ELEMENTARY PARTICLES AND FIELDS _ Theory

TAIGA—An Innovative Hybrid Array for High Energy Gamma Astronomy, Cosmic Ray Physics and Astroparticle Physics

N. Budnev^{1)*}, I. Astapov²⁾, P. Bezyazeekov¹⁾, E. Bonvech³⁾, A. Borodin⁴⁾,
M. Brückner^{5),6)}, A. Bulan³⁾, D. Chernov³⁾, A. Chiavassa⁷⁾, A. Dyachok¹⁾, A. Gafarov¹⁾,
A. Garmash^{8),9)}, V. Grebenyuk^{4),10)}, O. Gress¹⁾, T. Gress¹⁾, A. Grinyuk⁴⁾, O. Grishin¹⁾,
D. Horns¹¹⁾, Al. Ivanova¹⁾, A. Ivanova^{9),1)}, N. Kalmykov³⁾, V. Kindin²⁾, S. Kiryuhin¹⁾,
R. Kokoulin²⁾, K. Kompaniets²⁾, E. Korosteleva³⁾, I. Kotovschikov¹⁾, V. Kozhin³⁾,
E. Kravchenko^{8),9)}, A. Kryukov³⁾, L. Kuzmichev³⁾, A. Lagutin¹²⁾, Yu. Lemeshev¹⁾,
B. Lubsandorzhiev¹³⁾, N. Lubsandorzhiev³⁾, D. Lukyantsev¹⁾, R. Mirgazov¹⁾,
R. Mirzoyan^{14),1)}, R. Monkhoev¹⁾, E. Osipova³⁾, A. Pakhorukov¹⁾, A. Pan⁴⁾, M. Panasyuk³⁾,
L. Pankov¹⁾, D. Podgrudkov³⁾, V. Poleschuk¹⁾, E. Popova³⁾, A. Porelli⁶⁾, E. Postnikov³⁾,
V. Prosin³⁾, V. Ptuskin¹⁵⁾, A. Petrukhin²⁾, A. Pushnin¹⁾, R. Raikin¹¹⁾, E. Rjabov¹⁾,
G. Rubtsov¹³⁾, Y. Sagan^{4),10)}, V. Samoliga¹⁾, A. Sidorenkov¹³⁾, A. Silaev³⁾, A. Silaev, Jr.³⁾,
A. Skurikhin³⁾, M. Slunecka⁴⁾, A. Sokolov^{8),9)}, L. Sveshnikova³⁾, Y. Suvorkin¹⁾,
W. Tabolenko¹⁾, R. Togoo¹⁶⁾, N. Ushakov¹³⁾, P. Volchugov³⁾, D. Voronin¹³⁾,
R. Wischnewski⁶⁾, I. Yashin²⁾, A. Zagorodnikov¹⁾, A. Zhaglova¹⁾, and D. Zhurov^{1),17)}

Received December 23, 2020; revised December 23, 2020; accepted December 23, 2020

Abstract—The physics motivations and advantages of the hybrid detector complex TAIGA are presented. TAIGA aims to address gamma-ray astronomy at energies from a few TeV to several PeV units, as well as cosmic-ray physics from 100 TeV to several EeV units and astroparticle physics problems. In 2021 deployment and commissioning of the one square kilometer TAIGA setup in the Tunka valley ~50 km West from Lake Baikal will be finished. The first experimental results with the TAIGA are presented.

DOI: 10.1134/S1063778821030078

- ³⁾Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia.
- ⁴⁾Joint Institute for Nuclear Research, Dubna, Russia.
- ⁵⁾The Paul Scherrer Institute, PSI, Villigen, Switzerland.
- ⁶⁾DESY, Zeuthen, Germany.
- ⁷⁾Dipartimento di Fisica Generale Universiteta di Torino and INFN, Torino, Italy.
- ⁸⁾Budker Institute of Nuclear Physics of SB RAS, Novosibirsk, Russia.
- ⁹⁾Novosibirsk State University, Novosibirsk, Russia.
- ¹⁰⁾Dubna State University, Dubna, Russia.
- ¹¹⁾Institut fur Experimentalphysik, University of Hamburg, Hamburg, Germany.
- ¹²⁾Altai State University, Barnaul, Russia.

