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ELEMENTARY PARTICLES AND FIELDS
Experiment

The TAIGA Experiment—Current Status, Recent Results, and Development Prospects

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Abstract—The TAIGA observatory addresses ground-based gamma-ray astronomy at energies from a few TeV to several PeV, as well as cosmic ray physics from 100 TeV to several EeV and astroparticle physics. The TAIGA experiment current status, recent results and development prospects are presented.

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1. INTRODUCTION

The history of cosmic ray research is more than 100 years old. But there are still no satisfactory experimentally confirmed answers to questions about their origin. It is difficult to search for possible sources of cosmic rays by detecting only cosmic rays, since cosmic rays (protons and nuclei) are deflected by the magnetic field of the Galaxy, and this does not allow us to restore the direction to the source of the particle. This has largely determined the rapid development of gamma and neutrino astronomy in recent decades. Magnetic fields do not affect the trajectories of gamma-quanta and neutrinos, so they retain their direction to the source. A special place in these studies belongs to the search for sources of cosmic rays with an energy above 1 PeV, the so-called PeVatrons, which can be: supernova, pulsar nebulae, pulsars in binary systems, star clusters, a black hole in the center of the Galaxy, gamma-ray bursts, etc.

To date, the bulk of knowledge about high-energy gamma-quanta fluxes has been obtained using the H.E.S.S [1]. MAGIC [2] and VERITAS [3] facilities. which include from 2 to 5 Imaging Atmo-

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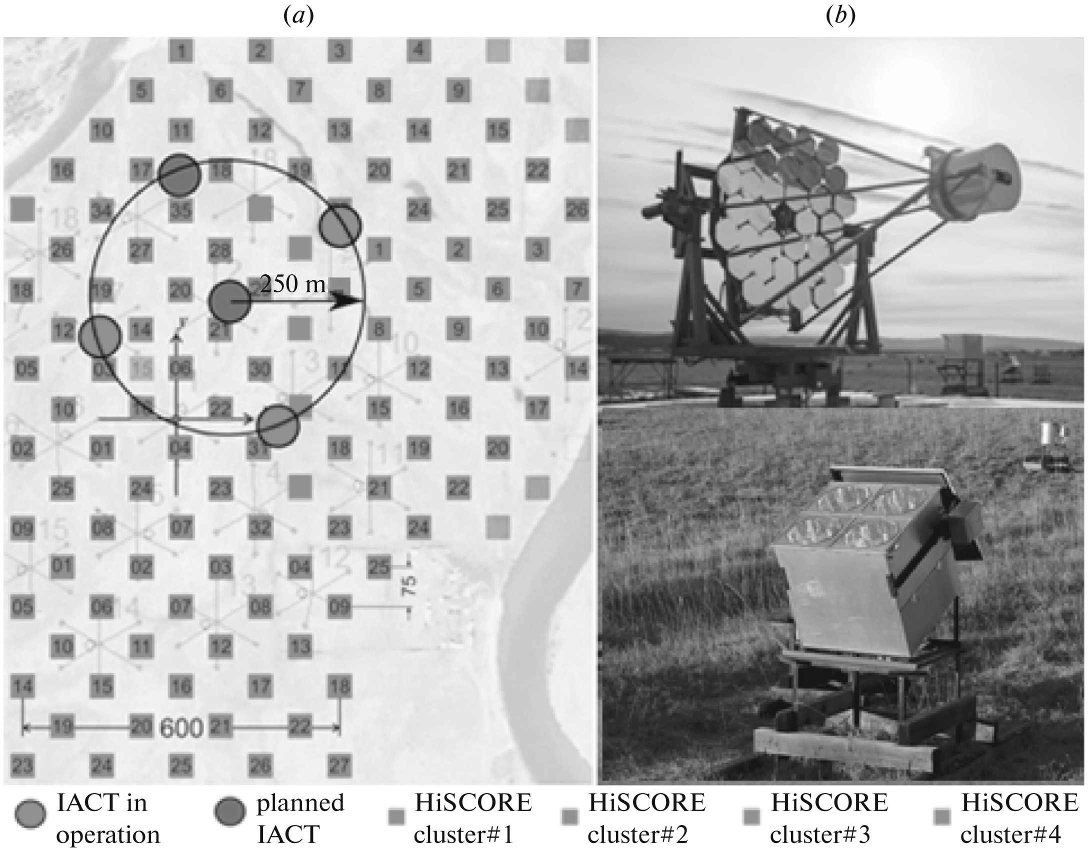

