PARAMETRIC DESCRIPTION OF HPGE DETECTOR ABSOLUTE EFFICIENCY FOR MEASURING SHIELDED SAMPLE ACTIVITY

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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 and 100 mm) in the presence of an absorbing screen made of 12X18N10T stainless steel of different thicknesses (from 3.40 to 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.

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INTRODUCTION

Radiation monitoring of nuclear facilities, which is necessary to ensure the radiation safety of the population of adjacent territories, is an important task of radiation ecology (or environmental research).

Control over all stages of the nuclear cycle (for example, production of nuclear fuel, processing and storage of nuclear waste) is necessary to prevent environmental pollution.

To solve these problems, it is necessary to have reliable information about the qualitative (isotopic composition) and quantitative composition of nuclear materials (fertile, fissile) and their decay products, which can be potential sources of radiation contamination.

In addition, this information is necessary for carrying out technical measures to eliminate (neutralize) the consequences of nuclear accidents (for example, Chornobyl NPP, Fukushima).

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 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 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.

EXPERIMENT

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

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, 8.0, 9.6, and 11.4 mm), placed at two distances from the detector of 50 mm and 100 mm for the specified energy range for 18 gamma lines, 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). 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 mm, 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.

As a result, we obtained a set of efficiency values depending on the source-to-detector distance in the presence of a shielding screen at a fixed thickness in the form of Fig. 1.

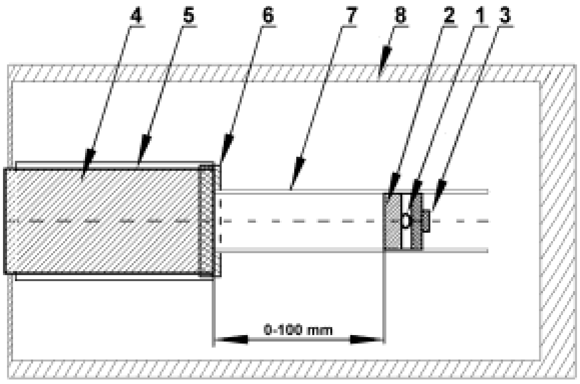

Fig. 1. The setup for measurements of the spectrometer efficiency dependence on the energy of gamma radiation, distance, and absorber thickness: 1 – certified point source of γ-radiation; 2 – absorbing screen made of stainless steel; 3 – fixation of the γ-radiation source; 4 – active volume of the HPGe detector; 5 – cadmium sheet [0.1 cm]; 6 – tube holder – tube fixation (material – plexiglass); 7 – tube for fixing the position of the point source (material – plexiglass); 8 – passive lead protection (thickness – 100 mm)

EFFICIENCY CALCULATION DEPENDING ON DISTANCE AT SHIELDED SOURCES

Experimentally, the detector efficiency is performed by the measurement of the standard samples containing different radionuclides with known activities. The full-energy – peak efficiency is defined as

$$\varepsilon = N_\gamma / N_S. \tag{1}$$

Taking into account the emitted number of photons N_s during a time t by a standard radionuclide with known activity A for the specific emission with intensity Y, the efficiency will be read as

$$\varepsilon = \frac{N_\gamma}{AYt}, \tag{2}$$

where N_γ – the counts – means the corresponding peak area in the spectrum.

The efficiency ε is used for the calibration of detectors for specific physical processes of photon scattering and absorbing [13, 14], as well as for samples with certain geometry (volume) [15], different source-to-detector distances [7, 9, 16, 17] in different energy ranges [18]. To determine the efficiency of the detector in the presence of an absorber, we will proceed from the reasonably successful formula depending on energy Eγ and x source-to-detector distance of absolute efficiency approximation in the form [9] was used as a basis:

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

$$g_0(x) = a_0 + b_0\sqrt{x}, \tag{4}$$

$$g_1(x) = -a_1 + b_1\ln(x/x_0), \tag{5}$$

$$g_2(x) = -a_2 + b_2 x, \tag{6}$$

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 result of efficiency measurement is shown in Fig. 2a.

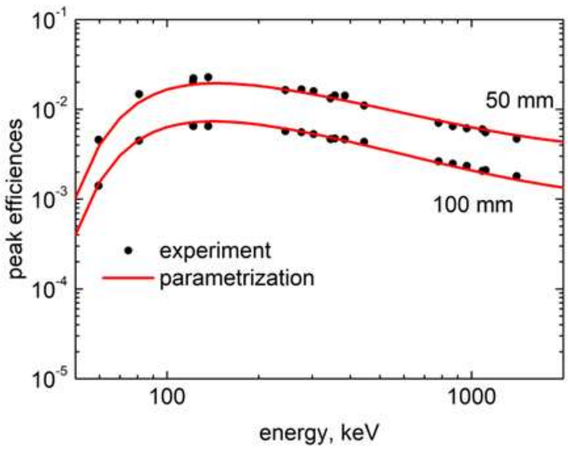

Fig. 2a. Experimental values of efficiency depending on energy for different source-to-detector distance x without absorber (black circles). Results of efficiency calculation with (3)–(6) for two value x of 50 and 100 mm with parameters of Table 2 (Red curves)

