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INTERACTION OF PLASMA, PARTICLE BEAMS, AND RADIATION WITH MATTER

Status of the TAIGA Experiment: Gamma Astronomy

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Abstract—The status of the TAIGA experiment (Tunka Advanced Instrument for cosmic-ray physics and Gamma-ray Astronomy) located in the Tunka Valley is presented. The paper presents mainly the tasks, developed approaches for their solution, and first results on high-energy gamma-ray astronomy (10 TeV and higher) obtained from a two- to three-year exposure. The current tasks of gamma-ray astronomy and plans for development of the installation are discussed.

Keywords: gamma-ray astronomy, extensive air showers, galactic sources of high-energy cosmic rays

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1. INTRODUCTION

Development of methods for registration of extended air showers (EAS) from the Cherenkov radiation of charged particles of the shower in the atmosphere has given the start to a rapid development of TeV gamma-ray astronomy, beginning from the first telescope [1] and up to a series of prominent results obtained with the help of imaging air Cherenkov telescopes (IACT) in the 21st century in the H.E.S.S. [2], MAGIC [3], and VERITAS [4] experiments. Cherenkov telescopes register the angular distribution of the Cherenkov radiation of EAS at the matrix of photomultipliers located at the mirror focus. This method (in the mono and stereo modes) made it possible to increase significantly the number of revealed gamma-ray sources in an energy range of 1–100 TeV, namely, ~200 for the past 30 years, among which several categories of the gamma-ray sources VHE have been established: pulsars and nebulae of the pulsar wind, remnants of supernovas, double systems, etc. It has appeared that there are very few high-energy gamma-ray sources, which are theoretically (see, for example, [5]) expected to be the main accelerators of cosmic rays from the supernovas of type Ia or IIbc with a powerful shock wave at the front of which the Fermi accel-

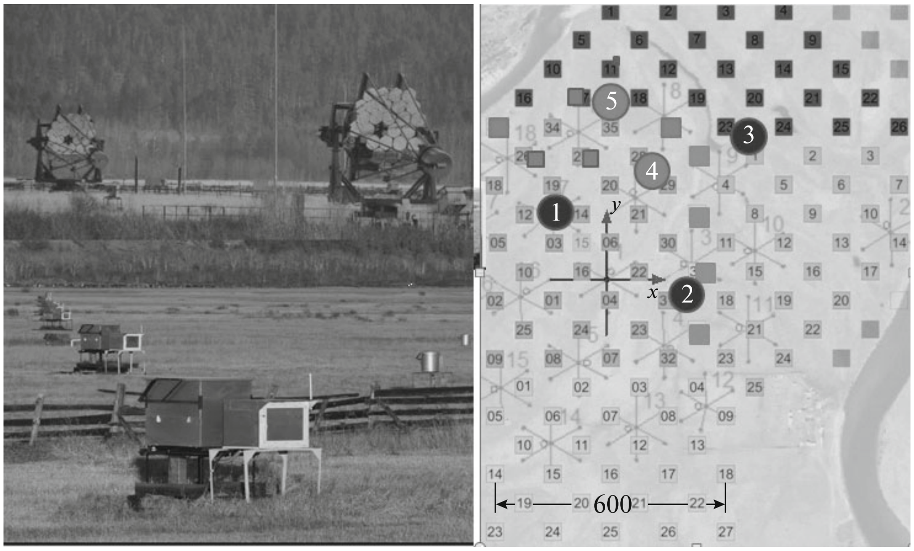

Fig. 1. Plan of the TAIGA complex: 120 stations of the TAIGA-HiSCORE complex and five telescopes, one of which is presented on the right, at the bottom; TAIGA-HiSCORE stations are presented on the right, at the top.

eration of the first kind occurs and particles can be accelerated up to PeV energies.