Fig. 1. (*a*) Layout of the Cherenkov detectors of the TAIGA-1 complex: circles—IACT, squares—detectors of the TAIGA-HiSCORE installation. (*b*) Upper: IACT-2 of the TAIGA-IACT installation. Lower—wide-angle Cherenkov detector of the TAIGA-HiSCORE.

spheric Cherenkov Telescopes (IACT). However, the limited size of the effective area (less than 0.1 km^2) of these facilities does not allow detecting gamma-quanta with energies above 100 TeV with significant statistics. A breakthrough in the study of PeVatrons occurred with the start of operation of high-altitude facilities detecting charged particles of extensive air showers (EAS): Tibet-ASgamma [4], HAWC [5] and LHASS0 [6, 7]. With their help, gamma-quanta with an energy of more than 100 TeV were detected from dozens of galactic sources; also from two sources (the Crab Nebula, J2032 + 4102) gamma-quanta with an energy of more than 1 PeV were detected.

In 2022, in the Tunka Valley (Republic of Buryatia) at a distance of 50 km from the South-West tip of Lake Baikal at (51.49 N, 103.04 E) the creation of the hybrid complex of TAIGA-1 [8, 9] was completed, which includes 120 wide-angle Cherenkov detectors of the TAIGA-HiSCORE installation [10, 11] grouped into 4 clusters and distributed over an area of 1.1 km^2 and three IACTs of the TAIGA-IACT array [11]. The last are located between the detectors of the TAIGA-HiSCORE installation at the vertices of a triangle with sides of 300, 400 and 500 m (Fig. 1). The same figure shows the location of IACT-4 (in the center), which will start the data taking in early 2025, and IACT-5 (in the upper left corner), which will be included in the data taking in 2026. In addition to the Cherenkov detectors, the TAIGA-1 complex includes the Tunka-Grande [12] and TAIGA-Muon [13] installations, which record the charged component of EAS.

This article presents some of the latest results obtained with the TAIGA-1 complex and plans for further development of the TAIGA project.

2. COSMIC RAY STUDIES

Research of the energy spectrum and mass composition of cosmic rays is being conducted using all installations of the complex TAIGA (Tunka Advanced instrument for Gamma Astronomy and cosmic ray physics). The Tunka project has developed the most advanced methods of measuring them using wide-angle Cherenkov installations [14], and the latest research results using the TAIGA-HiSCORE installation are presented in [15].

New opportunities for measuring of the partial spectra of cosmic rays for various groups of nuclei

