https://doi.org/10.18524/1810-4215.2024.37.312675

THE DESIGN AND MODELING OF HARD-RADIATION SPECTROGRAPHS FOR RECORDING OF THE FAST-FLOWING PROCESSES

Marko D. Doikov

Faculty of Physics and Technologies, Plovdiv University “Paisii Hilendarski”,

Plovdiv, Bulgaria, *marik.doikov@gmail.com*

ABSTRACT. Hard radiation spectra are associated with fast-flowing thermonuclear processes. For the registration of hard radiation spectra, a new generation of semiconductor detectors is developed and modeled. Their main difference is the presence in their composition of chemical elements with large atomic numbers. In particular, Pb and Lu, which are part of $CsPbBr_3$ and $Lu(SiO)_5$ crystals. The calculations of the detector design were performed using Giant4 open-source codes (Geant4 – School, 2024), which is an integrated engineering and physics constructor. The energy range of particles and quanta accompanying lightning flashes has been preliminarily determined. It was obtained that the totality of mechanisms of energy losses of quanta and particles in lightning discharges points to the energy interval (0.001 – 2) MeV. The necessary calculations have been carried out in order to select affordable, minimize the size and structure of the detection systems planned for operation. The detailed tracks of quanta, the values of energy losses, and their relation to the amplitudes of current pulses delivered to the high-voltage preamplifier are determined. The detailed tracks and quanta, energy loss values, and their relation to the amplitudes of current pulses delivered to the high-voltage preamplifier have been determined. The selection of a suitable electronic interface has been carried out, demonstrating the cost-effectiveness of fabrication and operation of the obtained detector-spectrograph. In particular, the possibility of its operation under normal conditions, which does not require deep cooling, was revealed. Two varieties of detectors were modeled and constructed. A two-layer one, with a silicon wafer of 1 mm x 1 cm x 1 cm, and either a $CsPbBr_3$ or a $Lu(SiO)_5$ crystal. The source of modulation of current pulses of the detector is chosen to be a directed radiation beam consisting of 50 X- or gamma-quanta. The detector efficiency is estimated. All basic elementary processes were taken into account on the basis of the Monte Carlo method. The energy of the beam entering the detector was set in the range from 1 kev to 1 MeV. At given time intervals, elementary scattering acts are visualized and tracks inside a given detector are plotted. A detailed relationship between the absorbed energy and the current pulse of a given detector is constructed.

Keywords: perovskite; total ionizing dose; CsPbBr3; detector; X-ray, gamma-irradiation of lightnings.

АНОТАЦІЯ. Зростання необхідності реєстрації спектрів жорсткого випромінювання, пов'язаного з швидкоплинними термоядерними процесами, вимагає розробки та моделювання нового покоління напівпровідникових детекторів. У обраних нами пристроїв спостерігається присутність у хімічному складі елементів з великими атомними номерами. Зокрема, розглядаються включення атомів Pb та Lu. Це є напівпровідники-кристали $CsPbBr_3$ та $Lu(SiO)_5$. Запропонована задача була вирішена за допомогою відкритих кодів Giant4-DNA версії 11.2 (Geant4 – School, 2024) у вигляді використання інтегрованого інженерно-фізичного конструктора. Зроблено моделювання рентгенівських та γ-спектрографів в інтервалі енергій (0,001 – 10) МеВ. Відмічено доступність у придбанні, мінімізації розмірів та структури, експлуатації детектуючих систем. Отримано детальні треки частинок та квантів, визначенні енергетичні втрати, їх зв'язок з амплітудами струмових імпульсів, що надходять на високовольтний підсилювач. На основі отриманих результатів зроблено вибір відповідного електронного інтерфейсу. Перевага запропонованої конструкції детектора-спектрографа полягає в експлуатації за нормальними умовами і не потребує глибокого охолодження. У роботі змодельовано детектор, який складається із двох шарів. Перший шар є силікатною пластиною для поглинання рентгенівського спектра розміром 1 х 10 х 10 мм. Другий детектор $CsPbBr_3$ або $Lu(SiO)_5$ має розміри 1 см х 1 см х 1 см і поглинає жорсткий рентген та м’яке γ-випромінювання. Між детекторами немає проміжку. Зроблено висновок, що у більшості випадків оптимальна геометрія детектора складається з 5 шарів $CsPbBr_3$ та 5 шарів кремнієвого ізолятора високої напруги. У наведеному прикладі всі шари мають однакові розміри, що пов'язано з необхідністю високоточного калібрування енергії падаючих на них квантів і частинок. Для модуляції ми обрали потік, що складається з 20 частинок рентгенівських або гамма-променів. Було змодельовано сценарій взаємодії цих квантів з матеріалом детектора. Враховано всі основні елементарні процеси з урахуванням методу Монте-Карло. Для певності розглянута енергія пучка, що входить у детектор в межах від 10 кеВ до 1 МеВ. На обраних інтервалах часу за допомогою даного методу візуалізовано елементарні акти розсіювання та побудовано треки всередині заданого детектора. Даний метод дозволив побудувати детальний зв'язок між поглинутою енергією та струмовим імпульсом даного шару детектора. Візуалізація всіх процесів та їх спектрів є на візуальних 3D малюнках.