Beginning from the 1990s, in the Tunka Valley (51.49 N, 103.04 E), at a distance of 50 km from the southern part of Lake Baikal, the method for registration of high-energy EAS by using the Cherenkov radiation with the help of an array of wide-angle Cherenkov stations started to develop. At the Tunka-133 setup designed in 2009, the cosmic-ray spectrum of cosmic rays was measured, their composition in the energy range of 6×10^{15}–10^{18} eV was established, and a new peculiarity in the cosmic-ray (CR) spectrum at an energy of ~2×10^{16} eV was revealed and confirmed in a series of experiments [6].

The success of the Tunka-133 experiment stimulated the creation of the astrophysical complex TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) in the Tunka Valley. This complex consists of two Cherenkov setups—TAIGA-HiSCORE and TAIGA-IACT. The TAIGA-HiSCORE setup is analogous to Tunka-133, however, with a lower energy threshold [7, 8]. The setup was tuned to register not only CRs, but EAS from high-energy gamma rays (tens of TeV), since in this energy range, the statistics of gamma-quanta collected by the IACT telescopes was insufficient. The registration method was adapted for new tasks: the threshold of each station and the distance between them were reduced. As a result, the energy threshold of the setup proved to be 100 TeV for hadrons and about 50 TeV for gamma-ray-induced EASs.

At the present time, the area of the TAIGA-HiSCORE setup has reached 1 km^2: 120 stations with a lower threshold of Cherenkov light registration of ~2000 photons per station, within a solid angle of 0.6 sr, located at a distance of about 100 m from each other. The nanosecond accuracy of registration of the pulse at each station made it possible to reproduce the angle of EAS arrival with quite a good accuracy: 0.1°–0.2° at more than ten triggered stations; the energy of gamma quantum in this case is higher than 100 TeV.

The TAIGA-IACT setup includes three IACTs arranged at a distance of about 300–500 m from each other. The third telescope started to operate in 2022. The detailed description of the setup can be found in [9, 10]. The IACT TAIGA-IACT has a sectional mirror of Davies–Cotton design with an area of ~10 m^2 and a focus distance of 4.75 m. At the focus of the mirrors, a registering camera containing 600 PEMs with a photocathode diameter of 19 mm was installed. The diameter of the camera's angle of aspect was 9.6°. The angle of aspect of each pixel was 0.36°. The description of the systems of information collection, trigger, and calibration can be found in [10]. The layout of the setup is shown in Fig. 1.

2. TASKS OF TIAGA EXPERIMENT

The main tasks of the TAIGA experiment are related to investigation of charged cosmic rays and gamma quanta in the energy range from tens of TeV to 1000 PeV. The first task—investigation of CRs—includes both the reconstruction of the energy spectrum of all particles and the average mass composition of CRs and reconstruction of the spectra of groups of nuclei. This investigation may carry the information on the change of the main CR sources at different energy ranges. The second task—investigation of high-energy gamma quanta—completes the first task. This is because gamma quanta make it possible to determine the direction toward the source, as distinct from the charged component, and understand in what sources CRs undergo acceleration. Both tasks are directly related to the problem of the origin of cosmic rays within an energy range higher than 1 PeV, which is still unsolved. The sources that accelerate particles up to PeV energies—PeVatrons—must be observed in the gamma rays with energy higher than 100 TeV (UHE—ultra-high-energy gamma quanta). Still three years ago, single gamma quanta with energies higher than 100 TeV were registered with the help of IACT and the question concerning the possibility of their existence in principle arose. The situation radically changed with publication of the new high-altitude (mountain) LHAASO setup, when already after observations lasting for a year, there was a report about 12 PeVatrons with a statistical significance of more than 7σ and a maximum energy of up to 1.4 PeV [11]. UHE gamma quanta were registered also at the Tibet ASgamma [12] and HAWC setups [13]. Recently, a new catalog of 43 PeVatrons, in which UHE gamma quanta were observed, was published [14]. This breakthrough occurred when passing from small-angle (up to 5°) telescopes and a limited time of observation of Cherenkov radiation during moonless nights with nice weather (15% of the total time) to wide-angle setups that register EASs twenty-four hours a day. In these setups, an absolutely different background-suppression system is used, which is based on a small amount of muons in gamma-ray showers (as in LHAASO) or on the width and inhomogeneity of EASs from hadrons in comparison with much narrower EASs from gamma quanta. The search for UHE gamma quanta using Cherenkov radiation is still relevant for coordination, verification, and correction of the results obtained at the high-altitude setups.

