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PHYSICAL DEVICES FOR ECOLOGY, MEDICINE, BIOLOGY

Scintillation Detector for Neutron Flux Monitoring at the BNCT Facility[1]

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Abstract—With the advent of new neutron sources for boron neutron capture therapy (BNCT) based on accelerators, it became necessary to create an independent system for monitoring the particle flux during patient irradiation. The results presented in this article showed that the proposed system based on a scintillator–optical fiber–silicon photomultiplier, using three different sensors, made it possible to measure the neutron flux, as well as to estimate the dose induced by gamma radiation. The use of two types of polystyrene scintillators: SC-301 and boron-enriched SC-331 manufactured by Logunov Institute for High Energy Physics (IHEP), National Research Center Kurchatov Institute, Protvino, makes it possible to estimate the contribution of neutrons, and the application of an additional sensor without a scintillator makes it possible to estimate the contribution to the signal from the Cherenkov radiation generated in the optical fiber. The implemented system for detecting optical signals based on silicon photomultipliers has a high quantum efficiency and the counting mode of operation of the readout electronics made it possible to achieve an intrinsic noise level of the order of several tens of hertz.

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1. INTRODUCTION

Boron neutron capture therapy (BNCT) is a thermal and epithermal neutron irradiation therapy that selectively delivers a boron compound ^{10}B to tumor cells. Thermal neutrons interact with ^{10}B in tumor cells and lead to their death due to the large magnitude of the linear energy transfer of the resulting α-particles and lithium-7 nuclei with minimal damage to neighboring normal cells due to the short range of the resulting particles. Currently, various methods are used to measure the parameters of therapeutic neutron beams. First, integral formed dose profiles are measured in the phantom using radiosensitive gels [1]. At the same time, research is actively underway to find more convenient diagnostic methods that allow direct measurement of neutron flux parameters during irradiation. In particular, pulsed gas fission chambers are used to measure the neutron flux, and ionization chambers are simultaneously used in current mode to measure the accompanying dose of gamma radiation [2]. The significantly increased intensity of neutron sources has also led to the need to create a new generation of diagnostic equipment. In particular, the expected neutron flux is near 10^9 neutrons/(cm^2 s) [3]. An example of such diagnostic systems under development are dual tissue-equivalent proportional counters [4]. Compared to gas detectors, scintillator-based detectors allow for significantly higher response speeds. In addition, they are much more compact. Thus, a scintillation detector was developed in Japan based on the polymerizable scintillator Bicron BC490, enriched with LiF powder, with fiber-optic information reading [5]. A similar design, but based on the Bicron BC454 boron scintillator, was previously tested by the same group [6]. In our country, the boron-containing polystyrene scintillator SC-331 is manufactured at the IHEP, which has a light yield of 56–60% of anthracene, a maximum luminescence of approximately 420 nm, a decay time of approximately 2 ns, and contains 6% orthocarborane, which contains natural boron [7]. Thus, for a detector with a sensitive volume of 1 mm^3, the expected flow of events will be approximately 2 MHz, which allows them to be registered with minimal miscalculations. In addition, the use of boron-containing scintillators allows direct modeling of the situation with the use of boron-containing drugs during irradiation.

2. DETECTOR DESCRIPTION

The detector sensors have the same design, where each of them contains three independent optical

