Silicon detectors with boron converters of different geometrical modifications for fast neutrons registration

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Abstract. In this article the development of the model for fast neutron detector is considered. The construction of detector is based on alternating layers of silicon as sensing material of charged particles and boron (enriched with ¹⁰B) as neutron converter located in moderator. Simulation in GEANT4 showed that detector with one layer of silicon and one layer of boron has very low detection efficiency for fast neutron (approximately 4%). The study of the possibility to increase detector efficiency due to geometry optimization of it is presented. It is shown that efficiency depends on the number of layers and their location in the materials of detectors and moderator. It was found that the optimal geometry is that where the layers of boron-silicon are angularly related to each other. It is shown that the detection efficiency for a model with set of boron-silicon layers angularly related to each other is up may reach 6%.

1. Introduction
In the article the model of fast neutron detector with small size and low power consumption is considered. The detector consists of neutron converter – layers of boron enriched in the isotope ¹⁰B and layers of pure silicon as the detector of the charged particles. The article offers the optimum size of the layers of boron and silicon, and the calculated detection efficiency of the detector for optimized model. The detection efficiency is ≈4% for the model of the detector with a thickness of 1 micron layer of boron and silicon layer 5.5 mm with parallel layers. The detection efficiency for a model where the set of boron-silicon layers are angularly related to each other is up to 6%.

2. Neutron flux to be registered by detector
The proposed detector is focused primarily on the fast neutrons detection. Modern powerful neutron sources are based on the nuclear reactions of the charged particles beam (including high-energy) with the target material [1]. The problem of registration of secondary neutrons produced by high-energy electrons and hadrons arises during the astrophysical observations in outer space in the high-energy gamma-range [2]. The mechanism of the neutron origin in the sources mentioned above is similar and consequently an energy range of the resulting neutron fluxes are similar. The average energy of evaporated neutrons is ~ 2 MeV, they have an isotropic angular distribution. The energy range of an evaporated neutrons is close to the range of fission neutrons with peak located at the energies from 0.5 MeV to 1 MeV.
In this paper the software package GEANT4 [3] is used to simulate the interaction of neutrons with a neutron detector and determine the detection efficiency using different designs of the detectors.

3. The principle of the neutron detection

One of the most popular reaction to convert slow neutrons into directly detected particles is the \( ^{10}\text{B}(n,\alpha) \) [4]. The reaction may be written:

\[
^{10}\text{B} + n \rightarrow ^{7}\text{Li}^{+\text{4}}\alpha + ^{3}\text{Li}^{+\text{2}}\alpha \quad \text{2.792MeV (ground state)}
\]

\[
^{10}\text{B} + n \rightarrow ^{7}\text{Li}^{+\text{4}}\alpha + ^{3}\text{Li}^{+\text{2}}\alpha \quad \text{2.792MeV (excited state)}
\]

Silicon detector is proposed to be used as monitor of charged particles that are born in this reaction. Given that 94% of all reactions is on the way in which the lithium nucleus born in the excited state and the reaction products are emitted in the exactly opposite directions it is possible to calculate \( E_{\text{Li}} = 0.84 \text{ MeV} \) and \( E_{\alpha} = 1.47 \text{ MeV} \), the energy of reaction (2310 keV) is shared between the alpha particle and a lithium nucleus. That is why the discrimination threshold in the model was set on energy 50 keV.

4. Overview of the similar design

The options for a detector based on layers of boron and silicon semiconductor were discussed in the earlier studies [5–7]. It was showed that the simplest version of detector geometry, where the layers of the semiconductor and converter are irradiated normally by the incident neutrons [5] has a low detection efficiency for thermal neutrons (about 4%) at the discrimination threshold 300 keV. As practice showed, the measured values of detection efficiency are usually lower than calculated, since it requires a higher level of discrimination that would exclude gamma rays. The modifications of the geometric arrangement of the layers were proposed to increase the efficiency. For example, in [7] the detector surface is fabricated with grooves into which the converter material is deposited. It is shown that such a structure can greatly improve the detection efficiency. Study presented in this article also aimed at searching for the simple optimum geometry of the detector layers of boron and silicon which can improve the efficiency of neutron detection without increasing of a cost of the detector.

5. Calculation of the geometry for the detector simplest version

Simplest versions of neutron detector have a vertical and horizontal parallel layers of boron and silicon placed in polyethylene as moderator for fast neutrons (figure 1 and figure 2) and have a combined thickness of 5 cm and dimensions 80x80 cm. The thickness of the polyethylene layer is 2.5 cm in construction with horizontal layers (Boron + Silicon) and 2 cm in construction with vertical arrangement of layers (Boron + Silicon). The material of the converter – Boron – is enriched with the isotope \(^{10}\text{B} \) to 90%.

