https://doi.org/10.46813/2026-163-070

INFLUENCE OF SCINTILLATOR THICKNESS ON THE SIGNAL OF A SCINTILLATOR–PHOTODIODE DETECTOR BASED ON ZnSe(Al)

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Previous studies by the authors demonstrated the possibility of model-based estimation of signals from scintillation detectors with a ZnSe(Al) scintillator thickness of 3.5 mm, based on the energy absorbed in the scintillator via the photoelectric effect. In the present work, it is confirmed that detector signals for ZnSe(Al) scintillators of different thicknesses (0.5, 1.5, 3.5 mm) are also determined by the fraction of X-ray energy absorbed in ZnSe(Al) due to the photoelectric effect. It is established that the X-ray energy absorbed in the scintillator via the photoelectric effect and producing the same detector signal level depends linearly on the ZnSe(Al) thickness. The study was carried out in the X-ray energy range of 20…150 keV (tube voltage 50…150 kV) using 4 mm aluminum filtration

PACS: 29.40.Mc; 61.82.Fk;79.60.Bm

INTRODUCTION

Digital radiographic systems (DRS) employing dual-energy X-ray absorptiometry (DXA) have found widespread application in medicine and customs inspection. In addition, there are numerous other fields where DXA is used. For example, in the food industry, DXA allows estimation of meat fat content, quality control of nuts, detection of foreign inclusions in food products, etc.

Currently, a wide variety of scanning-type DRS using scintillator – photodiode (SC-PD) detector arrays are produced worldwide. In medicine, such DRS employing DXA are considered the "gold standard" for osteoporosis diagnostics. Diagnosis can be performed for different bone regions, with the femoral neck considered the most accurate site, while forearm and finger phalanges are also used. Specialized DRS exist for each type of examination.

The main principle of medical X-ray application is obtaining sufficient information content at a minimal patient dose. In DXA for osteoporosis diagnostics, this corresponds to detecting small changes (~1.5…2%) in bone mineral density.

This necessitates optimization of each specialized DRS to achieve the best information parameter. Signals of SC-PD detectors are a convolution of many factors: the X-ray spectrum, energy dependence of attenuation coefficients in the object and filters, detector energy selectivity, etc. Due to the large number of influencing factors, optimization requires either extensive experimental studies or model-based calculations.

Previously [1], it was shown that the signal of an SC-PD detector based on ZnSe(Al) can be calculated from the fraction of X-ray energy absorbed via the photoelectric effect in a 3.5 mm thick scintillator in the energy range 20…150 keV under fixed filtration conditions.

This work is devoted to studying the possibility of model-based signal calculations when varying the thickness of the ZnSe(Al) scintillator.

1. METHODOLOGY

Calculation the variation of detector signals with system parameters is a key task of modeling. The aim of this work was to investigate the feasibility of modeling detector signals for SC-PD detectors with varying ZnSe(Al) thickness.

Experimental studies were carried out using a prototype three-energy DRS comprising three 128-channel detector arrays, each employing ZnSe(Al) scintillators with thicknesses of 0.5 mm, 1.5 mm, and 3.5 mm. The aperture of each channel was approximately 2.5×1.5 mm.

At the first stage, for each tube voltage (50…150 kV, step 10 kV), the tube current corresponding to a detector signal of ~60000 ADC codes (I_{a60000}) was determined. Thus, three values of I_{a60000} were obtained for each voltage, corresponding to different scintillator thicknesses.

At the second stage, the incident X-ray energy and the fraction absorbed via the photoelectric effect in ZnSe(Al) were calculated.

At the third stage, experimental and modeled results were compared.

For model calculations, experimentally measured X-ray spectra (Fig. 1) obtained using an AmpTek X-123 spectrometer (energy range up to 150 keV with a resolution ≈ 0.9 keV) were used [1].

The experimentally obtained X-ray spectra were corrected for the spectrometer dead time, the detector areas of the scanner and the spectrometer, and were normalized with relative to the X-ray tube current and the spectrum acquisition time [1].

Thus, to calculate the flux of X-ray photons through the scanner detector aperture at an anode voltage Ua, the normalized and corrected X-ray spectrum *f(E)* multiplied by a proportionality coefficient with respect to the X-ray tube current was used:

$$f'(E) = f(E)\cdot I_{a\,60000}/I_{norm}, \quad (1)$$

where $I_{a\ 60000}$ is the tube current corresponding to 60000 ADC codes, and I_{norm} is the normalization current.

Previous studies have shown good agreement between the results of model calculations and

experimental measurements when using X-ray spectra obtained with the AmpTek X-123 spectrometer.

