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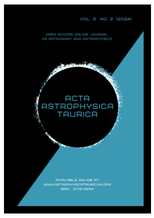

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Calibration of the prototype of a large-volume scintillation detector with photosensors based on silicon photomultiplier matrices

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ABSTRACT

In recent years, the staff of the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) has been elaborating the project for a large-volume scintillation detector at the Baksan Neutrino Observatory (BNO). The detector will become a part of the global network of neutrino detectors. One of the prototypes of such a detector being developed at BNO is an acrylic sphere with a diameter of 500 mm filled with liquid scintillator. The matrices of silicon photomultipliers (SiPMs) are used as photosensors of the detector. For many years such photosensors have been used in various physical experiments. In our case, unlike other experiments, the SiPM matrices are used not only to measure the total light output from the interaction of particles in the scintillator but also to obtain images of such events. This approach will allow us to separate useful (neutrino) events from background ones and monitor supernova explosions in our Galaxy.

Two matrices of 64 SiPMs (ARRAYJ-60035-64P-PCB by the SensL company) register photons passing through the optical collector of the detector from the interaction of particles inside the sphere volume of liquid scintillator. The optical collector consists of Fresnel lenses with a diameter of 300 mm and a focal length of 120 mm. With a LED mounted on the lever, measurements of the volume viewed by the matrices were carried out. The 128-channel data acquisition system is an MDU3-GI64X2 unit (manufactured by AiT Instruments) connected to the preamp boards by a flat micro-coaxial cable. Data reading to an online computer is implemented via a USB 3.0 interface.

Channels are calibrated in each measurement cycle. The charge spectrum in the detector is given, which is the total signal measured by 64 SiPMs of the matrix. The image of the event track is presented. Currently, the method for measuring and analyzing the data obtained is being worked out, and there are preparations for working with the next prototype of the detector, which is an acrylic sphere with a diameter of 1 m.

Key words: silicon photomultipliers, optical collector, track registration, Fresnel lenses

1 Introduction

The project for a large-volume scintillation detector is currently being elaborated at INR RAS. The suggested mass of the detector target is 10 kt. The creation of such a detector at BNO of INR RAS will become a part of the global network of neutrino detectors aimed at studying natural neutrino fluxes (Barabanov et. al., 2017; Malyshkin et. al., 2020; Petkov et. al., 2020).

One of the prototypes being developed at BNO is a 500 mm diameter acrylic sphere filled with liquid scintillator. Silicon photomultiplier (SiPM) matrices are used as photosensors. Such photosensors have been used for many years within various physical experiments. In our case, unlike other experiments, SiPM matrices are used not only to measure the total light output from the interaction of particles in the scintillator but also to obtain images of such events. This method of particle registration provides a fundamental possibility to separate and study different classes of events in the scintillator volume and may prove useful in designing new large detectors for neutrino astrophysics and geophysics (Petkov, 2016).

The work on the detector prototype continues research on the use of SiPM matrices to obtain images of events within the scintillator volume. The first version of the detector developed at BNO used a plastic scintillator cube, with a side area of 36 cm^2 being equal to the area of the ArrayC-60035-64P-PCB matrix. The images of events were obtained using two SiPM matrices as photosensors. Measurements were made with different configurations of the detector. In one configuration, the matrices were placed on the sides of the plastic scintillator; in another configuration, they were installed at the focus of the Fresnel lens collector. The results of these studies are presented in Yanin et al. (2018), Dzaparova et. al. (2015).

2 Prototype of a large-volume scintillation detector

The prototype we are currently working on is an acrylic sphere filled with liquid scintillator based on white spirit, which is applied in the scintillation counters of our devices. The scintillator used in the detector, developed at INR RAS, remains one of the best globally in terms of scintillation yield, short luminescence time, and stability of the scintillator (Voevodskii et al., 1970).

