EXPERIMENTAL AND THEORETICAL MODEL OF N-TYPE HPGe DETECTOR FOR RADIOACTIVITY MEASUREMENTS

H. A. SAUDI[1], DALAL ABDEL AZIZ[2], MOHAMED ABDEL-ATY[3], MOSTAFA AZIZ[2], H. M. DIAB[2], SHAMS A.M. ISSA[4], ANTOANETA ENE[5,*], HESHAM M. H. ZAKALY[6,7,*]

[1] Department of Physics, Faculty of Science, Al-Azhar University ('Girls' Branch), Nasr City, Egypt
[2] Egyptian Atomic Energy Authority, Cairo, Egypt
[3] Egyptian Nuclear and Radiological Regulatory Authority, Cairo, Egypt
[4] Department of Physics, Faculty of Science, Tabuk University, Tabuk, Saudi Arabia
[5] INPOLDE Research Center, Department of Chemistry, Physics and Environment, Faculty of Sciences and Environment, Dunarea de Jos University of Galati, 47 Domneasca St., 800008 Galati, Romania
[6] Department of Physics, Faculty of Science, Al-Azhar University, Assiut Branch, 71524 Egypt
[7] Institute of Physics and Technology, Ural Federal University, Yekaterinburg 620002, Russia
[*] *Corresponding authors*: antoaneta.ene@ugal.ro; h.m.zakaly@gmail.com

Received December 30, 2024

Abstract. For precise measurements of High Purity Germanium (HPGe) detector and in order to estimate the Full Energy Peak Efficiency (FEPE), a theoretical procedure using the Monte Carlo simulation method was established in the Central Laboratory for Environmental Radioactivity Measurements Inter-comparison and Training (CLERMIT), as a continuation of previous work. A set of standard point sources (^{133}Ba, ^{137}Cs, ^{60}Co and ^{22}Na) was used, employing a 8 cm distance from the detector and appropriate detection geometry. MCNP5 input file was constructed and the detector was simulated. The detector efficiency curve was normalized to the volume efficiency curve using a KCl solution. Experimental results were compared with those simulated by MCNP5. Uncertainty analyses were performed to determine the effect of each operational and design parameter on the efficiency curve. Another set of point sources with different activities was used for method verification. For the method validation, an IAEA-326 certified reference sample was used for verification. A good agreement between the two methods was achieved, with discrepancies of less than 5% (ranging from -1.10 to 2.63%). Some selected environmental samples with different matrices were measured and the natural radioactivity concentration for ^{238}U-series, ^{232}Th-series and ^{40}K were determined.

Key words: Monte Carlo simulation, MCNP5 model, n-type HPGe detector, radioactivity.

DOI: https://doi.org/10.59277/RomJPhys.2025.70.302

1. INTRODUCTION

A variety of detectors are used in gamma spectrometry measurements for radionuclides characterization and environmental monitoring [1–9], as well as nuclear investigations [10] and safety studies [3, 11]. High-purity germanium (HPGe) detector is an efficient tool used to detect γ-rays emitted from natural or artificial sources

[1–3, 12]. The main advantage of this detector is its high resolution, which gives the HPGe detectors a priority to be employed for the analysis of complex gamma spectra obtained from various radionuclides [1–5, 13].

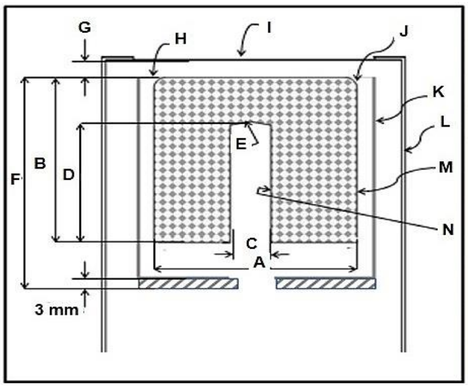
Many parameters should be considered to determine the activity concentration of different radioisotopes. Full Energy Peak Efficiency (FEPE) for the examined gamma energy line is one of the main parameters needed [6, 10, 14]. Also, several parameters describing the detector are necessary, such as the radius and length of the crystal, the position inside the end cap, and the thickness of the germanium dead layer [15]. The Monte Carlo method is well appropriate, requiring precise information about the detector characteristics and the sample. It is developed to perform the calibration and to determine the detector response for different matrices and geometries [13–18]. The Monte Carlo N-Particle (MCNP) is a robust computational method used for modeling the particle motion [4, 10, 11, 15, 19].

