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MONTE-CARLO SIMULATION OF RESPONSE OF CdZnTe DETECTORS OF BETA-RADIATION

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Response functions of CdZnTe detector, developed for measurement of electron energy spectra, are investigated. The experimental response of CdZnTe detector is compared to the spectra simulated by Monte-Carlo method. A satisfactory agreement of simulated and experimental data is reached with introduction in the theoretical detector model of two fitting parameters – products of mobilities and lifetimes of electrons and holes. It is shown that the main disagreement of experimental and simulated spectra is connected to the high level of noise in the preliminary amplifier.

KEY WORDS: CdZnTe detector, beta-radiation, Monte-Carlo method, response function

МОДЕЛЮВАННЯ МЕТОДОМ МОНТЕ-КАРЛО ВІДГУКУ CdZnTe ДЕТЕКТОРІВ БЕТА-ВИПРОМІНЮВАННЯ

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Досліджені функції відгуку CdZnTe детектора, що призначається для вимірювання спектрів енергії електронів. Виміряний експериментально відгук CdZnTe детектора порівнюється зі спектрами, розрахованими методом Монте-Карло. Задовільного узгодження розрахункових та експериментальних даних можна досягти при використанні в моделі детектора двох параметрів підгонки – добутків рухливості на середній час життя електронів та дірок. Показано, що основні розбіжності між експериментальними та розрахунковими спектрами пов'язані з високим рівнем шумів попереднього підсилювача.

КЛЮЧОВІ СЛОВА: CdZnTe детектор, бета-випромінювання, метод Монте-Карло, функція відгуку

МОДЕЛИРОВАНИЕ МЕТОДОМ МОНТЕ-КАРЛО ОТКЛИКА CdZnTe ДЕТЕКТОРОВ БЕТА-ИЗЛУЧЕНИЯ

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Исследованы функции отклика CdZnTe детектора, предназначенного для измерения энергетических спектров электронов. Экспериментально измеренный отклик CdZnTe детектора сравнивается со спектрами, рассчитанными методом Монте-Карло. Удовлетворительное согласие расчетных и экспериментальных данных достигается при использовании в модели детектора двух подгоночных параметров – произведений подвижности на средние времена жизни электронов и дырок. Показано, что основные расхождения экспериментальных и расчетных спектров связаны с высоким уровнем шумов предварительного усилителя.

КЛЮЧЕВЫЕ СЛОВА: CdZnTe детектор, бета-излучение, метод Монте-Карло, функция отклика

Semiconductor compounds CdTe and CdZnTe are widely used in manufacturing of gamma-ray detectors for operation at room temperatures. Absence of additional cooling allows creating compact highly effective devices which are used for various purposes in gamma-ray spectrometry and dosimetry. The shortcoming of CdTe (CdZnTe) is a low mobility of holes that worsens detectors' energy resolution in the high energy range of gamma quanta (higher than 0.5 MeV). In order to overcome this disadvantage a number of technical solutions has been offered recently [1, 2] which allowed to reach at 662 keV (^{137}Cs gamma-ray source) the resolution which is close to a theoretical limit.

Besides the tasks connected with measurement of gamma fields, room temperature CdTe (CdZnTe) detectors also have good prospects at the registration of beta radiation. In particular, considerable interest is attracted to a problem of the extraction of beta spectra from the measurement of the mixed gamma and beta radiation [3]. Detectors of beta particles are also in demand in research of radiation protective properties of materials when there are rigid restrictions on the admissible size and weight of protective designs [4].

At measurement of electron energy spectra an ultrahigh resolution of detectors is not required. This is due to the fact that intensive quasimonoenergetic lines are present only in spectra of a few beta sources (for example, groups of closely located lines of conversion electrons in ^{137}Cs spectrum). Besides, the interaction of electrons with air (not to mention more dense environments) leads to a considerable smearing of initial lines or their total disappearance. Therefore, one can expect that in measurements of beta spectra the energy resolution requirement to detectors of high-resistance semiconductor compounds CdTe and CdZnTe (i.e. the requirement to crystal quality) may be less stringent than at registration of gamma quanta. At the same time, higher density and average atomic number of CdTe (CdZnTe) in comparison with germanium and silicon provide more effective slowing-down of electrons in detector working volume that allows using less expensive thinner detectors.