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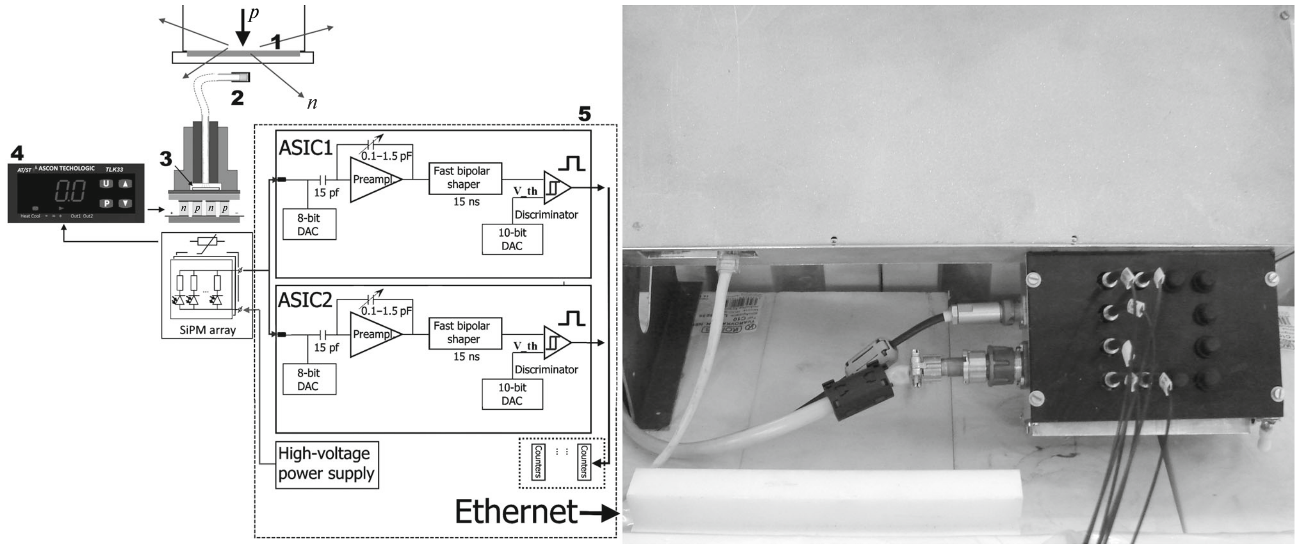

Fig. 1. Block diagram of the registration electronics and a photograph of the detector: (*1*) neutron-generating target, (*2*) sensor, (*3*) micropixel avalanche photodiode, (*4*) Peltier element controller, (*5*) reading electronics.