As an extension of previous work related to low-level radioactivity measurements [4], the present study aims to calibrate a coaxial n-type HPGe detector using the MCNP5 simulation code as a theoretical method. The detector was characterized and then modeled, and the efficiency curve was established for an energy range from 200 to 2000 keV. The results were verified using IAEA reference standard materials.

2. MATERIALS AND METHODS

2.1. DETECTOR SPECIFICATIONS

The characteristics of the ORTEC n-type coaxial HPGe detector, as given by the manufacturer, are shown in Fig. 1. The detector has a Be end-cap window (I) of thickness 0.5 mm. The detector crystal has a 68.5 mm length and 27.9 mm radius. A core cavity has a 4.55 mm radius and 59.8 mm height.



A – crystal diameter	55.8 mm
B – crystal length	68.5 mm
C – hole diameter	9.1 mm
D – hole depth	59.8 mm
G – space	4 mm
H – Al / Mylar	0.09 mm
I – Be	0.5 mm
K – Al	0.8 mm
L – Al	1 mm
M – Ge/B dead layer	0.3 micron
N – Ge/Li dead layer	700 micron

Fig. 1 – HPGe detector geometry and the main specifications stated by the manufacturer (after [4]).

The detector has 30% relative efficiency and 2.8 keV energy resolution for the ^{60}Co gamma ray of 1332 keV. The gamma spectra were recorded and analyzed using Genie-2000 software [4].

2.2. MONTE CARLO SIMULATION

A simulation of detector efficiency was conducted using the MCNP5 algorithm [11, 19], while considering the detector settings supplied by the manufacturer. The properties of the simulated HPGe detector are depicted in Fig. 2, as generated by the MCNP5 visual editor. The MCNP5 input file was constructed using the specifications of the detector, including its dimensions, Al-cap, Al-holder, and the distance from the detector crystal to the front of the detector cap. The result obtained from the simulation is referred to as a tally. Each tally is designated by a certain tally type, denoted by a number ranging from 1 to 8. The spectral response was produced by the MCNP scoring function F8. Simulations were conducted for each source configuration, studying various discrete values within the energy range of 80 – 1800 keV. The incident photon attenuation caused by the aluminum layer enclosing the detector laterally was disregarded as the photons were able to pass through the crystal *via* its upper surface. A 2.66 GHz processor was utilized for the computations of MCNP5. Each setup consisted of $N = 1 \times 10^7$ histories, each lasting 4 minutes and presenting an energy peak with a standard variation of 2%.

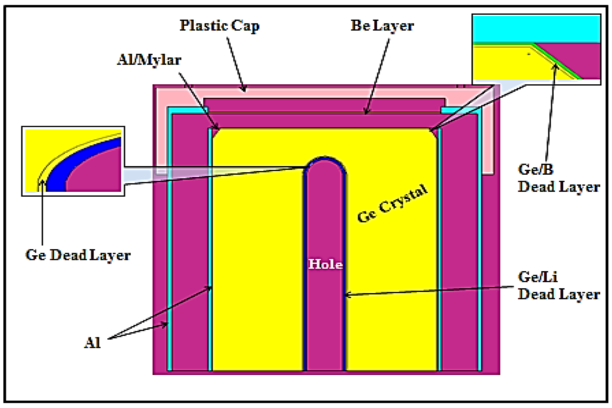


Fig. 2 – HPGe detector model simulated by MCNP5.

