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INFLUENCE OF DEAD LAYER ON THE RESPONSE FUNCTION OF PLANAR AND COAXIAL Ge DETECTOR USING MONTE CARLO METHOD

Germanium crystals have a dead layer that causes a decrease in efficiency since the layer is not useful for detection but strongly attenuates photons. The thickness of this inactive layer is not well known due to the existence of a transition zone where photons are increasingly absorbed. Therefore, using data provided by manufacturers in the detector simulation model, some strong discrepancies appear by changing the dead layer. Investigations into the Ge detector response functions for gamma rays have been conducted using straightforward physical mechanisms implemented by Monte Carlo simulations. The detector response function feature's most probable interaction mechanisms are described. The Monte Carlo method is applied to simulate the calibration of a HPGe detector in order to determine the total inactive germanium layer thickness and the active volume that is needed in order to study the response function for both types of detectors. Results indicated a strong impact of dead layer variations on the response function of the simulated detectors.

Keywords: dead layer, MCNPX, coaxial Ge, planar Ge, detection efficiency, gamma-ray.

1. Introduction

Certain radiation detection investigations that are constrained by experimental limitations, such as radioactive sources and device restrictions, can be realized via simulation thanks to the widespread use of Monte Carlo methods in experimental nuclear physics [1, 2].

The internal structure of the detector needs to be defined as precisely as possible in order to make the computed results of the Monte Carlo simulation resemble the actual experimental results. Moreover, the outcomes of the Monte Carlo simulation will be strongly impacted by the precision of its parameter values [3]. A crucial radiation detection tool, the High Purity Germanium (HPGe) spectrometer can be challenging for manufacturers to describe with precision. The same batch of spectrometer components has variations in geometric parameters as well. Also, as the spectrometer is used more frequently, the thickness of the dead layer of HPGe semiconductors changes. Much research has been done on the characteristics of the detector's dead layers utilizing various detectors. Yet, these criteria are necessary because the dead layer significantly influences low-energy rays. These elements lead to a discrepancy between the specification's parameters and the actual ones, which can result in errors during the Monte Carlo simulation [4 - 10].

Laboratory-grade HPGe spectrometers are frequently put through intricate characterization processes. Portable spectrometers are more compact than massive laboratory HPGe spectrometers and are typically employed in-situ measuring situations where frequent handling may affect the crystal structure. Also, the intense vibration of the cooler that is connected to the cooling appliance via electricity invariably interferes with the crystal. Because of these constraints, a portable HPGe spectrometer's settings must be subject to more frequent changes, and crystal characterization is required. The standards for precision might be somewhat lower, and it necessitates a simpler and quicker calibration process [4, 11].

HPGe detectors are broadly used in-ray spectrometry to identify radioactive isotopes and assess their concentrations in environmental samples, as well as in many other fields such as the search for dark matter, discovering new neutrino properties, and many aspects of physics. To acquire high-quality findings, precise knowledge of the detector efficiency appropriate for the unique measurement conditions of each sample is needed. It is not possible to achieve a full calibration solely on the basis of experiments because of the variety of variables, including measurement design, sample type, volume, and matrix. Monte Carlo simulations of detection systems have emerged as an alternative to or a complement to experimental efficiency calibrations thanks to increased processing capacity and the availability of several types of computer codes [12 - 15].

However, a precise understanding of detector parameters, such as window thickness, crystal diameter and length, detector active volume, distance from the end-cap to the detector crystal, and dead layer thicknesses, is necessary for precisely determining the efficiency curve (front, lateral, and back). The aforementioned parameters are typically provided by detector manufacturers, but occasionally, the manufacturer’s information may significantly deviate from the actual ones, particularly if the detector under investigation is old and has been moved around a lot as the detector geometry can change during transporttation. Laboratories use X-ray photographs of the detectors to precisely measure window thickness, detector active volume, and the distance from end-cap to crystal to check whether the detectors maintain their original design [16].

The front, lateral, and back dead layer widths are crucially ambiguous elements that influence the full-energy peak (FEP) efficiency. The undepleted detector region at the outer surface that was doped with lithium atoms to create a semiconductor junction corresponds to the dead layer. Before the photon enters the active volume of the crystal and is counted, it must pass through this region. As the lithium atoms continuously disperse inside the germanium crystal, increasing the thickness of the dead layers over time, it is impossible to establish the thickness of this region using an X-ray image, and the manufacturer's information may differ from the actual thickness. Thus, it is very important to periodically determine a detector’s efficiency curve [17].