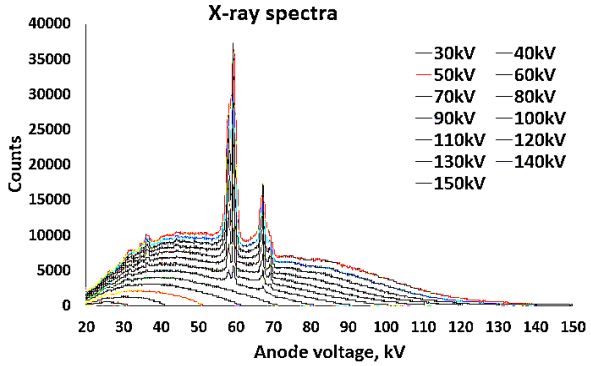


Fig. 1. X-ray spectra of the Isovolt Titan 160 source measured at different anode voltages. The X-ray tube current is ≈284 μA, the aluminum filter thickness is 4 mm, the acquisition time is 200 s, and the spectrometer detector aperture is ≈0.07 mm² [1]

2. RESULTS

According to the methodology described above, 33 values of $I_{a\,60000}$ were obtained experimentally (for eleven values of U_a per one channel in each of the three 128-channel detector arrays).

X-ray tube current values corresponding to a detector signal of approximately 60000 ADC codes for SC-PD detectors based on ZnSe(Al) with thicknesses of 0.5, 1.5, and 3.5 mm at anode voltages of 150, 90, and 50 kV

a) 150 kV

I_a, mA	1.5 mm	3.5 mm	0.5 mm	$P=I_a \cdot U_a$, W
0.39		58436	61234	58.2
0.41		61318	64331	61.2
0.33	61230	49331	51778	49.05

b) 90 kV

I_a, mA	1.5 mm	3.5 mm	0.5 mm	$P=I_a \cdot U_a$, W
1.07	64012	44710	60539	96.93
1.45	–	60324	–	131.22
1.02	60515	42302	57249	91.71

c) 50 kV

I_a, mA	1.5 mm	3.5 mm	0.5 mm	$P=I_a \cdot U_a$, W
5.9	51467	30090	60262	294.75
11.86	–	60257	–	592.95
6.9	60270	35213	–	345.15

Selected experimental data are summarized in Table I. The left column lists the values of $I_{a\,60000}$ for SC-PD detectors based on ZnSe(Al) with thicknesses of 0.5, 1.5, and 3.5 mm. The right column presents the X-ray tube power, defined as $P=I_aU_a$. The dependence of the X-ray tube power required to produce a detector signal of 60000 ADC counts for ZnSe(Al)-based detectors on the anode voltage is shown in Fig. 2.

As shown in Fig. 2, the maximum X-ray tube power ($P \approx 600$ W) is observed at low anode voltage ($U_a = 50$ kV) and a scintillator thickness of 3.5 mm. This is attributed to the high self-absorption of X-ray radiation in ZnSe(Al). Low-energy X-rays are absorbed within the near-surface layer of the scintillator (up to ~1 mm), while additional attenuation occurs along the optical path to the photodetector (~40% per 1 cm in ZnSe(Al)).

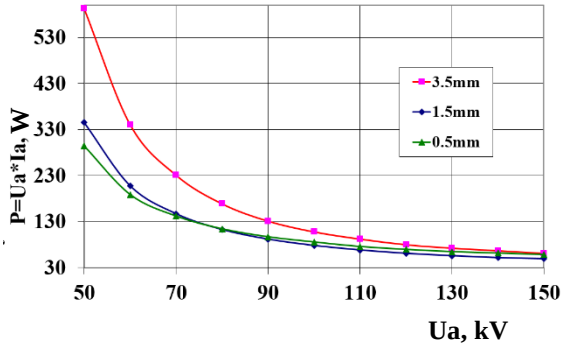


Fig. 2. X-ray tube power corresponding to a detector signal of ≈60000 ADC codes for SC–PD detectors based on ZnSe(Al) with thicknesses of 0.5, 1.5, and 3.5 mm. X-ray filtration: 4 mm Al

The total incident X-ray energy on the detector aperture and the energy absorbed in ZnSe via the photoelectric effect per second were then calculated. The X-ray attenuation in ZnSe was evaluated using reference data [2, 3] and the exponential attenuation law:

$$S = S_0 \cdot e^{-\mu_m \cdot \rho \cdot x}, \qquad (2)$$

where S_0 is the initial X-ray intensity, μ_m is the mass attenuation coefficient, ρ – is the material density, and x is the thickness along the propagation direction.