3. THE MAIN METHODS USED IN THE TAIGA EXPERIMENT FOR SEPARATION OF GAMMA QUANTA

To study the entire energy range available for observation, three modes of EAS registration are used in the TAIGA experiment. The mono mode is used for registering the gamma quanta with energies higher than 3–5 TeV (depending on the source declination) by only IACT [15]. To detect gamma quanta with energies higher than 10 TeV, it is possible to use a stereo approach—an EAS is registered by two and more IACTs [16]. A hybrid approach consists in using combined data obtained with the help of IACTs and wide-angle HiSCORE stations [17]. This method is unique for modern gamma experiments and is aimed at registration of gamma quanta with energies higher than 40–60 TeV (depending on the source declination). In this method, the reconstruction of the primary-particle energy, direction, and position of the EAS axis are performed by analyzing the data obtained at the TAIGA-HiSCORE setup. To determine the type of primary particle generated by the EAS, the data obtained at the IACT setup are used; they allow separating the gamma-induced events according to the shape of their image in the telescope [15].

4. FIRST RESULTS OBTAINED IN THE MONO, STEREO, AND HYBRID MODES WHEN OBSERVING THE CRAB NEBULA

For twenty years, each new gamma observatory started its operation from registering gamma radiation coming from the Crab Nebula, which is considered as a “standard source” [1]. Investigations in the TAIGA experiment also started from reconstructing the spectra from this source. Observations of the source in the TAIGA experiment are being carried out in the *wobble* mode proposed in [18] and realized in some experiments, including the TAIGA experiment [19]. Observations are being carried out from August to May with time sharing between several main sources. The initial procedure of reconstructing the parameters and images of EASs in our experiment is described in detail in [17]; the Monte Carlo calculations that justify the approached are described in [20]. All the Hillas parameters, including *dist* (the angle between the image center of gravity and the source position in the camera) and *alpha* (the angle between the main axis of the Hillas ellipse and the vector directed from the image center of gravity to the source position), are reconstructed for both the true source position in the camera (ON events) and several points in the camera displaced by a certain angle with respect to the source position (OFF events).

At present, in the TAIGA experiment, we use the *reflected-region-background* method for choosing the background points, which was specially developed for the *wobbling* procedure of source observation [21]. We chose from 5 to 16 such points $N_{\rm bcg}$ for the selection of the OFF events, which leads to an increase in the significance of the excess of events obtained, which can be found according to the formula taken from [22]:

$$\text{Excess} = (N_{\rm ON} - \langle N_{\rm OFF}\rangle)/\text{sqrt}(N_{\rm ON} + \langle N_{\rm OFF}\rangle/N_{\rm bcg}). \quad (1)$$

Along with the Hillas parameters, for each event in the mono mode, the energy with an accuracy of 25–30% and the angle between the direction toward the source and that of the EAS arrival were determined. This angle is reconstructed with an accuracy of ~0.2° and is determined by the method proposed in [23].