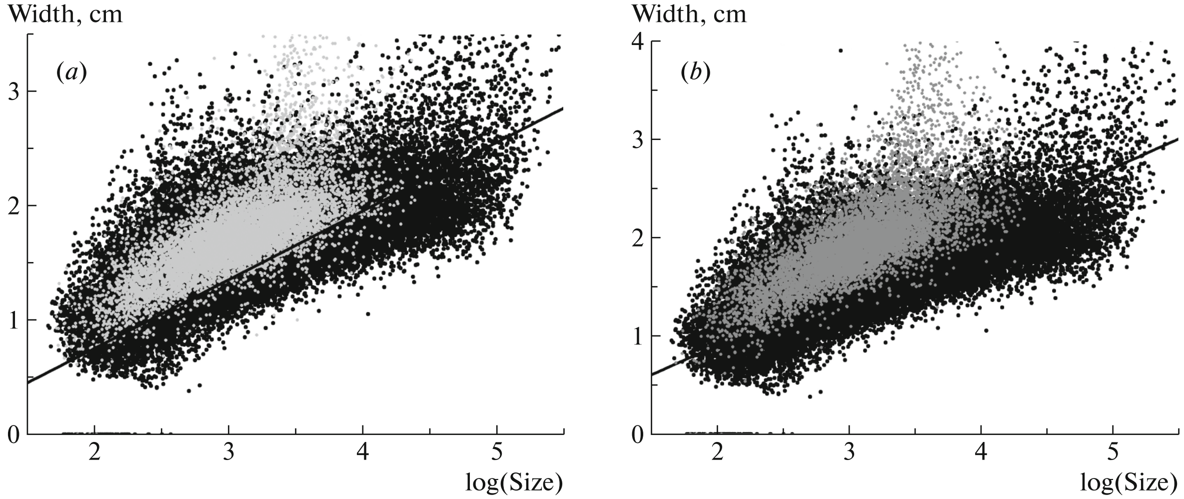

Fig. 2. Dependence of the Width parameter on the log(Size) for different nuclei: proton—oxygen (*a*), proton—iron (*b*). Lines are the cuts for separation of light component. Dark points—protons.

appeared with the start of IACT operation as part of the TAIGA-1 complex. In the joint operation of the TAIGA-HiSCORE wide-angle setup and IACT, the energy, direction and position of the EAS axis are reconstructed based on the TAIGA-HiSCORE data, and the parameters of the EAS image in Cherenkov light are used to determine the type of particle that generated the EAS [16]. To do this, using the Monte Carlo method, the parameters of the EAS images sensitive to the mass of the primary nucleus were determined and the optimal criteria for selecting the light nuclei were found, then the spectra of all detected by both TAIGA-HiSCORE array and IACT (hybrid) events and the spectra of light nuclei (protons + helium) were calculated. Then, for all hybrid events and events selected using the found criteria of the light component, the effective areas were calculated.

The simulation showed that the most effective parameters, as in gamma-ray astronomy, are the Width(Size) of the EAS image ellipse width depending on the total number of photoelectrons Size, as well as the third moment Kurt(Size), which characterizes the sharpness of the image peak. The logarithms Width(Size) (see Fig. 2) and Kurt(Size) linearly depend on Size for the energy of EAS generated by light nuclei in the energy range of 200—2000 TeV and 200—4000 TeV for EAS from iron nuclei. The conditions Width(Size) $<\alpha + \beta$ log(Size) and Kurt(Size) $<\gamma + \delta$ log(Size) are used as criteria for selecting light nuclei. The choice of parameters: α, β, γ and δ are optimized was based on the requirement for the maximum fraction of (P + He) and the minimum admixture of heavy and medium nuclei.

Figure 3 shows the results of the analysis of hybrid events in the range of angles 0—30 degrees, detected by the TAIGA-HiSCORE setup and IACT-1 in the period 2022—2023, when the optical stations of the TAIGA-HiSCORE array were directed vertically upward. From the obtained spectra, the following conclusions can be drawn:

1. At energies of 3 PeV, a classic knee in the CR spectrum is observed, and it is clear that the knee is determined by the light component, the share of which decreases by 3 times at this energy.

2. There is no sharp decrease in the share of the light component up to an energy of about 1000 TeV, as was obtained in the ARGO-YBJ experiment [17].

3. The second feature in the light component is clearly seen at an energy of about 20—30 PeV; it coincides with the decrease in the slope of the spectrum of all particles at an energy of 20 PeV, discovered in the experiments of Tunka [18], KASCADE-Grande [19] and others, but is observed for the first time in the light component.

On Fig. 4 the new all-particle energy spectrum reconstructed using Tunka-Grande data were got during 7 observation seasons from 2017 to 2024 (16200 hours of observation) is presented. In this spectrum, in addition to the decrease in the spectrum slope at an energy of 20 PeV, its increase at an energy of 100 PeV is also clearly seen, which is in good agreement with the results of other experiments.