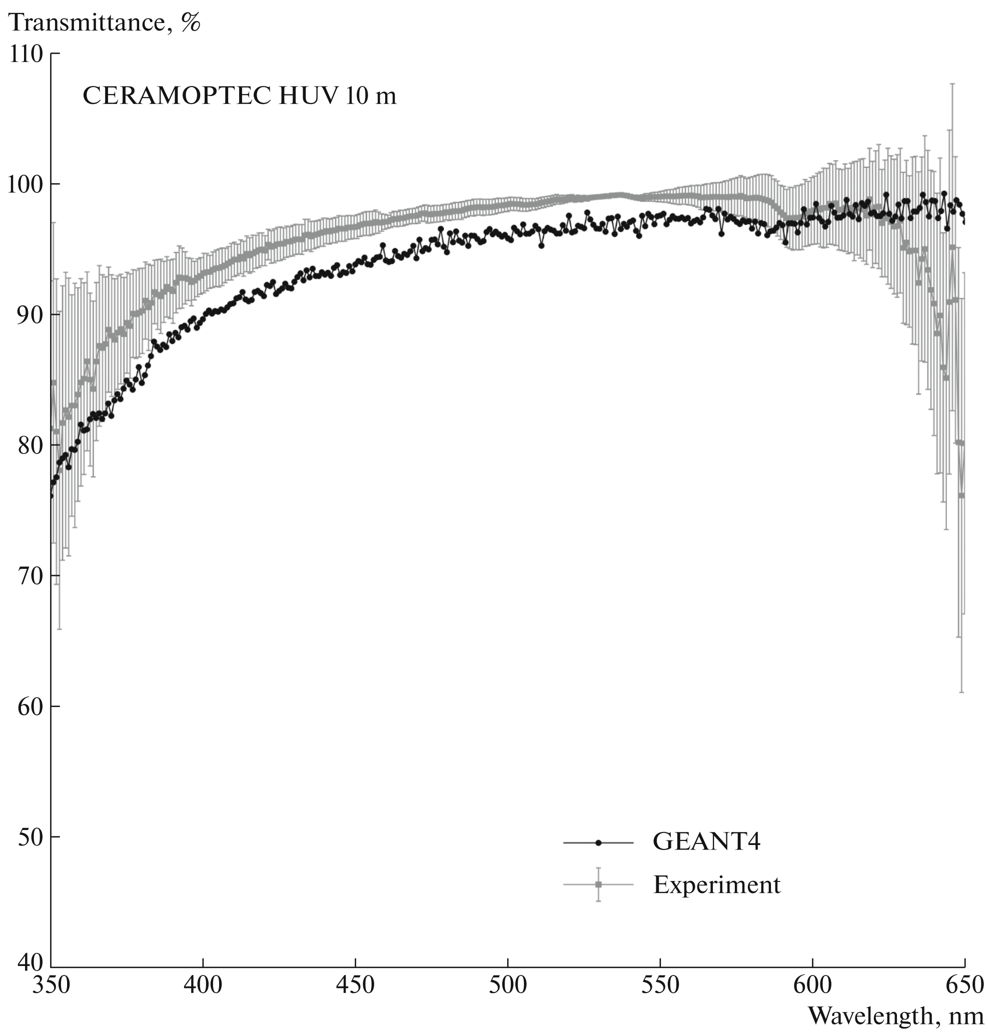

Fig. 2. Transmission spectrum of CeramOptec HUV optical fiber.

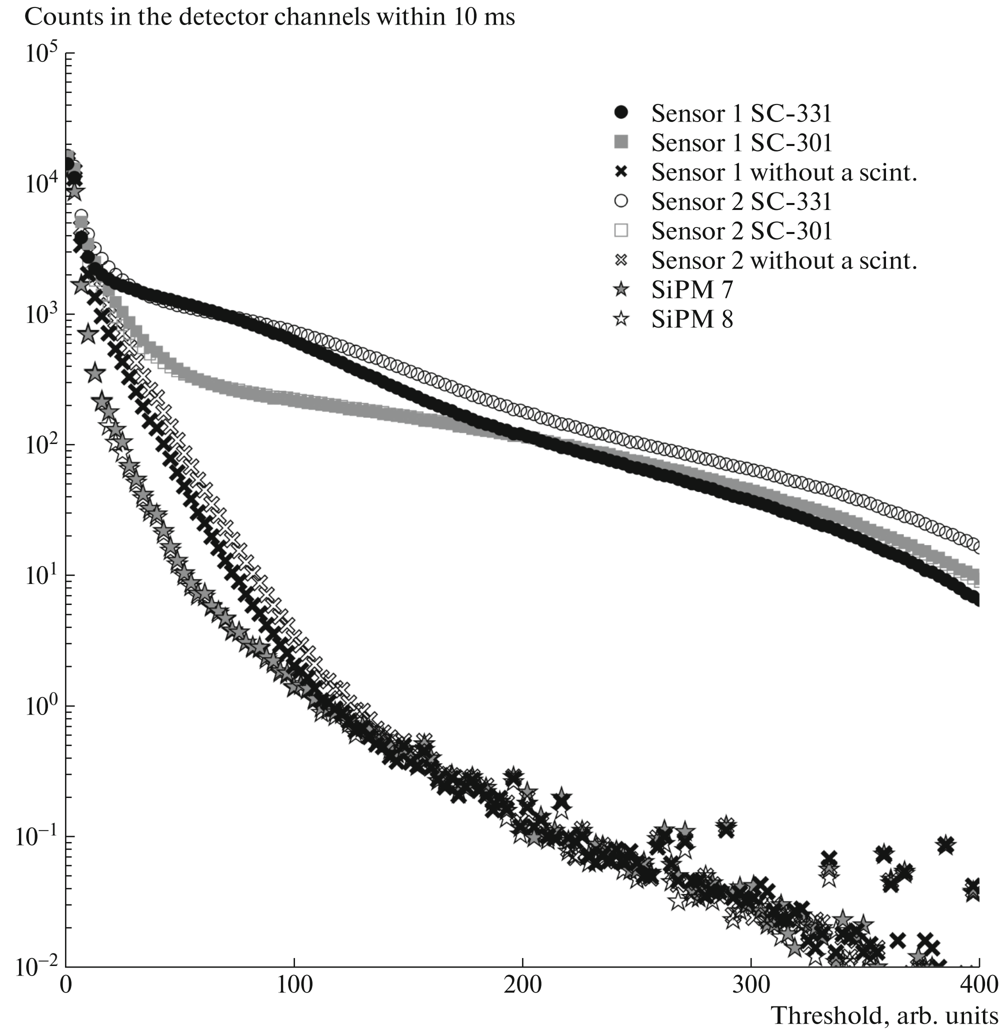

Fig. 3. Dependence of the count in the registration channels on the threshold value for two sensors and two separate micropixel avalanche photodiodes under neutron irradiation.

