New large-volume detector at the Baksan Neutrino Observatory: Detector prototype

N A Ushakov, A N Fazliakhmetov, A M Gangapshev, V N Gavrin, T V Ibragimova, M M Kochkarov, V V Kazalov, D Yu Kudrin, V V Kuzminov, B K Lubsandorzhiev, A D Lukanov, Yu M Malyskhin, G Ya Novikova, V B Petkov, A A Shikhin, A Yu Sidorenkov, E P Veretenkin, D M Voronin and E A Yanovich

1 Institute for Nuclear Research of the Russian Academy of Sciences, Prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
2 Kabardino-Balkarian State University, Chernyshevskogo Street 173, Nalchik, Kabardino-Balkaria 360004, Russia
3 Joint Institute for Nuclear Research, Zholio-Kyuri 6, Dubna, Moscow Region 141980, Russia
4 Institute of Astronomy of the Russian Academy of Sciences, Pyatnitskaya Street 48, Moscow 119017, Russia

E-mail: nikitaushakoff@gmail.com

Abstract. At the Baksan Neutrino Observatory (Institute for Nuclear Research of the Russian Academy of Sciences, Moscow) deployed in the Caucasus mountains, it is proposed to create, at a depth corresponding to about 4700 mwe (meter water equivalent), a large-volume neutrino detector on the basis of a liquid scintillator with a target mass of 10 kt. This article describes the current state of the first stage of the project, namely a prototype detector with a scintillator mass of 0.5 t. The design of the detector, the equipment and methods used are described.

1. Introduction

A new large-volume Baksan neutrino telescope (10 kt ultrapure liquid scintillator) will be created at the Baksan Neutrino Observatory of the Institute for Nuclear Research (BNO INR) RAS [1].

This multipurpose neutrino detector for detecting neutrino and antineutrino flows from the Sun, the Earth, and astrophysical sources will be located in the underground zone of the BNO at a depth of about 4700 mwe (meter water equivalent). This detector will be a three-zone design. The central zone serving as the target for neutrinos will be filled with an ultrapure liquid scintillator (based on linear alkylbenzene) and surrounded by a second zone filled with a non-scintillating organic liquid to suppress signals from inner photodetectors. Photodetectors will be installed on the inner surface of the second zone. The outer zone filled with water and its tracked photodetector system will serve to record Cherenkov radiation residual background events caused by cosmic rays (the method of anticoincidence).

The detector will be an order of magnitude larger in working volume than the most sensitive present detector that detects neutrinos using a liquid scintillator, Borexino [2], and one of the largest of all planned detectors using the same method. In addition to a tenfold increase in volume, the background that impedes the identification of neutrino signals will be significantly...
reduced, which is determined by the depth, new methods for cleaning the scintillator and the distance of the Baksan neutrino observatory from industrial nuclear reactors—nuclear power plants. In terms of the latter parameter, BNO is one of the best underground laboratories in which it is planned to place large-scale neutrino telescopes [1, 3]. Thus, the detector will become one of the most sensitive detectors and one of the key participants in the worldwide network of new generation multi-purpose neutrino detectors, which will include the currently created installations KamLAND [4] (Japan), Jinping [5] (China), JUNO [6] (China), SNO+ [7] (Canada). Among the applied problems that can be solved with the help of a network of large scintillation detectors, the important task for the IAEA to control the operation of atomic reactors should be noted.

New methods and technologies have been developed: for cleaning the scintillator of radioactive impurities used for the Baksan underground scintillation telescope (BUST) and the Borexino detector; for calibrating the detector and searching for sterile neutrinos using an artificial radioactive source; for constructing deep underground laboratories. It will be necessary to improve existing methods and technologies for cleaning the scintillator of natural radioactivity and develop new technologies for cleaning impurities from the $^{14}$C isotope, since the requirements for the purity of the scintillator will be more stringent than in any existing instruments. It will require selection and adaptation of existing technologies for creating the central volume of the detector (film, as in Borexino or KamLAND, or thin plexiglass, as in Double Chooz [8], Daya Bay [9], RENO [10]). It will be necessary to create a new technique for collecting and processing data, taking into account the possible partitioning of the detector.