The first results of detection of the gamma quanta coming from the Crab Nebula by means of a AChT01 telescope during two seasons—2019–2020 (101 h) and 2020–2021 (49 h)—were obtained as follows. At the first stage, suppression of the background and separation of gamma-like showers were carried out according to the criteria determining the size and shape of the image, tuned as a result of the Monte Carlo modeling; at the final stage, to separate the gamma-like events,

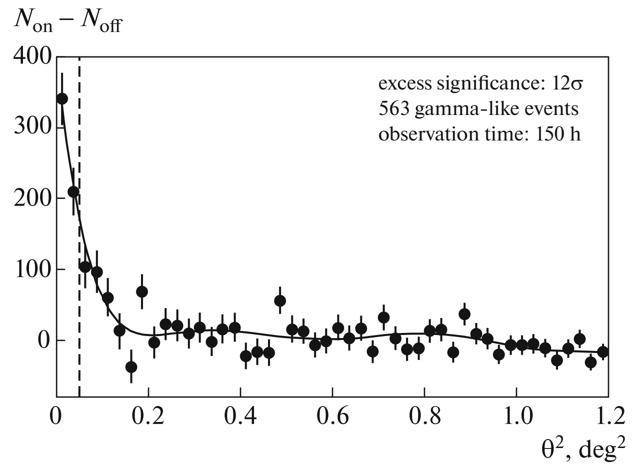

Fig. 2. Distribution $N_{ON}(\theta^2) - \langle N_{OFF}(\theta^2)\rangle$ after background suppression according to criterion (1) in the mono mode of observations. In the region where $\theta^2 < 0.05$, the excess is 563 gamma-like events obtained with the significance of 12σ.

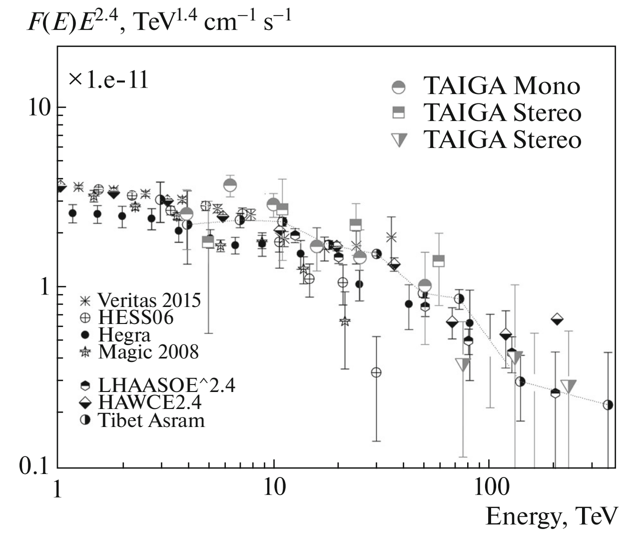

Fig. 3. Reconstructed spectrum of gamma radiation from the Crab Nebula obtained by different methods: in the mono mode of operation of one telescope; in the stereo mode with two telescopes, and in the hybrid mode HiSCORE + IACT. The data of other experiments: IACTs [24–27], LHAASO, Tibet AsGamma, HAWC [11–13].

the distribution of the difference $N_{ON} - \langle N_{OFF}\rangle$ over the parameter θ^2 was constructed. Figure 3 shows the distribution $N_{ON}(\theta^2) - \langle N_{OFF}(\theta^2)\rangle$.

To pass to the flux of gamma quanta, we calculated the effective area of the setup S_{eff}, which reflects the area from which the gamma-like events are detected after passing the selection criterion. For the mono mode, $S_{eff} \sim 0.08$ km^2 at energies higher than 10 TeV; at an energy of 5 TeV, it is smaller and its value is 0.03 km^2. Figure 3 shows the energy spectrum of gamma quanta obtained for 150 h of observation. In the last bin (30–80 TeV) of the spectrum, 16 events are registered. A satisfactory agreement with the spectra measured in some other experiments is observed.

