https://doi.org/10.46813/2025-157-058

USING APPARATUS SPECTRA OF X-RAY FOR CALCULATION OF SIGNALS OF DETECTORS SCINTILLATOR-PHOTODIODE TYPE BASED ON ZnSe(Al)

O.D. Opolonin, A.V. Krech, N.L. Karavaeva, S.V. Makhota
Institute for Scintillation Materials, NAS of Ukraine, Kharkiv, Ukraine
E-mail: zdobuvach2021@gmail.com

This work explores the possibility of evaluating the signals of scintillation detectors of X-ray radiation (XR) based on model calculations using experimentally obtained XR spectra in the energy range of 20…150 keV at an anode voltage of the XR source between 50…150 kV. It is shown that for XR energies up to 90 keV, the signal of a scintillator-photodiode (SC-PD) type detector based on ZnSe(Al) with a thickness of 3.5 mm can be evaluated both by the energy of the XR falling on the detector's aperture and by the energy of XR absorbed in the detector via the photoelectric effect. For XR energies of 100…150 keV, the signal can be evaluated by the energy of the XR falling on the detector's aperture. Under unchanged conditions of PV filtering, the detector signal can be unambiguously estimated from the PV energy absorbed by the scintillator due to the photoelectric effect.

PACS: 07.85.Fv; 52.70.La; 87.59.bf

INTRODUCTION

Radiographic systems are widely used in various fields, including medical diagnostics, customs control and security systems, non-destructive testing, and the food industry.

Digital radiography offers new possibilities compared to film radiography. For instance, digital technologies allow the implementation of the dual-energy X-ray absorptiometry (DXA) method for obtaining radiographic images.

Fig. 1 shows a simplified model of a digital radiographic system (DRS) using the DXA method. Optimizing such systems requires forming the detector's energy-selective properties, considering the XR spectrum.

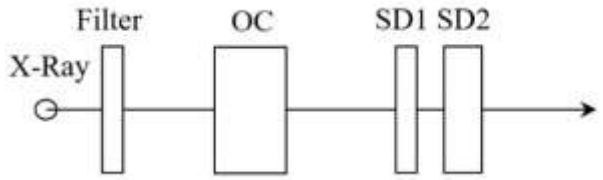


Fig. 1. Simplified model of DRS using the DXA method. OC – object under control; SD1, SD2 – scintillation detectors of low- and high-energy components of XR, respectively; X-Ray – X-ray radiation source

The energy-selective properties of scintillation detectors depend on the type and thickness of the scintillation element. DRS optimization can be done experimentally or using model calculations.

Model calculations of scintillation detector signal critically depend on the XR spectrum used. Modern semiconductor spectrometers (e.g., the X-123 spectrometer from AmpTek) allow the measurement of XR spectra with an energy resolution of 0.9 keV and a maximum energy of up to 150 keV.

Typically, model calculations of scintillation detector signals account for the characteristics of light-reflecting coatings and adhesives used to optically couple the SC and PD, as well as optical matching of the SC emission spectrum and the PD spectral sensitivity.

These studies are based on the assumption that the detector signal can be estimated from the energy of the RB absorbed in the SC due to the photo effect, regardless of energy losses during light reflection, optical mismatch, etc.

Thus, the paper explores the possibility of evaluating the signals of SC-PD type detectors based on zinc selenide (ZnSe(Al)) using experimentally obtained XR spectra.

RESULTS OF PREVIOUS RESEARCH

During the NATO SfP 982823 grant project, we created a three-energy X-ray scanner (hereinafter referred to as the scanner), which included three detector arrays of type SC-PD based on ZnSe(Al) with different thicknesses (0.5; 1.5; 3.5 mm). We obtained a series of X-ray images in various energy ranges using this scanner. For example, in [1], we used the following modes for spectrum formation of the X-ray:

Parameters of X-ray spectrum formation in three energy ranges where the signal level of the detector is 60,000 in ADC codes

	U_a, kV	I_a, mA	Cu, mm	Al, mm	Ta, mm
H	150	7.352	5	2	–
M	90	9.084	–	2	0.2
L	50	19.04	–	6	–

where U_a and I_a are the anode voltage and current of the X-ray source; Cu, Al, Ta are the filter materials; H, M, L are the modes for high, medium, and low-energy X-rays, respectively.

