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PARAMETRIC DESCRIPTION OF THE HPGE DETECTOR ENERGY EFFICIENCY WHEN CALIBRATED WITH SHIELDED GAMMA-RAY SOURCES

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The paper presents the results of experimental studies of the energy efficiency of an HPGe detector measured at fixed distances between the calibration source and the detector (50 i 100 mm) in the presence of an absorbing screen made of 12X18N10T stainless steel of different thicknesses (3.40…11.4 mm). Based on experimental data, an empirical description of the efficiency dependence on the thickness of the absorbing stainless-steel screen for fixed distances between the gamma-radiation source and the detector is obtained. The obtained parametric dependencies were tested and experimentally confirmed on another detector. These results are necessary for optimizing the process of conducting γ-spectrometric measurements of shielded fissile materials during the analysis of their isotopic composition.

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INTRODUCTION

Information on the isotopic and quantitative composition of nuclear materials (fissile) is necessary for solving nuclear engineering problems related to their safe use and control of their circulation and non-proliferation. As a rule, these materials are in hermetic containers (for example: stainless steel).

One of the main non-destructive methods for determining the isotopic and quantitative composition of unshielded and shielded nuclear materials (actinides) is based on gamma spectrometric measurements of their characteristic or stimulated gamma radiation [1-3]. As a rule, such nuclear materials are stored in sealed containers [2, 3].

In addition, during the analysis, there is a need for gamma spectrometric measurements of high-intensity γ-radiation fluxes from high-level nuclear materials. Therefore, there is a need to attenuate the intensity of γ-radiation to reduce miscalculations associated with detector loading (its dead time) and, accordingly, corrections for cascade summation [4, 5].

To attenuate the intensity of γ-radiation during spectrometric measurements, the distance between the sample and the detector working surface is increased (this leads to a weakening of the effect of cascade summation of γ-quanta due to a decrease in the geometric efficiency of the detector [4]), or use filters (absorbing screens) that are inserted between the sample and the working surface of the detector (this also reduces the intensity due to the absorption and scattering of gamma radiation by the material (or materials) from which the filter is made [6]).

The accuracy of spectrometric measurements depends on the accuracy of the HPGe- detector calibration for energy efficiency, which must take into account corrections associated with the measurement geometry and the absorption and scattering of gamma radiation by the materials of the sealed containers (screens).

Experimental studies of the efficiency of measurements with absorbing screens are rather scarce [6, 7]. When performing theoretical calculations of the efficiency-energy dependence for specific types of detectors and measurement schemes, difficulties arise due to the uncertainty of the detector dead layer thickness, which can lead to incorrect final simulation results [5]. Therefore, it is not always possible to experimentally determine the absolute detection efficiency of gamma radiation from shielded nuclear materials.

As a rule, empirical formulas for describing the absolute efficiency of detectors for cases of various geometric measurement conditions with and without absorbing screens, obtained from sets of experimental data using detectors, take into account geometric corrections and corrections associated with transmitting γ-radiation by absorbing screens [7-9].

The present work aims to obtain the universal empirical description (or parameterization) of the dependence of the efficiency of the HPGe- detector for fixed source-to-detector distance in the presence of a stainless-steel absorbing shield of different thicknesses and its absence for a wide energy range.

To accomplish this task, the following were done:

– experimental studies were performed to determine energy efficiency at fixed distances: γ-radiation source-detector in the presence and absence of an absorbing screen;

– refinement of previously obtained empirical formulas for the dependence of the energy efficiency of the detector on the distance [9] in the presence of an absorbing screen of fixed thickness [7] by adding parameters that take into account the presence of an absorbing screen of arbitrary thickness between the γ-radiation sources and the detector;

– testing a universal formula for describing energy efficiency with and without an absorbing screen on another HPGe- detector.

1. EXPERIMENT

Gamma spectrometry measurements have been performed using the HPGe-detector ORTEC, 150 cm^3, model: Gem 40195, Serial No: 27 P1892A [7, 9].