1. INTRODUCTION

The most effective way to investigate the nature of galactic and metagalactic high-energy cosmic-ray sources is studying their gamma-ray fluxes. To date, the most significant results in high-energy gammaray astronomy have been obtained using HEGRA [1], H.E.S.S. [2], VERITAS [3], and MAGIC [4] experiments, which include 2 to 5 Imaging Atmospheric Cherenkov Telescopes (IACT). Using these facilities more than 200 sources of gamma rays with energy above 1 TeV were discovered, however, few photons with energy above 100 TeV were detected due to insufficient effective area of the installations

¹⁾Irkutsk State University, Irkutsk, Russia.

²⁾National Research Nuclear University MEPhI, Moscow, Russia.

¹³⁾Institute for Nuclear Research of RAS, Moscow, Russia.

¹⁴⁾Max-Planck-Institute for Physics, Munich, Germany.

¹⁵⁾IZMIRAN, Troitsk, Moscow, Russia.

¹⁶⁾Institute of Physics and Technology Mongolian Academy of Sciences, Ulaanbaatar, 210651 Mongolia.

¹⁷⁾Irkutsk National Research Technical University, Irkutsk, Russia.

^{*}E-mail: **nbudnev@api.isu.ru**

for such energies. The CTA project [5] plan to cover 4.5 km² using 70 Small Size Telescope (SST) to study gamma-ray sources in energies above 10 TeV. In addition to Cherenkov telescopes, important information about gamma-ray sources has recently been obtained from high-altitude installations that detect charged particles of extensive air showers (EAS): Tibet-III [6] and HAWC [7]. In 2021 in Tibet, it is planned to commission a complex installation called LHASSO [8].

In the TAIGA (Tunka Advanced Instrument for Gamma Astronomy and cosmic-ray physics) project a hybrid approach for studding of high-energy gamma rays and cosmic rays is in development [9]. Its future is the integration of IACTs of TAIGA-IACT array and timing Cherenkov wide-angle array TAIGA-HiSCORE as well as Tunka-Grande and TAIGA-Muon scintillation arrays for detection of EAS electrons and muons. This approach makes it possible to reduce the cost of installations with an area of 10 and more square kilometers for studying fluxes of ultrahigh-energy gamma rays. The main goals of the TAIGA experiment: search for PeVatrons—galactic objects in which protons are accelerated to energies of 1–100 PeV; search for energy limits of particle acceleration in supernova remnants and pulsar nebulae; search for an excess of diffuse gamma radiation with energies above 100 TeV; search for correlations with neutrino events from the IceCube neutrino observatory; investigation of the shape of the gamma-ray spectrum with energies above 10 TeV from blazars, which will also allow obtaining upper bounds on the density of Extragalactic Background light, EBL [10]; search for photon transitions in axion-like particles, ALPs [11], which may be associated with a higher transparency of the Universe than even for the minimum EBL [12]; search for violations of Lorentz invariance [13] and dark matter; search for astrophysical optical transients in the nanosecond range, search for electromagnetic tracking of mergers of black holes and neutron stars and interaction of star-like objects from antimatter with the galactic environment; search for superheavy dark matter in the framework of the Starobinsky cosmological inflation model. Using the data obtained with the TAIGA astrophysical complex, the energy spectrum and mass composition of cosmic rays in the energy range 0.1 PeV-1 EeVwill be reconstructed in detail. In this energy range, one expects a change in the main sources of acceleration in the Galaxy and a transition from Galactic to Metagalactic sources or to Galactic sources of a new type, capable of accelerating CR to energies of 0.1-1 EeV. A new method for measuring the parameters of stars, based on Intensity Interferometry on a large base with an angular resolution of the order of several tenths of a microsecond, will be introduced into the TAIGA complex.