Gamma-ray spectrometry routinely starts by developing a computer model using Monte Carlo simulation using point sources to ascertain efficiency calibration. Dead layer thicknesses are adjusted through a process of trial-and-error until calculated and measured efficiencies are equal in order to optimize the results acquired from Monte Carlo simulations with the experimental ones. The dead layer thicknesses are taken into account as adjustable parameters in the efficiency determination processes because they might not match the real values for a variety of reasons, such as the dead layer thicknesses might not be constant across the contact and the electric field might vary throughout the crystal volume, resulting in a variety of charge collections in the crystal active volume [16, 18].

The efficiency calibration process is a complex and time-consuming process of varying the dead layer thicknesses. On top of that, the impact of crystal back dead layer thickness is frequently neglected. We are aware of no quantitative work examining the impact of front, lateral, and back dead layer thicknesses on the HPGe detector efficiency curve. Since this would save time and decrease the effort to match calculated and measured efficiencies [19 - 23].

A unique modeling setup of a detector's top and lateral surfaces has been used to examine the dead-layer variation and its effect on the response function of two types of Ge detectors (planar and coaxial). A dead-layer variation was incorporated into the detector model thanks to comparisons between the results of two types of detectors by Monte Carlo simulations. The Ge spectrometer’s internal structure will alter which will have a big impact on how accurate the modeling simulation findings are. This study examines the Ge spectrometer’s structural parameters characterization approach and presents the characterization findings. Radioactive source ^{137}Cs with monoenergetic line 661.660 keV is used for Monte Carlo simulations. The thickness of the dead layer on the front and lateral surfaces is studied successively. The effect of front, lateral, and back dead layer thicknesses separately on the efficiency curve could be determined. The findings of this study would be used as a resource by the labs calibrating the effectiveness of various detectors for gamma-ray spectrometry Also, it can be used as a guide in Ge detector manufacturing. The results are discussed and interpreted.

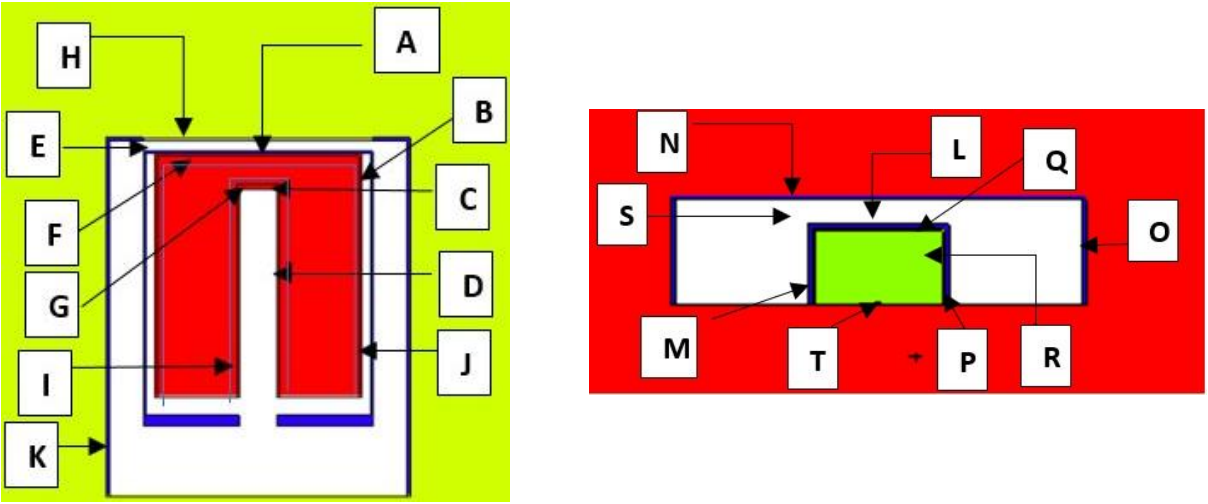
2. Simulation

The response function of various detector types for various applications has also been effectively studied using general-purpose Monte Carlo codes like MCNP, GEANT4, and PENELOPE. General-purpose codes have the benefit of being very adaptable instruments because they can model radiation transport in a variety of materials and complex geometries [16 - 29].