3. GAMMA-RAY STUDIES

3.1. Methodology for Detecting Gamma-Quanta with the TAIGA-1 Astrophysical Complex

According to the TAIGA-1 complex data, the separation of EAS generated by gamma- quanta from the hadron background is possible in four modes:

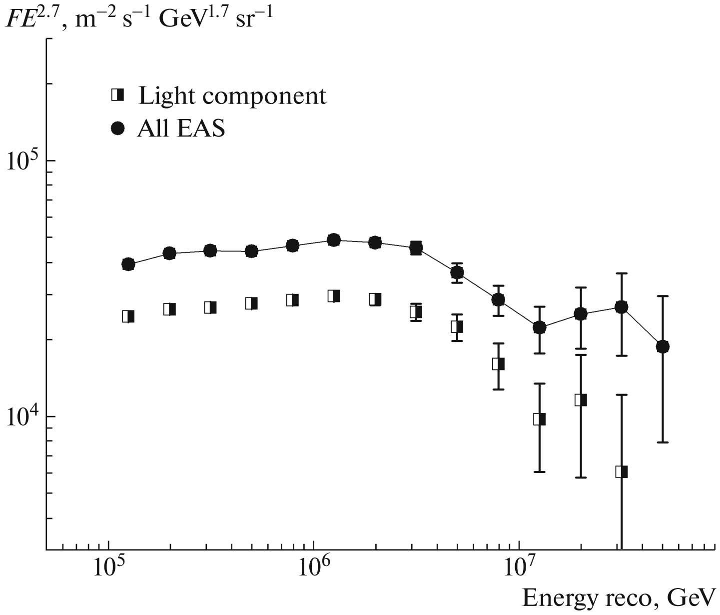

Fig. 3. Spectra of all hybrid events and the light component for angular interval of observation 0–30 degrees.

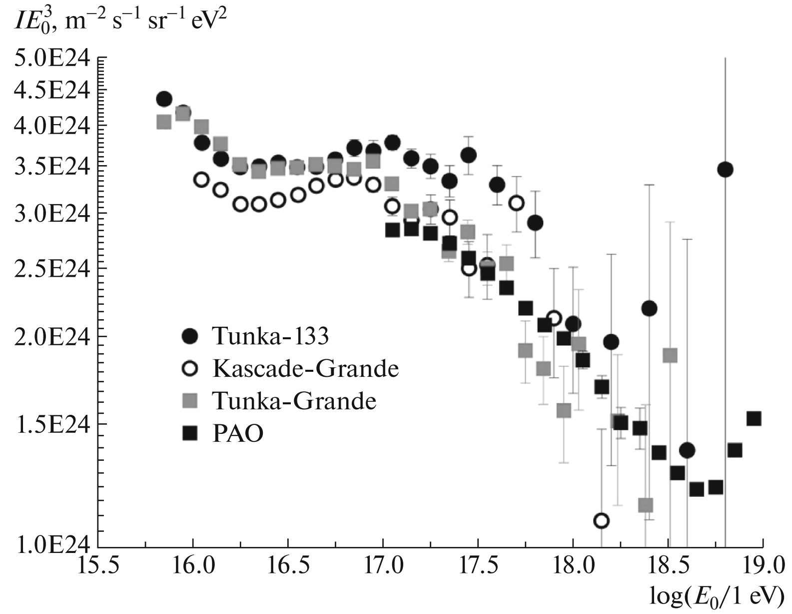

Fig. 4. Seven years differential primary cosmic-ray energy spectrum (gray squares—Tunka-Grande, black circles—Tunka-133, open circles—KASCADE-Grande and black squares—PAO).

1. Standalone mode of IACTs operation, when separation of gamma events is made according to the data of one independently operating IACT. This method works most effectively for the energy range from 2–3 TeV up to 50–60 TeV [20, 21]. The suppression of the hadron background in this mode is about 10^{-4}.

2. Stereoscopic mode for large distances between the IACTs when the selection of gamma-ray events is made according to the data of 2 or more IACT. This method works at the energy more than 8 TeV [22]. The suppression of the hadron background in this mode is about 5×10^{-5}.

3. Hybrid mode—joint operation of the wide-angle timing TAIGA-HiSCORE array and some IACTs. The energy threshold for this method is 40 TeV [23], the effective area of gamma-quanta detection exceeds 1 km^2, hadronic background rejection $\sim 10^{-4}$.