The detector was used under the required temperature conditions and screened to reduce the influence of external background radiation. Experimental studies of the effectiveness of the detector with an absorber for four different thicknesses (3.4 mm, 8.0, 9.6, and 11.4 mm), placed at two distances from the detector of 50 and 100 mm for the specified energy range, were performed.

The absolute efficiency of the detector was determined with the help of 8 standard point sources of gamma radiation: Na-22, Co-57, Co-60, Cd-109, Ba-133, Cs-137, Eu-152, Am-241. The spectrometric standard sources were produced by the Metrology Institute and Eckert & Ziegler Isotope Products GmbH (California, USA).

Photo of the ORTEC detector with a holder for γ-sources and an absorb screen (a – without an absorber, b – with absorber) are presented in Fig. 1.



a *b*

Fig. 1. Photo of the HPGe detector with the calibration γ-sources fixation (a – without an absorber, b – with absorber)

The amplitude analysis was carried out with the help of a multichannel ORTEC analyzer (Model: N5608X3, serial No 387 1069), connected with the computer interface HEWLETT PACKARD. During the measurements, the drift of the energy scale and the spectrometer resolution were constantly monitored using point standard γ-sources Co-57 and Co-60. The drift of these parameters did not exceed – 1 %.

The measured γ-ray spectra were processed using the "WINSPECTRUM" program package [10].

Stainless steel discs (steel grade 12X18H10T [11,12]) with a diameter of 34 mm and a height of 3.4, 8.0, 9.6, and 11.4 mm were used as screens (absorbers). This steel grade is widely used for the industrial production of containers for packaging (subsequent storage and use) of highly active radioactive materials.

The efficiency calculation procedure is described in detail in our previous works [7, 9].

The statistical error of efficiency measurements did not exceed 3…5% for the entire energy range.

The scheme of the installation for measuring is presented in Fig. 2.

2. CALCULATION OF EFFICIENCY DEPENDENCE ON DISTANCE FOR SHIELDED GAMMA-SOURCES

To determine the efficiency of the detector in the presence of an absorber, we will proceed from the reasonably successful formula depending on energy E_γ and x source-to-detector distance of absolute efficiency approximation in the form [9] was used as a basis:

$$\ln \varepsilon_0(E_\gamma) = -g_0(x) + g_1(x) \ln\left(\frac{E_\gamma}{E_0}\right) - g_2(x) \ln^2\left(\frac{E_\gamma}{E_0}\right) + g_3 \ln^3\left(\frac{E_\gamma}{E_0}\right) - g_4 \left(\frac{E_\gamma}{E_0}\right)^{-\delta}, \quad (1)$$

$$g_0(x) = a_0 + b_0\sqrt{x}, \quad (2)$$

$$g_1(x) = -a_1 + b_1 \ln(x/x_0), \quad (3)$$

$$g_2(x) = -a_2 + b_2 x, \quad (4)$$

where ε_0 – efficiency of the detector, E_0= *1 keV*, x_0 = 1 mm.

As a starting point, we will perform an experiment without an absorber for the two selected distances (x = 50 and 100 mm).

The results of measurements of the dependence of energy efficiency at fixed distances without absorber are presented in Fig. 3. The experimental values of efficiency are represented by black circles.

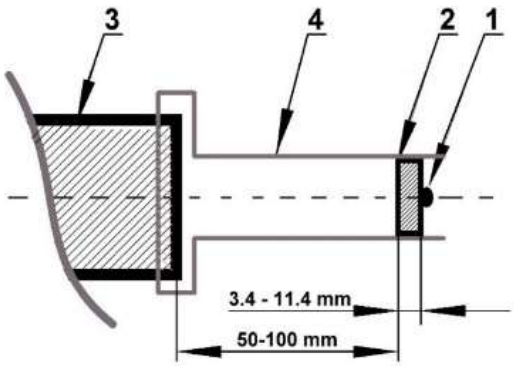


Fig. 2. Scheme of the installation for measuring the dependence of the spectrometer efficiency on the gamma radiation energy on the distance and thickness of the absorber: 1 – certified point source of γ-radiation; 2 – absorbing screen made of stainless steel; 3 – active volume of the HPGe detector; 4 – tube for fixing the position of the point source (material – plexiglass)

Formulas (1)–(4) were used to describe the obtained experimental efficiency values with the help of the parameters of [9] (Table 1).