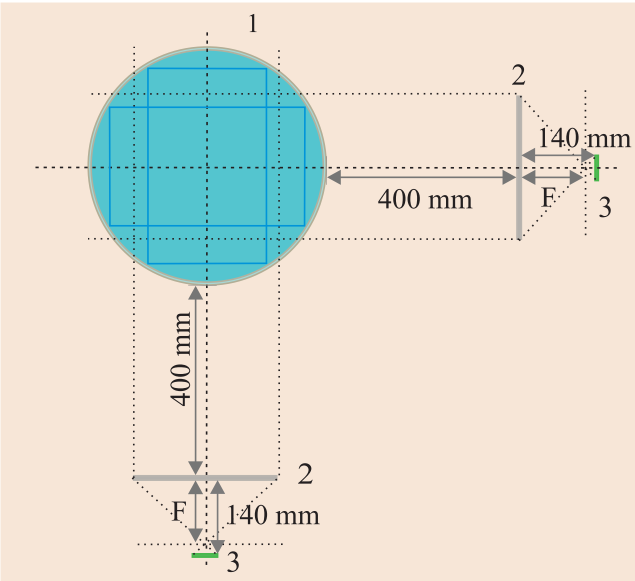

Fig. 1. Optical scheme of the detector. Top view: 1 – acrylic sphere, 2 – Fresnel lens, 3 – silicon photomultiplier matrix.

The optical system of the detector is based on Fresnel lenses (Fig. 1). Two Fresnel lenses with a diameter of 300 mm and a focal length of 120 mm are used. The SiPM matrices made by the Irish company SensL were selected as photosensors, with their maximum sensitivity (420 nm) coinciding with the maximum spectral sensitivity of our scintillator. The J-series matrices (ARRAYJ-60035-64P-PCB) were chosen also because they have an ultra-low typical dark count rate of 50–150 kHz/mm^2.

The results presented in this study represent an advance in the measurement methodology and in the presentation of the data obtained (visualization of events, analysis and separation into different classes of events). The next stage will be to work with the detector prototype, with an acrylic sphere of 1 m in diameter. This detector will be located in one of the rooms of the Baksan Underground Scintillation Telescope (Alekseev et al., 1980). The telescope is located in a rock excavation at a distance of 550 m from the entrance to the horizontal mine shaft. The effective thickness of the soil above the telescope is 850 g/cm^2 (850 meters of water equivalent, with 300 meters of rock soil). In these conditions, the muon intensity is reduced by three orders of magnitude as compared to the surface background, allowing the study and separation of different event classes within the scintillator volume. The large-volume scintillator will be located in an underground room at a depth of about 4000 meters from the mine entrance. The effective soil thickness is equivalent to 4800 meters of water equivalent. The muon intensity at this depth is $(3.0 \pm 0.15) \times 10^{-9}\ \mu/(\mathrm{cm}^2 \cdot \mathrm{s})$. Such a low background (one muon per square meter for 10 hours) allows searching for rare astrophysical neutrino events.

2.1 Measurements of the volume viewed by the matrix

The 500 mm diameter acrylic detector is made by gluing together two hemispheres. Each hemisphere is made by blowing from a transparent acrylic sheet (Plexiglas) and is thinned from 12 mm at the edge to 3.6 mm toward the center of the hemisphere. The integration of the optical path characteristics of Fresnel lenses and the optical properties of the detector's acrylic sphere required measurements to estimate the volume viewed by the matrix.

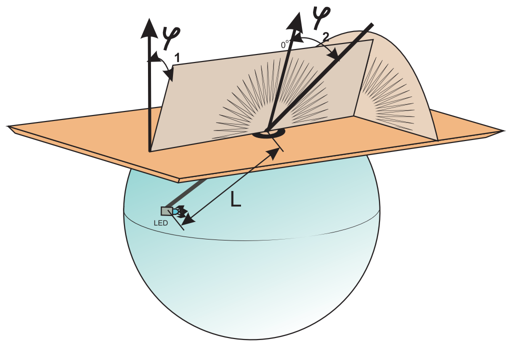

Fig. 2. Sketch of the scheme for measuring the sphere volume viewed by the matrix. The LED position in the sphere volume is determined by three coordinates – two angles φ_1 and φ_2 in mutually perpendicular planes and the length of the lever L.