The stereo mode makes it possible to improve significantly the accuracy of the reconstructed EAS parameters [16]. To determine the direction of EAS arrival, the positions of the principal axes of images in the camera of each telescope are calculated. The point of intersection of these axes in the common field of telescopes corresponds to the position of the gamma-quanta source. The position of the EAS axis in the plane perpendicular to the direction of the shower arrival is determined as the point of intersection of the straight lines passing through the center of gravity of the image and the source position in the camera [16]. In addition, it is possible to reconstruct the depth of the maximum of the shower development and the particle energy. The following accuracies of these parameters are obtained: θ is determined as the difference between the true source position and its reconstructed position in the camera—0.15°; the position of the EAS axis is reconstructed with an accuracy of 5 m; the position of the maximum shower development is determined with an accuracy of 36 g/cm^2; the resolution of the reconstructed gamma-quanta energy spectrum is ~10%; the effective area depends on the selection criteria and is about 0.6 km^2; the hadron background suppression is $\sim 10^{-5}$ at such an effective area.

The observations of the Crab Nebula in the stereo mode were carried out by the first two telescopes of the TAIGA-IACT setup from October to February of the 2020–2021 season; there were only 36 h of observation. According to the calculated criteria, we selected $N_{ON} - \alpha N_{OFF} = 37$ gamma-like events at seven points of background; therefore, the significance of the excess was 5.3σ. For the selected gamma-like events, the energy reconstruction was performed by using the values of three parameters of these events: *size*, R_0, and the depth of the maximum of EAS development (X_{max}). Figure 3 shows four points of the intensity of radiation coming from the Crab Nebula within the energy range from 5 to 100 TeV.

The hybrid method for gamma-quanta registration was worked out and verified by using the data of the first two clusters of the HiSCORE setup (58 stations) and the first IACTs of the TAIGA experiment on observation of the Crab Nebula for three seasons from 2019 to 2022. The total exposition was 250 h, during which the combined IACT1 + HiSCORE events coinciding in time in a window of 3000 ns were selected. To separate the IACT gamma-like events, we used the same parameters that were used in the mono events obtained with one telescope (*size*, *dist*, *width*, *length*, ...); however, significant parameters of the shower obtained from the HiSCORE data were added, namely, the reconstructed position of the EAS axis at the Earth, the distance from the EAS axis to the telescope R_{tel}, the reconstructed EAS energy *Energy*, and the angle between the direction toward the source (background) and the reconstructed direction of EAS arrival *dgam*. This parameter is final when revealing the gamma-like events [17]; therefore, the accuracy of its determination is important. It strongly depends on the number of triggered stations: it is about 0.12° in the case of ten triggered stations and worsens to 0.4° in the case of four triggered stations. At energies higher than 100 TeV, there are usually 5–10 stations from which the parameters of EAS are found [28]. To increase the statistical significance of the observed signal, when choosing the background, we used *reflected-region-background* [21] from nine points as at the previous points. In this case, each background point in the camera of a telescope was recalculated to the celestial coordinates, which made it possible to use the same background position for two setups from which the parameter *dgam* is counted.

To select the gamma-like events, using Monte Carlo modeling [17], we obtained the optimal selection criteria for the parameters at which the hadron background suppression is maximal; however a significant part of gamma-quanta is preserved. It appears that the most efficient suppression of the hadron background occurs when using the combined parameter *dist* (R_{tel}) and *width* (*size*). The first is determined from IACT, and the second is determined from the HiSCORE data:

$$0.2 < \text{width} < 1.15 + 0.1\log(\text{size});$$

$$2.3 + 0.055\text{Rtel} < \text{dist} < 1 + 0.04\text{Rtel}.$$

Using the limitations obtained, we constructed the distribution over the parameter *dgam* (Fig. 4). The maximum of events is in the region of up to 0.25°, where the average number of background events is 199; the number of events from the source is 224.

To pass to the particle spectrum, using the Monte Carlo calculations, we estimated that the effective area is 0.3 km^2; it is necessary to pass to the absolute intensities of particles. In Fig. 3, there are three points obtained by the hybrid method. At energies higher than 100 TeV, there are ten events. Large errors at the last two points are related to quite a large background remaining after suppression.