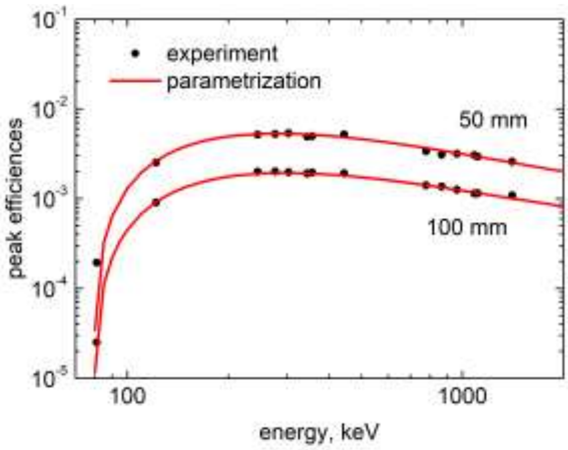

Fig. 2b. The same with absorber (black circles). Results of efficiency calculation with (3)–(8) for source-to-detector distance x with absorb (black circles) for 9.6 mm thickness at the exact distances with fixed parameters of Table 1 and fitted parameters of Table 2. (Red curves)

Formulas (3)– (6) were used to describe the obtained experimental efficiency values with the help of the parameters of [9] (Table 1).

Table 1

Parameters to calculate the detector efficiency [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

We can use the same procedure for measuring the efficiency as a function of the energy $E\gamma$ and x distance in the presence of an absorber with a thickness of 9.6 mm. The result of efficiency measurement with an absorber is shown in Fig. 2b. Instead of direct fitting using formulas (3) - (6) to obtain experimental data of the efficiency of the detector with an absorber, we will put use the expression according to formulas (3)–(6) with fixed parameters from [9], multiplied by the factor *f(Eγ,x):*

$$\ln \varepsilon(E_\gamma, x) = \ln \varepsilon_0(E_\gamma, x)\, f(E_\gamma, x), \quad (7)$$

$$(E_\gamma, x) = \left[g_5 + g_6 \ln\left(\frac{E_\gamma}{E_0}\right) + g_7 \ln^2\left(\frac{E_\gamma}{E_0}\right)\right](1 + g_8 x) \quad (8)$$

containing at least 4 free parameters. For the fit we used the least squares analysis [19].

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

Table 2

Results of the efficiency fit of (7) and (8) with shield

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	

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. 3. For fitting the experiment, the same form of efficiency formula (3) with different parameters depending on absorber thickness d was used:

$$\varepsilon(E_\gamma, d) = -g_0 + g_1(d) \ln\left(\frac{E_\gamma}{E_0}\right) - g_2(d) \ln^2\left(\frac{E_\gamma}{E_0}\right) + g_3(d) \ln^3\left(\frac{E_\gamma}{E_0}\right) - g_4\left(\frac{E_\gamma}{E_0}\right)^{-\delta(d)}. \quad (9)$$

A formula is proposed to describe each of the efficiency sets of Fig. 4 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 (3) 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:

$$g_j(d) = a_j(1 - bd), \quad (10)$$

$$\delta(d) = e - fd\,. \quad (11)$$

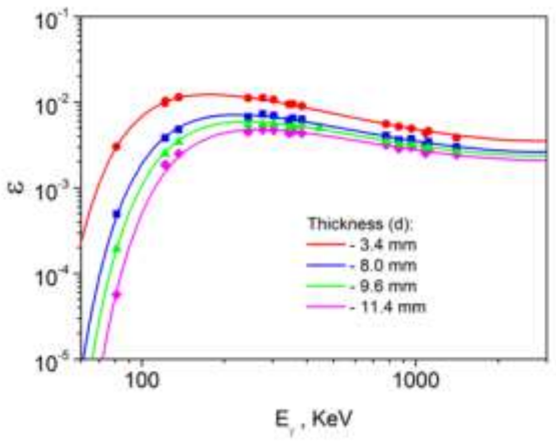

Fig. 3. Experimental values of efficiency ε depending on energy E_γ for the different screen (absorber) thickness (red circles for d = 3.4 mm; blue squares for d = 8.0 mm; green triangles for d = 9.6 mm and magenta diamonds for d = 11.4 mm. The dependence of detector efficiency on γ-radiation energy and thickness of absorbing screens for the four cases mentioned at x = 50 mm source-to-detector distance corresponds to colored solid curves

Table 3

Results of the efficiency fit of (9), (10), and (11)

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	

So, the fitting uses only 2+3+3 parameters instead of 4 x 6. Combining fit expressions (9) and (10), (11), 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 (10) and (11). The result of the least squares fit is presented in Fig. 3 and Table 3.

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 absorb thicknesses.

CONCLUSIONS

The measuring system was constructed to investigate the efficiency dependence on absorber thickness d for the 3.40…11.4 mm range. 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 (9) – (11) 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 photonuclear reactions, where the statistic is not so high.

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