THERMAL NEUTRONS DETECTION MODULE CAPABLE OF ELECTRON AND GAMMA-SEPARATION AND BACKGROUND SUPPRESSION

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(Received February 9, 2016)

The modeling of the registration of thermal neutrons by Si planar detector with natural metallic Gd neutron converter and gamma background suppression was performed. The responses of Si planar detector in different ways were calculated. Spectra dependence consisted of the spectra conversion electrons in energy range 30...200 keV with maximum at energy 70 keV and Gd CXR lines were received. Background gamma radiation was suppressed by two detectors data subtraction. The programs were designed using $C++$ and function under execution control of OS Red Hat LINUX 6.2 FEDORA by free code GEANT 4.8.2 usage.

PACS: 03.65.Pm, 03.65.Ge, 61.80.Mk

1. INTRODUCTION

Planar silicon detectors (PSD) are widely used in high-energy physics (CERN), in nuclear physics researches, in nuclear power engineering, in nuclear medical apparatus, and in nondestructive nuclear detection systems. The use of gadolinium converter allows PSD usage for neutron detection. High gadolinium neutron capture cross-section allows much more effective to diagnose the thermal neutron flux than the traditional methods of detection: counters ^{10}B, ^{3}He, ^{6}Li, scintillator, and so on. The advantages of PSD with gadolinium converter refers the efficiency removal of information, low working voltage, small footprint, small thickness detection and converting layers.

Perspectives and relevant of a new neutron detectors development is determined by relevance and task expansion of neutron physics. This is the modern energy and experimental facilities, the widespread introduction of neutron physics in the diagnosis and treatment of cancer. The problem of control over the distribution, maintenance, transportation of fissile materials and the fight against terrorism becomes more and more of current interest.

The series of works devoted to the development of this method [1 - 6]. When using PSD with gadolinium converter for recording the thermal neutron flux is very important task is to separate the signal from the companion neutron capture gamma radiation, which is in their spectral characteristics close to the background radiation [7] Neutron's very low fluxes detection(less on the order than accompanying gamma radiation) can cause the errors of neutron detection by means of secondary particles detection (internal conversion electrons – ICE). The proposed two-detector technique allows reliable separation electron response to significantly exceed background of gamma-quanta.

2. WORKING OUT, REALIZATION, MODEL TESTING

Detection of weakly intensive flows of thermal neutrons with use of the gadolinium converter allows determining reliably presence and intensity of the thermal neutron flow by the conversion electron spectrum. However, with a decrease in the intensity of the neutron flux, increases the contribution of concomitant capture gamma radiation, as well as the effect of gamma background environment. The basis of the developed method is based on the selection of the spectral distribution of the conversion electrons from a mixed gamma electron beam. This separation is supposed to receive by the usage of a two-channel detection module, containing two planar silicon detectors with gadolinium converters. To prevent electrons penetration in one of the detectors between the converter and the PSD is installed plastic screen with sufficient thickness to completely absorb the conversion electrons (Fig. 1). Thus the method for separating gamma–neutron signal based on discrimination of the spectral distribution of the conversion electrons produced by gadolinium nucleus capture of neutrons was developed. The requirement for reliable identification of characteristic energies in the spectral distribution of the electrons imposes a lower limit due to the statistical nature of the method. Thus for the reliable identification of the conversion electrons require a certain minimum statistics (the minimum amount of absorbed electrons) in which the accuracy of the presence in a mixed stream of neutrons will

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have sufficient credibility. At extremely low statistics is expected to develop the identification of the most probable electron energy in the spectral distribution of the ICE, in our case, $Ee = 71\,keV$ [8] (see Fig. 6, 8), and develop algorithm for determining the value of the primary thermal neutron flux too.