In 2021 deployment and commissioning of the TAIGA pilot complex with hybrid detectors system on one square kilometer area in the Tunka valley \sim 50 km West from Lake Baikal will be finished.

2. THE TAIGA PILOT COMPLEX

The TAIGA pilot complex includes 120 wideangle (field of view 0.6 sr) optical stations of the timing Cherenkov array TAIGA-HiSCORE, distributed with spacing of 106 m over an area of about 1 km² and three Imaging Atmospheric Cherenkov Telescopes of the TAIGA-IACT array (Fig. 1), for a detailed description of the installation, see [14].

Simulation results show that combining of information about EAS axis direction, core position and energy measured with timing TAIGA-HiSCORE array with shower image parameters reconstructed using TAIGA-IACT data dramatically suppresses the cosmic-ray background even for large distances (300–500 m) between core position and IACT [15]. To test this idea experimentally three telescopes of TAIGA-IACT are installed at the vertices of a triangle with sides of 300, 400, and 500 m approximately between TAIGA-HiSCORE optical stations (Fig. 2).

3. THE TAIGA PILOT COMPLEX PRELIMINARY RESULTS

The procedure of the EAS parameters reconstruction from the TAIGA-HiSCORE data is based on methods and algorithms developed for Tunka-133 data processing [16]. Zenith angle θ and azimuth angle ϕ of the shower direction are reconstructed by fitting the measured delays with the curve shower front: $\Delta T = T_i - T_f = R (R + 500)/(cF)$, where T_f is the estimated delay for a plane front, R the perpendicular distance from the shower axis in meters, c the speed of light, and F the third variable parameter (together with θ and ϕ). The accuracy of the zenith angle θ reconstruction is $0.1^{\circ}-0.4^{\circ}$ degrees depending on the number of hit optical stations. The reconstruction of the EAS core position is performed by fitting the measured amplitudes A_i with an amplitude-distance function. The accuracy of EAS core position determination is about 5-10 m. The primary particle energy is reconstructed using the Cherenkov light flux density at a distance of 200 m from the EAS axis with an accuracy of about 15%. The energy threshold of the TAIGA-HiSCORE array for gamma-ray detection is 40-50 TeV, for cosmicrays-80-100 TeV.

Figure 3 shows the preliminary results of reconstructing of the energy spectrum of the cosmic-rays



Fig. 1. A wide-angle optical station of the timing Cherenkov array TAIGA-HiSCORE (right), an Imaging Atmospheric Cherenkov Telescopes of the TAIGA-IACT array (in the background).



Fig. 2. The scheme of the TAIGA pilot complex detectors location. Squares—optical station of the timing Cherenkov array TAIGA-HiSCORE, circles—IACT.

using the TAIGA-HiSCORE and the Tunka-133 [17] data. Our energy spectrum obtained by the Cherenkov method is in good agreement in the lower energy range with the results of the ATIC-2 and

NUCLEON balloon experiments and the results obtained in the HAWC experiment, beyond the energy of 100 PeV, our spectrum is consistent with those from

PHYSICS OF ATOMIC NUCLEI Vol. 84 No. 3 2021



Fig. 3. Energy spectrum of primary cosmic rays according to the TAIGA-HiSCORE and Tunka-133 data in comparison with the results of other experiments.



Fig. 4. (*a*) Hillas parameters used to select events generated by gamma rays. (*b*) An example of a joint hybrid "gamma-like" event. Image Hillas parameters are: Size—709 photoelectrons, Width = 0.13° , ALPHA = 8.9° .

the Telescope Array and the Pierre Auger Observatory.