2.3. EXPERIMENTAL SETUP

The HPGe gamma-ray spectrometer was configured according to the diagram in Fig. 3. Table 1 displays a collection of standard point sources (^{133}Ba, ^{137}Cs, ^{22}Na and ^{60}Co) distributed over a range of gamma energies from 81 keV to 1332 keV. These sources were securely placed at the top of the standard container used in the Central Laboratory for Environmental Radioactivity Measurements Inter-comparison and Training (CLERMIT). The separation distance between the source and detector cap has been modified to 8 cm and fine-tuned to achieve the highest count rate while minimizing counting losses caused by pile-up and dead time (less than 2%).

Figure 3 also presents a typical spectrum of the measured isotopes in the standard point sources.

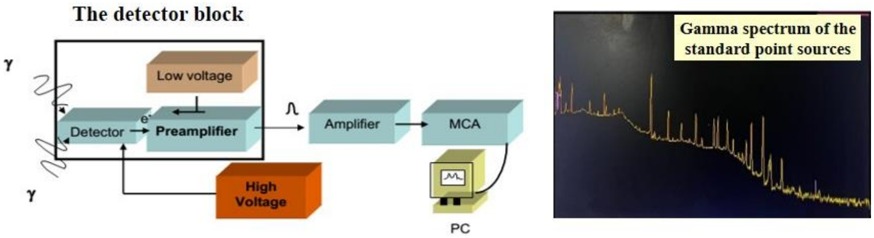


Fig. 3 – The block diagram of the gamma-ray spectrometry system and a typical spectrum of the measured isotopes.

Table 1

Certified point sources specification (reference date: 15/1/2007) used for the determination of the detector's efficiency

Radionuclide	Energy [keV]	Activity [kBq]	Half-life [days]	Combined standard uncertainty
Ba-133	81 276.4 302.05 356.02 383.85	3.093	3897	0.5%
Cs-137	661.7	16.850	11019	0.7%
Na-22	1274.53	5.429	950	0.5%
Co-60	1173 1332.5	10.920	1925.4	0.4%

The experimental efficiency ε at a given energy E is determined by the following formula:

$$\varepsilon = \frac{N}{t\,A\,P} \tag{1}$$

with: N – the number of net counts in each gamma line, t – the counting time, P – the emission probability at the given energy E, A – the activity of each certified point source (in Bq) [8, 16].

The efficiency calibration curves for a high-performance germanium detector were produced and the number of simulated histories was calculated [14]. The efficiency curve was optimized and standardized by fitting it to the volume efficiency curve with a potassium chloride (KCl) solution.

Taking into account the difference between the experimental and computed efficiency values [18], the percentage discrepancy is determined by the equation:

$$\Delta[\%] = [(\varepsilon_{\mathrm{exp}} - \varepsilon_{\mathrm{cal}}) / \varepsilon_{\mathrm{exp}}] \times 100 \tag{2}$$

where ε_{exp} and ε_{cal} are the calculated and measured efficiency values for a given gamma-ray energy, respectively.

2.4. METHOD VERIFICATION

An IAEA-certified reference sample was used for volume source verification. The sample was measured and the background gamma radiation was determined using an empty Marinelli beaker in the same condition as the measured samples.

The activity concentration A of each radionuclide was calculated using the following formula [4, 9]:

$$A\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right] = \frac{N}{t\ \varepsilon\ P\ W} \tag{3}$$

where N is the count rate under the full-energy peak areas, adjusted for background, ε is the full-energy peak efficiency for the energy of interest, P the likelihood of γ-ray emission, and W – the mass of the selected sample, in kilograms.

The activity concentration of ^{226}Ra was measured using the gamma lines of ^{214}Pb and ^{214}Bi at 295.21 keV, 351.92 keV, and 609.92 keV, 1120.28 keV, and 1764.49 keV, respectively. The activity concentration of ^{228}Ra was additionally measured using the gamma lines of ^{228}Ac at 338.32 keV, 911.02 keV, and 969.11 keV. For ^{40}K, the 1460.83 keV gamma ray was used [3, 6].

