Comparison of calculation results of neutron detection efficiency for models with silicon semiconductor detector and plastic scintillator for GAMMA-400 telescope

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Abstract. Monte Carlo calculations were performed for two models of neutron detector. The first model of the neutron detector includes the layer of polyethylene as a moderator, boron as a target for \((n, \alpha)\) reaction and silicon as a detector of \(\alpha\)-particles. The second model consists of polyethylene layers alternating with layers of plastic-boron scintillators. Calculations were performed for parallel neutron flux with evaporation spectrum. The calculation results of neutron detection efficiency for two proposed models were analyzed and compared. The high neutron detection efficiency is attained by using a plastic-boron scintillator. Using natural boron the 10% of detection efficiency is attained and in the case of enriched boron more than 15% of detection efficiency is attained when the detector thickness is 4 cm. The model using silicon detectors provides the detection efficiency about 4%.

1. Introduction

Geant4 [1] software toolkit is used for simulation and Monte Carlo calculation of neutron detection efficiency of the new detector model, which has been developed at the Department “Applied nuclear physics” of MEPhI. This neutron detector will be used in the GAMMA-400 telescope [2]. The GAMMA-400 telescope is intended for investigation of gamma fluxes from discrete sources of high energy gamma radiation (the rests of supernovae, pulsars, black holes, molecular clouds etc.) in the range of energy from 0.1 to 3000 GeV, for measurement of gamma radiation spectra from galactic and extragalactic sources, for study of gamma splashes from space and gamma radiation of active Sun, etc.

When high-energy particles such as protons, pions, or electrons encounter matter on their way, they interact with that matter through the strong and/or electromagnetic interaction. In this process, the particles lose energy, e.g., through ionization of the medium in which they travel. They may also create numerous secondary particles (charged particles, neutrons, etc.) through nuclear reactions or through radiative processes (bremsstrahlung). This process, called shower development, eventually leads to (almost) complete absorption of the energy of the initial particle [3]. The number of neutrons produced in hadronic shower development is greater than the number of neutrons produced in electromagnetic shower. So, by using the difference of the number of neutrons between hadronic shower and electromagnetic shower, we can separate protons from gamma rays or electrons. The proposed model of neutron detector mainly performs the particle identification and may also be used for the background neutron monitoring in space.
2. Simulation and results
In these calculations, the neutron spectrum, which was obtained in preceding Geant4 calculations, after interaction of high energy hadrons (protons with energy 100 GeV) with the detector materials was used (figure 1). In all cases plane-parallel flux of neutrons is incident to the detector and the C4 layer (figure 2). The number of incident neutrons was $10^5$ neutrons.

![Figure 1. Neutron spectrum obtained in the Geant4 calculation.](image1)

![Figure 2. Diagram of the detector with the layers of boron and silicon. C4 - a plastic scintillator, with 1.5 cm thickness.](image2)

The diagram corresponding to the first model is shown in figure 2. According to the diagram, the layer of polyethylene (the moderator for neutrons), boron (the target for (n, α) reaction) and silicon (the detector of α-particles) were used and the neutron detection efficiency for this model was calculated. The transverse sizes of the neutron detector model (x × y) are 80 × 80 cm and its thickness (z) is 5 cm. The thickness of each layer of the polyethylene moderator is 2.5 cm. The thickness of the layers of silicon and boron was chosen on the basis of Geant4 calculation results. The outline of calculations model, which was developed to choose the optimal thickness of boron and silicon, is shown in figure 3.

![Figure 3. The outline of calculations to determine the optimal value of the thickness of the boron and silicon layers.](image3)

![Figure 4. The energy deposit of alpha particles in the layer of boron. Axis X – depth of the layer (µm), axis Y – dE/dx.](image4)
Natural boron consists of two isotopes: $^{10}\text{B}$ (20%) and $^{11}\text{B}$ (80%). Slow neutrons interact intensively with the nuclei of the isotope $^{10}\text{B}$. In this reaction $\alpha$-particle with energy 1.47 MeV and the nucleus of $^7\text{Li}$ with energy 0.83 MeV are produced with the probability value of 0.93. Therefore in the calculation alpha particles and lithium nuclei having above mentioned energy values interact with the layers of boron and silicon.

Then the energy deposit of alpha particles in the layers of boron and silicon was calculated. In figure 4 the energy deposit of alpha particles in the layer of boron is illustrated, and in figure 5 the energy deposit of alpha particles in the layer of silicon is presented. According to calculations, the range of alpha particles reaches 2.7 µm in a layer of boron and 4.4 µm in the silicon layer. Therefore, for calculations the values of thickness were chosen equal to 2.5 µm and 1 µm for the boron layers, because alpha particles are able to leave boron layers for these values of thickness. For silicon layers thickness 5 µm is advisable to choose, in which the alpha particles are completely absorbed. Using these values of thickness for boron and silicon layers, neutron detection efficiency according to the diagram shown in figure 2 was calculated. In these cases the detection efficiency varies from $4.1 \pm 0.1\%$ for the model with 1 µm thickness of boron layer to $3.8 \pm 0.1\%$ when the thickness of boron layer is 2.5 µm.

According to the second model, the detector consists of two identical modules. Each module is made of polyethylene layers, layers of plastic-boron scintillator and optical conductor layers. We used the optical conductor made of polystyrene without the scintillating additives and the concentration of boron in a plastic-boron scintillator is 5% [4]. Calculations were performed for parallel neutron flux with spectrum shown in figure 1. Detector structure for the second model is shown in figure 6.

Two calculations were carried out for model with natural boron and boron which is enriched by 80% of boron-10 isotope. The transverse sizes in the second model are $80 \times 80$ cm and the thickness of the detector varies from 2 cm to 10 cm, depending on the number of modules. In one module the thickness of the polyethylene layers is 1 cm, the thickness of boron-plastic scintillator layers is 3 mm and the thickness of optical conductor layers is 7 mm. So, one module of the detector has 2 cm thickness and the thickness of the whole detector, which includes two modules, is 4 cm. The dependences of the neutron detection efficiency on the number of modules (thickness of the detector) are shown in figures 7 and 8.
3. Conclusion
The results of the calculations of neutron detection efficiency for two proposed models were analyzed and compared. The high value of neutron detection efficiency is attained by using plastic-boron scintillators. 10% of detection efficiency is reached for the model with natural boron and more than 15% of detection efficiency is reached for the model with enriched boron when the detector thickness is 4 cm. The model with silicon detectors provides the detection efficiency about 4%.

References
[1] http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides
[2] Galper A M et al 2011 Scientific tasks and present status of the GAMMA-400 project Bull. Rus. Acad. Sci.: Phys. 75 875–877
[3] Wigmans R 1998 Rev. Sci. Instrum. 69 3723
[4] Britvich G I, Vasilchenko V G, Gilitsky Yu V et al 2004 A prototype neutron detector based on boron plastic scintillator Preprint IHEP 2004-9 Protvino