Processing of Cherenkov images of EAS in the

telescope cameras and restoring image parameters consists of the following steps. 1) Reconstruction of the amplitude matrix Am (X_i, Y_i) $(X_i, Y_i$ —pixel

PHYSICS OF ATOMIC NUCLEI Vol. 84 No. 3 2021



Fig. 5. The preliminary distribution of the detected EASs depending on the α angle for 80 hours of a source observation in the Crab nebula. Selection criteria: Size >125 p.e., $0.36^{\circ} < \text{dist} < 1.44^{\circ}$, width $< 0.0756(\log \text{Size}) - 0.468^{\circ}$, length $< 0.312^{\circ}$, $c^2 > 0.54$.

coordinates) with subtraction of the values of the pedestal in each pixel; the values of the pedestal are determined as the average value for every 2 minutes. 2) Reading information from the telescope tracking files and determining the source position in the camera (On) and the background position point (Off). 3) Excluding pixels with instrumental interference in the PMT and subsequent electronics, as well as pixels with traces of stars and background signals from charged cosmic rays physically passing through the PMT. 4) Cleaning images from random distortions (Cleaning procedure): only pixels with an amplitude greater than N_1 were selected and yet they had at least one neighboring pixel larger than N_2 , as well as neighboring pixels. We chose $N_1 \sim 6\sigma_i$, $N_2 \sim$ $3\sigma_i$, where σ_i is the root-mean-square value of the background (pedestal), usually varying from 1.8 to 3 photoelectrons depending on snow cover and cloud conditions. The total number of selected pixels, Npix, and the total number of detected photoelectrons, S(image size) were measured. 5) Calculation of Hillas parameters [18]: width, length, size, DIST, ALPHA (Fig. 4a), and other image parameters. 6) Background suppression and the detection of gamma-like showers in the parameters of the images. In particular, the ALPHA angle should be small (less than 10°) for gamma events. Figure 4b shows an example of a "gamma-like" event detected by the first IACT and the TAIGA-HiSCORE array. The asterisk in this figure indicates the projection of the position of the EAS axis on the plane of the telescope camera with the scaling factor taken into account: Rp/Rc = 1500(Rp is the distance from the telescope to the EAS axis locating, Rc is the distance from the center of the camera to the asterisk), the line in the figure is a direction of the EAS axis, restored according to the TAIGA-HiSCORE array data.

In 2019–2020, the telescope monitors the Crab in the Wobbling Mode [19]: the central axis of the telescope is directed at a point shifted relative to the direction of the Crab at ± 1.2 degrees (changing the direction every 20 minutes). Figure 5 shows the preliminary distribution of the detected EASs depending on the ALPHA angle for 8 hours of a source observation in the Crab nebula in winter 2019–2020. The distribution is constructed both for events when the telescope is pointed on the source (ON distribution) and to the background region without the source (OFF distribution). The distribution shows an excess Exc = 213 events for ON distributions at ALPHA < 10°, which indicates the detection of gamma rays from the Crab nebula by the first TAIGA-IACT.

4. CONCLUSION

The combined operation of the Cherenkov imaging array and the timing array is the most costeffective way to create an array, whose effective area is tens of square kilometers, to explore superhighenergy gamma quanta. The expected integral sensitivity of the 1-km² TAIGA setup will be about $2.5 \times$

PHYSICS OF ATOMIC NUCLEI Vol. 84 No. 3 2021

 10^{-13} TeV cm⁻² s⁻¹ for detection of gamma quanta at energy 100 TeV during 300 hours source observation. The TAIGA experiment will be the northernmost gamma-ray experiment, and its location provides advantages for observation of the sources with large declinations.

ACKNOWLEDGMENTS

This work is supported by Russian Foundation for Basic Research (grant nos. 19-52-44002, 19-32-60003) the Russian Science Foundation (grant nos. 19-72-20067 (Section 2), 19-72-20230 (Section 3)), the Russian Federation Ministry of Science and High Education (projects FZZE-2020-0017, FZZE-2020-0024).