We present below a research of a response of a planar CdZnTe detector to the irradiation from a reference ^{90}Sr/^{90}Y source. The main objective of the work was a restoration by the Monte-Carlo method of the response function of CdZnTe detector to beta radiation. For comparison we use and cite here for the first time the experimental data received previously during the adjustment of a measuring channel in papers [4, 5]. Besides the electron spectra measured with an unshielded ^{90}Sr/^{90}Y source, spectra of electrons, which have passed through aluminum and lead slowing-down filters, were also investigated. In all cases we compared the response functions measured with CdZnTe detector to the response functions simulated by the Monte-Carlo method. We established that satisfactory agreement of simulated and experimental response functions due to the introduction in the detector model of two fitting parameters: products of carriers mobility and average lifetime. Meanwhile, the remained observed discrepancies necessitate considerable decreasing of noise level in devices with detecting units based on CdTe (CdZnTe) crystals for registration of beta radiation below 100 keV. An agreement between experimental results and simulation data is considerably improved with the application of thin metal filters in measurements or with the increase in the lower discrimination threshold.

MEASUREMENTS OF BETA-SPECTRA

Registration of the radiation from ^{90}Sr/^{90}Y source was carried out at the measuring bench created at NSC KIPT. It consists of CdZnTe detector sized 6×6×3 mm^3, a charge sensitive preliminary amplifier (the measured ratio of charge-voltage transformation was 0.96 mV/fC), Canberra Model 2026 Spectroscopy Amplifier, the analogue-digital Canberra Model 8706 converter (ADC) and the Canberra Model 3106D power supply. The operational detector displacement voltage was U_b = 150 V. Efficiency of charge collection (CCE) in the CdZnTe detector at the indicated displacement voltage was about 34%. The detector was placed in the silumin case of 2 mm thickness. A beryllium window of 23 micron thickness, located in a front part of the case, allows a transmission of electrons with the minimum energy loss. Measurements of ^{90}Sr/^{90}Y radiation spectrum were carried out with the reference source of beta radiation 1SO-135 which was placed at about 12 mm above the detector surface. The spectrometry of ^{90}Sr is an important task [3]. Besides, a wide range of electron energies allows using this source for an assessment of radiation protective properties of different materials [4, 5].

The initial (theoretical) spectrum of the ^{90}Sr/^{90}Y source is shown in Fig. 1. The data presented in Fig. 1 are the results of simulation with a universal package Geant4 [6] modeling the interaction of nuclear radiation with matter. The electron spectrum consists of two branches: the initial part up to the energy about 0.5 MeV corresponds mainly to the electrons which are formed at decay of ^{90}Sr ($T_{1/2}$ = 28.74 years) → ^{90}Y. The high-energy branch of the spectrum is formed at the subsequent disintegration of ^{90}Y ($T_{1/2}$ = 64.1 hours) → ^{90}Zr [7]. At decay of ^{90}Y an insignificant number of γ-quanta (Table 1) also is formed, which do not influence essentially the general detector pulse statistics. When modeling the line of γ-quanta with energy of 1.76 MeV they were distributed over two neighbor energy sampling levels with total intensity of $(5.2 + 6.3 = 11.5)\times10^{-5}$ quantum per decay that corresponds to the probability of the relevant channel of disintegration: 0.011% (Table 1).

Table 1.