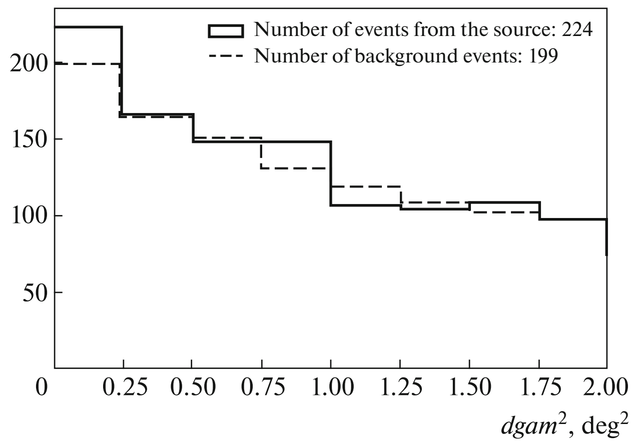

Fig. 4. Distribution over the parameter *dgam*^{2} after application of optimal limitations on the parameters of joint events.

5. FIRST RESULTS OF INVESTIGATION OF EXTENDED SOURCES

5.1. Boomerang

Among 12 sources registered in the LHAASO experiment as potential PeVatrons [11], 11 sources proved to be extended (about 1°), and it is not always clear to what this extent is related. In the TAIGA experiment, the source Boomerang has been observed already for three seasons. From the astrophysical point of view, this is a very interesting source with a complex structure [29]. It is assumed that the pulsar nebula with a pulsar J2229+6114 and the supernova remnant (SNR) G106.3+2.7 are the result of the same outburst of a supernova with a pulsar, since the entire structure is located at the edge of the bubble I with extended regions of molecular gas inside and a size of about 800 ps, while the supernova outburst occurred in the region of active star formation. From the experimental point of view, its spectrum measured in the Milagro [30] and HAWC experiments is of interest; the intensity measured in the energy range of about 100 TeV is comparable with that from the Crab Nebula. However, in the energy range of about 5–10 TeV, its value is an order of magnitude lower. According to the estimates made, about ten high-energy particles and about 50 particles with energies higher than 20 TeV should have been observed.

The procedure described in the previous section was applied to searching for gamma quanta from this source. In the mono mode, from the IACT1 and IACT2 data, the distributions over α and θ similar to those presented in Fig. 3 were obtained. However, by the present time, no radiation excess with significance better than 2.5σ was registered. In the stereo mode, no radiation excess was registered. We consider that the main reason for such a result is related to the effect of the extent of this source by 1°. By the example of the source Boomerang, we started to develop the methods for registration of extended sources.

5.2. Dragon Fly

This is a pulsar nebula in the Sygnus constellation in which the star-formation process continues. This nebula was generated and is being fed by the energy of rotation of the PSR J2021+3651 pulsar. It is characterized by high-energy TeV radiation discovered earlier by

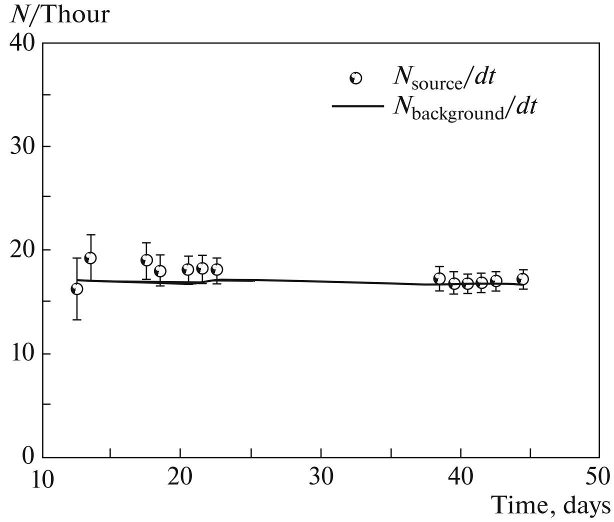

Fig. 5. Search for the excess of particles with energies higher than 200 TeV in the direction toward the Cocoon Nebula of the Sygnus constellation during the hypothetical outburst [31]. Along the *y* axis, the cumulative number of particles from the beginning of observations up to the date fixed on the *x* axis (days are counted from October 1, 2020) is shown. Circles refer to the experimental data in the Cocoon Nebula direction; lines, in the background direction.

