Δ%) was calculated by

$$\Delta\% = \frac{CF_{\text{Geant4}} - CF_{\text{KORSUM}}}{CF_{\text{Geant4}}}^{*} 100. \quad (7)$$

The results were tabulated in Table 4 and showed an excellent compatibility between the two methods. This indicated that this simulation technique using Geant4 is correct to calculate the CS corrections by simple and faster computations.

Secondly, the FEP efficiency was determined experimentally using cylindrical and Marinelli beaker radioactive sources with different volume according to section 2. This efficiency was compared with the simulated FEP efficiency by using monoenergetic and radionuclide tracks as shown in Figure 8 for cylindrical sources and Figure 9 for Marinelli beaker sources. The results indicated that the experimental and radionuclide simulated FEP efficiency have almost the values energy ranges, but the monoenergetic simulated FEP efficiency is higher, that is due to the existence of the CS in experimental and radionuclide simulated methods.

Finally, from the ratio between the monoenergetic and radionuclide simulated FEP efficiency, the correction factor of the coincidence summing effect for the HPGe detector using all present radioactive sources was calculated in Table 5. It is clear that the lower volume has the higher correction factor, for example, the correction factor for cylindrical source C1 = 1.143 (400 ml) and for C2 (500 ml) is 1.112, that

Table 5: The correction factor of the coincidence summing effect using different radioactive volumetric sources.

Energy	CF			
	C1	C2	M1	M2
121.78	1.143	1.112	1.143	1.136
244.7	1.188	1.156	1.188	1.181
344.28	1.160	1.116	1.119	1.078
411.12	1.104	1.091	1.117	1.106
443.97	1.147	1.133	1.160	1.147
778.91	1.063	1.042	1.071	1.061
867.38	1.171	1.158	1.188	1.189
964.082	1.115	1.103	1.131	1.133
1085.84	1.035	1.028	1.058	1.055
1112.08	1.086	1.089	1.119	1.108
1212.95	1.066	1.047	1.079	1.067
1299.15	1.097	1.077	1.107	1.091
1408.01	1.134	1.112	1.143	1.127

is due to the absorption of source container. If the volume increases, the self-absorption will increase, and then the correction factor will decrease.

5. Conclusion

The FEP efficiency of HPGe detector was calculated by radionuclide and monoenergetic tracks in Geant4 simulation using different shapes and volumes radioactive sources. The correction factor of CS was evaluated based on the two simulated efficiencies by fast and accurate way compared with evaluating the correction factor by total efficiency calculation. The FEP efficiency by using MT is higher than the FEP efficiency by RT et al. discussed energies, where at 244.7 keV from 1000 ml cylindrical source, the FEP efficiency in by using MT was 0.01161 and the FEP efficiency by using RT was 0.009948, while at 1408.1 keV, the FEP efficiencies were 0.00301and 0.00271, respectively. The CF was calculated for cylindrical and Marinelli beaker sources with different volumes. The lower volume has the higher correction factor in the same shape of radioactive sources, that is due to the self-absorption of the volumetric source.

Data Availability

All data are available in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors express their gratitude to Princess Nourah bint Abdulrahman University researchers supporting project number (PNURSP2022R57), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

References

[1] R. Jedlovszky, *Coincidence-Summing Corrections*, Report of the alpha-, beta-, gamma-ray spectrometry group of the International Committee for Radionuclide Metrology, Report OMH 8301 (ICRM-S-10), 1982.

[2] D. Arnold and O. Sima, "Total versus effective total efficiency in the computation of coincidence summing corrections in gamma-ray spectrometry of volume sources," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 248, no. 2, pp. 365–370, 2001.

[3] T. M. Semkow, G. Mehmood, P. P. Parekh, and M. Virgil, "Coincidence summing in gamma-ray spectroscopy," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 290, no. 2-3, pp. 437–444, 1990.

[4] M. Korun and R. Martinčič, "Coincidence summing in gamma and X-ray spectrometry," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 325, no. 3, pp. 478–484, 1993.

[5] O. Sima, D. Arnold, and C. Dovlete, "GESPECOR: a versatile tool in gamma-ray spectrometry," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 248, no. 2, pp. 359–364, 2001.

[6] D. Arnold and O. Sima, "Extension of the efficiency calibration of germanium detectors using the GESPECOR software," *Applied Radiation and Isotopes*, vol. 61, no. 2-3, pp. 117–121, 2004.

[7] K. Debertin and U. Schotzig, "Coincidence summing corrections in Ge(Li)- Spectrometry at low source-to-detector distances," *Nuclear Instruments and Methods*, vol. 158, pp. 471–477, 1979.