For this purpose, a platform was mounted horizontally at the position where the lid is fixed in the technological hole of the acrylic sphere. Two protractors were placed on it in mutually perpendicular planes (Fig. 2). A lever with a LED attached to its end was inserted through the center of the platform. All LED positions within the sphere volume where the image of the LED still fell on the edges of the matrix were recorded. Thus, each LED position in the sphere volume was determined by three coordinates – two angles φ_1 and φ_2 in mutually perpendicular planes and the length of the lever L. The distance from the Fresnel lens to the sphere surface was chosen so that the image on the matrix from the LED at the near wall differed in size by no more than 1.2 times from the image on the matrix when the LED was positioned at the far wall of the sphere.

All measurements were made with the optical system components shown in Fig. 1. Constructing the coordinates obtained during the measurement allowed us to determine that, with the chosen arrangement of the Fresnel lens, matrix and sphere, the matrix views the volume that forms a rectangular parallelepiped. The measurements obtained the coordinates of all eight vertices and the coordinates of points at the center of all sixteen edges of the parallelepiped. In Fig. 1, two rectangles with sides of 17 cm and 44 cm are superimposed on the sphere – the top view of the measured working volumes for each matrix. The common cubic volume at the center of the sphere allows an image of the event to be captured in two projections. Thus, a matrix with an area of 25.44 cm^2 views a volume at the center of the sphere with a side area toward the matrix of 289 cm^2, which projects an 11-fold reduced image onto the matrix. During measurements at the Earth's surface, not in low background conditions, the detector mainly registers a high background of atmospheric muons. This scale, determined by the arrangement of the optical system components – Fresnel lens, matrices, and sphere – was chosen for muon registration.

2.2 Data acquisition system MDU3-GI64X2 of the detector

Previously, a registration system based on the CAEN V792A charge-to-digital converter (CDC) was used to acquire data from SiPM matrices (Yanin et al., 2017). The use of the MDU3-GI64X2 data acquisition system of AiT Instruments, specifically designed to work with matrices of 64 SiPMs, offers significant advantages.

The data acquisition system is a compact unit that allows measurements to be started quickly. The unit has a flexible trigger selection. In addition, the total signal from each matrix and the sum of all 128 SiPMs output on the front panel connectors. The MDU3-GI64X2 unit contains two 64-channel boards of 12-bit charge-to-digital converters. The data acquisition system can operate from an external trigger and has the ability to use different internal triggers.

We carried out measurements using a built-in discriminator, which receives the sum of all 128 channels. The accuracy of the discriminator trigger threshold is determined by a 16-bit digital-to-analog converter within the 1 V range. The discriminator threshold has been chosen to register the muon peak (under surface measurement conditions). Data transfer to the computer is via a USB 3.0 port whose controller transmits CDC data at a rate of over 150 Mb/s.

A design for mounting the XP4500/B photomultiplier, which observes the entire working volume, is currently being developed, and it is planned to further use an external trigger from it. To do this, one of the 8-channel TTL port outputs of the data acquisition system must be programmed as an input. Communication with the AiT MDU3 devices is via the Microsoft Windows.NET platform. The data acquisition program can be written after studying the operation and selecting the optimum mode for the MDU3-GI64X2 unit with the detector prototype.

2.3 Measurement results

The design features of the detector, such as the absence of reflective surfaces and the use of an optical collector, result in a weak light signal. Under these conditions it is important to minimize light losses and to consider the pedestals in each CDC channel when working with digitized data. The test program of AiT Instruments records data in a file by series. For each series of measurements, the minimum value in each channel is found and the average pedestal value within 50 channels is calculated.