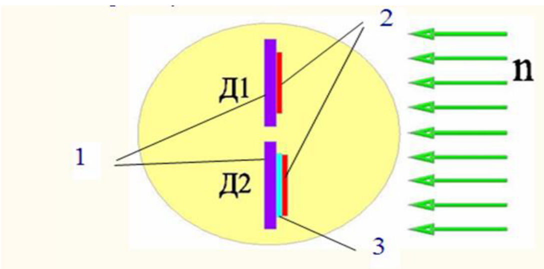


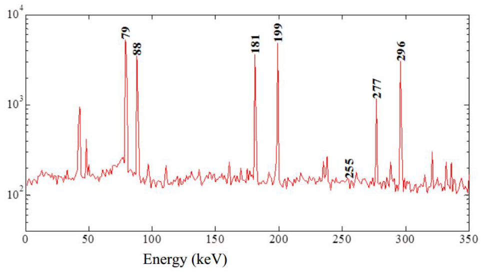
Fig.1. *Two detector model scheme. 1 -– PSD; 2 – gadolinium converters; 3 — polyethylene screen*

Fig.1 shows a model of two detector system implements the separation scheme of a gamma neutron flux. Two uncooled PSD ($5 \times 5\,mm$ with the sensitive layer $300\,\mu m$ thick) placed in a single metal (aluminum) housing. Gadolinium converters (2) were installed at each of placed detector. Unlike of the detector $D1$, the plastic screen (3) on the $D2$ detector, is located between the PSD and gadolinium foil. The separation method is based on the fact that in an isotropic field of gamma-ray (background radiation + capture gamma-radiation produced by the thermal neutrons absorbed in gadolinium converter) in both detectors ($D1$, $D2$) is adjudged to approximately the same spectral distribution of gamma radiation. The $D1$ detector fall is mixed gamma-electron beam, while in the protected by polyethylene screen $D2$ detector electrons do not fall. According the assumption that the gamma-response of both detectors are equal, from the spectral distribution of the detector $D1$ is subtracted distribution corresponding to only the gamma-response from $D2$ data. This method allows even with a substantial excess of γ-background over electron distribution, securely receive, according to the algorithm of subtraction, the spectral distribution of the conversion electrons only. Another advantage of the technique is the following: the higher is gamma-ray background the more uniform are the readings from $D1$ and $D2$ relative to gamma radiation. The presented model of two modular schemes is implemented on the basis of the previously developed single-module schemes based on the PSD with gadolinium converter [6]. Software package "Si-Convertor" was developed to optimize the layout, materials, energy range and the geometry of the detector system. The "Si-Convertor" package allows tracing the neutron and secondary particles transport under conditions of real geometrical sizes. The program has an interactive service, with the ability to track the trajectory of the secondary radiation transfer in the 3D geometry. Upon the completion of model calculation, the program creates a series of spreadsheets with the spectral distribution of the primary flow (thermal neutrons), and for the secondary particles of gamma rays, secondary electrons, as well as distribution ("energy deposition") for each structural element. The program complex is allowed to test the separation of the conversion electrons from the mixed response of gamma-neutron flux methodology by simulating the actual geometry and structure of the planar silicon detectors, by taking to account of the location of gadolinium converters, plastic shield. The neutron flux capture and energy deposition efficiency as functions of flow angular distribution, the geometrical dimensions of metallic converter and silicon wafers and their relative placement was investigated too. Development and implementation of software package "Si-Convertor" was conducted with the help of freely available CERN GEANT4 package eighth version (GEANT 4.8.2), under the control of OS platforms Red Hat LINUX 6.2 FEDORA [8]. Constantly updated library QHSP-BIC-HP, (which includes NeutronHPElastic, NeutronHPInelastic, NeutronHPCapture, NeutronHPFission) allows to simulate the interaction of neutrons with matter in a wide range of energies from ultracool (with an energy of $10^{-7}\,eV$) to neutrons with energies of tens of MeV [9]. When neutrons cross sections were calculated the real distribution of isotopes ^{155}Gd and ^{157}Gd in a natural gadolinium was taking to account. The complexity of the registration of the conversion electrons generated during neutron capture reaction is a large output of captured gamma radiation. Also, the problem of the use of gadolinium as converter for the electron detection is a small runs of electrons in materials with a large charge number. For example, the runs for electrons with energies up to $100\,keV$ in gadolinium do not exceed a few microns (see Table).