recording channels. The first registration channel is based on the SC-331 scintillator with boron, the second on the SC-301 without boron, and the third is optical fiber without a scintillator. The scintillators are made in the form of cylinders with a diameter of 1 mm and a length of 1 mm. The sides of the scintillator, as well as the end of the third optical fiber, are covered with white reflective paint. Scintillators are mounted on the ends of the optical fiber using optical silicone rubber SKTN-MED brand D (OOO SUREL) and are protected by a light-proof plastic housing. Optical pulses are recorded using micropixel avalanche photodiodes MPPC S13360-3050CS (HAMAMATSU).

The registration electronics are implemented on the basis of a specialized 32-channel EASIROC microcircuit (CITIROC in a later modification) [8]. Each channel includes an 8-bit digital-to-analog converter, a programmable gain preamplifier, a bipolar pulse shaper, and a discriminator. The fact that boron-enriched and boron-free scintillators have slightly different light outputs [9, 10] necessitates the use of different detection thresholds in the readout electronics. In this case, two chips were connected in parallel to be able to register the same events with two different thresholds. The number of registered events in each channel of the registration electronics is continuously accumulated and transmitted to the computer at 10 ms intervals for further processing. During operation, the control program monitors the temperature of the board where the photodiodes are mounted and, if necessary, regulates their bias voltage to maintain a constant gain. In addition, to reduce the amount of intrinsic noise of micropixel avalanche diodes, all photodetectors are cooled to a temperature of 0°C using a Peltier element. The difference in readings of the two sensors with and without boron allows us to estimate the contribution of the neutron component recorded by the detector. The difference between the counts in the channel of the detector without a boron and the number of events registered in the channel without a