**Figure 1.** Design of detector with horizontal arrangements of layers (B+Si).

**Figure 2.** Design of detector with vertical arrangements of layers (B+Si).
6. The optimum thickness of layers of silicon and boron

First and foremost to optimize the detector efficiency and geometry it is necessary to determine the optimum thickness for the silicon and boron layer. To do this, the mean free path of the particles in the materials of the proposed structure has been calculated and compared with the literature [4]. The converter layer must be kept thin because of the limited range of the reactions product in solid. For alpha particles it is equal to 3.6 \(\mu\)m in boron, 1.6 \(\mu\)m in lithium and 5.5 \(\mu\)m in silicon. Particles range in solid boron for alpha particles – 3.6 \(\mu\)m and for lithium – 1.6 \(\mu\)m. For silicon layer particles range for alpha particles is 5.5 \(\mu\)m. It is proposed to choose the thickness of the boron from 1 \(\mu\)m to 2.5 \(\mu\)m in order to alpha particles and nuclei of lithium will be able to leave a layer of boron. For silicon layer is advisable to choose a thickness 5.5 \(\mu\)m, so that all the alpha-particles are completely absorbed in it. The values of the neutron detection efficiency with different thicknesses of boron converter (1 \(\mu\)m and 2.5 \(\mu\)m) were calculated. In these calculations, the thickness of the silicon layer was 5.5 \(\mu\)m. The number of layers (Boron+ Silicon): 3 layers in model with horizontal layers (Boron+ Silicon) and 80 layers in the model with a vertical arrangement of layers. The detection efficiency value was found in the range 3.80 – 4.56% for all designs. The efficiency is slightly better for the design with boron layer thickness 1 \(\mu\)m than with the thickness 2.5 \(\mu\)m in both construction of the neutron detector. The design with vertical layers get a slightly better detection efficiency.

7. The detector surrounded by layers of boron and silicon

Further calculations were performed for the embodiment of the neutron detector, surrounded by layers of boron and silicon on all sides as it is showed in figure 3. The thickness of the silicon layer is fixed at 5.5 \(\mu\)m. Simulation gave the values of the neutron detection efficiency in range (4.1–4.2)±0.1%.

![Side view of the detector](image)

**Figure 3.** The design of the neutron detector, surrounded by layers of boron and silicon on all sides.

The additional layers (or grater thickness) do not provide a significant increase in the efficiency of the neutron detection. However, we must consider the fact that the increase in the number of layers or increase the thickness of converters and recorders leads to the growth in the size and price of the neutron detector.

8. The detector with layers of silicon and boron angularly related to each other

The construction of the neutron detector with layers of silicon and boron angularly related to each other as it is shown in figures 4 and 5. The layers of the converter and sensor laid at the angle of 45° to each other. The energy discrimination level was equal 50 keV. The simulated efficiency of the detectors was found to be not more than 6.0±0.5%.
Figure 4. Design of neutron detector. The layers of silicon and boron angularly relating to each other are placed in polyethylene as moderator.

Figure 5. Design of neutron detector. The layers of silicon and boron angularly relating to each other are placed in polyethylene as moderator. The angles are different.

The dependence of the efficiency on the energy discrimination level and the angle between the layers were simulated. These dependences are shown in figures 6 and 7. The simulation of efficiency for various models and various discrimination threshold showed that the improvement of the registration efficiency is not significant when the discrimination threshold and the angle between the layers are changed.

Figure 6. The dependence of the detection efficiency on discrimination threshold energy release.

Figure 7. The dependence of the detection efficiency on the angle between layers B and Si.

9. Conclusion
According to the results of the calculations for neutron detector it is advisable to limit the thickness of the boron layer to 1 μm and the thickness of the silicon to 5.5 μm. Registration part of the detector has a limited size, because it is a semiconductor detector. Due to the lack of sophisticated electronics and systems for collecting the optical signal power consumption of the detector will be minimal. The main drawback of such a detector is the low detection efficiency. In the design of the neutron detector with a horizontal and vertical layout of the boron and silicon layers detection efficiency is about 4%, which confirmed the previously published data [4].

The detection efficiency of neutron detector can be increased by changing the geometry of the detector. The efficiency of the detector, wherein the layers are angularly related to each other, reaches ~6%. 

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References
[1] Report 2005 Development opportunities for small and medium scale accelerator driven neutron sources Report of a technical meeting held in Vienna, 18-21, IAEA-TECDOC-1439
[2] Topchiev N P et al. 2015 The experiment "Gamma-400": Status and Prospects Bulletin of the Russian Academy of Sciences: Physics, ISSN: 1062-8738 79(3) 417-20
[3] URL: http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper
[4] Knoll G F 2010 Radiation Detection and Measurements (John Wiley & Sons, 4-th Edition) p 521
[5] McGregor D S et al. 2003. Design Considerations for Thin Film Coated Semiconductor Thermal Neutron Detectors, Part I: Basics Regarding Alpha Particle Emitting Neutron Reactive Films Nucl. Instrum. Meth. A 500 272-308
[6] Wielunski M et al. 2004 Spectral identification of thin-film-coated and solid-form semiconductor neutron detectors Nucl. Instrum. Meth. A 517 180-7
[7] Jahan Q et al. 2007 Neutron Dosimeters Employing High-Efficiency Perforated Semiconductor Detectors Nucl. Instrum. Meth. B 263 183-5