For model calculations, X-ray spectra were obtained at anode voltages from 30 to 150 kV in steps of 10 kV.

Obtaining X-ray Spectra

The scanner includes the Isovolt Titan 160 X-ray source with a W anode and a Be exit window, with a thickness of 0.8 mm. X-ray spectra and scintillation detector signals were measured using the scanner.

The layout of the scanner components for obtaining X-ray images and measuring the X-ray spectra is shown in Fig. 2.

To reduce the X-ray flux intensity and, consequently, the dead time of the X-123 spectrometer, a tungsten collimator with a thickness of 36 mm and a hole Ø 0.3 mm was used, and the current of the X-ray tube was set to a minimum of approximately 284 μA. The X-ray spectra obtained with the X-123 spectrometer are shown in Fig. 3.

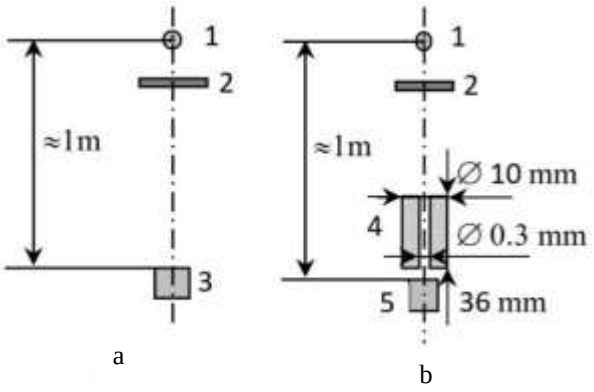


Fig. 2. Layout of the scanner elements and the spectrometer for obtaining X-ray images (a) and measuring X-ray spectra (b). 1 – X-ray source; 2 – filter; 3 – SC-PD based on ZnSe(Al); 4 – tungsten collimator with a hole Ø 0.3 mm; 5 – CdTe detector of spectrometer X 123

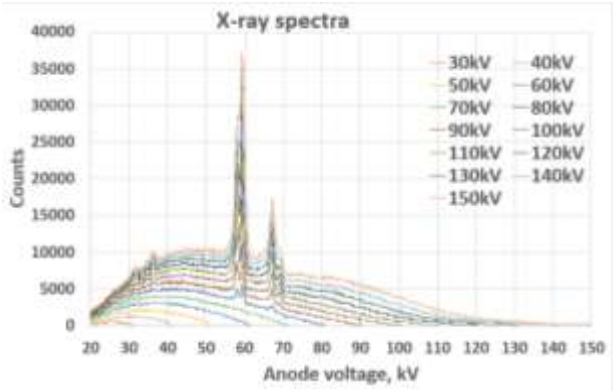


Fig. 3. X-ray spectra of the Isovolt Titan 160 source measured with the X-123 spectrometer at different anode voltage values. X-ray tube current ≈284 μA, 4 mm aluminum filter, accumulation time 200 sec, spectrometer detector aperture ≈ 0.07 mm²

The obtained X-ray spectra were corrected and normalized before the model calculations as follows:

1) Dead-time correction:

$K_{DT}=1+DT/100$, where DT is the dead-time (determined by the X-123 spectrometer in %).

2) Current normalization:

$K_I=I_a/I_L$, where I_a is the actual X-ray tube current; I_L is the current level for normalization.

3) Detector area correction:

$K_s=S_{det}/S_{detSpec}$, where S_{det} is the aperture area of the scanner detector, $S_{detSpec}$ is the aperture area of the spectrometer detector.

4) Accumulation time normalization:

$K_t=1/T_{int}=1/200$, where T_{int} is the accumulation time of the spectrum.

Since the distance from the focal spot to the scanner and spectrometer detectors is practically the same (see Fig. 2), no correction for distance was made.

Thus, the output X-ray spectrum falling on the scanner detector aperture in 1 s at the X-ray tube current I_L was calculated as:

$$f(E) = f_0(E) * K_{DT} * K_I * K_s * K_t \,, \qquad (1)$$

where $f_0(E)$ is the experimental X-ray spectrum.

RESULTS OF MODEL CALCULATIONS AND EXPERIMENTAL DATA PROCESSING

According to the conditions of X-ray spectrum formation in three energy ranges presented in Table, and using (1), the X-ray spectra were calculated, as shown in Fig. 4.