Table 1

Parameters for calculating the efficiency of a detector without an absorber [9]

Parameter	Value
a_0	10.40
b_0	1.398
a_1	5.459
b_1	$0.4589 \cdot 10^{-1}$
a_2	0.9620
b_2	$-0.4550 \cdot 10^{-3}$
g_3	$0.4845 \cdot 10^{-1}$
g_4	$38.00 \cdot 10^{4}$
δ	3.000

The results of efficiency calculations according to (1)–(4) for two values of (x) 50 and 100 mm with

parameters from Table 1 are presented by red curves in Fig. 3.

We can use the same procedure for measuring the efficiency as a function of the energy *Eγ* and x distance in the presence of an absorber with a thickness of 9.6 mm.

The result of the efficiency measurement with the absorber is shown in Fig. 4 by black circles.

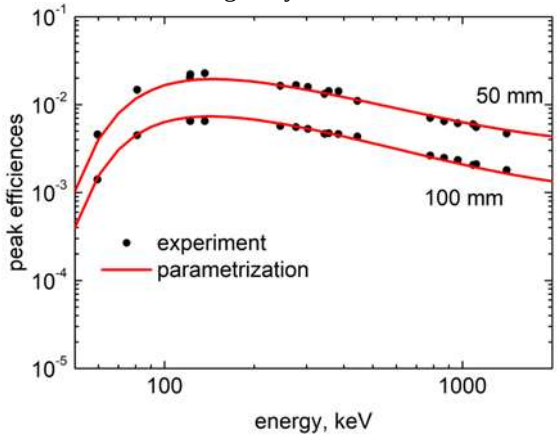


Fig. 3. Parametric description of the dependence of the HPGe detector (Gem 40195) efficiency on the energy of γ-rays at fixed distances without absorber

Instead of direct fitting using formulas (3) - (6) to obtain experimental data of the efficiency of the detector with an absorber, we will put to use the expression according to formulas (3)-(6) with fixed parameters from [9], multiplied by the factor *f(Eγ,x):*

$$\ln \varepsilon(E_\gamma, x) = \ln \varepsilon_0(E_\gamma, x)\, f(E_\gamma, x), \quad (5)$$

$$(E_\gamma, x) = \left[g_5 + g_6 \ln\left(\frac{E_\gamma}{E_0}\right) + g_7 \ln^2\left(\frac{E_\gamma}{E_0}\right)\right](1 + g_8 x), \quad (6)$$

containing at least 4 free parameters.

The least squares method was used for calculations [18].

The results of efficiency calculations using (1)–(6) for distances x from the source to the detector (50 and 100 mm) with an absorber (thickness – 9.6 mm) with fixed parameters from Table 1 and fitted parameters in Table 2 are presented in Fig. 4 by red curves. Accordingly, the fitting result is given in Table 2.

Table 2

Best fitting parameters of the detector efficiency with an absorber

Parameter	Value	Error
g_5	-2.193	0.205
g_6	0.7008	0.0738
g_7	$-0.4561 \cdot 10^{-1}$	$0.631 \cdot 10^{-2}$
g_8	$0.1223 \cdot 10^{-1}$	$0.904 \cdot 10^{-2}$
χ^2 /dof	1.60	

Accordingly, the fitting result is given in Table 2. From the comparison of both results, it can be seen that the used modified efficiency formula successfully describes the experimental data of the detector efficiency at different distances in the case with the absorber.