Radiation characteristics of ^{90}Sr/^{90}Y source

Nuclide	Probability of the decay channel, %	electrons		γ-quanta
		E_{max}, keV	E_{middle}, keV	E_γ, keV
^{90}Sr ($T_{1/2}$ = 28.74 year)	100	546.0	195.8	–
^{90}Y ($T_{1/2}$ = 64.1 hour)	99.989	2280.1	993.7	–
	0.011	519.4	185.6	1760.7
	1.4×10^{-6}	93.8	25.0	2186.2

The spectrum of 1SO-135 source, obtained with the above measuring bench, is shown in Fig. 2. Time of measurement was 1 hour. The energy calibration of the measuring bench (the top axis in Fig. 2) was carried out using the measurements of photopeak centroid positions in the spectra of ^{137}Cs and ^{241}Am reference gamma-ray sources (Fig. 3). The maximum energy of the registered electrons corresponds to the maximum energy of the electrons which are formed at beta-decay of ^{90}Y (2.28 MeV).

The shape of the initial section of the spectra in Fig. 2 (E < 0.1 MeV) essentially differs from theoretically predicted one (Fig. 1) as a result of a considerable noise level in the preliminary amplifier (equivalent noise charge (ENC) is about 400 e$^-$ units of the electron charge, the maximum of the measured noise spectrum corresponds to energy about 100 keV). Other sections of the experimental spectrum (Fig. 2) also have some differences from the simulated spectrum of ^{90}Sr/^{90}Y source in Fig. 1. In particular, a shape of curve at the energy, where the spectra of electrons formed at disintegrations of ^{90}Sr and ^{90}Y ($E \approx$ 0.5 MeV) come together, appears strongly blurred in comparison with the simulated spectrum in Fig. 1.

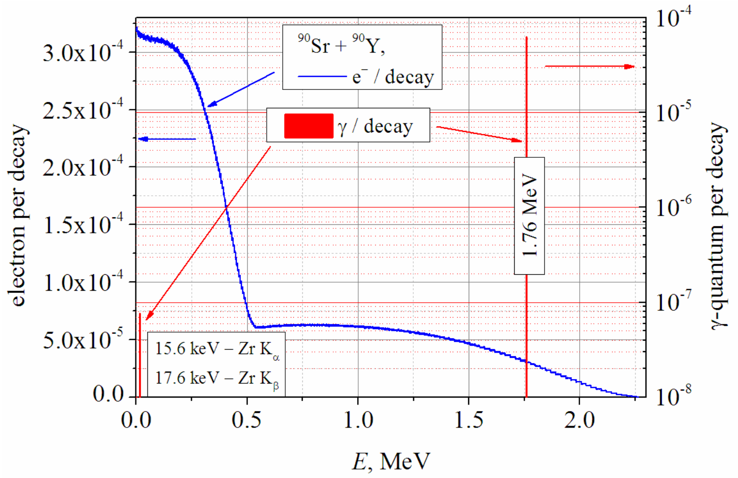

Fig. 1. Simulated energy spectrum of ^{90}Sr/^{90}Y source.

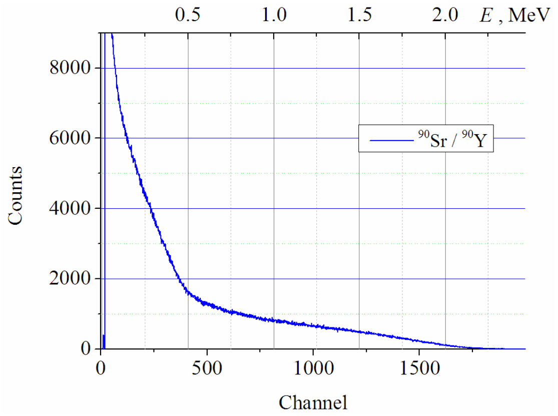

Fig. 2. 1SO-135 source spectrum, measured with CdZnTe detector.

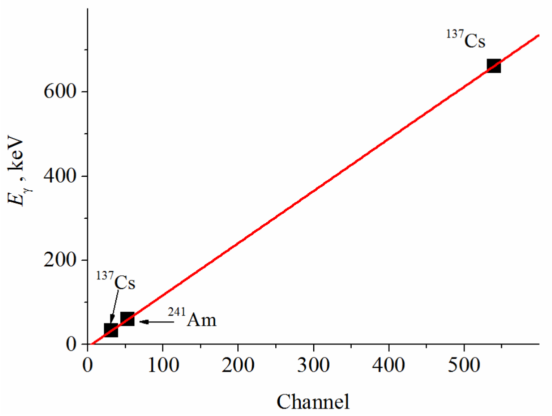

Fig. 3. Calibration dependence for determination of the ADC step size in terms of energy.