[8] E. T. Yoon, M. Y. Kang, I. J. Kim, G. M. Sun, and H. D. Choi, "Coincidence summing correction for a voluminous ^{152}Eu source," *Nuclear Engineering and Technology*, vol. 52, no. 6, pp. 1266–1270, 2020.

[9] T. Vidmar, G. Kanisch, and G. Vidmar, "Calculation of true coincidence summing corrections for extended sources with EFFTRAN," *Applied Radiation and Isotopes*, vol. 69, no. 6, pp. 908–911, 2011.

[10] M. C. Lepy, L. Ferreux, and S. Pierre, "Coincidence summing corrections applied to volume sources," *Applied Radiation and Isotopes*, vol. 70, no. 9, pp. 2137–2140, 2012.

[11] T. Kajimoto, S. Endo, N. Tat Thanh, and K. Shizuma, "Calculation of coincidence summing in gamma-ray spectrometry with the EGS5 code," *Applied Radiation and Isotopes*, vol. 95, pp. 53–58, 2015.

[12] H. Yucel, A. N. Solmaz, E. Ko¨se, and D. Bor, "A semi-empirical method for calculation of true coincidence corrections for the case of a close-in detection in *c*-ray spectrometry," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 283, no. 2, pp. 305–312, 2010.

[13] A. Taibi, G. M. Ishak-Boushaki, and Z. Idiri, "Coincidence summing corrections factors calculated for volume 152Eu sources in γ-ray spectromtery using Monte Carlo techniques," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 324, no. 2, pp. 687–696, 2020.

[14] M. García-Talavera, J. P. M. Laedermann, M. Décombaz, M. J. Daza, and B. Quintana, "Coincidence summing corrections for natural decay series in gamma-ray spectrometry," *Journal of Radiation and Isotopes*, vol. 54, pp. 769–776, 2001.

[15] M. García-Talavera, H. Neder, M. J. Daza, and B. Quintana, "Towards a proper modeling of detector and source characteristics in Monte Carlo simulations," *Applied Radiation and Isotopes*, vol. 52, no. 3, pp. 777–783, 2000.

[16] E. García-Torano, M. Pozuelo, and F. Salvat, "Monte Carlo calculations of coincidence-summing corrections for volume sources in gamma-ray spectrometry with Ge detectors,"

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 544, no. 3, pp. 577–583, 2005.

[17] G. Giubrone, J. Ortiz, S. Gallardo, S. Martorell, and M. C. Bas, "Calculation of coincidence summing correction factors for an HPGe detector using GEANT4," *Journal of Environmental Radioactivity*, vol. 158-159, pp. 114–118, 2016.

[18] R. G. Helmer and R. J. Gehrke, "Calculation of coincidence summing corrections for a specific small soil sample geometry," *Radioactivity and Radiochemistry*, vol. 8, no. 1, pp. 18–29, 1997.

[19] S. Hurtado, M. García-León, and R. García-Tenorio, "GEANT4 code for simulation of a germanium gamma-ray detector and its application to efficiency calibration," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 518, no. 3, pp. 764–774, 2004.

[20] M. Jurado-Vargas and A. Guerra, "Application of PENELOPE code to the efficiency calibration of coaxial germanium detectors," *Applied Radiation and Isotopes*, vol. 64, no. 10-11, pp. 1319–1322, 2006.

[21] G. J. McCallum and G. E. Coote, "Influence of source-detector distance on relative intensity and angular correlation measurements with Ge(Li) spectrometers," *Nuclear Instruments and Methods*, vol. 130, no. 1, pp. 189–197, 1975.

[22] D. M. Montgomery and G. A. Montgomery, "A method for assessing and correcting coincidence summing effects for germanium detector efficiency calibrations," *Journal of Radioanalytical and Nuclear Chemistry Articles*, vol. 193, no. 1, p. 71, 1995.

[23] J. Morel, B. Chauvenet, and A. Kadachi, "Coincidencesumming corrections in gamma-ray spectrometry for normalized geometries," *The International Journal of Applied Radiation and Isotopes*, vol. 34, no. 8, pp. 1115–1122, 1983.

[24] B. Quintana and F. Fernández, "An empirical method to determine coincidence-summing corrections in gamma spectrometry," *Applied Radiation and Isotopes*, vol. 46, no. 9, pp. 961–964, 1995.

[25] S. Rizzo and F. Tormachio, "Numerical expressions for the computation of coincidence-summing correction factors in gamma-spectrometry with HPGe detectors," *Applied Radiation and Isotopes*, vol. 85, pp. 555–560, 2010.