EFFICIENCY TRANSFER FACTORS CALCULATION FOR A GAMMA-RAY DETECTOR USING MONTE CARLO CODES

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Received February 5, 2025

Abstract. Gamma-ray detectors are used for radioactive sources calibration and testing in ionizing radiation metrology laboratories, as more than 90% of radionuclides are gamma-ray emitters. When measuring the activity of radioactive sources with complex geometries and matrices for which standard reference sources are unavailable, an accurate understanding of efficiency transfer factors is required. This is the case in testing laboratories where cotton wipes/smears are widely used to assess non-fixed radioactive surface contamination. The efficiency transfer factors were determined by simulating the full-energy peak efficiency using Monte Carlo codes such as FLUKA, MCNP, and GESPECOR.

Key words: gamma-ray detector, metrology, Monte Carlo, MCNP, FLUKA, GESPECOR.

DOI: https://doi.org/10.59277/RomJPhys.2025.70.301

1. INTRODUCTION

The Monte Carlo simulation method has proven to be an excellent tool for Full Energy Peak Efficiency (FEPE) calibration of high-purity germanium (HPGe) detectors, complementing experimental calibration based on radioactive standard sources. It is now widely applied in various fields, including environmental radioactivity monitoring, radioactive waste management [1], and *in situ* radiological assessment [2], among others. For FEPE calibration, two Monte Carlo methods can be employed: the direct Monte Carlo calculation method and the Monte Carlo efficiency transfer method. The direct Monte Carlo calculation method involves performing a full Monte Carlo simulation to directly compute the FEPE. However, a key challenge reported in the literature is that the detector geometry parameters provided by the manufacturer often do not allow for precise efficiency calculations. This issue has been demonstrated by discrepancies between computed and experimental efficiency values. To address this, one solution adopted by scientists was to adjust the detector geometry parameters iteratively until achieving a satisfactory agreement between the two data sets [3–10]. The second method, the Monte Carlo efficiency transfer method, calculates FEPE by incorporating a transfer factor that depends on gamma-ray energy values. This approach has proven to be highly effective for determining the full-energy peak efficiency of radioactive samples with geometries differing from available standard sources and with unknown activity. This method is implemented by measuring radioactive standard sources with various characteristics, such as geometry, matrix, and composition, using the same detector. The full-energy peak efficiency is then calculated for each radionuclide to generate the efficiency curve [11]. The efficiency transfer approach is a fast, user-friendly method that requires fewer computational resources and is particularly advantageous, as it eliminates the need for experimental detector calibration for unknown sources. This method is especially useful in environmental assessments [12], where high-accuracy measurements, such as those required in metrology laboratories, are not necessary, and a large number of samples need to be analyzed. The approach operates by calculating the ratio of the efficiencies for the standard sample and the sample of interest, then multiplying this ratio by the experimental FEPE of the standard sample. A key advantage of the efficiency transfer method, as highlighted in the scientific literature, is that many uncertainties in the detector model are expected to cancel out in the calculated efficiency transfer factor ratio. This allows for accurate efficiency determination even when the technical specifications provided by the manufacturer are incomplete or not precisely described.

In this study, the Monte Carlo efficiency transfer method was implemented for the high-resolution HPGe detector at the Ionizing Radiation Metrology Laboratory (LMRI), Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH), and the results were compared with those obtained from standard source experiments. IFIN-HH/LMRI is the owner of the primary and national standard of activity unit (Bq) in Romania. The paper presents a performance evaluation of the Monte Carlo efficiency transfer method applied to various sources, along with a discussion on its implementation using key Monte Carlo simulation codes. The simulation codes used in this study include FLUKA [13–15], MCNP [16–18], and GESPECOR (dedicated software for gamma-ray spectrometry) [19].

2. METHOD

2.1. DETECTOR MODELING AND STANDARD SOURCES

In this study, the high-resolution ORTEC HPGe detector (2007), model GEM25P4, from the LMRI (IFIN-HH) was employed to determine the efficiency curve for both point-like radioactive standard sources (enclosed by a plastic envelope) and a SARPAGAN cylindrical volumetric standard source. The efficiency curve was derived using a multi-gamma-ray emitting SARPAGAN source and five point-like radioactive standard sources (^{241}Am, ^{133}Ba, ^{152}Eu, ^{137}Cs, ^{60}Co, as shown in Fig. 1), covering the energy range from 59.54 keV (^{241}Am) to 1408.01 keV (^{152}Eu).