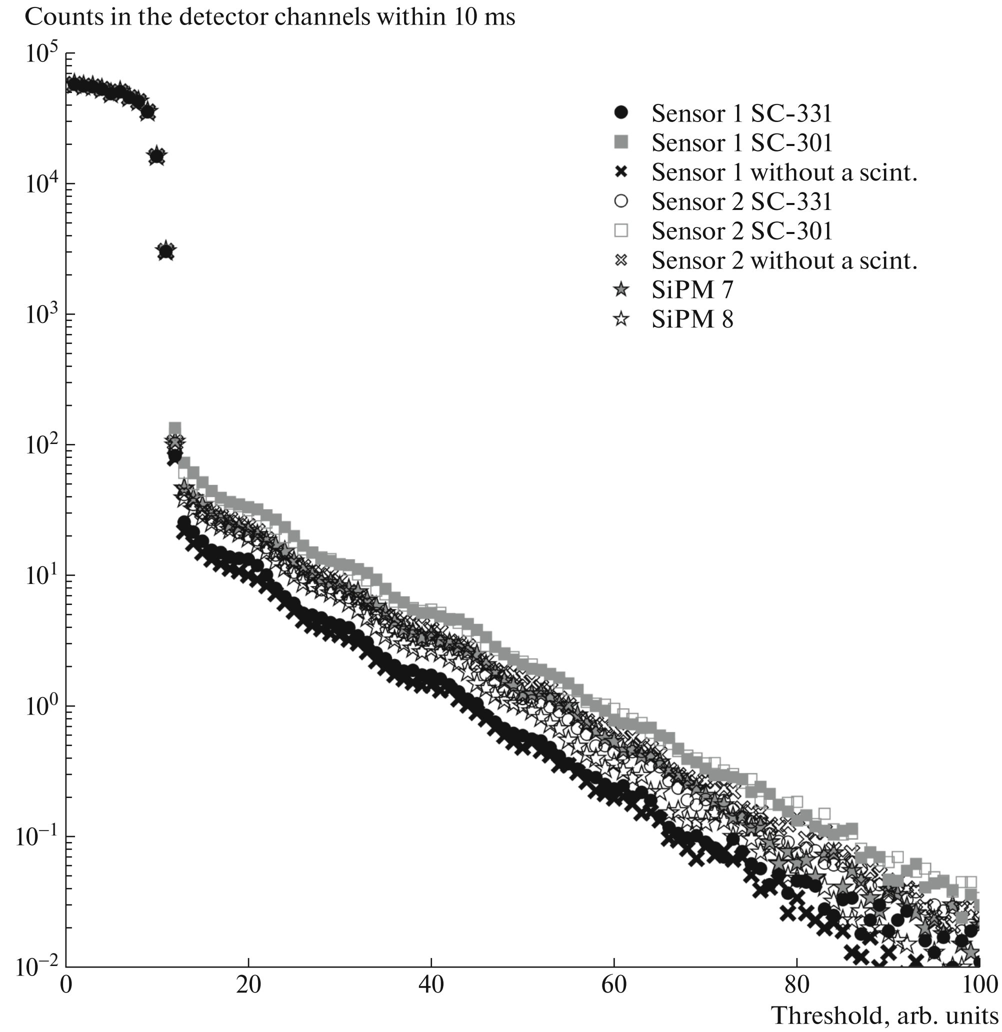

Fig. 4. Dependence of the noise pulse count in recording channels on the threshold value under laboratory conditions.

scintillator gives a signal proportional to the dose of gamma radiation at the measurement point. Figure 1 shows a simplified block diagram of the registration electronics (left) and a photograph of the experimental setup (right).

3. RESULTS AND DISCUSSION

In the initial version of the detector, we used a plastic fiber optic cable ASAHI SC-1000 (Japan) with a diameter of 1 mm to transmit light to the photodetectors. Despite the high numerical aperture value NA = 0.6, this type of cable has significant absorption near 40% over a length of 8.5 m in the region of maximum scintillator emission, and plastic fiber optic cables demonstrated limited radiation resistance [11]. Therefore, in the new version of the detector, we used a quartz fiber also with a diameter of 1 mm CeramOptec HUV (Germany) with a numerical aperture of NA = 0.5. The smaller angle of light capture in this fiber is compensated by significantly increased light transmission. Figure 2 shows the result of measuring the optical transparency of the fiber on a stand based on the MDR-12U monochromator, LOMO. For comparison, the results of simulation in the GEANT4 package are presented. It is evident that the parameters of the materials used in the modeling allow us to obtain results that coincide with the experimental results within 2% and, accordingly, can be used in further calculations to optimize the detector design.

Figure 3 shows the count value in the detector channels depending on the registration threshold for two connected sensors when they are irradiated with a neutron flux at the BNCT facility at the Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences). The presented dependences clearly demonstrate the excess counting in channels with a boron-enriched scintillator. In addition, channels SiPM7 and SiPM8 show the intrinsic noise of the micropixel avalanche photodiodes without any sensors connected to them. It is evident that, in the region of small thresholds (small signals), the intrinsic noise is significantly less than the contribution from the Cherenkov radiation generated in the quartz fiber.

For comparison, Fig. 4 shows the noise level in the same channels under laboratory conditions. During the measurement of the detector characteristics, the integral charge of protons on the neutron-generating target was approximately 70 C (10 mA h). At this scale, the sensors did not show any noticeable degradation of parameters and, therefore, require further study of their radiation resistance. The observed spread of signals between sensors is explained by the technological spread of their parameters during manufacturing, which is compensated for by preliminary calibration of the sensors on the X-ray source.

Unfortunately, CeramOptec quartz fiber has insufficient protection from ambient light due to the smaller thickness of the protective polyethylene coating (200 μm) on it compared to the standard cladding thickness (500 μm) on plastic fibers and requires the installation of additional screens.

4. CONCLUSIONS

The Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) has developed a neutron flux monitoring system for the BNCT facility based on a fiber-optic sensor and micropixel avalanche photodiodes. The increased transparency of the quartz fiber in the new modification of the detector made it possible to compensate for the decrease in light collection due to a smaller numerical aperture than that of the plastic fiber, and this type of fiber demonstrated the stability of its parameters on the scale of several irradiation sessions. However, further research into the radiation resistance of sensors and determination of their service life is necessary.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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