The response function $R(h, E)$ is defined as the probability density that a photon of energy E produces a pulse of height h in the pulse-height spectrum. On the other hand, when the pencil photon beam interacts with some of the elements of the detector before arriving at the active volume, there is a change in the spectrum of energy and particles striking the Ge crystal. In particular, we investigate the modifications introduced in the response function by the Be window and the Ge dead layer. The response function can be calculated as the deposited energy spectrum $D(\epsilon, E)$ and a Gaussian distribution $G(h, \epsilon)$:

$$R(h,E)=T(E)\int_0^\infty G(h,\epsilon)D(\epsilon,E)\,d\epsilon,$$

where $T(E)$ is the fraction of photons transmitted through the absorber materials in front of the active volume. In this paper, we present a simulated model for both types of detectors as shown in Fig. 1 to elaborate the response function of planar and coaxial HPGe detectors for incident photon energies 661.660 keV for radioactive source ^{137}Cs. The detector parameters used in MCNP simulation are shown in Tables 1 and 2.



a *b*

Fig. 1. Simulated detectors by MCNPX: *a* - coaxial Ge, *b* - planar Ge.
(See color Figure on the journal website.)

Table 1. **Parameters of the coaxial n-type HPGe detector as in Ref. [30]**

Geometrical parameters of coaxial Ge detector		Manufacturer's values
A	Crystal diameter, mm	49.8
B	Crystal length, mm	47.8
C	Crystal hole diameter, mm	8.8
D	Crystal hole depth, mm	39.5
E	Crystal-window distance, mm	3.0
F	Front dead layer thickness (inner), mm	1.0
G	Front dead layer thickness (outer), μm	0.3
H	Window thickness, mm	0.5
I	Side dead layer thickness (inner), mm	0.76
J	Side dead layer thickness (outer), mm	1.3
K	Side cap diameter (external), mm	70

Table 2. **Parameters of the planar n-type HPGe detector as in Ref. [31]**

Geometrical parameters of planar Ge detector		Manufacturer's values
L	Crystal diameter, mm	25.5
M	Crystal length, mm	15.0
N	Inner diameter of Al-cap, mm	78.0
O	Thickness of Al-cap side, mm	1.0
P	Boron layer thickness, mm	0.0004
Q	Front dead layer thickness, μm	0.389
R	Side dead layer thickness, μm	0.252
S	Detector face -end cap (mm)	5.0
T	Li-diffused contact, mm	Diameter = 1.159, Height = 0.5

3. Results

We selected the radioactive source ^{137}Cs to study the effect of dead layers on the response function of the detector at energy line 661.660 keV. Table 3 illustrates the different thicknesses of the dead layer that were simulated with different values for front and lateral surfaces for the coaxial Ge detector. The response function results of the front dead layer for coaxial Ge are shown in Fig. 2. with the actual dimension of the lateral one. Curve D1 represents the photopeak of ^{137}Cs at 661.660 keV measured by the actual dimensions of the detector as in the manufacture manual, D2 represents the same photopeak measured by the same detector but without dead layer, the curves from D3 to D7 represent the effect of front dead layer variation from the outer side at the detector cap and the inner side at the inner gap from the coaxial shape on photopeak shape of ^{137}Cs.

Table 3. **Dead layer variation for front and lateral surface for coaxial Ge detector**

Front surface, cm	Inner (F)	0.025	0.05	0.075	0.1	0.125
	Outer (G)	0.015	0.03	0.045	0.055	0.07
Lateral surface, cm	Inner (I)	0.25	0.5	0.75	1	1.25
	Outer (J)	0.015	0.03	0.045	0.06	0.075

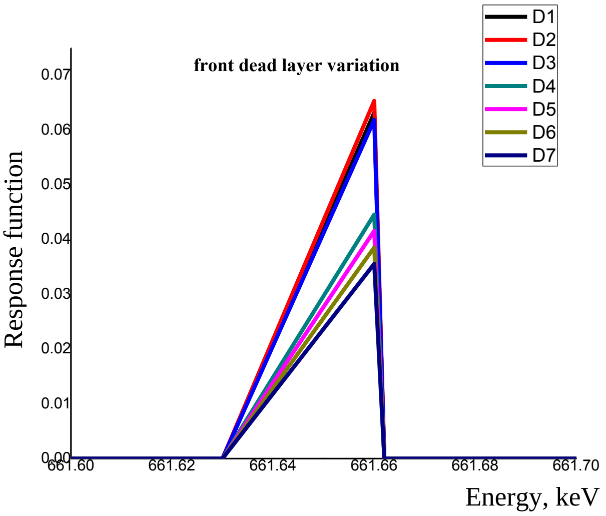


Fig. 2. Response function for coaxial Ge at front dead layer variation. (See color Figure on the journal website.)