3. EFFICIENCY CALCULATION DEPENDING ON ABSORBER THICKNESS

The next step was determining the efficiency dependence on the absorber's thickness. At the same installation, we obtained experimental values of detector efficiency at different absorber thicknesses at the fixed distance *x* = 50 mm. The results of the measurements are shown in Fig. 5. The experimental values of efficiency as a function of the thickness of the absorbing screen (absorber) are presented by red circles for d = 3.4 mm; blues squares for d = 8.0 mm; green triangles for d = 9.6 mm and purple diamonds for d = 11.4 mm.

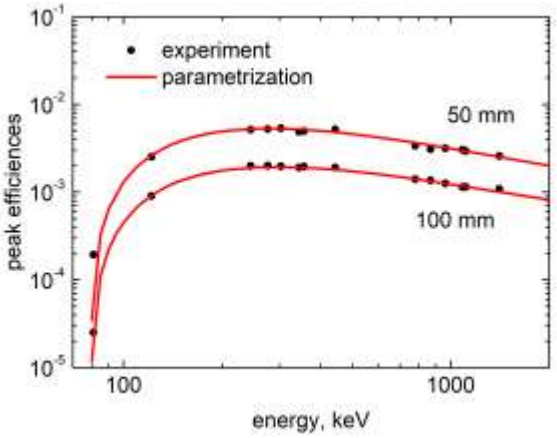


Fig. 4. Parametric description of the dependence of the HPGe detector (Gem 40195) efficiency on the energy of γ-rays at fixed distances with absorber

For fitting the experiment, the same form of efficiency formula (1) with different parameters depending on absorber thickness *d* was used:

$$\varepsilon(E_\gamma, d) = -g_0 + g_1(d) \ln\left(\frac{E_\gamma}{E_0}\right) - g_2(d) \ln^2\left(\frac{E_\gamma}{E_0}\right) + g_3(d) \ln^3\left(\frac{E_\gamma}{E_0}\right) - g_4 \left(\frac{E_\gamma}{E_0}\right)^{-\delta(d)}. \quad (7)$$

A formula is proposed to describe each of the efficiency sets of Fig. 5 measured at different shield screens (absorbers) with thickness *d* (3.40…11.4) mm and *x* = 50 mm distance for the mentioned energy range of calibration.

In the specific case of measuring the variable screen thickness between the sample and the detector, obtaining the system's efficiency as a function of the geometric (thickness) parameters is necessary.

This means that the parameters g_j take the form of $g_j(d)$. For the fitting, 4 x 6 parameters for various functions in form (1) must be used for all four sets of measured efficiency at different screen thicknesses. Some of them, namely g_1, g_2, g_3, and δ, were sensitive to the change in the screen thickness (d). Parameters g_0 and g_4 for all separate sets of measured efficiency have been obtained as simple parameters. The first four mentioned a_j and δ, $j=1,3$ can be approximated by simple linear functions:

$$g_j(d) = a_j(1 - bd), \quad (8)$$

$$\delta(d) = e - fd. \quad (9)$$

So, the fitting uses only 2+3+3 parameters instead of 4 x 6. Combining fit expressions (7) and (8), (9), we have performed the overall fit for all experimental points of efficiency *(ε)* as the function on energy and screen thickness, where $g_1(d)$, $g_2(d)$, $g_3(d)$, and $\delta(d)$ determined as (8) and (9).

The result of the least squares fit is presented in Fig. 5 and Table 3. The parametric description of the detector efficiency as a function of the γ-radiation energy and the thickness of the absorbing screens for the four thickness corresponds to the colored solid curves.