Electron energy run dependence

Ee, keV	29	39	71	78
Run in plastic, μm	11.1	19.1	54.5	64.9
Run in Si, μm	4.2	7.4	22.0	24.8
Run in Gd, μm	1.35	2.01	5.1	6.01

The gamma-ray large flow accompanying the capture, as a rule, is not absorbed by silicon detector, but there is always the probability of Compton scattering. Under the scattering process the electrons can be created with random energy distribution: from the maximum energy of the primary gamma-ray to the conversion electron energies diapason. Thus, even with a low probability of Compton scattering of gamma-rays with energies up to $5\,MeV$ and high probability of absorption of the conversion electrons in silicon detector, under certain conditions, the gamma background can significantly exceed the electron response and hinder the identification in the range of the conversion electrons. The model testing was conducted as for the adequate reproduction of the spectrum of the conversion electrons, and for accompanying gamma-radiation too. The simulated prompt gamma-ray spectrum is compared with the experimental standard [10] shown in Fig.2,a. The calculations showed that in gadolinium with a wide range of energy levels, gamma quanta were generated in the energy range up to 6 MeV.



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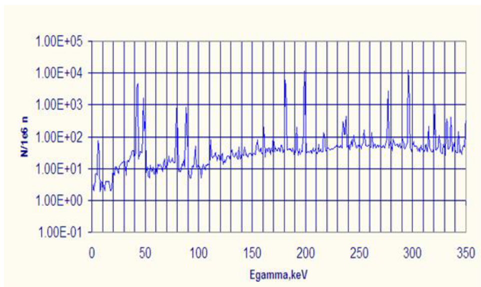

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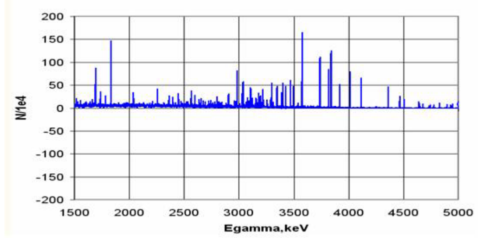
Fig.2. *Capture model testing in the range of* 350 keV. *a – experimental data [10]; b – "Si-Convertor" modeling data*

At the energy range up to 350 keV (see Fig.2), it should be noted the presence of characteristic X-ray emission lines of gadolinium with an energy of 48 and 43 keV, respective to K_α and K_β lines and 6 keV energy peak corresponding to L-line. The capture gamma spectrum emitted from gadolinium reaches 5 MeV and without scattering in the silicon detector, corresponds to the range and distribution of the background radiation spectrum (Fig.3).

When testing and comparing the simulation algorithm, the detectors D1 and D2 responses were analyzed taking into account not only the energy loss (energy deposition), but also balance of the radiation flow incident on the detector and emerging from the detector. Detectors for the measurement of total absorption conversion electrons (just as well as and Compton electrons) is necessary to ensure maximum contact with the gadolinium plate, as well as to optimize the thickness of the sensitive silicon layer corresponding to the maximum range of the electrons of the investigated energy range. For the elements with a large charge number, such as gadolinium, particularly, the gamma–quantum scattering can not to be neglected, at least in the energy range up to 100 keV. Characteristic capture lines generation can be superimposed on the distribution of the conversion electrons. In the developed model the rejection of the gamma and conversion electron response optimizes by the most transparent to gamma-background material–plastic usage and the most correct of the electron runs up to 100 keV taking to account. In addition the preliminary run calculations were carried out for the characteristic energy of the electrons, the secondary – Compton electrons that create "noise" under the reconstruction of the conversion electron spectrum was taking into account (see Table).



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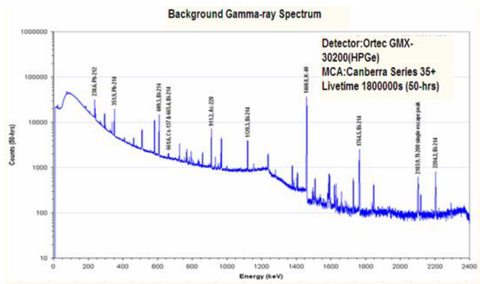

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Fig.3. *Thermal neutrons capture model testing up to* 5 MeV *(a); background radiation (b) [7]*

The electrons path calculation method is presented on Fig.4. It was a calculation of electron monoenergy passing through coefficient for different matter thickness.