The attenuation of X-rays in ZnSe for different thicknesses, including the contribution of the photoelectric effect, is shown in Fig. 3.

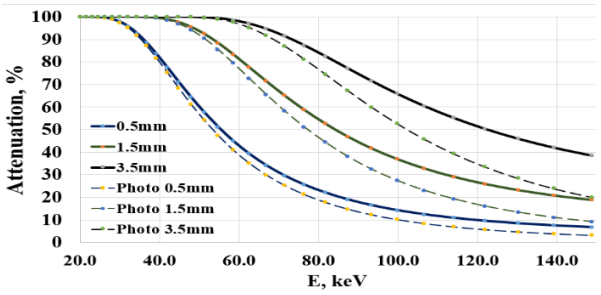


Fig. 3. X-ray attenuation in ZnSe for thicknesses of 0.5 mm, 1.5 mm, and 3.5 mm (solid lines), including the contribution of the photoelectric effect (dashed lines) [1]

The total energy of the X-ray flux incident on the detector aperture per second, i.e., the X-ray power, was then calculated as:

$$P_{(keV/c)} = \sum_{i_{min}}^{i_{max}} E_i \cdot N_i, \qquad (3)$$

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

Thus, (3) yields the X-ray power incident on the detector aperture corresponding to a detector signal of 60000 ADC counts. In addition, using (2), the fraction of X-ray power absorbed in ZnSe(Al) was calculated for

scintillator thicknesses of 0.5, 1.5, and 3.5 mm. The results are presented in Fig. 4.

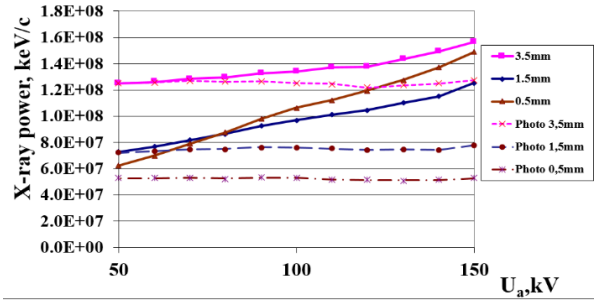


Fig. 4. X-ray power incident on the detector aperture for ZnSe(Al) based detectors with scintillator thicknesses of 0.5, 1.5, and 3.5 mm (solid lines), and the fraction absorbed via the photoelectric effect (dashed lines). All experimental data and model calculations correspond to a detector signal level of 60000 ADC counts

As previously shown in [1], for ZnSe(Al) based detectors with a thickness of 3.5 mm, the detector signal can be calculated from the fraction of X-ray energy absorbed in ZnSe(Al) via the photoelectric effect. From Fig. 4, it follows that the detector signals for ZnSe(Al) with thicknesses of 0.5 and 1.5 mm can also be estimated based on the absorbed X-ray energy due to the photoelectric effect. However, the absolute power level required to produce a detector signal of 60000 ADC counts varies with the scintillator thickness.

Conversion of power from keV/s to J/s is performed using the factor 1 eV=1.602 176 634·10^{-19} J.

For a ZnSe(Al) scintillator with a thickness of 3.5 mm, the incident X-ray power corresponding to a detector signal of 60,000 ADC codes is 19.9 nW. For thicknesses of 0.5 and 1.5 mm, the corresponding values are 12 and 8.3 nW, respectively (Fig. 5).

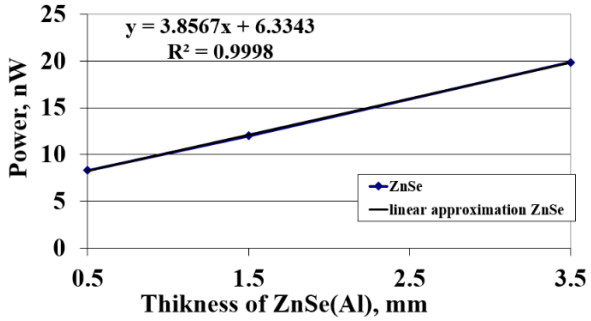


Fig. 5. X-ray power absorbed in the detector via the photoelectric effect as a function of ZnSe(Al) scintillator thickness, corresponding to a detector signal of 60,000 ADC codes

As shown in Fig. 5, the X-ray power required to produce a detector signal of 60000 ADC codes exhibits a linear dependence on the scintillator thickness with high accuracy.