Table 3

Best values of parameters describing efficiency with absorbing screens

Parameter	**Value**	**Error**
g_0	10.00	Fixed
a_1	4.627	0.152
a_2	0.9272	0.0488
a_3	$0.5323 \cdot 10^{-1}$	$0.395 \cdot 10^{-2}$
b	0.1301	$0.37 \cdot 10^{-2}$
g_4	$38.00 \cdot 10^{4}$	Fixed
e	2.846	0.011
f	0.2628	$0.88 \cdot 10^{-2}$
δ	3.000	Fixed
χ^2 /dof	1.82	

All the fitted parameters depend linearly on the thickness of the absorber. The account for this dependence needs only three more parameters for the global fit of the experimental values of the effectiveness at all selected absorbing thicknesses.

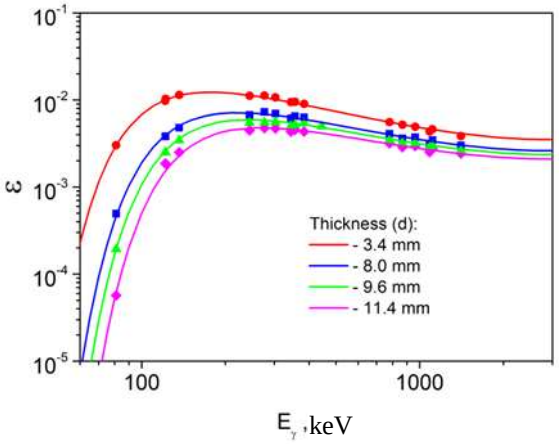


Fig. 5. Parametric description of the dependence of the HPGe detector (Gem 40195) efficiency on the energy of γ-rays and the thickness of the absorbing screens

4. PARAMETRIZATION TEST

The applicability of the parameterization to experimental data was tested on another type of detector, namely the ORTEC GEM-15190 (Serial No. 22-P-935B). The technical characteristics of the detector are presented in Table 4 [19]. The photo of this HPGe-detector with a with a holder for γ-sources and an absorb screen is present in Fig. 6.

Table 4

Characteristics of ORTEC GEM-15190

Parameter	Dimension, mm
Type	GEM-15190
Geometry	Ended coaxial
Crystal radius	25.4
Crystal height	41.2
Core radius	4.65
Core height	27.7
Absorbing layer	2.45 (Aluminum)
Inactive Ge	2500
End cap to crystal distance	5



Fig. 6. Photo of the ORTEC detector with a holder for γ-sources and an absorb screen

The same series of measurements under the conditions above were performed. In this case, we are using formula (1), which has somewhat simplified coefficients g_i (since we have less experimental data on this detector) and contains only eight parameters, three of which are fixed:

$$g_0(x) = a_0 + b_0 \ln(x/x_0), \quad (10)$$

$$g_1 = a_1 + b_0 \ln(x/x_0), \quad (11)$$

$$g_2(x) = a_2 + b_2 \ln(x/x_0). \quad (12)$$

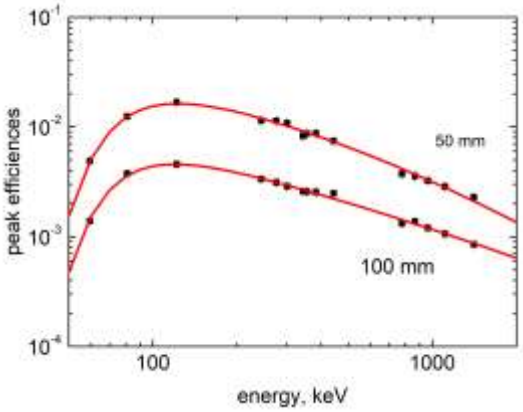


Fig. 7. Dependence of the efficiency of the HPGe detector (ORTEC GEM-15190) on energy at fixed distances of 50 and 100 mm in the absence of an absorbing screen

To calculate the dependence of the detector's efficiency on energy and distance, data measured on the ORTEC GEM-15190 detector for detector-sample distance of 50 mm and 100 mm (Fig. 7) and with a steel absorber with a thickness of 9.6 mm (Fig. 8) were used.

Experimental values of efficiency ε depending on energy Eγ for fixed distances (50 and 100 mm) without absorber are presented by black squares in Fig. 7. The results of efficiency calculations according to formulas (1) and (10)–(12) with parameters from Table 5 are presented by red curves in the same figure.