The common Minimum Detectable Activity (MDA) values for ^{226}Ra, ^{228}Ra, and ^{40}K are 0.20 Bq/kg, 0.2 Bq/kg, and 0.7 Bq/kg, respectively, determined by using the equation [4]:

$$\mathrm{MDA}\left[\frac{\mathrm{Bq}}{\mathrm{kg}}\right] = \frac{2.71+4.66\sqrt{B}}{T_{\mathrm{S}}\ \varepsilon\ P\ W} \tag{4}$$

where B represents the background counts and T_S is the counting time expressed in seconds.

The calculation of the relative combined efficiency measurement uncertainty, u(ε), was performed using the following equation [4]:

$$u(\varepsilon) = \sqrt{(\delta A)^2 + (\delta N)^2 + (\delta C(E))^2} \tag{5}$$

where: δA denotes the relative uncertainty of the total activity in the standard, δN is the relative counting uncertainty and $\delta C(E)$ is the relative uncertainty resulting from coincidence correction factors. Insignificant errors were observed in the measurement time (t) and mass of the standard (W). At a confidence level of $2s$ (s = standard deviation), the relative total measurement uncertainty $u(\varepsilon)$ for all gamma-ray energies was less than or equal to 5% [4].

Some selected environmental samples of different types, densities and concentrations were measured. The obtained theoretical and experimental results were compared, and the estimated error was calculated.

3. RESULTS AND DISCUSSION

MCNP5 Monte Carlo code was used to compute the FEPE values (ε) for several gamma lines ranging from 180 keV to 2000 keV for different radionuclides. The efficiency values were determined using the gamma-ray spectrum of ^{133}Ba, ^{137}Cs, ^{60}Co and ^{22}Na sources. The efficiency curve was plotted and the fitting functions and parameters that fitted the efficiency curves were obtained. The decay of these point sources was simulated using MCNP5 and the spectrum of photon counts was analyzed. The FEPE values of the MCNP5 method in comparison with the experimental method are presented in Table 2 and Fig. 4. As seen in Fig. 4 and Table 2, the FEPE value decreases as gamma-ray energy increases. The data obtained confirm the good agreement between the experimental and the MCNP5 efficiency values.

The maximum discrepancies between MCNP5 and experimental results were found in the low energy range, of less than 180 keV, while in the energy range higher than 250 keV, the discrepancies between them were strongly reduced. The experimental error was calculated, its value being around 2.6%.

Table 2

Full-energy peak efficiency (ε) for eight gamma energy lines based on experimental method and MCNP5 simulation and the relative discrepancy Δ%

Standard source	Energy line [keV]	Full-Energy Peak Efficiency (ε)		Δ%
		experimental	based on MCNP5	
Ba-133	81	0.017844 ± 2.4 E-04	0.0177111 ± 2.5 E-05	0.74
	276.4	0.009198 ± 2.4 E-04	0.0092993 ± 3.5 E-05	–1.10
	302.85	0.008648 ± 1.4E-04	0.0085699 ± 3.6 E-05	0.90
	356.02	0.007312 ± 9.6E-05	0.0073790 ± 3.9 E-05	–0.92
	383.85	0.007009 ± 1.6 E-04	0.0068837 ± 4.1 E-05	1.79
Cs-137	661.7	0.004305 ± 5.1 E-05	0.0042523 ± 5.0 E-05	1.22
Co-60	1173	0.002787 ± 1.2 E-04	0.0027248 ± 6.2 E-05	2.23
	1332.5	0.002509 ± 1.1 E-04	0.0024650 ± 6.5 E-05	1.75
Na-22	1274.53	0.002665 ± 1.1E-04	0.0025950 ± 7.0 E-05	2.63