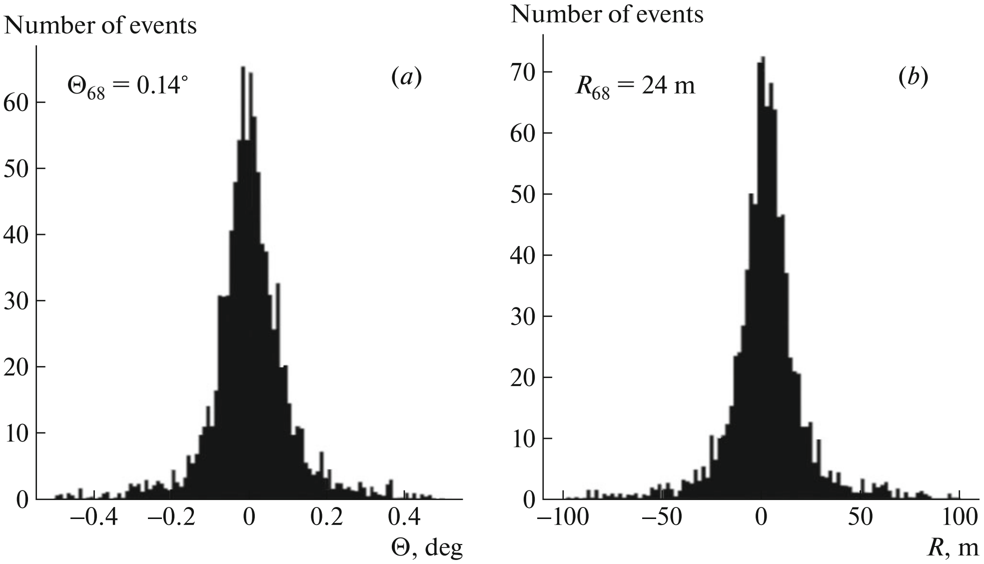

Fig. 5. Accuracy of reconstructing the direction (*a*) and position of the EAS axis (*b*) for EAS initiated by gamma-quanta and detected by a system of five IACT of TAIGA-IACT array.

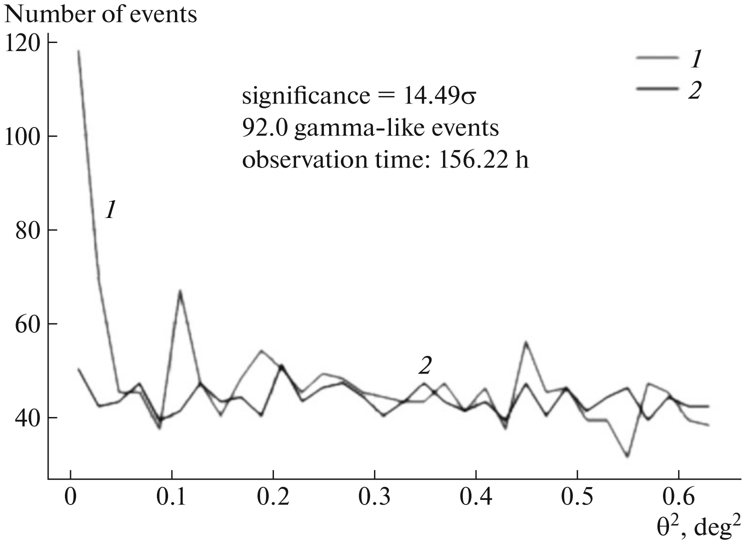

Fig. 6. Distribution of events, recorded in 156 hours depending on the θ^2. Line *1* (gray) indicates events with arrival directions near the position of the Crab Nebula, Line *2* (dark) indicates the average number of events for all estimated background regions.

4. According to the TAIGA-HiSCORE setup data for energy more than 300 TeV, but additional hadron suppression is required using, for example, data of muon detectors.