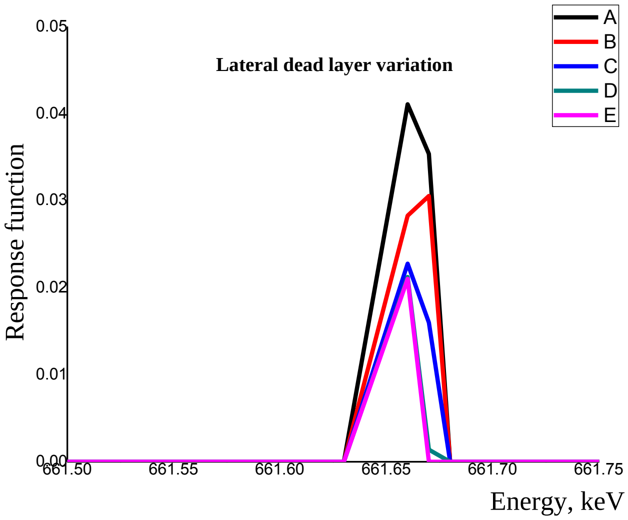


Fig. 3. Response function for coaxial Ge at lateral dead layer variation. (See color Figure on the journal website.)

In Fig. 3, the broadening appears for photopeak due to the change in the lateral dead layer of the coaxial Ge detector. The reason for that is a large volume of coaxial detectors that leads to receiving large amounts of photons produced from an isotropic source that incident on the lateral surfaces of the crystal and deposited in the area under the peak which causes peak broadening. The curves from A to E are produced as a result of changes of inner and outer sides of lateral dead layers as elaborated in Table 3. In this Figure, the front dead layer is fixed at the actual value of the detector's manufacture.

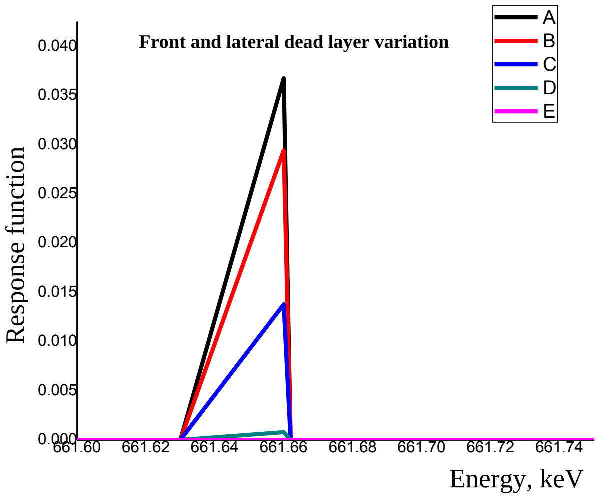


Fig. 4. Response function for coaxial Ge at the front and lateral dead layer variation. (See color Figure on the journal website.)

Fig. 4 shows the dead layer variation for both the front and lateral sides. These curves indicate to strong dead layer effect on the photopeak of ^{137}Cs which causes total deformation by increasing the dead layer thickness and decreasing the active volume of Ge crystal. We applied the same cases on the planar Ge detector with different values of dead layer thickness that depend on the planar detector dimensions. Table 4 describes the values of the dead layer used in the simulation code.