SIMULATION OF CdZnTe DETECTOR RESPONSE

For simulation of CdZnTe detector response to the radiation of ^{90}Sr/^{90}Y source we used model of a wide-gap radiation detector which was in detail described in our previous papers [8, 9]. For speeding-up the calculations we assumed that the thickness of the ^{90}Sr/^{90}Y source equals zero. In each numerical experiment 4×10^7 decay chains of ^{90}Sr were modeled. Simulated and experimental response functions of a CdZnTe detector were compared in absence and in the presence of filters from aluminum and lead which slow down electrons.

As is evident from Fig. 4 and 5, the proposed model provides as a whole a good agreement between the simulated and experimental response functions of CdZnTe detector to ^{90}Sr/^{90}Y radiation source. Also satisfactory agreement of average pulse amplitude is observed (Fig. 6), which was calculated as $E_{mid} = \sum_i i\cdot N_i \Big/ \sum_i N_i$. Here i is the number of ADC channel, N_i is the number of pulses in the channel. The only fitting parameters of the applied model were products of mobility μ and average life time τ of electrons and holes in CdZnTe detector. Direct experimental measurements of products $(\mu\tau)_{e,h}$ are impossible without disassembling and damaging the detector [10]. Response functions of the CdZnTe detector in Fig. 4, 5, 7 and 8 were obtained for values $(\mu\tau)_e = 2.2\times10^{-4}$ cm^2/V, $(\mu\tau)_h = 1\times10^{-5}$ cm^2/V. The fitting values of $(\mu\tau)_{e,h}$ correspond to the measured efficiency of charge collection, CCE ≈ 34 %.

Fig. 4 displays the simulated and experimental response functions of CdZnTe detector without slowing-down filters. It is evident that in the experimental pulse distribution the region, where the electron spectrum is formed due to the disintegrations of ^{90}Sr and ^{90}Y, remains more distorted in comparison to the simulated spectrum. At the same time, in the presence of slowing-down filters the simulated and experimental spectra in this region agree much better (Fig. 5). The better agreement in Fig. 5 against Fig. 4 could be explained with the assumption that between the radiation source and detector an additional thin slowing-down layer is present, unaccounted in the simulation model. This assumption is corroborated by the fact that the experimental value of average pulse amplitude in the presence of slowing-down filters appeared constantly lesser in comparison with the simulation data (Fig. 6). Probably for electrons such additional slowing-down mechanism is created by the contact gold plate on the detector surface which is covered by a layer of an electrical insulating material. However, we did not manage to select the effective thickness of this layer, which would improve the agreement of simulated and experimental average pulse amplitudes.

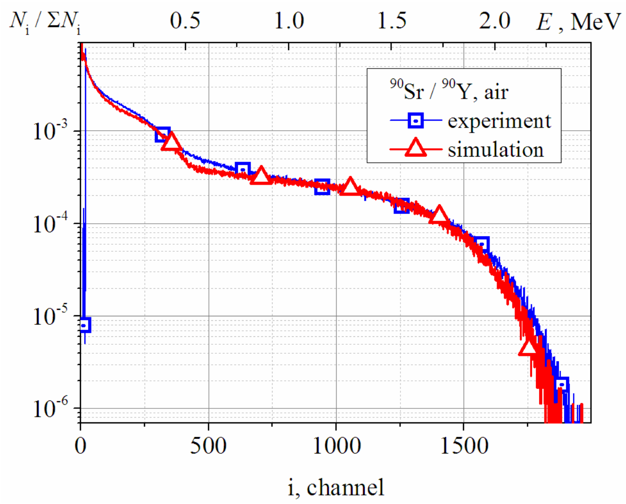

Fig. 4. 1SO-135 source spectrum without any slowing-down filter.