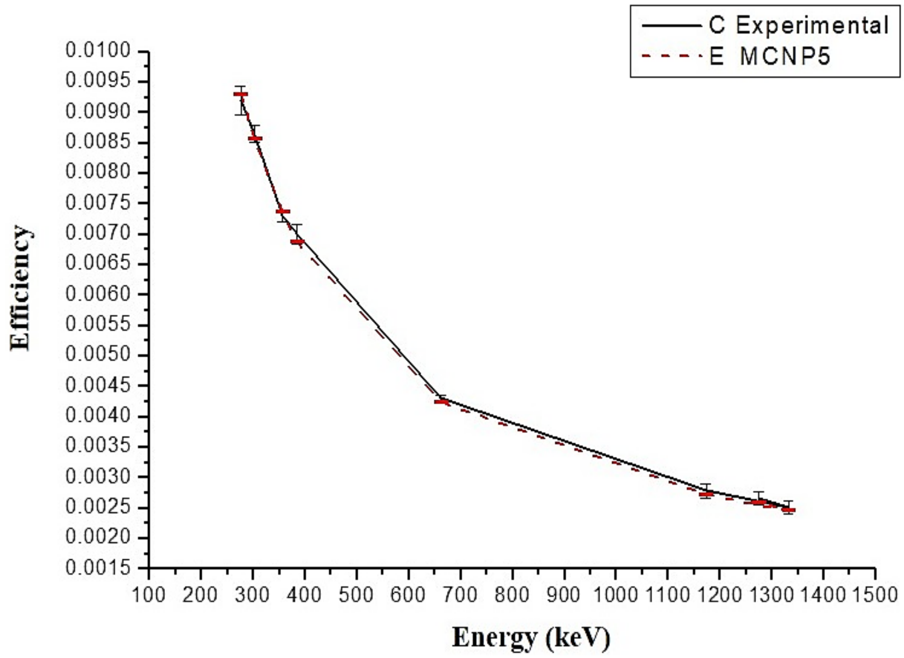


Fig. 4 – Comparison between experimental and MCNP5 efficiency calculation.

The obtained calibration curve was validated using a mixed source. As Table 3 shows, a deviation has appeared for gamma energies below 186 keV. Other point sources can be added to improve the efficiency of gamma energies below 186 keV.

The relative discrepancy for both the experimental method and MCNP5 was within 1.2%. At gamma energies below 100 keV, the mass attenuation coefficients and, consequently, the self-absorption correction factors exhibit substantial variation among various materials. In this work, the correction factors for gamma lines, including the real summing coincidence, mass attenuation coefficients, and self-absorption correction factors, were excluded [20, 21].

Since the soil sample and the standard point sources are different in terms of geometry, chemical composition and density, a standard soil sample containing standard radioactive material (IAEA-326) was measured.

As shown in Table 4, the same behaviour is observed for both the experimental method and MCNP5, and the relative discrepancy for both methods was lower than 2%.

The concentrations of the radionuclides referenced in Table 5 were determined by experimental calculations utilizing the net count rates and the MCNP calibration matrix for certain environmental samples. The estimates of the respective uncertainty were also reported. Quantification of the radiation levels of all three radionuclides was conducted on soil, sediment, and zircon samples. The efficiency ratios generated from MCNP simulations for each sample fall within the acceptable range of ± 2% against experimental values. Both instruments demonstrate reliability for calibrating the FEPE in the energy range of the HPGe detector and the multi-gamma standard source employed in this specific study.

Table 3

The comparison of the estimated activity for certified gamma-ray sources and the certified value