Ключові слова: перовськіт; сумарна іонізуюча доза; $CsPbBr_3$; детектор; рентгенівське та гамма-випромінювання, блискавки.

1. Introduction

Design features of hard radiation detectors depend on the range of energies received by the receiver (hereinafter referred to as the Detector) and its physical and chemical structure. Depending on the tasks to be solved, the geometry and types of compositions of different materials have to be taken into account. This leads to the complication of the design of the Detector body itself and its electronic interface. There is also a qualitative dependence of the radiation spectrum conversion processes inside the Detector (Doikov, 2022; 2023). The calculations of the spectroscopic response of various crystals to incident hard radiation were previously carried out using the codes G. Weber (see link) and test tasks in (Geant4-School, 2024). The calculations showed that the entire long-wavelength wing of X-ray radiation is effectively absorbed due to photo absorption in a 1 mm thick layer of silicon semiconductors in the energy range $E_\gamma \leq 10$ keV. Semiconductor crystals CsPbBr3 and $Lu(SiO)_5$ were used to register photons up to 1 MeV.

2. Energy transport in Absorber and Detector

Increasing the efficiency of the Detector required introduction of additional layers with the necessary materials into its construction. Until recently, silicon semiconductors were used in computed tomography (CT). Their widespread use in such tasks was due to their availability, the history of the development of semiconductor device research. The results of my X-ray transport calculations for silicon semiconductors are shown in Fig. 1 – Fig. 4. As can be seen from the presented results, taking into account multiple scattering and geometry of the Detectors (e.g., their thickness) significantly changes the percentage contribution of the scattering and absorption mechanisms. Despite the significant photoabsorption of the long-wavelength wing of X-rays, a transparency window convenient for obtaining lightning spectra is located in the wavelength interval 2.2 nm – 4.4 nm. For this purpose, the Detector must be in sufficient proximity to the lightning. In these "windows" the extinction is many times less than in the adjacent wavelength intervals. Let's call the source object whose spectrum is recorded by the Emitter. The medium between the Detector and the Radiator is further called the Absorber. Photon beams from the Emitter are separated in this energy range. Taking into account miniaturization possibilities and dielectric properties of silicon semiconductors, the first layer of the Detector is a receiver of soft X-ray radiation – Fig. 5 or Fig. 6. The rest of the Detector is a combination of insulator layers and detector material. For simplicity, this paper presents vari-