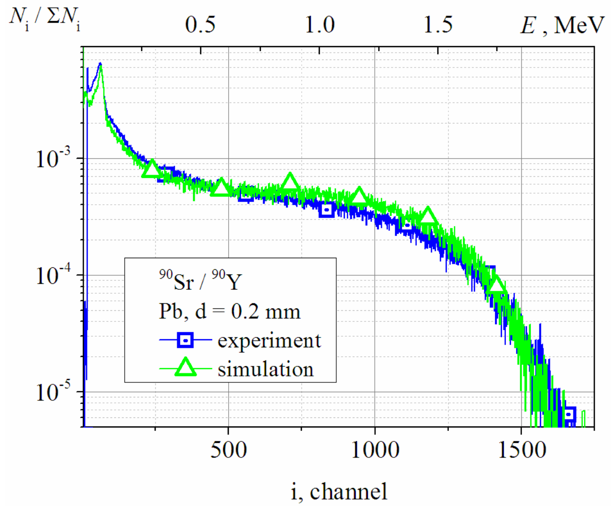

Fig. 5. 1SO-135 source spectrum taken with lead filter.

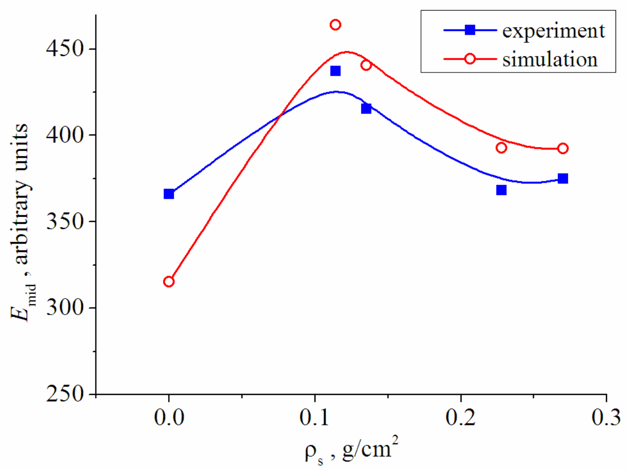

Fig. 6. Dependence of average pulse amplitude of CdZnTe detector on the surface density of a slowing-down filter.

Table 2 compares the modifications in experimental and simulated electron spectra due to the installation of the slowing-down filters from aluminum and lead between the source and detector. The energy flux, which is registered by CdZnTe detector, is determined by the expression $W_e = E_{ADC} \sum_i i \cdot N_i$, where E_{ADC} is the ADC step size in MeV. The relative change in the energy flux, recorded by CdZnTe detector in the presence of a filter, is determined as $W_{e\ \mathrm{filter}}/W_{e\ \mathrm{air}}$ ratio. For all filters the energy flux, calculated according to the applied model, appears permanently larger at 3–5 %.

The average amplitude of the spectrum measured without slowing-down filters, considerably exceeds the corresponding value for the simulated spectrum (Fig. 6). In the presence of filters the reversed situation is observed: the average amplitude of the simulated spectrum exceeds the value of E_{mid} for the experimental spectrum.

Table 2.

Characteristics of electron spectra of ^{90}Sr/^{90}Y measured with CdZnTe detector

Filter	Thickness, mm	Relative energy flux $W_{e\ \mathrm{filter}}/W_{e\ \mathrm{air}}$		Relative average amplitude $E_{\mathrm{mid\ filter}}/E_{\mathrm{mid\ air}}$		Relative average amplitude $E_{\mathrm{mid}}/E_{\mathrm{mid\ Al}}$	
		experiment	simulation	experiment	simulation	experiment	simulation
1	2	3	4	5	6	7	8
No filter (air)	–	1.00	1.00	1.00	1.00	0.88	0.72
Al	0.5	0.53	0.57	1.14	1.40	1.00	1.00
Al	1	0.29	0.34	1.02	1.24	0.90	0.89
Pb	0.1	0.43	0.48	1.19	1.47	1.05	1.05
Pb	0.2	0.17	0.20	1.01	1.24	0.89	0.89

In Table 2 the changes in the pulse amplitude averaged over the spectrum were determined in columns 5 and 6 by the ratio $E_{\mathrm{mid\ filter}}/E_{\mathrm{mid\ air}}$. As a result, we have a more than 20 % disagreement between the simulated and experimental data. If to consider relative change of average amplitudes only in the presence of filters, the simulated and experimental values appears identical (Table 2, columns 7 and 8).