Standard source		Energy line (keV)	Activity (Bq) estimated based on: Experimental method	Activity (Bq) estimated based on: MCNP5 Simulation	Reference activitiy (Bq)	Estimated error% $\frac{\text{Ref} - \text{MCNP5}}{\text{Ref}}$	Estimated error% $\frac{\text{Ref} - \text{EXP}}{\text{Ref}}$	Estimated error% $\frac{\text{EXP} - \text{MCNP5}}{\text{EXP}}$
MIXED POINT SOURCE	Eu-152	244.7	3220.3 ± 273	3235.6 ± 272	3084.8 ± 92.5	–4.9	–4.4	–0.5
		344.28	3270.9 ± 350	3309 ± 328	3084.8 ± 92.5	–7.3	–6	–1.2
		778.9	3202.2 ± 190	3198 ± 185	3084.8 ± 92.5	–3.7	–3.8	0.1
		964	2929.2 ± 244	3024.9 ± 240	3084.8 ± 92.5	1.9	5.1	–3.3
		1085.7	2827.6 ± 160	2927 ± 196.9	3084.8 ± 92.5	5.1	8.3	–3.5
		1112	2726.92 ± 197	2825 ± 196	3084.8 ± 92.5	8.5	11.6	–3.6
		1408.01	2745.5 ± 253	2829.6 ± 247	3084.8 ± 92.5	8.3	10.9	–3.1
	Eu-154	723.3	1432.9 ± 152	1471.3 ± 149	1594.4 ± 47.8	7.7	10.1	–2.7
		756.76	1484 ± 168.7	1525.2 ± 164	1594.4 ± 47.8	4.3	6.9	–2.8
		873.19	1502.8 ± 160	1548.9 ± 155	1594.4 ± 47.8	2.9	5.7	–3.1
		1004.72	1591.8 ± 177	1645.2 ± 171	1594.4 ± 47.8	–3.2	0.2	–3.4
	Eu-155	105.31	479.5 ± 25.4	473.7 ± 25	508.66 ± 15.3	6.9	5.7	1.2
		86.55	417.6 ± 20.9	424.4 ± 20	508.66 ± 15.3	16.6	17.9	–1.6
Cs-137		661.7	1391.1 ± 224	1425.8 ± 233	1468.9 ± 44.1	2.9	5.3	–2.5
Na-22		1274.53	1478.7 ± 378	1534.7 ± 362	1574.5 ± 48.8	2.5	6.1	–3.8
Mn-54		834.85	27.8 ± 1.4	29.4 ± 1.3	30.9 ± 1	4.8	10.1	–5.8
Co-60		1173	915 ± 33.3	948.8 ± 32.8	921.05 ± 27.6	–3.1	0.7	–3.7
		1332.5	911.9 ± 21	947.8 ± 21.2	921.05 ± 27.6	–2.9	1	–3.9

Table 4

The comparison of the estimated activity concentration (Bq/kg) for the certified reference material IAEA-326 and the certified value

Radio-nuclide	Experimental activity	Activity estimated based on MCNP5	Certified value	Estimated error% $\frac{\text{EXP} - \text{MCNP5}}{\text{EXP}}$	Estimated error% $\frac{\text{Ref} - \text{MCNP5}}{\text{Ref}}$	Estimated error% $\frac{\text{Ref} - \text{EXP}}{\text{Ref}}$
^{226}Ra	31.07 ± 3.3	30.6 ± 2.56	32.60 ± 6.20	1.5	6.1	4.7
^{228}Ra	42.1 ± 2.7	41.37 ± 2.3	40.10 ± 4.20	1.7	–3.2	–4.9
^{40}K	532.02 ± 17.6	531.2 ± 16.5	580.00 ± 56	0.2	8.1	8.3

Table 5

The estimated activity concentration for some selected samples

Matrix type and density (g/cm^3)	Radionuclide	Activity (Bq/kg)		Estimated error% $\frac{\text{EXP} - \text{MCNP5}}{\text{EXP}}$
		Experimental	MCNP5	
Soil 1.56	^{226}Ra (^{238}U)	16.9 ± 1.46	16.7 ± 0.87	1.2
	^{228}Ra (^{232}Th)	9.623 ± 0.9	9.47 ± 0.69	1.6
	^{40}K	741.5 ± 25	740.4 ± 17.9	0.14
Raw sample (zircon) 1.96	^{226}Ra (^{238}U)	3127 ± 70	3079.8 ± 62.6	1. 6
	^{228}Ra (^{232}Th)	724.5 ± 30.7	712.4 ± 21.6	1.6
Sediment 1.56	^{226}Ra (^{238}U)	55.94 ± 2.6	55.05 ± 1.33	1.6
	^{228}Ra (^{232}Th)	20.18 ± 1.53	19.86 ± 0.99	1.6
	^{40}K	308.979 ± 11.7	308.52 ± 11.34	0.15