(a)

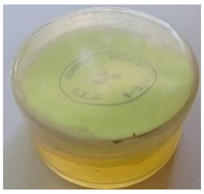

(b)

Fig. 1 – a) Point-like radioactive standard sources; b) SARPAGAN geometry source.

To validate the efficiency transfer method using the simulation codes, new radioactive sources with different geometries were prepared: two cotton discs in Petri dishes and two cotton discs enclosed in very thin plastic bags (50 μm thickness). These sources were prepared using a ^{137}Cs (661.66 keV, as shown in Fig. 2) standard solution, following the gravimetric method.

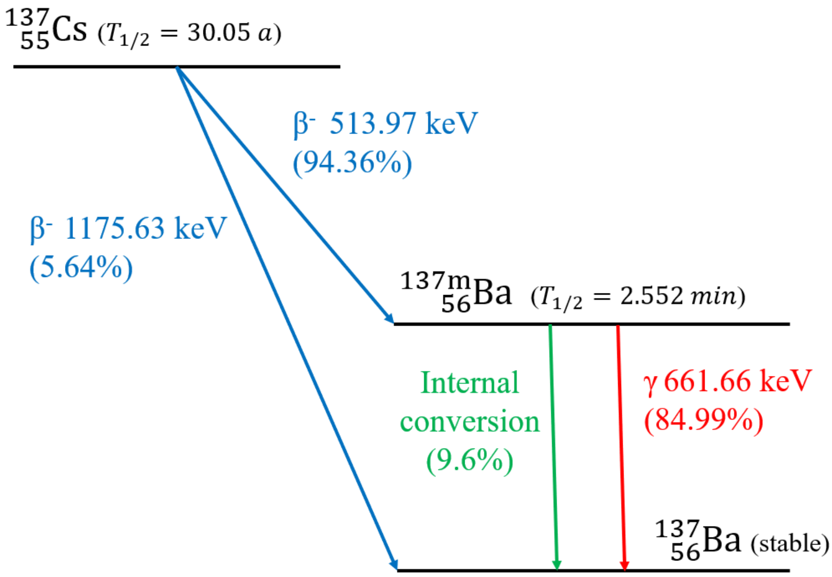
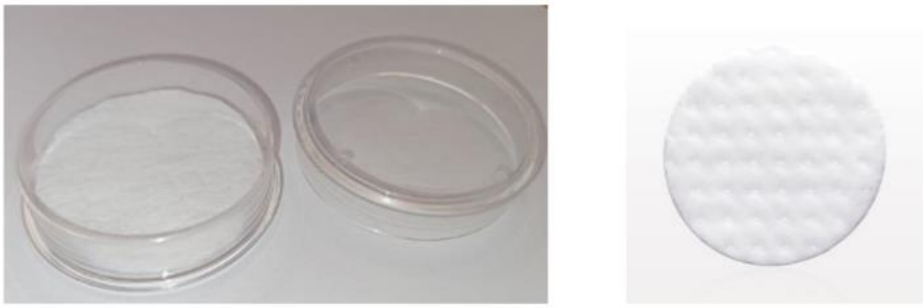


Fig. 2 – ^{137}Cs decay scheme [20].

The ^{137}Cs solution was uniformly distributed across the cotton discs. The ^{137}Cs standard sources (shown in Fig. 3) will be utilized by the “Radioactive, Nuclear and Non-Radioactive Materials Testing Laboratory (DRMRLAB)” which assess non-fixed radioactive surface contamination by using cotton wipes/smears. In this study, similar geometry standard radioactive sources were prepared.



(a) (b)

Fig. 3 – Newly prepared standard sources: a) cotton disk in Petri dish; b) cotton disk in a thin plastic bag.