Table 4. **Dead layer variation for front and lateral surface for planar Ge detector**

Front surface, cm (Q)	0.1	0.2	0.3	0.4	0.5
Lateral surface, cm (R)	0.1	0.2	0.3	0.4	0.5

In Fig. 5, curve B illustrates the response function in the case of the actual specification of the planar Ge detector, and curve C indicates its response without adding the dead layer in the simulated file. The curves from D to H indicate the increase in lateral dead layer thicknesses from 0.1 to 0.5 cm as shown in Table 4. The effect of the front dead layer variation on the response function for planar Ge is mostly similar to that in Fig. 5 that's because it has a bulk shape with a few millimeters difference between its height and diameter. So, the energy deposition at energy line 661.660 keV gives the same effect. Fig. 6 describes its variation on the front and lateral sides of the detector. Also, the dead layer thickness variation doesn't change only the photopeak, but the Compton region

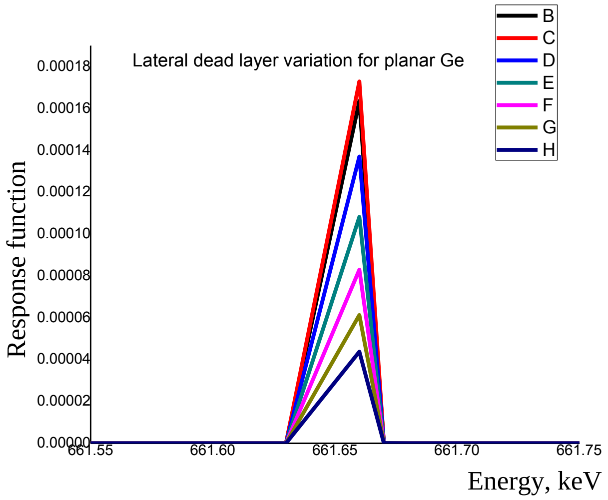


Fig. 5. Response function for planar Ge at lateral dead layer variation. (See color Figure on the journal website.)

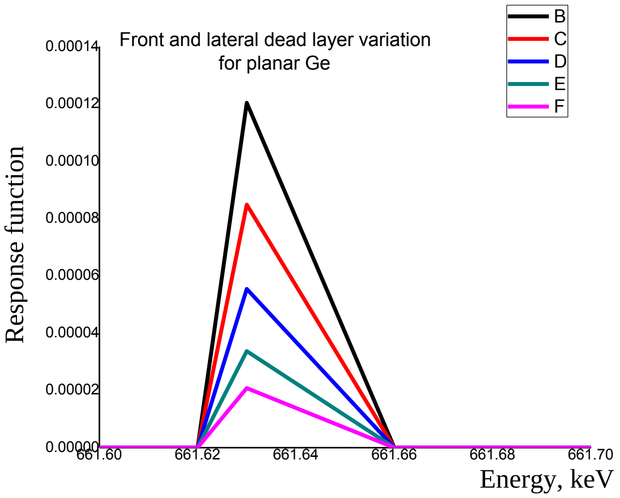


Fig. 6. Response function for planar Ge at the front and lateral dead layer variation. (See color Figure on the journal website.)

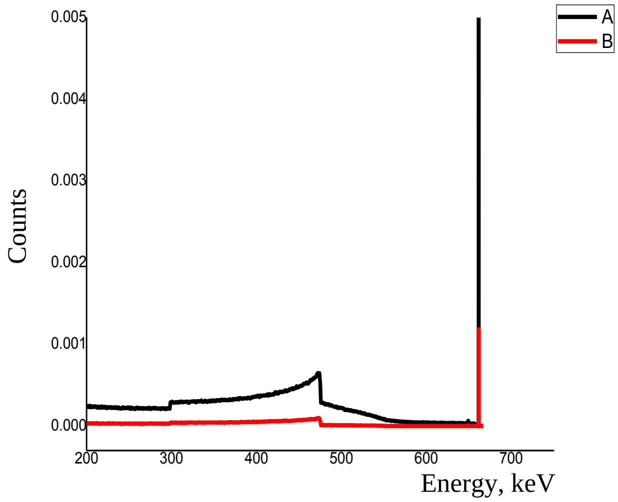


Fig. 7. Response function at Compton region for ^{137}Cs using coaxial and planar Ge (spectrum A for the coaxial Ge and spectrum B for the planar Ge). (See color Figure on the journal website.)