The detector project includes four stages. The first stage (2017–2019) is the creation of a prototype with a mass of liquid scintillator 0.5 t, placed in the laboratory of gallium-germanium neutrino telescope (GGNT) BNO. The second stage (2019–2021) is the creation of a prototype with a mass of liquid scintillator 5 t, also located in the GGNT laboratory, for testing the applied scientific and technological methods and approaches. The third stage (2021–2024) is the design and creation of a large-scale prototype with a scintillator mass of 100 t. At this stage, water purification systems and a scintillator, located in special rooms underground, will be required. In addition to developing methods and technologies for a full-scale detector, this prototype will be able to solve urgent scientific problems, for example, to monitor supernova explosions with a collapsing core in the Galaxy. The main independent task of the 100-t detector is related to an experiment to search for sterile neutrinos with an artificial source of antineutrinos from $^{144}$Ce decays. In parallel with the 100-t detector, work will begin on the design and creation of a full-scale installation.

Finally, the fourth stage is the design (2021–2023), creation and launch (2023–2027) of a full-scale detector capable of solving the whole range of tasks posed in the project. The working volume of this large detector can be increased by creating additional detached sections. The effectiveness of the telescope for solving individual problems can be increased from the point of view of the development and use of additives in the liquid scintillator, as well as the possible replacement of photodetectors with more sensitive ones (if developed).

The work of the new generation full-scale neutrino scintillation detector will be mainly focused on solving several physical problems:

- Measurement of antineutrino fluxes from beta decays of isotopes of the natural radioactive families $^{238}$U and $^{232}$Th, as well as $^{40}$K contained in the bowels of the earth (geoneutrino). Reliable registration of these particles will make it possible to establish the contribution of energy release from the radioactive decay of these isotopes to the total heat flux of the Earth; test the hypothesis that a chain reaction of fission occurs in the center of the Earth by searching for the antineutrino flux from the “georeactor”; determine the Th/U ratio within the planet, which will allow us to answer a number of pressing questions about the internal structure, origin and evolution of our planet.
• Registration of the isotropic flux of antineutrinos accumulated in the Universe as a result of gravitational collapses of the nuclei of massive stars and the formation of neutron stars and black holes.

• Study of the dynamics of a supernova explosion by recording the intensity and spectrum of a neutrino burst in the case of a supernova explosion with a collapsing core at a distance of up to 200 kpc.

• Registration of the total flux of antineutrinos from all available nuclear power reactors on Earth.

At the moment, the first stage of the project is completed. The prototype detector with a mass of liquid scintillator 0.5 t was built and launched in test mode in the laboratory GGNT BN0. This stage, supported by a grant from the Russian Science Foundation, allowed forming the basis for the future project. The prototype detector design is given in section 2. Section 3 describes modeling of the detector operation. The properties and characteristics of the selected scintillator, as well as the cleaning process, are described in section 4. Section 5 describes the detection system, including electronics and software, photomultiplier tubes (PMTs) characteristics, the trigger system and, finally, the detector test run. Conclusions describe plans and prospects of working with the existing 0.5-t prototype and the being developed 5-t prototype.

2. Detector design

The prototype of the geoneutrino detector includes two zones. The central zone serving as a target for neutrinos is filled with an ultrapure liquid scintillator and is surrounded by a second zone filled with water, which serves to protect against external radioactivity and muon veto.

The scintillator is contained within a sphere with the radius of 50 cm and varying thickness of approximately 1 cm, therefore the volume of the sphere is 492.8 m³. As a solvent for the scintillator, linear alkylbenzene (LAB) was chosen, it has a density 863 kg/m³, therefore the total mass of the scintillator in the sphere is approximately 425 kg. The sphere is made of acrylic, a transparent material with the refraction index similar to the one of LAB.

It is placed in a water-filled cylindrical polypropylene tank. The diameter and height of the tank are 240 and 280 cm respectively. Its dimensions are constrained by the requirement to fit the tunnel during the transportation underground. The value is 11.5 m³. Water is supplied through a sophisticated water purification and storage system in the GGNT laboratory, including the set of filters, quartzing, etc.

Scintillator sphere is surrounded by twenty 10-inch Hamamatsu R7081-100 PMTs placed at vertices of a regular dodecahedron at about 75 cm distance measured from the sphere center to PMT equators. The PMTs and acrylic sphere are mounted on a stainless steel frame using fluoropolymer mounts. Figure 1 shows the frame with the acrylic sphere and PMTs installed on it, the water tank (in the background) and a container of high-density polyethylene from which the scintillator is injected into the sphere.