Atmospheric muons are the main contributors to the surface measurements. The spectrum of the total charge signal

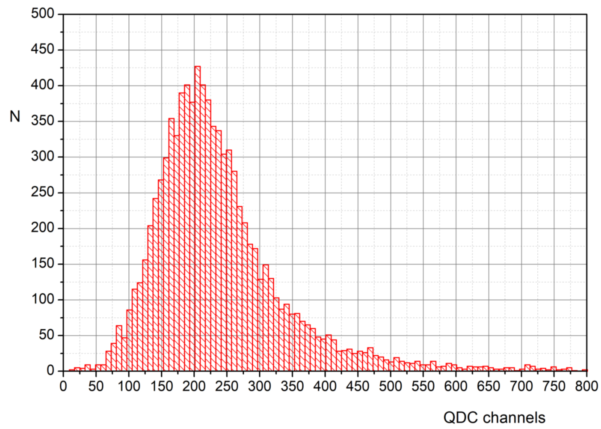

Fig. 3. Total charge spectrum of matrix No. 1.

from matrix No. 1 is shown in Fig. 3. Ten thousand events were processed. In each event, charges were measured from analog signals of 128 SiPMs. The event sums the values of 64 SiPMs for each matrix.

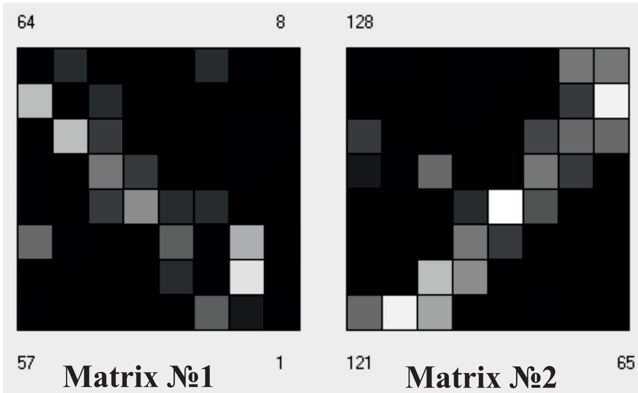

Fig. 4. Visualizing event No. 459: total charge of matrix No. 1 – 263, matrix No. 2 – 264 (in CDC counts).

To convert the measurement in CDC channels to the energy release in the scintillator, we need to create a program to simulate the detector response. As a rough approximation, the particle loss as it passes through the working volume of the scintillator can be estimated if the particle track length is known. An event selected for visualization is shown in Fig. 4. The image of this event shows a muon track recorded almost symmetrically, diagonally across both matrices. The total charge in matrices, after subtraction of pedestals, differs by only one channel. The volume observed by both matrices is a cube with an edge length of 17 cm. Constructing the event in this volume allows the determination of the track length L to be equal to 23 cm. The density of the scintillator material based on white spirit is 0.78 g/cm^2. The loss of particles passing through the scintillator material is known to be 2 MeV/(g/cm^2). Knowing these parameters, it is possible to estimate the particle loss in the volume of the scintillator for the selected event:

$$
\begin{aligned}
(\mathrm{dE/dx}) &= L \times \rho \times \Delta E \\
&= 23\ \mathrm{cm} \times 0.78\ (\mathrm{g/cm^2}) \times 2\ (\mathrm{MeV/(g/cm^2)}) \\
&= 36\ \mathrm{MeV}.
\end{aligned}
$$

3 Conclusions

We have obtained the first results of using the large-volume detector prototype. An optical system design based on Fresnel lenses was created for the 500 mm diameter acrylic sphere of the detector prototype. Test measurements with a LED positioned within the volume of the sphere were carried out to estimate the volume viewed by the matrix. Using the internal trigger of the block discriminator and the manufacturer's test program for working with the block, a data set was recorded by the MDU3-GI64X2 data acquisition system. To process the obtained data, the programs were elaborated to read and convert the data into the format for numbering ARRAYJ-60035-64P-PCB matrices, to define and calculate the pedestals in the CDC channels for each series of measurements, and to visualize the events. After refining the measurement technique and writing the data acquisition program, the next stage will be to pass on to measurements with the next detector prototype – an acrylic sphere with a diameter of 1 m. An optical collector of this detector prototype has to be elaborated. Placing the detector in one of the rooms of the Baksan Underground Scintillation Telescope will allow us to study and separate events into classes not only by energy release but also by analyzing the images of these events.

The work was carried out with the Baksan Underground Scintillation Telescope at the Baksan Neutrino Observatory of INR RAS.

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