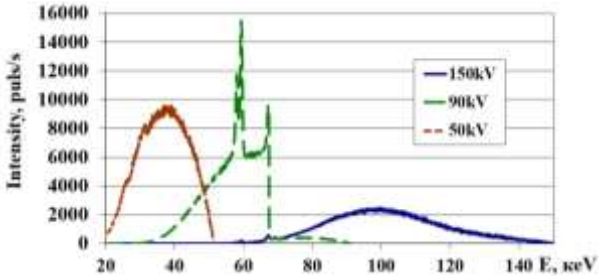


Fig. 4. X-ray spectra used to obtain radiographic images in three energy ranges

The X-ray spectra shown in Fig. 4 correspond to the same signal level of the scintillation detector based on ZnSe(Al), with a thickness of 3.5 mm, approximately 60,000 ADC codes.

Using the X-ray spectra shown in Fig. 4, we evaluated the total energy that falls on the detector aperture and the fraction absorbed in the ZnSe detector with a thickness of 3.5 mm due to the photoelectric effect.

The X-ray spectra calculated by formula (1) were scaled according to the X-ray tube current that gives a signal of 60,000 ADC codes in the detector ($I_{60,000}$):

$$f(E)_{60000}=f(E)\cdot I_{60000}/I_L.$$

Then, the total energy of the X-ray flux falling on the detector aperture in 1 s was calculated as:

$$E_\Sigma = \sum_{i_{\min}}^{i_{\max}} E_i \cdot N_i \,, \qquad (2)$$

where i_{min} and i_{max} are the spectrometer channel numbers corresponding to 20 and 150 keV energies, respectively; N_i is the number of pulses recorded in the i spectrometer channel; E_i is the energy of the X-ray quanta corresponding to the i spectrometer channel.

The results of the calculation of the energy of the X-ray flux falling on the aperture of the SC-PD detector based on ZnSe(Al), with a thickness of 3.5 mm, and the energy absorbed in ZnSe due to the photoelectric effect are shown in Fig. 5.

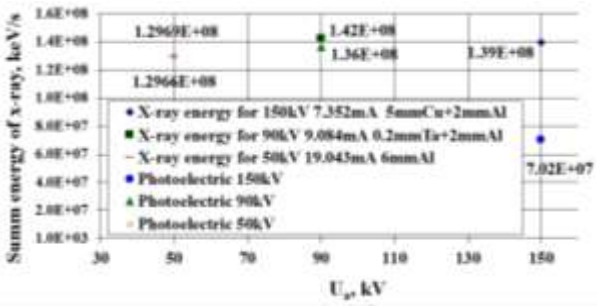


Fig. 5. X-ray energy falling on the aperture of the SC-PD detector based on ZnSe, 3.5 mm thickness, and energy absorbed in ZnSe due to the photoelectric effect

As can be seen from Fig. 5, for energies up to 90 keV, almost all of the X-ray energy is absorbed in 3.5 mm ZnSe due to the photoelectric effect. At an anode voltage of 150 kV, with aluminum and copper filtration, to achieve a signal level of 60,000 ADC codes, the total energy of the X-ray flux falling on the detector aperture is approximately the same as for 90 and 50 kV. However, the energy absorbed in ZnSe due to the photoelectric effect at 150 kV is almost twice as low as the energy falling on the detector aperture.

This result can be explained by the influence of two factors.

Firstly, at high energies, a significant part of the X-rays passes through the scintillation element without being absorbed. Using the mass attenuation coefficients of ZnSe [2], we calculated the X-ray attenuation dependence on the energy of X-ray quanta for different ZnSe thicknesses (0.5, 1.5, and 3.5 mm). The calculation results are shown in Fig. 6.

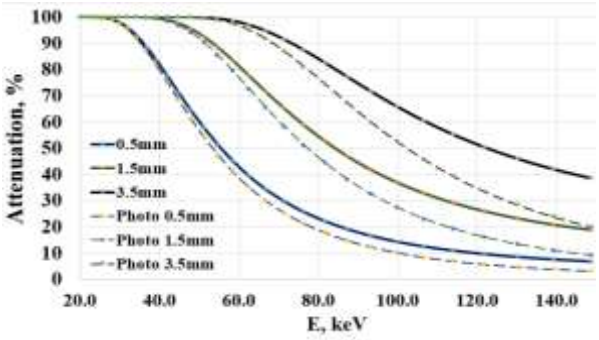


Fig. 6. X-ray attenuation in ZnSe with thicknesses of 0.5 mm, 1.5 mm, and 3.5 mm (solid lines), including photoelectric effect (dashed lines)

From Fig. 6, it can be seen that ZnSe with a thickness of 3.5 mm practically completely absorbs X-rays with energies up to 60 keV. However, at 100 keV X-rays, about 35% of X-ray quanta pass through the scintillation element, and approximately half of the X-ray quanta are absorbed due to the photoelectric effect.