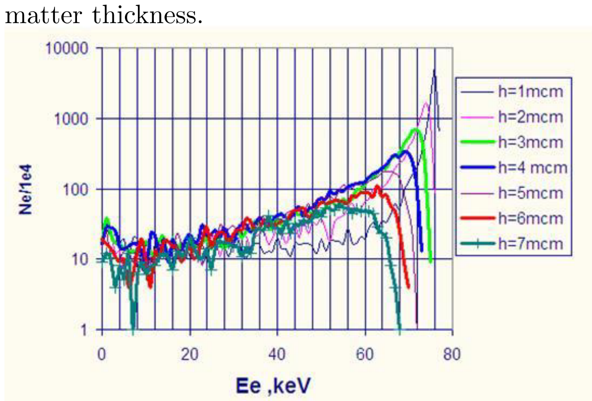


Fig.4. *Electron spectrum output dependence on gadolinium thickness. Primary electron energy* $E_e = 78\,keV$

The simulation of the absorption of the background radiation in a wide energy range in a planar silicon detectors has shown that the main mechanism for the registration of the primary radiation is the transfer of the high energy gamma-quanta to secondary electrons. Under the Compton scattering, the energy of the secondary electrons can achieved a few hundred keV at the primary energy gamma-ray up to and more than $1\,MeV$ or may be a few tens of keV, getting to absorption internal conversion electron range. The results of modeling of the scattering of the characteristic lines emerging from gadolinium: $43\,keV$, $48\,keV$, and the lines of capture gamma radiation of 79.5 and $89.0\,keV$ are presented in Fig.5.

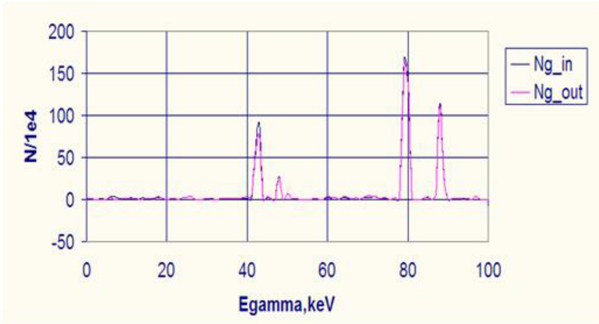


Fig.5. *γ-quantum absorption in Si-detector in the energy range up to $100\,keV$*

In K_α-line case the absorption reaches 10% and significantly decreases with increasing quantum energy (see Fig.5). Preliminary modeling has shown that the electron yield optimization from the converter is achieved by reducing the thickness of the converter to a thickness of several microns. In this case, for the generation of conversion electrons are responsible only neutrons with energies up to $0.0252\,eV$. In this case conversion electron emission is determined by small (corresponding to the thickness of the gadolinium) neutrons runs in gadolinium and in the case of the isotropic field of thermal neutron, concomitant capture gamma-radiation contribution does not substantially affect the registration and identification of the electron neutron response [8]. However, in this case it decreases overall efficiency of neutron capture, while the relative contribution of background radiation, its flow rate, which is independent of the detector's geometry, will increase. It can lead to a substantial excess the background signal range – above the expected signal due to conversion electrons.

3. METHOD REALIZATION PRELIMINARY RESULTS

In the investigated two-detector module to be used the converter based on backscattering and complete absorption of the entire spectrum of the neutrons. In the case of backscatter and conversion thickness of 300 microns, it will be implemented over the full primary neutrons spectrum capture, which in turn will lead to a significant excess of gamma-background on the range of the conversion electrons. Calculations have been made at twenty fold excess of gamma-radiation on the flow of conversion electrons in the geometric model shown in Fig.1. To determine the best possible relations between conversion electrons and capture radiation flow, the efficiency of conversion, the software "Si-Convertor" complex was modeled so-called the effect of ≪internal absorption≫ - inner deposit energy. The objective of these calculations have been testing for the getting the data of conversion electrons generation per captured neutron, without taking into account the scattering, reflection from the interface, self-absorption and re-emission material of the converter (Fig.6).