3. DISCUSSION

This work, together with previous results [1], confirms the feasibility of predicting the signal level of SC-PD detectors employing ZnSe(Al). The modeling approach is based on the assumption that the detector signal is determined by the fraction of X-ray energy absorbed in the scintillator via the photoelectric effect.

While [1] experimentally validated this approach for ZnSe(Al) with a thickness of 3.5 mm, the present study demonstrates that, within the thickness range of 0.5…3.5 mm, the X-ray energy absorbed via the photoelectric effect corresponding to a detector signal of 60000 ADC codes exhibits a linear dependence on the scintillator thickness (see Fig. 5).

Thus, it has been demonstrated that, for ZnSe(Al), model-based calculation of the detector signal is feasible under specified conditions. The experiments were performed under fixed X-ray filtration, and the detector design and components, except for the scintillator thickness, were identical for all detectors (photodiodes, optical coupling material and thickness, reflective coating, etc.).

ZnSe(Al) does not exhibit a K-edge absorption in the considered energy range (20…150 keV). However, many scintillation materials contain relatively heavy elements (e.g., CsI, CWO, GOS) that exhibit K-edge absorption within this range.

In the presence of a K-edge, the detection efficiency may change abruptly when the X-ray spectrum contains a high-energy component with $E_{x\text{-}ray}>E_K$, where E_K is the K-edge energy. Nevertheless, it is expected that the detector signal can still be predicted based on the fraction of X-ray energy absorbed via the photoelectric effect. However, the dependence shown in Fig. 2 may exhibit deviations when the maximum X-ray energy $E_{max}>E_K$, where E_{max} is determined by the anode voltage U_a, and exceeds E_K.

The use of experimentally measured X-ray spectra obtained with semiconductor spectrometers is expected to improve the accuracy of model calculations.

Further studies are required to investigate the effect of X-ray filtration, which alters the balance between high- and low-energy components in the X-ray spectrum.

It is reasonable to assume that, even for SC-PD detectors employing scintillation materials containing heavy elements with a K-edge in the 20…150 keV range, the applicability and accuracy of the modeling approach will generally be consistent with the results of this work. However, in the presence of a K-edge, the linear dependencies shown in Fig. 4 may exhibit discontinuities when Ua increases such that $U_a \rightarrow E_{max} > E_K$.

ACKNOWLEDGEMENTS

This work was carried out using equipment acquired and developed within the framework of the NATO SfP 982823 grant as part of the targeted research program of the National Academy of Sciences of Ukraine “Nuclear and Radiation Technologies for the Energy Sector and Societal Needs.”

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn.

1. The signal of scintillator–photodiode (SC-PD) detectors based on ZnSe(Al) can be calculated from the power (energy) of X-ray radiation absorbed in ZnSe(Al) via the photoelectric effect. However, the level of X-ray

power required to produce the same detector signal depends on the thickness of the scintillation element.

2. The X-ray power required to produce the same detector signal exhibits a linear dependence on the thickness of the ZnSe(Al) scintillation element, at least within the thickness range of 0.5…3.5 mm.

3. The fundamental possibility of optimizing X-ray detectors by varying the scintillator thickness for digital radiographic systems based on scintillator–photodiode detectors using ZnSe(Al) has been demonstrated.

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Article received 30.04.2026

ЗАЛЕЖНІСТЬ СИГНАЛУ ДЕТЕКТОРА ТИПУ СЦИНТИЛЯТОР – ФОТОДІОД НА БАЗІ ZnSe(Al) ВІД ТОВЩИНИ СЦИНТИЛЯЦІЙНОГО ЕЛЕМЕНТА

О.Д. Ополонін, А.В. Креч

Попередні дослідження авторів показали можливість модельної оцінки сигналів сцинтиляційних детекторів при товщині сцинтиляційного елемента 3,5 мм ZnSe(Al) за енергією, що поглинається у сцинтиляційному елементі за рахунок фотоефекту. Підтверджено, що сигнали детекторів на базі сцинтиляційних елементів різної товщини ZnSe(Al) (0,5; 1,5; 3,5 мм) також визначаються долею енергії РВ, яке поглинається у ZnSe(Al) за рахунок фотоефекту. Встановлено, що енергія РВ, яке поглинається у сцинтиляційному елементі ZnSe(Al) за рахунок фотоефекту та спричиняє однаковий рівень сигналу детектора, лінійно залежить від товщини ZnSe(Al). Дослідження проведено для діапазону енергій РВ 20…150 кеВ (анодна напруга джерела РВ 50…150 кВ) при застосуванні фільтрів з алюмінію товщиною 4 мм.