VERITAS and HAWC: in the energy range of about 10 TeV, the radiation intensity is comparable with that of the Crab Nebula; however, at energies higher than 37 TeV, it decreases exponentially, even though events in the energy range of about 100 TeV are also observed. The data of this source were processed in the mono (80 h) and stereo (40 h) modes during autumn in 2020 and 2021. The threshold values for selection of gamma-like showers according to the values of their normalized width and angle of arrival were chosen for two different zenith angles. On the whole, summarizing the results for two samples with different angles, we registered 144 ON events and 100 OFF events; the excess was 44 events; with consideration of five background points, it corresponds to the significance of 3.37σ.

5.3. Cocoon Nebula

The excess of high-energy gamma-quanta from the Cocoon Nebula in the Sygnus constellation was not confirmed during the hypothetical outburst in October—November 2020 registered in the Carpet 2 experiment at the Baksan Neutrino Observatory [31], where an excess of events with the intensity comparable with the background hadron flux at a very high threshold energy of ~300 TeV was revealed. According to the data of the HiSCORE stations, the estimate of the excess of particles in the direction toward this source was performed. For this purpose, the data registered for about 20 h at the maximum of the outburst over the period from October to December 2020 were used. Figure 5 shows the intensity of particles with energies higher than 200 TeV in the cone with an angle $\psi < 0.5°$ in the direction toward the Cocoon Nebula source and toward the nearest background within an angle of 1°—2°. We have also verified this effect with a larger observation-cone angle and with different threshold energies. The upper limit for the flux is estimated as $F(E)E^2 < 4 \times 10^{-11}$ cm^{-2} s^{-1} TeV.

6. CONCLUSIONS

In 2022, the deployment of the first stage of the TAIGA complex consisting of 120 stations HiSCORE and 3 IACTs was finished. On the basis of the wide Monte Carlo modeling, we developed and tested the methods for registration of gamma quanta, their separation from the hadron background, the methods for calculation of the effective areas and sensitivity, and the methods for reconstruction of gamma-quanta spectra in three modes: (a) by single telescopes; (b) by ACT01 + ACT02 in the stereo mode; (c) by a hybrid ACT01 + HiSCORE method. After three testing sessions performed in 2019—2022, we obtained the first results on observation of the Crab Nebula by using three different methods at different energy ranges and obtained consistent spectra that agree with other experiments. A signal from the blazar Mrk-421 at a level of 4σ was registered. The significance of the signal from Mrk-501, Boomerang, and Dragonfly were registered at a level of 2—3σ. The analysis of the data continues.

The works on creation of wide-angle cameras based on SiPM for the combined operation with HiSCORE to enlarge the angle of aspect when searching for gamma-quanta have started.

The TAIGA observatory will be the northernmost observatory and this position provides some advantages for observation of the sources with large declinations: the gamma-radiation source located in the remnants of Tycho's Supernova, STA-1, will be in the field of vision of the detectors of the TAIGA observatory for 500 h per year.

In the near future, it is planned to continue the observation and investigation of the energy spectrum of gamma quanta coming from galactic sources PWN: Crab Nebula, Dragonfly Nebula, SNR: J2227+610 (G106.3+2.7), J2031+415 (Cygnus Cocoon), Tycho's Supernova, STA-1, and the selection and observation of northern sources from the new catalog of the LHAASO setup.

It is proposed to carry out a long-term monitoring and investigation of the end of the energy spectrum of bright blazars (Mrk-421, Mrk-501, etc.) as a method for searching for anomalies in the gamma-quanta distribution in the Universe and searching for axion-like particles. The works have started and the search for the gamma quanta associated with high-energy neutrinos and gamma-quanta bursts will be performed.

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CONFLICT OF INTEREST

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

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