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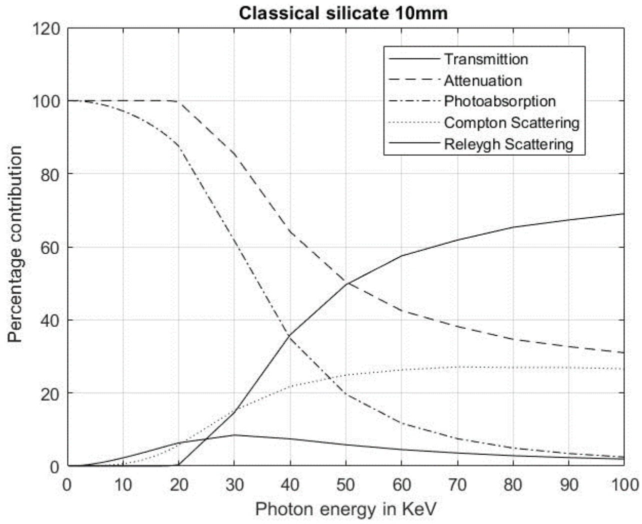

Figure 1: Radiation transport in SiO_2. Target length 10 mm in different scales across axis of energies.

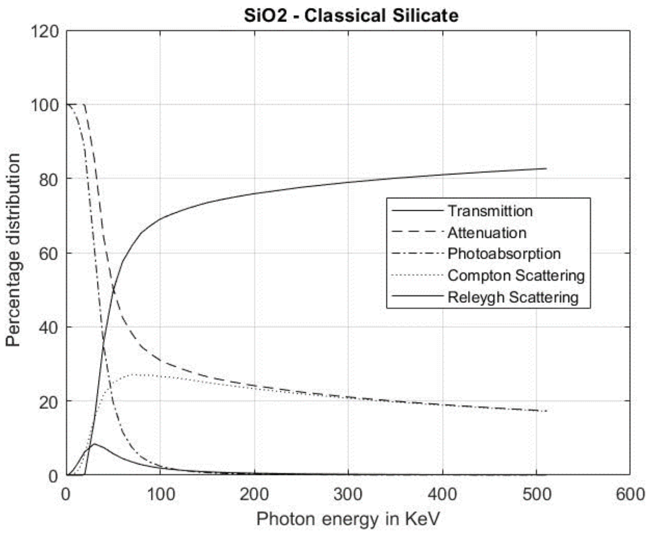

Figure 2: Ibid. At a four times greater energy scale

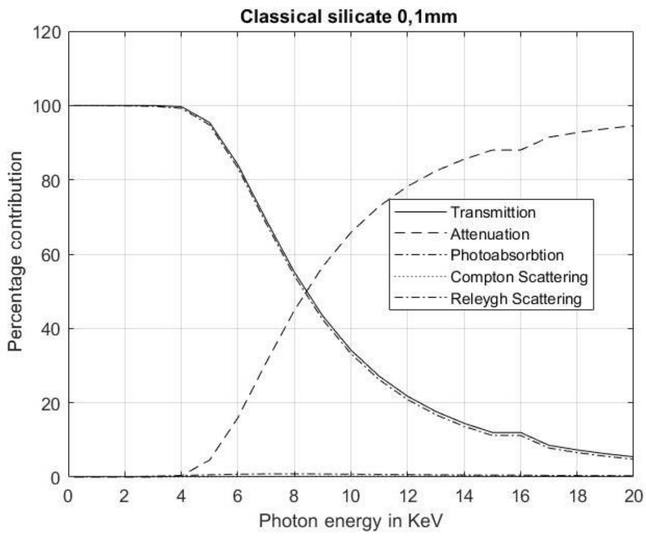

Figure 3: Ibid. Target length 0.1 mm

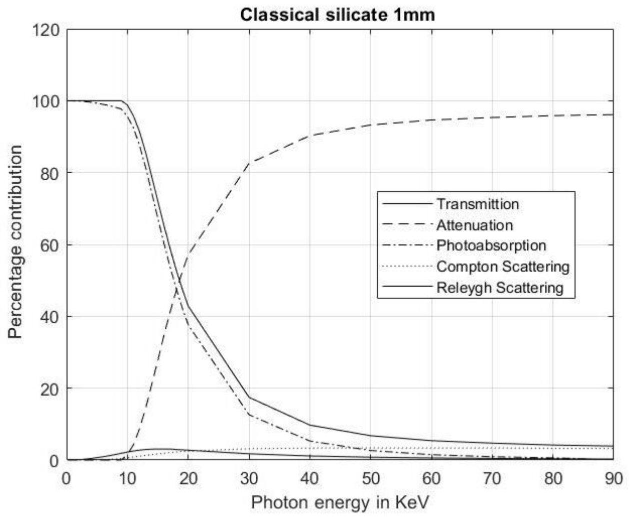

Figure 4: Ibid. Target length 1 mm

ants of the detector in 2 layers. Their design, physical and chemical structure, and geometry are such that efficient signal processing is possible in the energy range 10 keV≤Eγ≤1.3 MeV. This is due to the specificity of the flow of thermonuclear reactions in the objects under consideration and the formation of their own spectrum of hard radiation.

3. Modeling of detectors. Objects of study

Lightning in thunderstorm and volcanic clouds. The main processes occur in millisecond time intervals. The energy resource in the peak of discharge reaches 200 MeV. The main reactions can proceed with effective energies up to 10 MeV. The rest of the energy of relativistic electrons is spent on impact ionization and braking radiation. Photo visual observations confirmed the step character of the lightning trajectory. The observed numerous local bends of the trajectory of relativistic electrons leads to the formation of cyclotron radiation. Depending on the conditions of discharge flow in the spectrum of the Emitter we have a combination of braking, and in some cases synchrotron. Thus, Following X-ray radiation transformation by the Absorber, we obtain the spectrum of the quantum flux entering the Detector. It follows from the obtained results that on such geometrical scales the extinction of the directed flux of quanta is due to Compton incoherent scattering. In this case the detector registers a wide range of continuous X-ray spectrum. The probability of registration of X-ray and gamma pulses increases.