3.2. Some Results Obtained by the Stereo Method

After the deployment two additional telescopes TAIGA-IACT setup will include five IACT (Fig. 1). The distance between the central telescope and the peripheral ones will be 250 m. As shown in work [14], the accuracy of reconstructing the direction of arrival of gamma quantum initiated EAS in stereoscopic mode will be 0.14°, and the accuracy of reconstructing the position of the axis of the EAS axis—24 m (Fig. 5). Accuracy is understood as the angle θ_{68} and the radius of the circle R_{68}, which contain 68% of the reconstructed events. The position of the maximum of the EAS development $X_{\max}$ is reconstructed with an accuracy of 34 g cm^{-2}. Such accuracy of reconstruction of the axis parameters and $X_{\max}$ allows to reconstruct the EAS energy with an accuracy of $\sim$10%.

When detecting gamma-quanta from a point

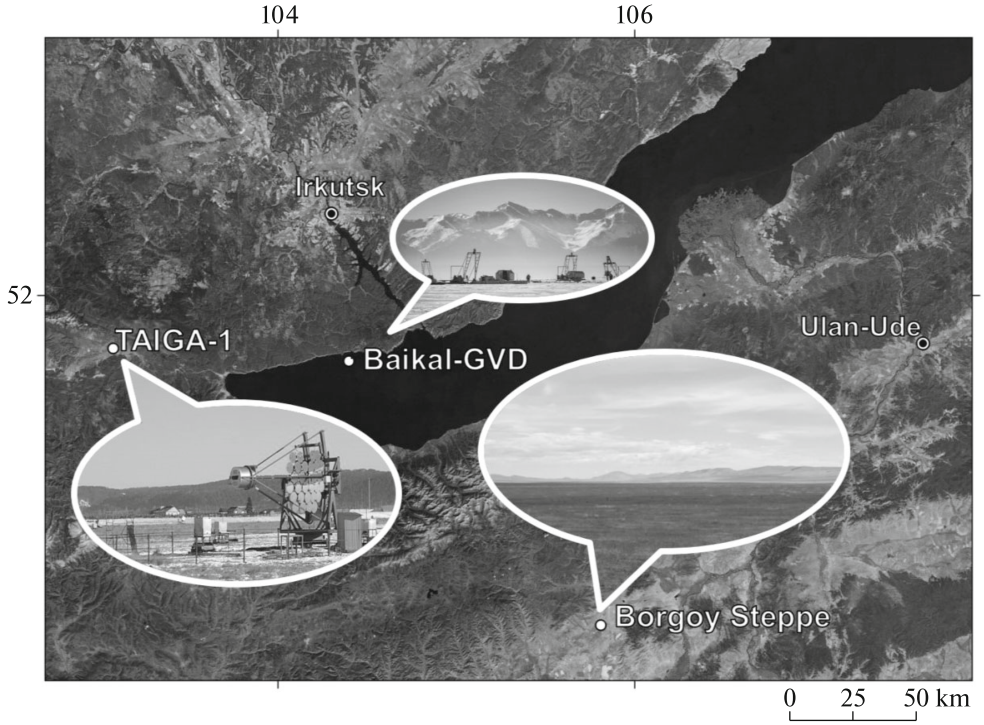

Fig. 7. The location of the Borgoy steppe—a preferred site for the creation of the installation TAIGA-100.

source, the differential sensitivity of 5 telescopes, with 4 bins per order of magnitude in energy for 100 hours of observations will be 2×10^{-12} erg cm^{-2} s^{-1} in the energy range of $30X_{\max}$ 100 TeV, provided that the signal is selected above the background at a level of 5σ. The effective area will be 0.7 km^2 at an energy of 100 TeV. Provided that gamma-quanta are selected a level of 3σ, the effective area will increase to 1 km^2 at an energy of 100 TeV [24].

During 156 hours of observation of the Crab Nebula by two telescopes in the period from 2020 to 2022, 92 gamma-ray quanta with energy more than 10 TeV were detected using the stereo method, at a significance level of 14.5σ (Fig. 6). The preliminary energy spectrum for these data is in good agreement with the spectrum obtained at the high-altitude LHAASO setup [25].