4. CONCLUSIONS

Efficiency curve of the HPGe detector utilized in CLERMIT was computed using MCNP5 simulation software. The physical dimensional specifications and material composition of the detector were obtained from the nominal manufacturer. Radionuclide sources (^{133}Ba, ^{137}Cs, ^{22}Na, and ^{60}Co) were analyzed by calculating their activities using the detector's absolute Full Energy Peak Efficiency (FEPE) determined by the MCNP5 model. An empirical investigation of uncertainty has been conducted to ascertain the impact of individual operational and design parameters on the efficiency curve. A comparison was made between the computed results and the certified measurements. An exceptional concordance was attained between experimental and Monte Carlo computations, taking into account the size of the detector. The FEPE was calculated for multi-gamma point sources and reference-certified samples to validate the developed detector model. Based on our expertise and comparison of several FEPE calculation methods, we have found that the Monte Carlo method is a favourable tool. Enhanced reliability of results can be achieved by incorporating additional experimental details into the design of the simulated detector. Presently, this simulation study is ongoing.

Acknowledgements. The work of the author A.E. was partially supported by the research grant with contract no. 9187/2023, funded by Dunarea de Jos University of Galati.

REFERENCES

1. Z. Wu, B. Wang, J. Sun, Y. Wang, and C. Zhao, *In-situ γ-ray analysis of ground surface radioactivity using portable HPGe γ spectrometer*, Sci. Rep. **12**, 9418 (2022). https://doi.org/10.1038/s41598-022-13770-5