For the simulations, two multipurpose Monte Carlo codes, FLUKA and MCNP, along with GESPECOR, a Monte Carlo-based software dedicated to gamma-ray spectrometry, were used. FLUKA features an intuitive graphical interface, FLAIR, which facilitates the preparation of input data, including the geometry, source type, position, simulation parameters, and the visualization of results. The combination of FLUKA with FLAIR provides the advantage of a user-friendly interface, in contrast to other Monte Carlo codes that rely on a command-line interface, which can be more challenging for users. The FLUKA code includes various physics packages for simulating particle transport through matter, covering key interaction processes such as ionization, Compton scattering, the photoelectric effect, electron-positron pair production, and Bremsstrahlung (X-rays). The ratio of photons depositing their full energy in the active volume of the detector crystal to the total number of primary events was recorded using the DETECT scoring card, with results stored event-by-event in a text file. Each simulation run consisted of 10^7 events and typically took around 10 minutes on a ten-core PC. The statistical uncertainty of the simulated efficiency was below 0.12%.

MCNP 6.2 offers a similar output option for pulse height tally (F8), which was used in the simulations. The MCNP code models arbitrary three-dimensional configurations of materials in geometric cells, bounded by first- and second-degree surfaces, as well as fourth-degree elliptical tori. A combination of cell cards, surface cards, and data cards was employed to simulate the HPGe detector system, which includes the Ge crystal, mount cup, endcap, lead castle, and dead layers, based on the specifications provided by the manufacturer.

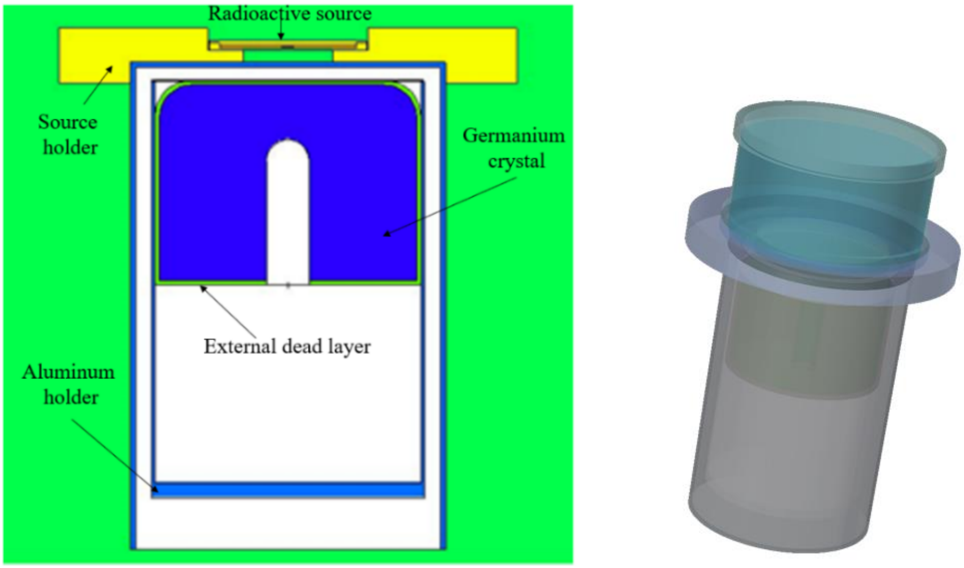
GESPECOR (Germanium SPectra CORrection) is a Monte Carlo-based software specialized in gamma-ray spectrometry, capable of calculating efficiency transfer factors, self-absorption correction factors, and coincidence summing corrections. The optimized procedure in GESPECOR allows for obtaining results in a relatively short time.

The main geometry parameters of the detectors provided by the manufacturer are listed in Table 1. The vertical section view of the detector, modeled in the Monte Carlo simulations, is shown in Fig. 4. The statistical uncertainties of the Monte Carlo simulations were below 1%.

Table 1

Detector parameters provided by the manufacturer

Parameters	Values (cm)
Crystal diameter (including the side dead layer)	5.88
Crystal length (including the top dead layer)	4.6
Front and side dead-layer thickness	0.07
Hole radius	0.465
Hole depth	3.27
Thickness of internal dead-layer	0.00003
Distance between the detector endcap and point-like radioactive standard sources	0.26
Distance between the detector endcap and SARPAGAN sources	0.16



(a) (b)

Fig. 4 – Section view of the HPGe detector modeled in Monte Carlo simulation:
a) MCNP HPGe geometry with point-like radioactive standard source (2D);
b) FLUKA 3D-HPGe geometry with a SARPAGAN source.