X-ray and possible gamma-ray bursts in double star systems may be rarer and shorter. Some white dwarfs have a companion star nearby. If matter from the companion star falls out in proper amounts, a hydrogen-helium mixture in a degenerate state form on the surface of the white dwarf. The explosive burning of this mixture results in a prominent flare in all ranges of the spectrum. For the most part, this is a rare event. However, monitoring such flares is important for understanding the conditions for the origin of type I supernova explosions. Flares are most common in some double systems where the magnetic field of the white dwarf reaches 10^3T or more. Observations show that several times a year there is a powerful flare in the optical range. Our previous calculations showed that if we take into account protons and helium nuclei, which make up the bulk of the matter falling along the magnetic column, the formation of X-ray and gamma-ray flares during the near-surface explosion is expected.

In the previously proposed binary detector (Doikov, 2022; 2023), the combined use of monitoring equipment was based on the operation of two separate detectors. In the present work, a multilayer detector of X-ray and gamma radiation emitted in such explosions is proposed. Since the proposed detector consists of several, sequentially alternating layers, the current pulses coming from these layers are processed within a single electronic interface. The height of each unit pulse is determined by the quantum contribution of the corresponding energy. The percentage quantum contribution is determined by the absorbed energy of a given layer. The parameter of such estimation is the percentage contribution to the total extinction called “Attenuation” and is presented in Fig. 1 – Fig. 4.The calculation of the time interval of soft gamma-ray and hard X-ray flares is microseconds. At the same time, its optical component lasts about a week. At the peak of the flare, the flux of X-ray and gamma-ray quanta from the AM Her double system on the near-Earth detector can be 10 – 100 quanta/$cm^2 \cdot s$. This is noticeably above its sensitivity limit.