2. S. Kim, T. Kim, and H. Yang, *Design of a low-resolution gamma-ray spectrometer for monitoring radioactive levels of wastewater*, Appl. Sci. **12**, 5613 (2022). https://doi.org/10.3390/app12115613
3. A. Ene, A. Pantelică, F. Sloată, H. M. H. Zakaly, and H. O. Tekin, *Gamma spectrometry analysis of natural and man-made radioactivity and assessment of radiological risk in soils around steel industry*, Rom. J. Phys. **68**(7–8), 803 (2023). https://doi.org/10.59277/RomJPhys.2023.68.803
4. D. A. Aziz, H. A. Saudi, H. M. H. Zakaly, W. El-Melegy, and H. M. Diab, *Steps toward optimizing HPGe detector efficiency in the context of low-level radioactivity detection*, Rom. J. Phys. **68** (9–10), 305 (2023). https://doi.org/10.59277/RomJPhys.2023.68.305
5. D. Gurau, E. Ionescu, L. Done, and D. Stanga, *Radiological evaluation approach for oversized radioactive waste resulted from VVR-S nuclear reactor decommissioning*, Rom. Rep. Phys. **76**, 801 (2024). https://doi.org/10.59277/RomRepPhys.2024.76.801
6. D. M. Montalván Olivares, M. V. M. Guevara, and F. G. Velasco, *Determination of the HPGe detector efficiency in measurements of radioactivity in extended environmental samples*, Appl. Radiat. Isot. **130**, 34–42 (2017). https://doi.org/10.1016/j.apradiso.2017.09.017
7. J. Nikolic, T. Vidmar, D. Jokovic, M. Rajacic, and D. Todorovic, *Calculation of HPGe efficiency for environmental samples: comparison of EFFTRAN and GEANT4*, Nucl. Instr. Meth. A **763**, 347–353 (2014). https://doi.org/10.1016/J.NIMA.2014.06.044
8. H. M. H. Zakaly, M. A. Uosif, S. Issa, M. Saif, M. Tammam, and A. El-Taher, *Estimate the absolute efficiency by MATLAB for the NaI (Tl) detector using IAEA-314*, AIP Conf. Proc. **2174**, 020248 (2019). https://doi.org/10.1063/1.5134399
9. M. A. M. Uosif, A. M. A. Mostafa, A. Ene, Z. A. Alrowaili, R. Elsaman, and H. M. H. Zakaly, *Natural radioactivity variation with some soil properties*, Rom. Rep. Phys. **76**, 705 (2024). https://doi.org/10.59277/RomRepPhys.2024.76.705
10. G. ALMisned, H. M. H. Zakaly, F. T. Ali, S.A.M. Issa, A. Ene, G. Kilic, V. Ivanov, and H. O. Tekin, *A closer look at the efficiency calibration of LaBr3(Ce) and NaI(Tl) scintillation detectors using MCNPX for various types of nuclear investigations*, Heliyon **8**, e10839 (2022). https://doi.org/10.1016/j.heliyon.2022.e10839
11. H. O. Tekin, G. ALMisned, S. A. M. Issa, and H. M. H. Zakaly, *A rapid and direct method for half value layer calculations for nuclear safety studies using MCNPX Monte Carlo code*, Nucl. Eng. Technol. **54**, 3317–3323 (2022). https://doi.org/10.1016/j.net.2022.03.037
12. E. Uyar and M.H. Bölükdemir, *The effect of front edge on efficiency for point and volume source geometries in p-type HPGe detectors*, Nucl. Eng. Technol. **54**, 4220–4225 (2022). https://doi.org/10.1016/j.net.2022.06.009
13. W. Khan, Q. Zhang, C. He, and M. Saleh, *Monte Carlo simulation of the full energy peak efficiency of an HPGe detector*, Appl. Radiat. Isot. **131**, 67–70 (2018). https://doi.org/10.1016/j.apradiso.2017.11.018
14. J. G. Guerra, J. G. Rubiano, G. Winter, A. G. Guerra, H. Alonso, M. A. Arnedo, A. Tejera, J. M. Gil, R. Rodríguez, P. Martel, and J. P. Bolivar, *A simple methodology for characterization of germanium coaxial detectors by using Monte Carlo simulation and evolutionary algorithms*, J. Environ. Radioact. **149**, 8–18 (2015). https://doi.org/10.1016/j.jenvrad.2015.06.017
15. J. Ordóñez, S. Gallardo, J. Ortiz, M. Sáez-Muñoz, and S. Martorell, *Intercomparison of full energy peak efficiency curves for an HPGe detector using MCNP6 and GEANT4*, Radiat. Phys. Chem. **155**, 248–251 (2019). https://doi.org/10.1016/j.radphyschem.2018.06.049
16. M. T. Haj-Heidari, M. J. Safari, H. Afarideh, and H. Rouhi, *Method for developing HPGe detector model in Monte Carlo simulation codes*, Radiat. Meas. **88**, 1–6 (2016). https://doi.org/10.1016/j.radmeas.2016.02.035
17. G. ALMisned, W. Elshami, G. Kilic, E. Rabaa, H. M. H. Zakaly, A. Ene, and H.O. Tekin, *Utilization of three-layers heterogeneous mammographic phantom through MCNPX code for breast and chest radiation dose levels at different diagnostic X-ray energies: A Monte Carlo simulation study*, Front. Public Health **11**, 700 (2023). https://doi.org/10.3389/FPUBH.2023.1136864
18. D. Gurau, D. Stanga, L. Done, O. Sima, and E. Ionescu, *Computational characterization of coaxial HPGe detectors using Monte Carlo simulation and nonlinear least squares optimization*, Rom. Rep. Phys. **75**, 806 (2023). https://doi.org/10.59277/RomRepPhys.2023.75.806

19. J. F. Briesmeister, *MCNP^{TM}–A General Monte Carlo N–Particle Transport Code*, Version 4C, LA–13709–M Manual, Oak Ridge, TN, 2000. https://s3.cern.ch/inspire-prod-files-7/78c669e8d3bb59ccf6fb868a6061450c
20. J. Knezevic, D. Mrdja, J. Hansman, K. Bikit, S. Forkapic, I. Bikit, D. Velimirovic, and P. Kuzmanovic, *Corrections of HPGe detector efficiency curve due to true coincidence summing by program EFFTRAN and by Monte Carlo simulations*, Appl. Radiat. Isot. **189**, 110421 (2022). https://doi.org/10.1016/j.apradiso.2022.110421
21. N. Marković, P. Roos, X. Hou, G. Lutter, and S. P. Nielsen, *Calibration of HPGe–HPGe coincidence spectrometer through performing standardization of ^{125}I activity by X-ray-gamma coincidence spectrometry using two HPGe detectors*, Nucl. Instr. Meth. A **880**, 194–200 (2018). https://doi.org/10.1016/J.NIMA.2017.10.086