2.2. MONTE CARLO EFFICIENCY TRANSFER METHOD

By using the transfer factors obtained for different gamma-ray energy values through the Monte Carlo efficiency transfer method, the full energy peak efficiency can be calculated based on the detector parameters provided by the manufacturer. The transfer factors, which relate Monte Carlo-computed FEPEs using the manufacturer's detector data to measured values, are energy-dependent.

The Monte Carlo efficiency transfer method can be described by the following formula:

$$\mathrm{FEPE}_{\text{new source}}(E) = \mathrm{FEPE}_{\text{ref. source}}(E) \times F_T(E)$$

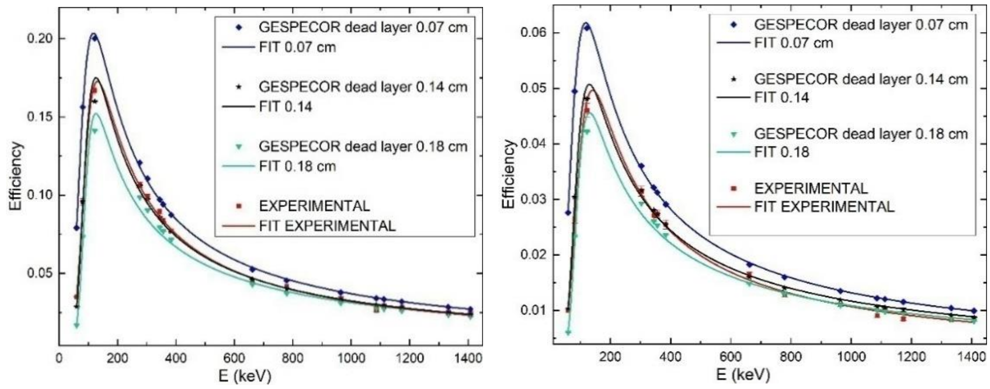
where $\mathrm{FEPE}_{\text{new source}}$ represents the full energy peak efficiency for photons with energy E for the new source, and $\mathrm{FEPE}_{\text{ref. source}}$ is the full energy peak efficiency of the detector for the standard (reference) source (either a point source or SARPAGAN). The efficiency transfer factor, $F_T(E)$ is defined as the ratio of the simulated efficiency for the new sources to that of the reference geometry [21].

3. RESULTS AND DISCUSSION

A critical geometrical parameter influencing detection efficiency, particularly for low gamma-ray energies, is the thickness of the detector crystal dead layer. To estimate this thickness in the present case, the GESPECOR dedicated software was used to vary the dead layer thickness. It was observed that there is a discrepancy between the initial dead layer thickness provided by the manufacturer (0.07 cm) and the experimental values.

The experimental and simulated full energy peak efficiencies for the best-matching dead layer value of 0.14 cm are shown in Fig. 5. The adjusted R-squared values are 0.9973 for the point sources curve efficiency and 0.9961 for the SARPAGAN sources, where adjusted R-squared is a measure of model accuracy (goodness-of-fit). The experimental values were calculated using point-like radioactive standard sources placed in a Plexiglas holder on top of the detector, with the distance between the detector endcap and the point source set to 2.6 mm. To characterize the full energy peak efficiency (referred to as efficiency) across the detector's energy range (up to 2900 keV), a 4-parameter function (A, b, C, d) [22] was used to fit both the experimentally obtained and GESPECOR-simulated efficiencies.

$$\text{Efficiency} = \frac{A \times \text{Energy}^{b}}{1000 \times C + \text{Energy}^{d}}$$



(a) (b)

Fig. 5 – Experimental and GESPECOR simulated efficiency curves:
a) point sources; b) SARPAGAN standard sources.