Table 5

Best values for the efficiency description parameters without the shield

Parameter	Value	Error
a_0	5.677	0.608
b_0	-1.203	0.226
a_1	2.489	0.029
a_2	0.3134	0.0229
b_2	-0.1187	0.0139
g_3	0	Fixed
g_4	$-38.00 \cdot 10^4$	Fixed
δ	3.000	Fixed
χ^2 /dof	0.25	

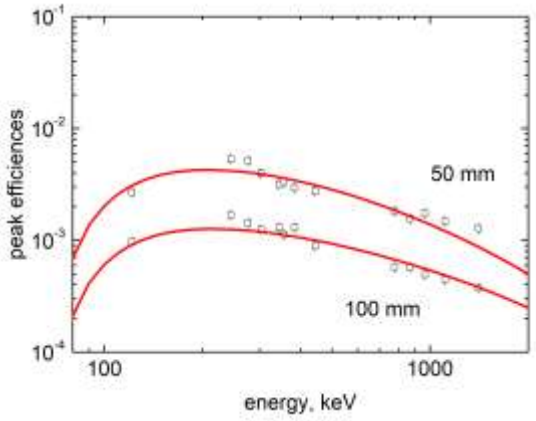


Fig. 8. Dependence of the efficiency of the HPGe detector (ORTEC GEM-15190) on energy at fixed distances of 50 and 100 mm with an absorbing screen

Acting as above, to calculate the efficiency with an absorber of the same thickness, we use the expression for $ln\varepsilon 0$ with params (10)–(12), multiplied by the factor $f(E_\gamma, x)$ from (5), (6). Parameters obtained with fitting the efficiency with the shield are given in Table 6.

Table 6

Best values for the efficiency description parameters with an absorbing screen

Parameter	Value	Error
g_5	-3.829	0.421
g_6	0.9845	0.1454
g_7	$-0.7452 \cdot 10^{-1}$	$0.63 \cdot 10^{-2}$
g_8	$0.1197 \cdot 10^{-1}$	$0.955 \cdot 10^{-2}$
χ^2 /dof	2.55	

Experimental values of efficiency ε depending on energy Eγ for distances (50 and 100 mm) with absorber screen are presented by light squares in Fig. 8. The results of efficiency calculations according to formulas (1) and (10)–(12) with fixed parameters from Table 6 and fitted parameters from Table 5 are presented by red curves in the same figure.

CONCLUSIONS

An experimental setup was created to study the dependence of efficiency on the absorber thickness d (3.40…11.4 mm) for fixed distances: the gamma radiation source – the working surface of the detector.

The universal empirical formula was proposed to calculate the detector efficiency depending on energy Eγ and source-to-detector distance. In addition, the formula for calculating the detector efficiency depending on absorb thickness was obtained. The formulas (7)–(9) can be used successfully, at least in the studied range of the absorber thickness, to calibrate the efficiency of semiconductor detectors in a wide range of energies and distance, especially in the case of actinides photofission, where the statistic is not so high.

The obtained parametric dependencies (on the thickness of the absorber at fixed distances: the surface of the detector – the source of γ-rays) were tested and experimentally confirmed on another HPGe detector.

The results of the presented studies are necessary for optimizing the process of conducting γ-spectrometric measurements of fissile nuclear materials packed in sealed of 12X18H10T stainless steel containers during the analysis of their isotopic composition.