REFERENCES

- 1. F. Aharonian, AIP Conf. Proc. 410, 1631 (1997).
- 2. F. Aharonian et al., Astropart. Phys. 34, 738 (2011).
- V. A. Acciari, E. Aliu, T. Arlen, T. Aune, M. Beilicke, W. Benbow, S. M. Bradbury, J. H. Buckley, V. Bugaev, K. Byrum, A. Cannon, A. Cesarini, L. Ciupik1, E. Collins-Hughes, W. Cui, R. Dickherber, et al., Astrophys. J. Lett. **730**, L20 (2011).
- 4. J. Albert et al. (MAGIC Collab.), Astrophys. J. **639**, 761 (2006).
- 5. CTA: https://www.cta-observatory.org/
- 6. M. Amenomori et al. (Tibet AS γ Collab.), Phys. Rev. Lett. **123**, 051101 (2019).
- G. Sinnis (on behalf of the Milagro and HAWC Collabs.), Nucl. Instrum. Methods A 623, 410 (2010).
- Q. An, Y. X. Bai, X. J. Bi, Z. Cao, Zhe Cao, J. F. Chang, G. Chen, L. H. Chen, M. J. Chen, T. L. Chen, Y. T. Chen, S. W. Cui, B. Z. Dai, Danzengluobu, C. F. Feng, B. Gao, et al., Nucl. Instrum. Methods A 644, 11 (2011).

- 9. N. Budnev et al., Nucl. Instrum. Methods A 845, 330 (2017).
- R. Aloisio, P. Blasi, P. L. Ghia, and A. F. Grillo, Phys. Rev. D 62, 053010 (2000).
- 11. H. Vogel, R. Laha, and M. Meyer, arXiv: 1712.01839v1.
- 12. D. Horns and M. Meyer, JCAP 1202, 033 (2012).
- 13. M. Galaverni and G. Sigl, Phys. Rev. Lett. 100, 021102 (2008).
- N. Budnev, I. Astapov, P. Bezyazeekov, E. Bonvech, V. Boreyko, A. Borodin, M. Brückner, A. Bulan, D. Chernov, D. Chernykh, A. Chiavassa, A. Dyachok, O. Fedorov, A. Gafarov, A. Garmash, V. Grebenyuk, et al., JINST 15, C09031 (2020).
- L. Kuzmichev, I. Astapov, P. Bezyazeekov, V. Boreyko, A. Borodin, M. Brückner, N. Budnev, A. Chiavassa, O. Gress, T. Gress, O. Grishin, A. Dyachok, S. Epimakhov, O. Fedorov, A. Gafarov, V. Grebenyuk, et al., EPJ Web Conf. 145, 01001 (2017).
- V. V. Prosin, S. F. Berezhnev, N. M. Budnev, A. Chiavassa, O. A. Chvalaev, O. A. Gress, A. N. Dyachok, S. N. Epimakhov, N. I. Karpov, N. N. Kalmykov, E. N. Konstantinov, A. V. Korobchenko, E. E. Korosteleva, V. A. Kozhin, L. A. Kuzmichev, B. K. Lubsandorzhiev, et al., Nucl. Instrum. Methods A **756**, 94 (2014).
- B. A. Antokhonov, D. Besson, S. F. Beregnev, N. M. Budnev, O. B. Chvalaev, A. Chiavassa, O. A. Gress, N. N. Kalmykov, N. N. Karpov, E. E. Koresteleva, V. A. Kozhin, L. A. Kuzmichev, B. K. Lubsandorzhiev, N. B. Lubsandorzhiev, P. M. Mirgazov, M. I. Panasyuk, et al., Nucl. Instrum. Methods A 639, 42 (2011).
- 18. A. M. Hillas, in *Proceedings of the 19th ICRC, La Jolla* (1985), Vol. 3, p. 445.
- 19. Fomin, V. P., et al. "The False Source Method for Detecting TeV Gamma-Ray Sources." International Cosmic Ray Conference. Vol. 1 (1991).