Table 2 presents a comparison between the experimental and simulated detection efficiencies for the considered source geometries, specifically for the ^{137}Cs radionuclide. The experimental values include true coincidence summing correction factors. The agreement between the simulations and experimental values is typically within 6.5%. The uncertainties (u_x) were considered for $k = 1$. Deviations are attributed to inaccuracies in the dimensions and/or material composition (distribution and density) of the detector's internal structure used in the simulations. Additionally, any volume source, such as SARPAGAN, may exhibit some degree of inhomogeneity, both in terms of activity distribution and matrix composition.

Table 2

Full energy peak efficiency simulations and experiment

^{137}Cs Source geometry	$FEPE_{exp.}$ (× 10^{-2})	u_{exp} (%)	**FLUKA**			**MCNP**			**GESPECOR**		
			FEPE (× 10^{-2})	u_F (%)	Rel. diff. (%)	FEPE (× 10^{-2})	u_M (%)	Rel. diff. (%)	FEPE (× 10^{-2})	u_G (%)	Rel. diff. (%)
Point-like radioactive standard source	4.49	3.12	4.70	0.07	4.7	4.61	0.14	2.7	4.63	0.17	3.1
SARPAGAN	1.65	4.85	1.61	0.11	–2.5	1.65	0.24	0.3	1.61	0.26	–2.4
PETRI (SP)	–	–	3.94	0.07	–	4.02	0.15	–	–	–	–
COTTON DISK (S)	–	–	4.13	0.07	–	4.06	0.15	–	–	–	–

Efficiency transfer factors for ^{137}Cs were computed using FLUKA, MCNP, and GESPECOR for both the Petri dish and cotton disk (Table 3). The efficiency transfer factor is defined as the ratio of the simulated efficiency for the new sources to that of the reference geometry. The reference geometries used were the point source and the SARPAGAN source.

Table 3a

Efficiency transfer factors from the point-like radioactive standard source to the Petri (SP) and cotton disk (S) sources

^{137}Cs Source code	$F_{T-FLUKA}$	u (%)	F_{T-MCNP}	u (%)	$F_{T-GESPECOR}$	u (%)
SP	0.84	0.10	0.87	0.21	0.83	0.33
S	0.88	0.10	0.88	0.21	0.87	0.33

Table 3b

Efficiency transfer factors from the SARPAGAN source to the Petri (SP) and cotton disk (S) sources

^{137}Cs Source code	$F_{T-FLUKA}$	u (%)	F_{T-MCNP}	u (%)	$F_{T-GESPECOR}$	u (%)
SP	2.45	0.13	2.43	0.28	2.39	0.34
S	2.57	0.13	2.45	0.28	2.49	0.34

Using the efficiency transfer factors, we calculated the activity of the new sources and compared the results with the reference activity of the standard ^{137}Cs solution prior to source preparation. It can be observed that results presented in Table 4 and Table 5 show better agreement when the point-like radioactive standard sources are used as a reference, with a relative difference below 12%, compared to the SARPAGAN sources, which have relative differences below 14%.

Table 4

Activity calculation (Λ) using efficiency transfer factors from point-like radioactive standard sources to the Petri (S1P, S2P) and the cotton sources (S1, S2)

^{137}Cs Source code	Reference activity (Bq)	u_{exp} (Bq)	**FLUKA**			**MCNP**			**GESPECOR**		
			Λ (Bq)	u_F (Bq)	Rel. diff. (%)	Λ (Bq)	u_M (Bq)	Rel. diff. (%)	Λ (Bq)	u_G (Bq)	Rel. diff. (%)
S1P	679.3	6.8	670.9	21.5	–1.2	643.7	20.6	–5.2	676.30	21.8	–0.4
S2P	705.2	7.1	650.4	20.8	–7.8	624.0	20.0	–11.5	655.62	21.1	–7.0
S1	689.2	6.9	676.2	21.6	–1.9	674.3	21.6	–2.2	682.55	21.9	–1.0
S2	671.0	6.7	633.7	20.3	–5.6	631.9	20.3	–5.8	639.63	20.6	–4.7

Table 5

Activity calculation (Λ) using efficiency transfer factors from SARPAGAN sources to the Petri (S1P, S2P) and the cotton sources (S1, S2)