As is evident from Fig. 4 and 5, the most appreciable disagreement of the calculated and measured response functions of CdZnTe detector is observed at low energy. In this region of experimental spectra the pulses of low energy electrons are superimposed with noise pulses. In Fig. 7 and 8 the simulated and experimental response functions of CdZnTe detector to the ^{90}Sr/^{90}Y radiation source are shown in the case when the lower discrimination level of a measuring channel E_{discr} is set for 180 keV (channel no. 150). The selected value of the lower discrimination level is somewhat higher than the lower limit of the registered energies range of the commercial scintillation beta-spectrometers. For example, for the AT1315 Gamma Beta Radiation Spectrometer the lower limit of the operating energy range is 150 keV [11].

The spectra obtained in the presence of slowing-down filters display no essential changes (Fig. 5 and 8). At the same time, in the absence of slowing-down filters the agreement of simulated CdZnTe detector response functions with experimental data in the low energy range (from 0.2 to 0.5 MeV) is considerably improved (Fig. 7).

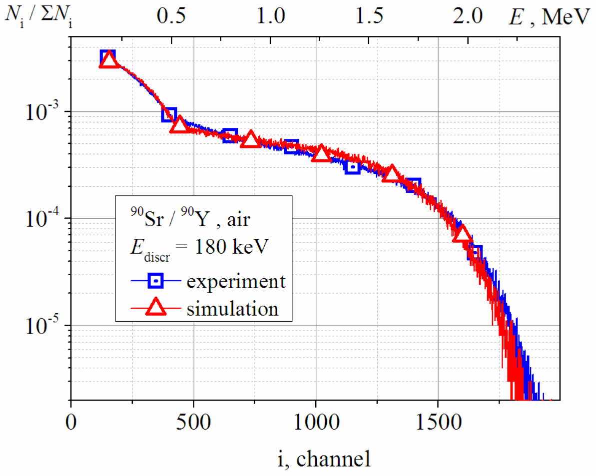

Fig. 7. 1SO-135 source spectrum without any slowing-down filter.

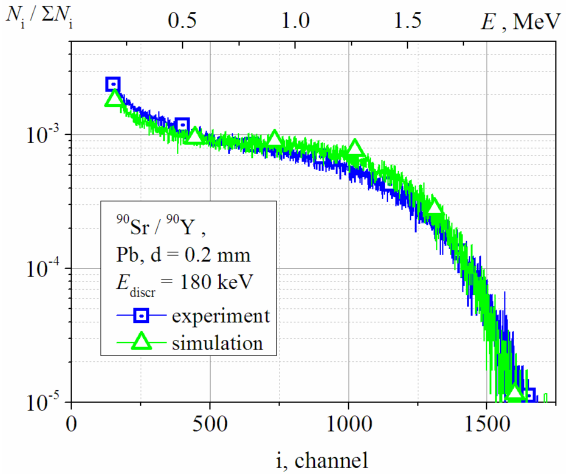

Fig. 8. 1SO-135 source spectrum taken with lead filter.

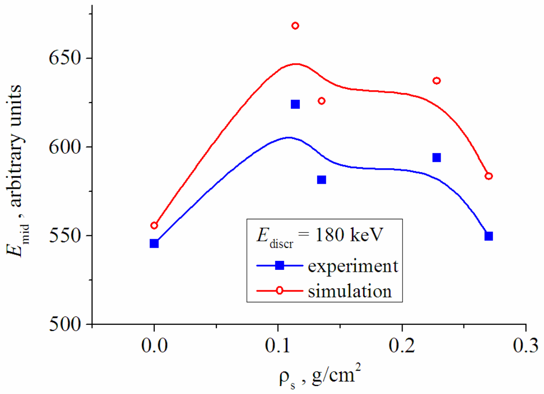

Fig. 9. Dependence of average pulse amplitude of CdZnTe detector on the surface density of the slowing-down filter.