3.3. Search for TeV-Energy Gamma-Ray Quanta from Gamma-Ray Bursts

The discovery of gamma-ray quanta with energies of about 1 TeV in several gamma-ray bursts has deepened our understanding of the physics of gamma-ray bursts and opened up a new energy range for their observation. The flux and energy spectrum of gamma-ray quanta from the gamma-ray burst 190114C, registered by the MAGIC gamma-ray telescope, demonstrate the possibility of detecting gamma-ray quanta in the energy range from 3 to 10 TeV from nearby gamma-ray burst sources ($z < 0.1$) by telescopes of the TAIGA astrophysical complex. For this purpose, alert notifications from the GCN and AMON were implemented in the TAIGA observatory database. To receive and automatically analyze alerts, the TAIGA GCN Monitor program was developed, which analyzes the received information and, if the developed criteria are met, automatically adds a GRB observation task. During 2020, the system included GRB alerts from the FERMI, SWIFT and INTEGRAL satellites; since September 2023, the analysis of AMON alerts from the ICE CUBE neutrino telescope and the HAWC high-altitude facility has been added. The pointing time to the gamma-ray burst source depends on the current orientation of the telescopes, but does not exceed 2 minutes. Over two seasons, about 15 alerts were issued: 8 gamma-ray bursts (2 short and 6 long), one from a coincidence of alerts from the IceCube neutrino telescope and the HAWC facility, one neutrino alert from the IceCube observatory and several alerts from other astrophysical events. The observation data are being analyzed.

4. PROSPECTS FOR THE DEVELOPMENT OF THE TAIGA PROJECT

In the next two years, the following upgrade of the TAIGA-1 complex is planned: commissioning of 2 additional IACT of the TAIGA-IACT installation,

Astroclimat	Topographis features	Infrastructure
high share of cloudless night events—68–71%;	altitude of ~800 m a.s.l.; area > 100 km^2;	200 km from the regional center (Ulan-Ude);
low rainfall and low content of water vapor in the atmosphere (3.1–3.3 kg/m^2);	area surface slope angle $\leq 5°$; the soil is suitable for excavation at a depth of at least 3 m;	road, rail and air communication; power supply—3 power lines from 35 to 110 kV;
low level of aerosols pollution in the atmosphere (AOT $\approx$ 0.11);	water for water Cherenkov detectors is available; the absence of permafrost on the area.	availability of radio engineering and optical telecommunication systems.
low level of light pollution snow cover thickness—2–3 cm		

Fig. 8. The main characteristics of the Borgoy Steppe.

which will increase the effective area of the TAIGA-1 complex for measurements in stereo mode to 1 km^2 at gamma-quanta energies above 100 TeV; deployment of the outer ring of wide-angle optical stations of the TAIGA-HiSCORE installation, which will increase its effective area to 1.5–2 km^2; deployment of 5 clusters of scintillation detectors of the TAIGA-Muon installation, each of which will have 16 underground muon counters with an area of 1 m^2 and 4 similar ground counters, which will increase the accuracy of restoring the mass composition of cosmic rays and additionally suppress the hadron background in the hybrid mode of measurement; creation of an experimental underground water Cherenkov muon detector.

The world experimental data shows that serious advances in the field of PeV gamma-ray astronomy require installations with an area of at least several tens of square kilometers. The experience of creating and operating the TAIGA-1 complex has shown that the hybrid approach used in the project can be used as a basis for the next-generation TAIGA-100 installation with an area of 100 km^2. The expected statistics of gamma-quanta with an energy higher than 0.5 PeV when observing local sources with such an installation over the course of a year will be 10–50 times higher than that of LHAASO.

The basic detectors of the new installation will be wide-angle Cherenkov stations with a field of view of $\sim$1 ster and water Cherenkov muon detectors with an area of about 40 m^2. The energy threshold of the system of these detectors will be about 300 TeV. In addition, the installation will include IACTs with mirrors of 4–10 meters in diameter, fluorescence detectors, scintillation detectors and radio antennas. Such a detector complex will allow searching for gamma-quanta of sub-TeV energies from gamma-ray bursts, will have the best sensitivity for studying sources of galactic cosmic rays of PeV energies and searching for cosmological gamma-quanta (gamma-quanta from the GZK process) in the energy range of 10^{17}–10^{18} eV, will also allow a detailed study of the mass composition of cosmic rays up to an energy of 10^{19} eV and searching for phenomena beyond the Standard Model (dark matter in the form of both heavy weakly interacting particles and superlight particles—axions, searching for violation of Lorentz invariance, etc.).