4. Layout modeling of detectors

Thus, the use of semiconductors based on heavy elements-perovskites allows us to solve two problems at once. The first detector must efficiently absorb gamma and X-ray quanta and convert the energy into a current pulse. The presented figures Fig. 5 and Fig. 6 show the layout modeling and individual trajectories of quanta during their motion in the Detector. The use of new engineering and physical methods of modeling detectors accelerates their fabrication and reduces the cost of their bench testing. The following tasks were set and solved during modeling and prototyping:

1. Size and geometry, chemistry composition and emission spectrum of the incoming radiation detector.
2. Graphical interface tracked each individual trajectory.
3. During the motion of the quanta, its trajectories are generated and then its average characteristics are determined as shown in the figures.
4. In this work, the part of energy loss that forms the current pulse of the high voltage preamplifier is highlighted.

The obtained results of modeling and prototyping of detectors are presented in Fig. 5 and Fig. 6 allowed to select the optimal size, shape and chemical composition of detectors. Quanta with energy higher than 10 keV cross the silicon substrate and are trapped by the second layer of the detector up to 200 keV. Multiple scattering in the range from 200 keV to 511 keV leads to defocusing of the directed beam of quanta passing through the spectrograph aperture. Fig. 5 and Fig. 6 show the results of such scattering.

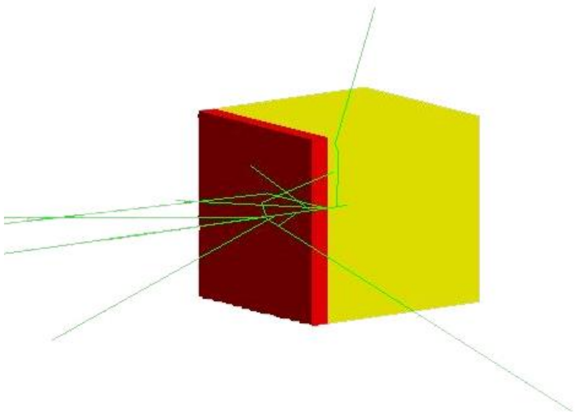

Figure 5: Model of bilayer detector $CsPbBr_3$ 1 x 1 x 1cm and SiO_2 0.1 x 1 x 1 cm. Eγ=511 KeV

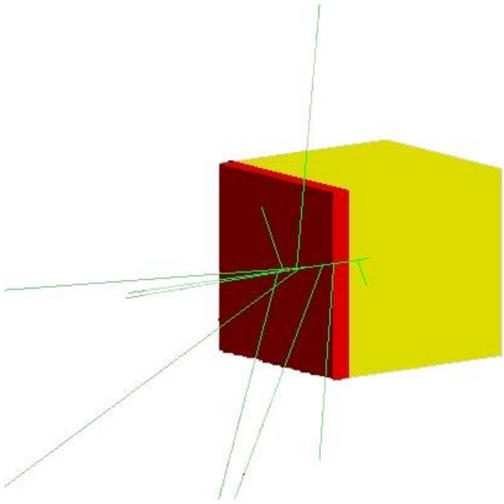

Figure 6: Model of bilayer detector $Lu(SiO)_5$ 1 x 1 x 1 cm and SiO_2 0.1 x 1 x 1 cm. E_γ=511 KeV

5. Discussion

Long-term operation of detectors under normal conditions requires elimination of surface degradation of these crystals. Therefore, they are placed in an isolation volume in which the air is evacuated and the high-voltage preamplifier can be operated. However, this leads to energy losses in the long-wavelength X-ray wing. In an open space environment, there is no need to resort to such procedures (Ma et al., 2023).

6. Conclusion

In the present work, the detector parameters necessary for their design are calculated. The method of selection of geometrical and physicochemical characteristics of used semiconductor crystals including chemical elements with large atomic numbers is proposed. Their operation does not require deep cooling and the signal-to-noise ratio is insensitive to changes in ambient temperatures. All major elements of the detector and electronic interface are publicly available.

Acknowledgements. I express my gratitude to the speakers of the Giant4 School in Pavia, Italy and their help in implementing the codes in solving the present problem. Prof. Gotsulskiy V.Y. and Senior Researcher INFN, Italy Pandola L. for productive discussion.

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