Secondly, ZnSe(Al) has a high light absorption coefficient at a wavelength of 590…610 nm (the maximum of ZnSe(Al) radioluminescence), which is about 0.4 cm^{-1}. Considering the exponential law of X-ray absorption in the material, the largest number of X-ray quanta will be absorbed, and thus, optical quanta will be formed in the scintillation element on the side of the X-ray flux.

According to the conditions listed in Table , we calculated the energy distribution transferred to the photoelectrons along the direction of X-ray propagation in the ZnSe scintillation element with a thickness of 3.5 mm (Fig. 7).

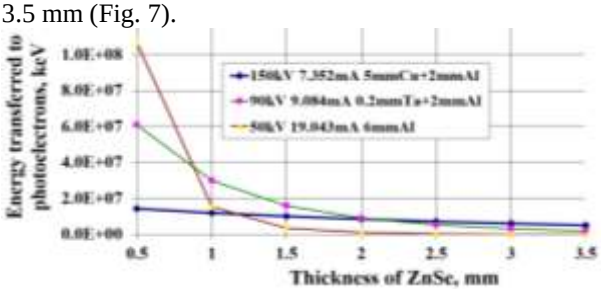


Fig. 7. Energy distribution transferred to the photoelectrons along ZnSe with a thickness of 3.5 mm for different X-ray spectra

As seen from Fig. 7, at the X-ray spectrum corresponding to Figure 4 (curve for 50 kV), most of the X-ray energy is absorbed in 0.5 mm of ZnSe. According to the energy distribution absorbed due to the photoelectric effect, the brightness of the scintillator changes. At low X-ray energies, optical photons are formed in the surface part of the scintillator and must pass through approximately 3 mm of absorbing medium before reaching the photodetector.

At the X-ray spectrum corresponding to Fig. 4 (curve for 150 kV), light quanta are formed in the scintillation element almost uniformly across the crystal volume. That is, a significant portion of the light reaches the photodetector with minimal absorption in the scintillator.

Thus, for a ZnSe thickness of 3.5 mm, for X-ray energies up to 70…90 keV, the detector signal can be evaluated both by the energy falling on the detector aperture and by the energy absorbed in the scintillator due to the photoelectric effect. For X-ray energies of 100…150 keV, the detector signal can be evaluated by the X-ray energy falling on the detector aperture.

Detector signal estimation under constant filtration conditions

Under constant filtration conditions, namely, using an aluminum filter with a thickness of 4 mm, the following experiment was conducted.

For each value of the anode voltage (from 50 to 150 kV with a step of 10 kV), the X-ray tube current was set at which the detector signal was equal to 60,000 ADC codes. The X-rays spectra corresponding to the anode voltage value (see Fig. 3) were scaled according to the measured X-ray tube current.

Next, according to equation (2), the total energy of the X-rays flow falling on the detector aperture in 1 s and the fraction of energy absorbed in the 3.5 mm thick ZnSe scintillator due to the photoeffect were calculated. The results of such calculations are shown in Fig. 8.

As can be seen from Fig. 8, the total energy of the X-rays falling on the detector aperture and causing the detector signal 60,000 in the ADC codes increases with increasing anode voltage. At the same time, the energy absorbed by the scintillator due to the photoelectric effect remains practically unchanged.