Table 3 compares the characteristics of simulated and experimental spectra of electrons when the lower discrimination level is set for 180 keV. In this case the spread of the relative change in average pulse amplitudes for experimental and simulated spectra makes only 4 – 6% (Table 3, columns 5 and 6) against more than 20% discrepancy with zero discrimination level. If to compare only the spectra with filters the relative changes of the experimental and simulated average amplitudes (Table 3, columns 7 and 8) again remain almost identical. The relative energy flux in the presence of slowing-down filters changes insignificantly compared to the previously considered case when the lower discrimination level equaled zero.

In the cases when the measuring the electron fluxes of low energy (below 100 keV) with CdZnTe (CdTe) detectors is needed, one has to decrease considerably the noise level of the measuring equipment (down to 10 keV) in order to avoid the essential distortion of the obtained experimental data.

The comparison of experimental and computed response functions at different discrimination levels shows, that the noise of the preliminary amplifier is a major factor in distortion of measurement data. It is necessary also to take into account that the temperature dependence of the noise can impede the correct comparison of measurements performed under different conditions. However, the simulation has shown that the increase in the lower discrimination threshold largely eliminates divergences between measurement and simulation data. A similar effect is achieved at the application of thin metal filters (in this case it is possible also to abandon the beryllium window in the detecting unit that simplifies its construction). In both cases the investigated model can be used for calibration of the response of CdZnTe detecting units to the radiation from different beta-sources.

Table 3.

Characteristics of electron spectra of ^{90}Sr/^{90}Y source at 180 keV discrimination level

Filter	Thickness , mm	Relative energy flux $W_{\mathrm{e\ filter}}/W_{\mathrm{e\ air}}$		Relative average amplitude $E_{\mathrm{mid\ filter}}/E_{\mathrm{mid\ air}}$		Relative average amplitude $E_{\mathrm{mid}}/E_{\mathrm{mid\ Al}}$	
		experiment	simulation	experiment	simulation	experiment	simulation
1	2	3	4	5	6	7	8
No filter (air)	–	1.00	1.00	1.00	1.00	0.94	0.89
Al	0.5	0.54	0.59	1.07	1.13	1.00	1.00
Al	1	0.29	0.35	1.01	1.05	0.95	0.93
Pb	0.1	0.44	0.50	1.14	1.20	1.07	1.07
Pb	0.2	0.17	0.20	1.09	1.15	1.02	1.02

CONCLUSIONS

The electron energy spectra of ^{90}Sr/^{90}Y radiation source were measured with a planar CdZnTe detector. The model of the wide gap semiconductor gamma-ray detector, developed earlier [8, 9], was used for the simulation of CdZnTe detector response functions by Monte-Carlo method. The simulated response functions of a CdZnTe detector agree well with the experimentally measured response functions after the introduction in the detector model of only two fitting parameters: products of mobility and average lifetime for electrons and holes. Other parameters of the model (bias voltage, equivalent noise charge, shaping time, detector unit geometry) correspond to the actual characteristics of the measuring channel. This agreement allows using instead of the measured response function the simulated one, obtained in the proposed detector model, for example, in the problem of extraction of beta radiation spectrum at measurements in the mixed beta and gamma fields (i.e., at in situ determination of ^{137}Cs and ^{90}Sr sources activity).

In research of radiation protection ability of a material the best agreement of experimental and simulated electron energy spectra is reached at rather high discrimination level (more than 100 keV). The noise of the preliminary amplifier is a major factor in distortion of measurement data. The simulation has shown that the increase in the lower discrimination threshold largely eliminates divergences between measurement and simulation data. A similar effect is achieved at the application of thin metal filters. In both cases the investigated model can be used for calibration of the response of CdZnTe detecting units to the radiation from different beta-sources. When exact measurement of beta spectra for energy less than 100 keV is needed, it is necessary to use a measuring channel with noise level of 10 keV and below.

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