^{137}Cs Source code	Reference activity (Bq)	u_{exp} (Bq)	**FLUKA**			**MCNP**			**GESPECOR**		
			Λ (Bq)	u_F (Bq)	Rel. diff. (%)	Λ (Bq)	u_M (Bq)	Rel. diff. (%)	Λ (Bq)	u_G (Bq)	Rel. diff. (%)
S1P	679.3	6.8	624.6	30.6	–8.1	628.5	30.9	–7.5	639.12	31.4	–5.9
S2P	705.2	7.1	605.5	29.7	–14.1	609.3	29.9	–13.6	619.58	30.5	–12.1
S1	689.2	6.9	660.7	32.4	–4.1	664.9	32.6	–3.5	648.96	31.9	–5.8
S2	671.0	6.7	619.2	30.3	–7.7	623.1	30.6	–7.1	608.15	29.9	–9.4

4. CONCLUSION

The full energy peak efficiency derived from direct GESPECOR computation, using the detector dead layer thickness from the technical sheet, showed significant discrepancies with the experimental values. Using GESPECOR dedicated software, the dead layer thickness of the HPGe detector was determined to be 0.14 cm. The FEPE of the HPGe detector for various types of radioactive sources was obtained using fully integrated particle physics Monte Carlo simulation packages, including FLUKA, MCNP, and GESPECOR. The Monte Carlo efficiency transfer method was applied to the full energy peak efficiency calibration of newly prepared standard sources used for non-fixed surface radioactive contamination sampling. Comparisons between calculations and point-like radioactive standard source experiments revealed that the relative deviations were 5% for point-like radioactive standard sources and 10% for SARPAGAN sources.

The results indicate that further studies are necessary to reduce these relative deviations.

Acknowledgements. This work was funded by the Romanian Ministry of Research, Innovation and Digitalization (MCID) through Core Project PN: 23 21 02 03.

REFERENCES

1. F.L. Bronson, L. Wang, *Validation of the MCNP Monte Carlo code for germanium detector gamma efficiency calibrations*, Waste Management, Tucson, AZ, USA, 1996.
2. R. Ocone, A. Kostezh, V. Kurinenko, A. Tyshchenko, G. Derkach, P. Leone, *Substrate characterization for underwater gamma spectrometry: tank measurement results utilizing efficiencies calculated via Monte-Carlo code*, Appl. Radiat. Isot. **61**, 129–132 (2004).
3. I.O.B. Ewa, D. Bodizs, Sz. Czifrus, Zs. Molnar, *Monte Carlo determination of full energy peak efficiency for an HPGe detector*, Appl. Radiat. Isot. **55**, 103 (2001).
4. M.J. Vargas, A.F. Timon, N.C. Diaz, D.P. Sanchez, *Influence of the geometrical characteristics of an HPGe detector on its efficiency*, J. Radioanal. Nucl. Chem. **253** (3), 439–443 (2002).