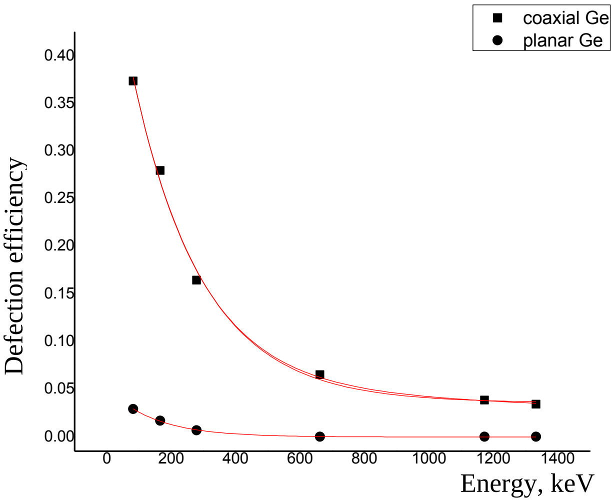


Fig. 8. Dependence of the detection efficiency curve with the energy for coaxial and planar Ge detector. (See color Figure on the journal website.)

is associated with the energy line of ^{137}Cs as illustrated in Fig. 7. However, the Compton region decreases with increasing the dead layer thickness and reducing the active volume of Ge, this is due to the reduction of the scattering probability for the incident photons on active volume. The dead layer variation appears in the detection efficiency curve with the energy for both detectors as shown in Fig. 8. We used different point sources for simulation of ^{60}Co at energy lines (1173 keV, 1333 keV), ^{203}Hg at 279 keV, ^{228}Th at 82 keV, ^{139}Ce at 166 keV, and ^{137}Cs at 661.660 keV. The coaxial Ge curve represents the efficiency curve using the dead layer dimensions by decreasing the thickness (inner: 0.05 cm, outer: 0.03 cm) for the front surface and (inner: 0.5 cm, outer: 0.03 cm) for the lateral surface, while the planar Ge curve represents the efficiency curve by decreasing the dead layer thickness 0.1 cm for front surface and lateral surface. With reducing the thickness for both detectors, the efficiency values at each energy line are reduced that's due to the decrease of the crystal volume consequently, the volume that receives the emitted photon becomes lower than the actual one.

4. Conclusion

The response function of coaxial and planar HPGe detectors has been studied at energy line 661.660 keV for ^{137}Cs. The detector's geometrical dimensions are required by our simulation using MCNPX. For both kinds of Ge detectors, the features of the detector response function have been proposed (coaxial and planar) designs. Due to variations in the dead layer inside the detector structure, the Monte Carlo simulation has demonstrated the effect of these variations through a photo peak of ^{137}Cs at energy line 661.660 keV. The findings made a promise for further, in-depth research in the future. To anticipate the specific features of Ge detector response functions of interest as a function of detector dimensions and incident photon energy, one could perform straightforward Monte Carlo simulations based on the specific dead layer thicknesses. The results proved that the variation of front and lateral dead layers for the coaxial is affected strongly by the peak shape of 661.660 keV while for the planar type, the photopeak still takes the Gaussian shape but changes in the number of photon deposition at this energy value. Due to the low scattering probability for the incident photon, the Compton region decreases with increasing the dead layer thickness and lowering the active volume for both kinds of detectors. The present work can be helpful in Ge detector manufacture development which is considered an important tool in radiation detection.

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ОЦІНКА ВПЛИВУ МЕРТВОГО ШАРУ НА ФУНКЦІЮ ВІДГУКУ ПЛАНАРНОГО ТА КОАКСІАЛЬНОГО Ge-ДЕТЕКТОРА ЗА МЕТОДОМ МОНТЕ-КАРЛО

Кристали германію мають мертвий шар, який спричиняє зниження ефективності, оскільки він поглинає фотони. Товщина цього неактивного шару не є чітко відомою через існування перехідної зони, де фотони поглинаються. Тому, використовуючи дані, надані виробниками для детектора, можна отримати значні розбіжності, зв’язані з товщиною мертвого шару. Дослідження функцій відгуку Ge-детектора для гамма-променів були проведені з використанням простих фізичних механізмів, реалізованих моделюванням за методом Монте-Карло. Описано найбільш імовірні механізми взаємодії при розрахунках функції відгуку детектора. Метод Монте-Карло застосовано для моделювання детектора HPGe з метою визначення загальної товщини неактивного шару германію та активного об’єму, який необхідний для розрахунків функції відгуку для обох типів (коаксіального та планарного) детекторів. Результати показали сильний вплив товщини мертвого шару на функцію відгуку змодельованих детекторів.

Ключові слова: мертвий шар, MCNPX, коаксіальний Ge, планарний Ge, ефективність детектування, гамма-випромінювання.

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