3. Modeling

A detailed overview of relevant physical processes in a liquid scintillator detector can be found elsewhere [11]. Briefly, the prototype has been modeled with the LSMC (liquid scintillator Monte Carlo) software in order to better understand the light absorption budget, impact of different geometry choices on light collection, and other aspects prior to the construction. In all simulations primary electrons with total energy of 1 MeV were generated uniformly over the entire liquid scintillator volume with isotropic directionality. Some smaller parts of the detector structures (like PMTs holding structures, cables etc) were omitted for simplicity. Figure 2 shows the various geometries of the central zone and the location of the PMTs.
Figure 1. A frame with the acrylic sphere and PMTs installed on it, the water tank (in the background) and a container of high-density polyethylene from which the scintillator is injected into the sphere.

The obtained results clearly show that the third structure, figure 2(c), has the best energy resolution. The impact of the use of light concentrators (various sizes) and the use of a black tank coating has been also considered. The percentage of photon absorption by various detector elements (scintillator, acrylic sphere, water, photo-cathode, etc) has been studied.

4. Scintillator
Linear alkylbenzene was chosen as a solvent, which has attracted much attention in recent years. This is due to some properties that make it better than other solvents, such as pseudocumene, toluene, cyclohexane and white spirit, used in the BUST.
LAB is a colorless, odorless liquid with a relatively high flash point of approximately 130 °C, has low toxicity and is environmentally friendly. It is readily available and fairly cheap because it is a component of the standard process for the production of detergents in the chemical industry. In addition, it is chemically compatible with acrylic, making it suitable for liquid
scintillation detectors. The organic substance 2,5-diphenyloxazole, known as PPO, was chosen as a scintillation additive.

To develop an effective method for cleaning the existing LAB, studies were carried out to determine the specific impurities contained in it (9-methyl anthracene, dimethylnaphthalene, decomposition products of alkylbenzenes hydroperoxides) and to determine the areas of light absorption by these impurities.

Based on the research results, the following purification procedure was developed. As an adsorber, an activated alumina powder is taken, previously annealed in an oven at a temperature of 300 °C for 3 hours. Aluminum oxide is completely filled and compacted into the steel column, through which LAB is pumped through the pump with a speed of about 6 L/h. The ratio of the volumes of sorbent and LAB is at least 1/8. To eliminate radon, LAB is purged with pure argon (approximately 10 L of argon per 1 L of LAB). To exclude oxidative processes, LAB is stored in a plastic container in an argon atmosphere.

Measurements were made of the main characteristics of the scintillator, namely, the light yield and the scintillation decay time. The measurements were carried out by irradiating the scintillator with 662 keV gamma rays from a $^{137}$Cs radioactive source. Figure 3 shows the effect of PPO concentration on the light yield and on the scintillation decay time.

According to the results obtained, it is clear that already at a PPO concentration of 2 g/L, the scintillator light yield is approximately 80% of the maximum possible light yield for this type of scintillation additive, while the absolute light yield reaches about 10 000 photons/MeV. The scintillation decay time at such a PPO concentration is about 5–6 ns. Thus, based on the results obtained and economic considerations, a concentration of exactly 2 g/L was chosen.

In order for the emitted photons to reach the photomultiplier, the basis of the scintillator—LAB must have good optical transparency. LAB transparency was quantified by the length of the attenuation of light using a spectrophotometer. LAB purification processes have led to a significant (about 2 times) increase in its transparency. The light attenuation length in the LAB at a wavelength of 420 nm exceeds 20 m. With a concentration of 2 g/L PPO scintillation additive in a purified LAB, practically no deterioration of the scintillator transparency is observed.
Figure 3. The dependences of (a) the light yield and (b) the scintillation decay time on the PPO concentration.

5. Detecting system
The detection system mainly consists of two parts: PMTs, which detect light from a scintillator and electronics that read and process signals from PMTs. In addition, such a system should have a trigger system capable of suppressing most of various noises and backgrounds.