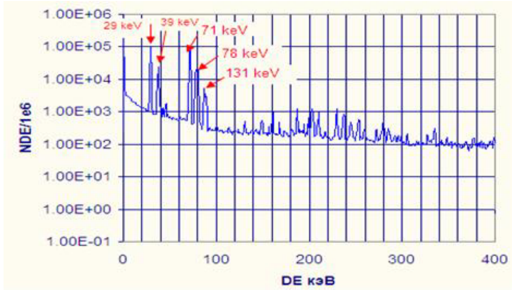
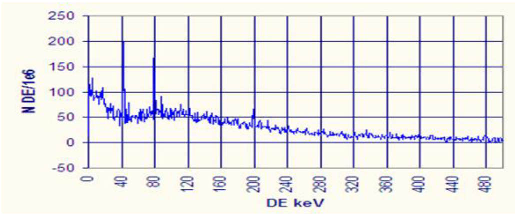


Fig.6. *Inner conversion electron self-absorption in gadolinium*

Presented in Fig.6 distribution corresponds to the distribution of neutron flux 10^6 while the electrons output from the converter into the detector was $1.7 \cdot 10^4$ ratio of γ-quanta/electron was 58.8. As seen in Fig.6 the generation of the characteristic lines has a most probability in the range up to $100\,keV$ energy levels but substantially generated – 300 to $200\,keV$. With the development of the internal conversion process, while continuing to observe the process of Compton electron scattering energy distribution ("background" in Fig.6). Conversion electron line output from gadolinium converter accompanied by blurring–electron energy losses from maximum energy to zero. But the maximum value of the conversion electrons energy, corresponding to the difference between the energy levels of the nucleus and electron shells is maintained (see Figs.4, 8). The calculations were carried out to optimize the matter and the thickness of the plastic screen (see Table). The criterion of the plastic screen choices was the thickness corresponds to the maximum electron run in the testing energy range, as well as conditions providing the minimum scattering of gamma rays (see Table, Fig.8,a). Fig.7,a shows the response of the detector $D2$ (spectral distribution of the energy loss from the past flow), protected by plastic screen with thickness of $100\,\mu m$.

Fig.7,b shows the energy distribution of the flow losses of γ-quanta and conversion electrons, calculated according to the model shown in Fig.1, for the detector D1. Fig.8,a shows the calculated spectra of the electron component of the mixed flux of γ-electron radiation incident on the detector$D1$ and $D2$, respectively, Fig.8,b presented the result of processing and comparing the response of the detector $D1$ and $D2$. Assuming that the simulated γ–background is uniform in both detectors, Fig.8,b presented the electron beam response only.



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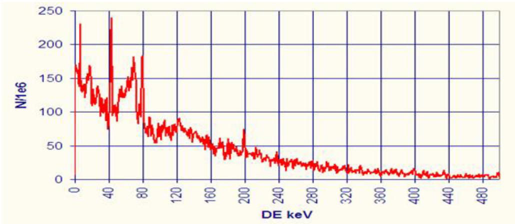

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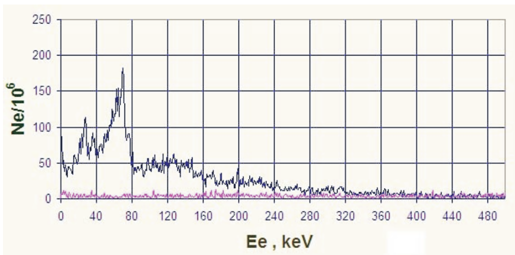
Fig.7. *a – D2 response $\Delta E(E)$; b – D1 response*



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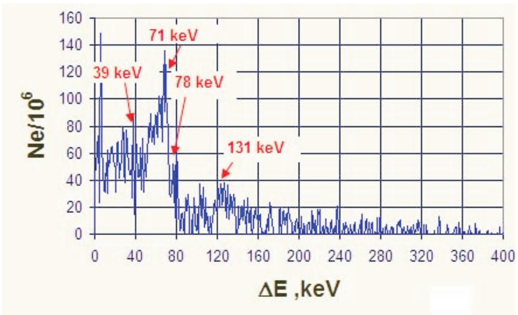

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Fig.8. *a – D1, D2 electron spectrums; b – $D1 - D2$ processing*

In case of simultaneous modeling of two detector system detection and then mixed flow impact comparison, the additional electron component can creates by Compton scattering in additional screen – polyethylene insert. It is also possible physical effect that influences on the total γ-ray flux entering into $D2$ detectors may be the effect of the gadolinium conversion electron conversion in stopping radiation in plastic. Also on the difference signals $D1$ and $D2$ may affect scattering – reduction of the gadolinium gamma-flux in plastic. All these effects create error for the determination of "pure spectrum" of the conversion electrons. However, the nature of these processes does not create addition lines – the electron distribution peaks, but only creates a further level of background which may not match to the $D1$ background.