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REFERENCES

1. M. Grdeń. Non-classical applications of chemical analysis based on nuclear activation // *J. Radioanal Nucl. Chem.* 2020, v. 323, p. 677-714.
2. H. Al Hamrashdi, S.D. Monk, D. Cheneler. Passive Gamma-Ray and Neutron Imaging Systems for National Security and Nuclear Non-Proliferation in Controlled and Uncontrolled Detection Areas Rev Past and Curr Status // *Sensors*. 2019, v. 19, 2638.
3. I.V. Pylypchynets, O.O. Parlag, V.T. Maslyuk, et al. Isotopic identification of photofissed nuclear materials in stainless steel containers using delayed gamma-rays // *Problems of Atomic Science and Technology*. 2022, v. 141, 103-109.
4. J. Knezevic, D. Mrdja, J. Hansman, et al. Corrections of HPGe detector efficiency curve due to true coincidence summing by program EFFTRAN and by Monte Carlo simulations // *Applied Radiation and Isotopes*. 2022, v. 189, Article number: 110421.

5. S. Kaya, N. Çelik, T. Bayram. Effect of front, lateral and back dead layer thicknesses of a HPGe detector on full energy peak efficiency // *Nucl Instr and Meth in Phys Res Sect A.* 2022, v. 1029. Article number: 166401.
6. I.V. Pylypchynets, A.I. Lengyel, O.O. Parlag, et al. Gamma-Ray Self-Absorption Corrections in Stainless Steel 12X18H10T for the Needs of Non-Destructive Isotopic Differentiation of Shielded Actinides // *Int. J. Innov Sci and Res Technol.* 2024, v. 9, p. 651-658.
7. I.V. Pylypchynets, A.I. Lengyel, O.O. Parlag, et al. Empirical formula for the dependence of HPGe-detector efficiency on energy and distance for shielded gamma-ray sources // *Probl. of Atom. Sci. and Technol.* 2023, N 3, p. 47-51.
8. L. Seenappa, H.C. Manjunatha, K.N. Sridhar, et al. Semi empirical formula for exposure buildup factors // *Rad. Eff. and Defects in Solids.* 2017, v. 172, p. 790-798.
9. I. Pylypchynets., A. Lengyel, O. Parlag, et al. Empirical formula for the HPGe detector efficiency dependence on energy and distance // *J. Radioanal Nucl. Chem.* 2019, v. 319, p. 1315-1319.
10. M.V. Strilchuk. User manual for Winspectrum. *KINR NAS of Ukraine (unpublished). Private communication.*
11. Characteristics of material 12X18H10T (In Ukrainian) https://www.splav-kharkov.com/mat_start.php?name_id=329. Accessed 08 Nov 2024
12. 12X18H10T: Characteristics of steel mark (In Ukrainian) https://steelservice.com.ua/12h18n10t/ Accessed 02 Nov 2024.
13. F. James, M. Ross. Function minimization and error analysis. MINUIT D506. CEREN Computer Centre Program library. 1967, p. 1-47.
14. S.M. Zamzamian, N. Vosoughi. Determining of experimental absolute and intrinsic peak efficiency of HPGe detector and benchmarking with Monte Carlo code using MCNP // *Adv. in Nat. and Appl. Sci*. 2014, v. 8(15), p. 15-20.

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ПАРАМЕТРИЧНИЙ ОПИС ЕНЕРГЕТИЧНОЇ ЕФЕКТИВНОСТІ HPGE-ДЕТЕКТОРА ПРИ КАЛІБРУВАННІ ЕКРАНОВАНИМИ ДЖЕРЕЛАМИ ГАММА-КВАНТІВ

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Наведено результати експериментальних досліджень енергетичної ефективності детектора HPGe, виміряної на фіксованих відстанях між калібрувальним джерелом і детектором (50 і 100 мм) за наявності поглинаючого екрана з нержавіючої сталі 12X18H10T різної товщини (3,40…11,4 мм). На основі експериментальних даних отримано емпіричний опис залежності ефективності від товщини поглинаючого екрану з нержавіючої сталі для фіксованих відстаней між джерелом гамма-випромінювання та детектором. Отримані параметричні залежності були перевірені та експериментально підтверджені на іншому детекторі. Ці результати необхідні для оптимізації процесу проведення γ-спектрометричних вимірювань екранованих подільних матеріалів під час аналізу їх ізотопного складу.