5.1. Detecting electronics
The main elements of the detecting electronics of the prototype of the geoneutrino detector are CAEN VME (versamodule eurocard) equipment, which includes VME crate V8100, digitizer V1730, HV PS (high voltage power supply) modules V6533, crate control module V2718, and PCI (peripheral component interconnect) board A2818 for communication between the control module and a PC (personal computer) via optical link.

The V1730 ADC (analog-to-digital converter) is 16-channel, 14-bit with a dynamic range of 2 V and a sampling rate of 500 MS/s. Thus, the best the resolution in amplitude is 0.122 mV, and in charge 4.88 fC. The V6533 has 6 channels, the maximum output voltage is 4 kV with a resolution of 100 mV, the output current is limited to 3 mA, as well as the slew rate and slope rate of 1–500 V/s.

For work with the above equipment, two programs with an intuitive graphical interface were developed. The first software is developed to control all the functions and settings of the digitizer, display, record and process the signal. The size of one frame can reach 2048 µs, however, the use of a large buffer significantly reduces the speed of the program. The software has a set of tools for measuring signal parameters, such as amplitude, charge, delay between two signals and some other tools for working with PMTs. It also provides for plotting measured value histograms in real time. There is a set of functions for signal extraction, such as setting a temporary gate, calculating the baseline, setting thresholds for amplitude and charge. To increase the speed of data acquisition at a high trigger frequency, it is possible to disable individual channels and reduce the frequency or completely disable the rendering.

The second software is developed to work with HV PS and provides the setting of the output voltage, the value of the maximum allowed output current, the rate of rise and fall of the voltage, as well as monitoring the actual values of the output voltage, output current and temperature on each channel. This program supports working with several HV PS modules (up to 32).
5.2. PMTs
As indicated above, 10-inch Hamamatsu R7081-100 PMTs was selected for the detector. These PMTs have 10 dynodes. The signal and voltage are transmitted along the same wire. Cable length is 80 m. The dividers of these PMTs are waterproof.

For accurate determination of the signal parameters, the characteristics of all PMTs, such as dark rate, single (SPE) and multi (MPE) photoelectron spectrum, transit time spread (TTS), nonlinearity, and afterpulses, were measured.

The setup (figure 4) used to measure PMTs characteristics includes the detecting electronics described in subsection 5.1 and LED (light-emitting diode) with a wavelength of 420 nm, synchronized with the digitizer using a generator. In addition, for TTS measurements that require better time resolution, the digitizer DRS4 (with 5 GS/s) was used.

All measurements were carried out with a PMT gain of $\sim 10^7$. In this case, a SPE pulse has a duration of approximately 40 ns, a rise time of 4.1 ns and an average amplitude of 4 mV on 50 Ohm terminating resistor. The PMT signals are amplified by a factor of 10 by fast amplifier. Figure 5 shows the final SPE signal waveform.

5.2.1. Dark current The noise frequency of the dark current (dark rate) was measured using a discriminator for trigger with a threshold of about 1/3 PE (photoelectron). Figure 6 shows the time dependence of the dark rate typical for the Hamamatsu R7081-100 PMTs (after installing and turning on) with a time constant $\tau \approx 40$–50 min, the average dark rate value is $1.74 \pm 0.87$ kHz, which is an excellent result for PMTs of this size.
Figure 5. SPE pulse waveform of the PMTs.

Figure 6. Typical the curve of the dependence of the dark rate on time for the PMTs.

5.2.2. SPE and MPE spectrum The average peak-to-valley ratio is $3.73 \pm 0.56$ and the SPE resolution is $0.68 \pm 0.06$. A typical SPE spectrum is shown in figure 7. Figure 8 shows the MPE spectrum reflecting the MPE resolution of the PMTs.
5.2.3. Transit time spread  The TTS indicator is very important for such experiments, since it imposes certain restrictions on particle tracking. In addition, it is necessary to measure the pre-pulse and delayed pulse parameters, which can cause false triggers. For detecting the pre-
pulse, the signal was supplied to the digitizer through a discriminator with a threshold of about 0.1 PE. The average jitter is $3.01 \pm 0.24$ (FWHM—full width at half maximum). The pre-pulse is ahead of the main pulse by approximately 26 ns, and the delayed pulse lags by approximately 63.5 ns. Figure 9 shows a typical TTS of the Hamamatsu R7081-100 PMTs.