In processing the signals of two detectors, these processes increase the gamma background and would lead to negative values and, thus, be considered and compensated for. Fig.8-b, represented the "pure" electron signal modeling. Under the simulation, the "negative" effect provided by these mechanisms, almost not observed, but it need for a thorough investigation. Also, it is obvious that the level of the experimental treatment, such effects will arise. Therefore, further development of the model is an adaptation to the actual experimental conditions, the possible introduction of correction factors in the event of a significant impact of these effects.

4. CONCLUSIONS

The proposed method makes it possible to reject the useful signal of internal conversion electrons from significantly higher gamma-ray fluxes. Efficiency of the method is determined by the integral flux of thermal neutrons, the neutron flux which should not to be less then suitable for fixing of conversion electron distribution maximum (maximum probability). It is $E_e = 71\,keV$ for conversion electrons of a gadolinium (see Figs. 6, 8, Table). Using compact planar silicon detector for reliable and rapid measurement of neutron fluxes will allow using it in a wide circle of problems in which it is impossible to establish the overall sophisticated detectors and require quick and reliability of the information. In future in context of model developing it plans to define the ultimate relationship: maximum flow of background gamma-radiation in which the developed method provides reliable information on the presence in the mixed flow of thermal neutrons, to define the limits of method application.

Publication are based on the research provided by the grant support of the State Fund For Fundamental Research (project N Ф69/51-2016).

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ДЕТЕКТИРУЮЩИЙ МОДУЛЬ ТЕПЛОВЫХ НЕЙТРОНОВ С ВОЗМОЖНОСТЬЮ ГАММА-ЭЛЕКТРОННОГО РАЗДЕЛЕНИЯ И ПОДАВЛЕНИЯ ФОНОВОГО ИЗЛУЧЕНИЯ

В. Н. Дубина, С. К. Киприч, Н. И. Маслов, В. Д. Овчинник

Было проведено моделирование регистрации тепловых нейтронов с помощью планарного кремниевого детектора с металлическим гадолиниевым конвертором, реализован метод подавления сопутствующего гамма-фона. Отклик кремниевого планарного детектора был просчитан для разных случаев расположения конвертора, толщин и геометрии модуля. Зависимости спектрального распределения конверсионных электронов в диапазоне энергий 30...200 кэВ, с максимумом распределения, соответствующего 70 кэВ, так же как и характеристических линий гадолиния, были получены для разных первичных энергий нейтронов так и толщин конвертера. Сопутствующее гамма излучение было подавлено за счет вычитания данных двух детекторов. Программа была разработана на языке C++ и реализована под управлением OS Red Hat LINUX 6.2 FEDORA с помощью свободно распространяемого кода GEANT версией 4.8.2.

ДЕТЕКТУЮЧИЙ МОДУЛЬ ТЕПЛОВИХ НЕЙТРОНІВ З МОЖЛИВІСТЮ ГАММА-ЕЛЕКТРОННОГО ПОДІЛУ ТА ПРИГНІЧЕННЯ ФОНОВОГО ВИПРОМІНЮВАННЯ

В. М. Дубина, С. К. Киприч, М. І. Маслов, В. Д. Овчинник

Було проведено моделювання реєстрації теплових нейтронів за допомогою планарного кремнієвого детектора з металевим гадолінієвим конвертером, реалізовано метод пригнічення супутнього гамма-фону. Відгук кремнієвого планарного детектора був розрахований для різних випадків розташування конвертера, товщини і геометрії модуля. Залежність спектрального розподілу конверсійних електронів у діапазоні енергій 30...200 кеВ, з максимумом у розподілу 70 кеВ, так само як і характеристичних ліній гадолінію, були отримані як для різних первинних енергій нейтронів і товщин конвертера. Супутнє гамма-випромінювання було пригнічено за рахунок віднімання даних двох детекторів. Програма була розроблена на мові C ++ і реалізована під керуванням OS Red Hat LINUX 6.2 FEDORA за допомогою вільно розповсюджуваного програмного коду GEANT версією 4.8.2