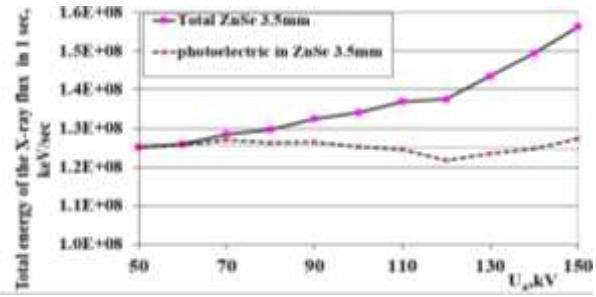


Fig. 8. Calculated total energy of the incident X-ray on the detector aperture, fraction of the energy absorbed in the 3.5mm thick ZnSe scintillator due to the photoeffect

Minor deviations of the calculated energy absorbed in the scintillation element due to the photoeffect from the linear character may be due to the discrete nature of the X-ray tube current regulation. With a minimal change in the X-ray tube current of the Isovolt Titan 160 apparatus, the value of the ADC signal changed by several hundred ADC codes. Therefore, the determination of the X-ray tube current at which the detector signal yields 60,000 in the ADC codes may contain an error.

In general, it can be concluded that under unchanged filtering conditions, the detector signal is determined by the fraction of the X-ray energy absorbed in the scintillation element due to the photoeffect.

DISCUSSION

The conducted studies confirm the possibility of estimating the signal of the X-ray detector of the SC-PD type by measuring the radiation energy absorbed in the scintillator due to the photoelectric effect.

It should be noted that when changing the thickness or material of the filter, the thickness or material of the scintillation element, the sensitivity of the photodetector, the light collection conditions, etc., the absolute value of the detector signal may change.

Also, the light absorption coefficient in the scintillator at the wavelength of its emission may affect the detector signal evaluation.

ZnSe(Al) in the considered energy range (20…150 keV) does not have an absorption *K*-edge. However, many scintillation materials contain heavy elements (CsI, CWO, GOS, etc.), which have an absorption *K*-edge in this energy range. In our opinion, the use of experimentally obtained X-ray spectra can improve the quality of model calculations and account for the peculiarities of scintillation detector signal formation.

When optimizing X-ray digital radiography systems (DRS) for medical diagnostics using the DXA method, the possibilities of model calculations of signals become most relevant [3]. The main criterion when developing such DRS is achieving a sufficient informational parameter (e.g., accuracy in determining changes in bone mineralization for osteoporosis diagnosis) while minimizing radiation exposure to the patient.

CONCLUSIONS

Based on the results of this work, the following conclusions can be made:

1. The X-ray spectra experimentally obtained with a spectrometer with an energy resolution of 0.9 keV provide a good match between model calculations of detector signals and experimental measurements.

2. When changing the anode voltage of the X-ray source and keeping the filtering of the X-ray unchanged, the signal of the ZnSe(Al)-based detector can be estimated from the total X-ray energy absorbed in the scintillation element due to the photoeffect.

3. Using different filters to form the X-ray spectrum requires an appropriate correction when calculating the scintillation detector signal.

4. The results of this work can be used to optimize DRS systems using the DXA method.

ACKNOWLEDGEMENTS

This work was performed using equipment purchased and created as part of the NATO SfP 982823 grant during the execution of the target scientific research program of the National Academy of Sciences of Ukraine “Nuclear and Radiation Technologies for the Energy Sector and Societal Needs.”

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Article received 14.04.2025

ВИКОРИСТАННЯ АПАРАТНИХ СПЕКТРІВ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ ДЛЯ ОБЧИСЛЕННЯ СИГНАЛІВ ДЕТЕКТОРІВ ТИПУ СЦИНТИЛЯТОР–ФОТОДІОД НА БАЗІ ZnSe(Al)

О.Д. Ополонін, А.В. Креч, Н.Л. Караваєва, С.В. Махота

Розглянуто можливість оцінки сигналів сцинтиляційних детекторів рентгенівського випромінювання (РВ) за результатами модельних обчислень з використанням експериментально отриманих спектрів РВ у діапазоні енергій 20…150 кеВ при анодній напрузі джерела РВ 50…150 кВ. Показано, що при енергіях РВ до 90 кеВ сигнал детектора типу сцинтилятор–фотодіод (СЦ-ФД) на базі ZnSe(Al) товщиною 3,5 мм може бути оцінений як за енергією РВ, що падає на апертуру детектора, так і за енергією РВ, що поглинається у детекторі за рахунок фотоефекту. При енергіях РВ 100…150 кеВ сигнал детектора може бути оцінений за енергією РВ, що падає на апертуру детектора. При незмінних умовах фільтрації РВ сигнал детектора однозначно може бути оцінений за енергією РВ, що поглинається у сцинтиляторі внаслідок фотоефекту.