5.2.4. Nonlinearity The intensity of the light flux from the scintillator can vary from several PE to several thousand PE, depending on the particle energy and the distance to the PMT. Therefore, the response of the PMT should be linear in a wide range. To measure the nonlinearity, two light sources similar to the aforementioned were used, whose signals were directed through the optical splitter to the PMT photocathode. The response of the PMT with simultaneous exposure of the photocathode by two LEDs was compared with the sum of the responses from each LED individually. A series of measurements was carried out, starting from low illumination intensities of the order of 10 PE and ending with an intensity of about 1000 PE. Nonlinearity of 5%, based on the data obtained for this type of photomultiplier, is achieved at a light intensity of approximately 550 PE.

5.2.5. Afterpulses Afterpulses, like a pre-pulse and a delayed pulse, can cause false triggers. Afterpulses were measured in two modes. Short afterpulses caused by elastic scattering of electrons at the first dynode were measured with relatively weak illumination of several PE, which is associated with a long front of the main pulse with greater exposure. These afterpulses are of little interest, since they fall into the dead time of the detector. Figure 10 shows a typical for the PMTs the distribution of short afterpulses delays.

Afterpulses caused by ions of the residual gas (long afterpulses) were measured with illumination of the order of several tens of PE. Figure 11 shows a typical for the PMTs the distribution of long afterpulses delays taking into account the substrate from dark currents. After fitting (using the Landau distribution), contributions from ions of various gases to the

![Figure 9. Typical TTS spectrum of the PMTs.](image-url)
final distribution were obtained. The ions are identified by calculating their transit time, $\Delta t$, using the electric potential distribution inside a hemispherical PMT. The calculated transit time assumes a quadratic potential such that,

$$\delta t = \frac{4}{\pi} \sqrt{\frac{2m}{qV_0}} L,$$

(1)

where $V_0$ is the electric potential at the first dynode, $q$ and $m$ are the ion charge and mass, respectively, and $L$ is the distance to the photocathode. Table 1 shows the characteristics of each peak of this distribution, however, for each individual PMT, the indicated values may slightly vary depending on the concentration of a gas in the PMT and the operating voltage.

We should also note the first peak at $0.605 \, \mu s$. Obviously, it should be caused by $H^+$, but the calculated delay ($\Delta t \approx 1 \, \mu s$) does not match the received one. In addition, this peak has a small standard deviation, and if ionization occurs between the photocathode and the first dynode, then the arrival time cannot be so sharp. One of the possible explanations may be if this afterpulse is caused by $H^+$ generated at the first dynode of adsorbed $H_2O$ [12].

In addition, with large illumination, the afterpulses peak at about $14 \, \mu s$ becomes noticeable, however, its fitting is hampered by the contribution of previous peaks. The characteristics of this peak are shown in table 1.

5.2.6. PMTs calibration  The next step was the calibration of all PMTs for HV. To do this, all PMTs were mounted on the frame, and in the geometric center of the acrylic sphere, a diffusely scattering sphere was located by a suspension. The acrylic sphere was filled with purified water, while the frequency of the PMTs dark rate did not change, which indicates a good level of water purification. Diffusely scattering sphere was connected via fiber optic to the already mentioned LED light source. The light intensity level was set to the level of SPE. Further, the HV of all channels were adjusted so that the positions of the SPE peaks of all PMTs coincided in the value of the charge corresponding to the gain of $10^7$ (figure 12).
Figure 11. Typical delay distribution of long afterpulses for the PMTs and its fit.

Table 1. Characteristics of the measured long afterpulses.

| Peak position, µs | Possible source               | The probability of occurrence, % |
|-------------------|-------------------------------|----------------------------------|
| 0.605             | H⁺ (from first dynode)        | 0.02                             |
| 1.047             | H⁺                            | 0.08                             |
| 1.854             | He⁺ or H₂⁺                    | 0.44                             |
| 5.657             | N₂⁺                           | 0.37                             |
| 6.768             | O₂⁺                           | 0.53                             |
| 7.848             | CO₂⁺                          | 0.35                             |
| ≈ 14              | CsO₂⁺                         | 0.02                             |