5. S. Ashrafi, A. Likar, T. Vidmar, *Precise modeling of a coaxial HPGe detector*, Nucl. Instrum. Methods Phys. Res. A **438**, 421–428 (1999).
6. D. Karamanis, V. Lacoste, S. Andriamonje, G. Barreau, M. Petit, *Experimental and simulated efficiency of a HPGe detector with point-like and extended sources*, Nucl. Instrum. Methods Phys. Res. A **487**, 477–487 (2002).
7. L. Liye, M.A. Jizeng, Z. Binquan, J. Yueru, *Efficiency calibration of a P-Type coaxial HPGe detector with measurements and an EGS4 user code HPGe-MC*, Proceedings of International Radiation Physics Society Workshop on Frontier Research in Radiation Physics and Related Areas, 2004 Chengdu, China.
8. J.C. Hardy, V.E. Iacob, M. Sanchez-Vega, R.T. Effinger, P. Lipnik, V.E. Mayes, D.K. Willis, R.G. Helmer, *Precise efficiency calibration of an HPGe detector: source measurements and Monte Carlo calculations with sub-percent precision*, Appl. Radiat. Isot. **56**, 65–69 (2002).
9. J. Boson, G. Ågren, L. Johansson, K. Lidström, T. Nylén, *Improving calibration of HPGe detectors for in situ measurements – a comparison of semi-empirical and Monte Carlo methods*, in: 11th International Congress of the International Radiation Protection Association, Madrid, Spain, 2004 (www.irpa11.com/new/pdfs/3h11.pdf).
10. Z. Binquan, M.A. Jizeng, C. Jianping, L. Liye, M. Yong, *Calculation of the detection efficiency of an HPGe detector in low energy photon measurement with Monte Carlo method*, Nuclear Electronics & Detection Technology **25** (3), 274 (2005).
11. L. Moens, J. De Donder, L. Xi-lei, F. De Corte, A. De Wispelaere, A. Simonits, J. Hoste, *Calculation of the absolute peak efficiency of gamma-ray detectors for different counting geometries*, Nucl. Instrum. Methods Phys. Res. **187**, 451–472 (1981).
12. G.R. Gilmore, *Practical Gamma-ray Spectrometry*, second ed., Wiley, New York, 2008.
13. C. Ahdida, D. Bozzato, D. Calzolari, F. Cerutti, N. Charitonidis, A. Cimmino, A. Coronetti, G.L. D'Alessandro, A. Donadon Servelle, L.S. Esposito, R. Froeschl, R. García Alía, A. Gerbershagen, S. Gilardoni, D. Horváth, G. Hugo, A. Infantino, V. Kouskoura, A. Lechner, B. Lefebvre, G. Lerner, M. Magistris, A. Manousos, G. Moryc, F. Ogallar Ruiz, F. Pozzi, D. Prelipcean, S. Roesler, R. Rossi, M. Sabaté Gilarte, F. Salvat Pujol, P. Schoofs, V. Stránský, C. Theis, A. Tsinganis, R. Versaci, V. Vlachoudis, A. Waets, M. Widorski, *New Capabilities of the FLUKA Multi-Purpose Code*, Frontiers in Physics **9**, 788253 (2021).
14. G. Battistoni, T. Boehlen, F. Cerutti, P.W. Chin, L.S. Esposito, A. Fassò, A. Ferrari, A. Lechner, A. Empl, A. Mairani, A. Mereghetti, P. Garcia Ortega, J. Ranft, S. Roesler, P.R. Sala, V. Vlachoudis, G. Smirnov, *Overview of the FLUKA code*, Annals of Nuclear Energy **82**, 10–18 (2015).
15. V. Vlachoudis, *FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA*, Proceedings of the International Conference on Mathematics, Computational Methods and Reactor Physics, Saratoga Springs, New York, 2009.
16. MCNP – A General Monte Carlo N-Particle Transport Code (https://mcnp.lanl.gov).
17. C.J. Werner (Ed.), MCNP user's manual – code version 6.2, Los Alamos National Laboratory, Report LA-UR-17-29981 (2017).
18. C.J. Werner, J.S. Bull, C.J. Solomon, F.B. Brown, G.W. McKinney, M.E. Rising, D. Dixon, R.L. Martz, H.G. Hughes, L.J. Cox, A.J. Zukaitis, J.C. Armstrong, R.A. Forster, L. Casswell, MCNP6.2 Release Notes, Los Alamos National Laboratory, report LA-UR-18-20808 (2018).
19. O. Sima, D. Arnold, and C. Dovlete, *GESPECOR: A Versatile Tool in Gamma-Ray Spectrometry*, J. Radioanal. Nucl. Chem. **248**, 359–364 (2001).
20. M.-M. Bé, V. Chisté, C. Dulieu, E. Browne, C. Baglin, V. Chechev, N. Kuzmenco, R. Helmer, F. Kondev, D. MacMahon, K.B. Lee, *Monographie BIPM-5, Table of Radionuclides (Vol. 3 – A = 3 to 244)*, 2006 BIPM, ISBN 92-822-2218-7, https://www.bipm.org/en/publications/monographies.
21. A. Luca, B. Neacsu, A. Antohe, M. Sahagia, *Calibration of the high and low resolution gamma-ray spectrometers*, Romanian Reports in Physics **64** (4), 968–976 (2012).
22. C.A Kalfas, M. Axiotis, C. Tsabaris, SPECTRW: *A software package for nuclear and atomic spectroscopy*, Nucl. Instrum. Methods Phys. Res. A **830**, 265–274 (2016).