It is impossible to create a facility with an area of tens of square kilometers at the location of the TAIGA-1 setup. According to the results of preliminary studies conducted in 2024, the optimal site for creating the TAIGA-100 facility, both from the point of view of the possibility of obtaining the great physical results and minimizing the costs of creating and operating the facility, is the Borgoy Steppe, Republic of Buryatia (Fig. 7). The geographic coordinates of the site are 105.81° E, 50.84° N, the altitude is 700–800 m above sea level, the distance to Ulan-Ude city is about 200 km and 140 km in a straight line from the Baikal-GVD neutrino telescope. The main characteristics of the site, obtained from data from the MODIS (Aqua, Terra) [26], VIIRS (NOAA) [27] satellite systems, the MAIAC algorithm (Aqua, Terra) [28] for 2019–2023 and the CALIPSO lidar [29] for 2016–2021, the QGIS geographic information system [30] and visual inspection, are given in Fig. 8. An analysis of the soil temperature in the Borgoy Steppe according to the ERA5 global reanalysis dataset showed that the minimum temperature at a depth of up to 3 m did not fall below $-1°$C for 5 years

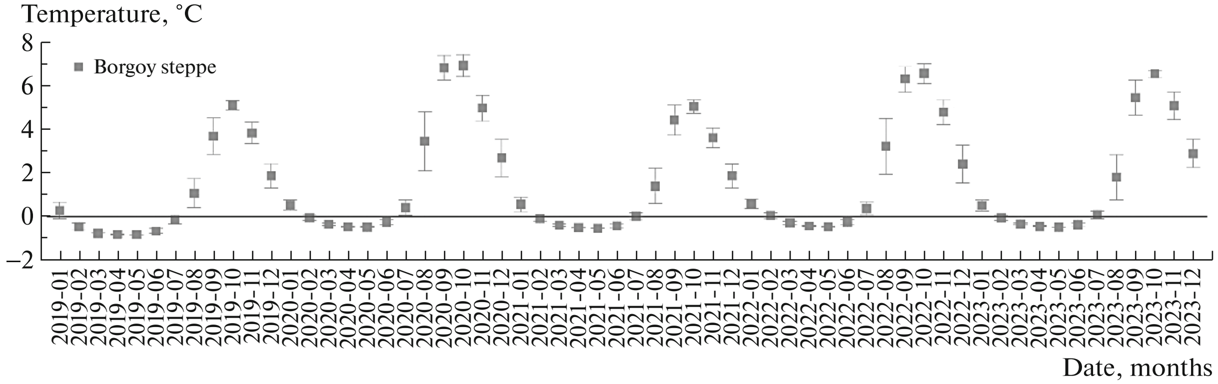

Fig. 9. The average monthly temperature at a depth of 1–3 m in the Borgoy Steppe.

(Fig. 9). This indicates the possibility of creating water muon detectors without additional heating.

5. CONCLUSIONS

The experience of the first years of operation of the TAIGA-1 confirmed the effectiveness of the hybrid approach to create an installation with an area of many tens of square kilometers for high energy gamma-astronomy and cosmic rays physics. In particular, first data about Crab Nebula gamma-ray energy spectra for $E > 100$ TeV by Cherenkov way both in stereo and hybrid modes were got.

The experience gained during the creation of the TAIGA-1 facility is the basis for designing the TAIGA-100 complex with a hybrid detector system on an area of about 100 km^2. It will allow to detect 30–50 gamma-ray quanta with an energy higher than 1 PeV from the Crab Nebula per year, which will help understand whether protons are accelerated to such energies in this source. TAIGA-100 will open up unique opportunities not only to solve many problems of ultra-high-energy gamma-ray astronomy and cosmic ray physics, to study transient phenomena of various natures and durations, including gamma-ray bursts but also will help to understand a lot of other problems of astroparticle physics.

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CONFLICT OF INTEREST

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

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