5.3. Trigger system and test run
In addition to the electronics specified in subsection 5.1, the detection system of the detector must have a trigger system. It was implemented as follows. The Hamamatsu R7081-100 PMTs used in the detector are connected to a dividing panel where the signal and HV are separated. From there, the signal is fed to the active splitter. The signal from one output of the splitter is connected directly to the digitizer. The second output through the amplifier is connected to the discriminator, on which the required threshold is set. Signals from all channels are fed to a 20-channel adder, and from it to another discriminator, on which a threshold is set corresponding to the required number of simultaneously triggered channels. The available adjustable delay in the digitizer allows you to compensate for the timing of the trigger signal. The wide capabilities of the software used for the digitizer allow you to set additional trigger parameters, a temporary gate and a threshold in amplitude and charge, for each individual channel. Figure 13 shows the schematic diagram of the detector detection system.
As a test run of the detector, 4 channels with PMTs from different layers with a sphere filled with untreated water were launched. At the same time, the noise on all channels increased by an average of 1.4 kHz compared to the launch with an empty sphere and purified water.
The hardware-software trigger system was configured so that the trigger is generated when a threshold of 10 PE is exceeded on any of the PMTs and 1 PE on any two others. Figure 14 shows an example of the received signals.

Figure 14. Signal with 4 PMTs for testing the trigger system.

Figure 15. Signal with 14 PMTs for testing the detector.
To check the full operability of the entire detector, the scintillator was filled and 14 available channels were launched. The trigger system was configured so that the trigger is generated when a threshold of 10 PE is exceeded on any of the PMTs and 2 PE on all the others. The trigger frequency of the trigger expectedly increased several times, even with large thresholds. Figure 15 shows example of the received signals.

6. Conclusions
The assembly of the prototype of the geoneutrino detector and the adjustment of all its systems was completed. The next step in the work on the prototype of the geoneutrino detector will be the adjustment of the missing detecting channels, the development and installation of light concentrators for PMTs, the development of algorithms and software for signal processing and modernization of existing elements.

Unfortunately, due to the small scintillation volume, there is no possibility of particle tracking due to the TTS (3 ns) and the sample width of the digitizer (2 ns). Therefore, the work on the second stage, namely the development of a 5 or 10-t detector, has already begun. Both prototype options are limited by the size of the tank with water: $4.33 \times 4 \text{ m}^2$. Due to its smaller volume, the 5-t prototype will have a greater thickness of passive water protection. On the other hand, it is obvious that a detector with a volume of 10 t will have greater sensitivity. For a 5-t detector, options of spherical and cylindrical geometry are considered. Spherical geometry has a maximum area-to-volume ratio, which minimizes the required number of PMTs and simplifies the reconstruction of events in the detector. However, cylindrical geometry gives a larger fiducial volume.

For a 10-t prototype, in addition to spherical and cylindrical geometry, a combination of two hemispheres and a cylinder in the form of a pill is considered.

Acknowledgments
The work was supported by the Russian Science Foundation, project No. 17-12-01331, and has been carried out at the Baksan Neutrino Observatory INR RAS (common-use center) with financial support of the Ministry of Science and Higher Education of the Russian Federation: agreement No. 075-15-2019-1640, project unique identifier RFMEFI62119X0025.

References
[1] Barabanov I R et al 2017 Phys. At. Nucl. 80 446–54
[2] Agostini M et al 2015 Phys. Rev. D 92 031101
[3] Wan L, Hussain G, Wang Z and Chen S 2017 Phys. Rev. D 95 053001
[4] Eguchi K et al 2003 Phys. Rev. Lett. 90 021802
[5] Beacom J F et al 2017 Chin. Phys. C 41 023002
[6] An F et al 2016 J. Phys. G: Nucl. Part. Phys. 43 030401
[7] Andringa S et al 2016 Adv. High Energy Phys. 2016 6194250
[8] Abe Y et al 2014 J. High Energy Phys. 2014(10) 086
[9] Adey D et al 2018 Phys. Rev. Lett. 121 241805
[10] Ahn J K et al 2010 RENO: An experiment for neutrino oscillation parameter $\theta_{13}$ using reactor neutrinos at Yonggwang arXiv:1003.1391
[11] Malyshkin Yu M et al 2020 Nucl. Instrum. Methods Phys. Res. A 951 162920 (arXiv:1909.03229)
[12] Ma K J et al 2011 Nucl. Instrum. Methods Phys. Res. A 629 93–100