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The TAIGA-HiSCORE Array Prototype: Status and First Results

I. I. Astapov[a], N. S. Barbashina[a], A. G. Bogdanov[a], V. Boreyko[b], N. M. Budnev[c], R. Wischnewski[d], A. R. Gafarov[c], V. Grebenyuk[b], O. A. Gress[c], T. I. Gress[c], A. A. Grinyuk[b], O. G. Grishin[c], N. Gorbunov[b], A. N. Dyachok[c], S. N. Epimakhov[e], A. V. Zagorodnikov[c], V. L. Zurbanov[c], A. L. Ivanova[c], Y. A. Kazarina[c], N. N. Kalmykov[e], N. I. Karpov[e], V. V. Kindin[a], S. N. Kiryuhin[c], R. P. Kokoulin[a], K. G. Kompaniets[a], E. E. Korosteleva[e], V. A. Kozhin[e], E. Kravchenko[f], M. Kunnas[g], L. A. Kuzmichev[e, *], A. Chiavassa[h], V. V. Lenok[c], B. K. Lubsandorzhiev[i], N. B. Lubsandorzhiev[e], R. R. Mirgazov[c], R. Mirzoyan[j], R. D. Monkhoev[c], R. Nachtigall[g], A. L. Pakhorukov[c], E. A. Osipova[e], M. I. Panasyuk[e], L. V. Pankov[c], A. A. Petrukhin[a], M. Popescu[k], A. Porelli[d], A. A. Pushnin[c], V. A. Poleschuk[c], E. G. Popova[e], E. B. Postnikov[e], V. V. Prosin[e], V. S. Ptuskin[l], G. I. Rubtsov[i], V. S. Samoliga[c], Y. A. Semeney[c], A. A. Silaev[e], A. A. Silaev, Jr.[e], A. V. Skurikhin[e], L. G. Sveshnikova[e], A. Sokolov[f], V. A. Tabolenko[c], B. A. Tarashchansky[c], L. G. Tkachev[b], A. V. Tkachenko[b], M. Tluczykont[g], O. L. Fedorov[c], D. Horns[g], C. Spiering[d], K. Yurin[a], and I. I. Yashin[a]

[a]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia*
[b]*Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia*
[c]*Irkutsk State University, Irkutsk, 664003 Russia*
[d]*DESY, 15738 Zeuthen, Germany*
[e]*Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[f]*Novosibirsk State University, Novosibirsk, 630090 Russia*
[g]*Institute of Experimental Physics, University of Hamburg, 20355 Hamburg, Germany*
[h]*University of Turin, 10124 Turin, Italy*
[i]*Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 117312 Russia*
[j]*Max Planck Institute, 80805 Munich, Germany*
[k]*Institute of Space Science, Bucharest, 077125 Romania*
[l]*Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Troitsk, Moscow, 108840 Russia*
**e-mail: kuz@dec1.sinp.msu.ru*

Abstract—The design for the TAIGA-HiSCORE array, a part of the TAIGA Gamma Ray Observatory, is considered. The observatory is being constructed in the Tunka Valley, 50 km from Lake Baikal. Preliminary results obtained using the first 28 optical stations of the array are presented.

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INTRODUCTION

There are a number of fundamental questions that have yet to be answered for the energy range of gamma rays above 30 TeV (the gamma ray astronomy of ultra-high energies). The first of these is the one about the sources of galactic cosmic rays with energies of around 1 PeV, the region immediately adjacent to the classic knee in the spectrum of all particles. It is noteworthy that so far, not a single photon with an energy exceeding 80 TeV has been detected. The Tunka Advanced Instrument for Cosmic Ray Physics and Gamma Ray Astronomy (TAIGA) [1] is designed to study gamma radiation and fluxes of charged cosmic rays in the energy range of 10^{13}–10^{18} eV. The array will include a network of wide-angle (solid angle, ~0.6 sr) Cherenkov TAIGA High Sensitivity Cosmic Origin Explorer (HiSCORE) stations [2] and 16 classic Imaging Atmospheric Cherenkov Telescopes (IACT) with image analysis (FOV, 10 degrees) arranged in an area of 5 km^2, along with muon sensors with a total area of 2000 m^2 distributed over an area of 1 km^2. The expected integral sensitivity of the observatory for detecting local sources of gamma rays in the energy range of 30–200 TeV is about 10^{-13} erg cm^{-2} s^{-1} over 500 hours of observing a source.

THE TAIGA HiSCORE ARRAY

The TAIGA-HiSCORE array currently consists of 28 optical stations distributed over an area of 0.25 km^2. Each optical station consists of four photomultipliers (PMs) with photocathode diameters of 20 cm. The effective area of each PM is increased 4 times by using Winston cones. The solid angle of observation is 0.6 sr. In order to increase the time of observing gamma rays from the Crab Nebula, all stations are tilted to the south at 25°. R5912, ET9352, and R7081 photomultipliers with photocathode diameters of 25 cm are installed at 14, 8, and 6 stations, respectively. Signals from the anodes of four PMs of one station are totalled, reducing the energy threshold by another 50%. The minimum distance between stations is 106 m. Each station is connected to a data collection center by an optical fiber cable for data transmission and synchronization. The synchronization error between optical stations is 0.1 ns. Each station operates independently. The local trigger of a station is activated when the sum of anode signals exceeds a predetermined threshold. This threshold is approximately 200 p.e., which corresponds to a Cherenkov light flux of 0.3 photon cm^{-2} [3]. At this threshold, the count rate per station is 10–15 Hz. The signals from the anode and the intermediate dynode are digitized by a DRS-4 board in steps of 0.5 ns. A more detailed description of data collection and synchronization systems can be found in [4].

MEASURING ANGULAR SENSITIVITY

To measure the angular sensitivity of the optical sensors and determine the optimum PM position inside a Winston cone, a stand was constructed that allowed us to measure the angular response from –60 to +60 degrees in steps of 0.8 degrees. The optical sensor was illuminated by brief (about 10 ns) light pulses from an LED located at a distance of 5 m. Measurements showed that the central part of the angular response (up to 30 degrees) had considerable asymmetry determined by the PM dynode system's orientation. The asymmetry of the central part grows along with the high voltage and is thus a result of the PM dynode system's design, rather than its rotation relative to the geomagnetic field. In an optical station (OS), one pair of PMs rotates 180 degrees relative to the other, so the overall OS asymmetry is less than that of an individual sensor. At angles greater than 30 degrees, the angular response does not depend on the orientation of the dynode system and is determined only by the operation of the Winston cone for a given PM depth in the cone. The optimum PM position in the cone is 45 mm from the top of the tube to the lower edge of the cone for a Hamamatsu R5912 photomultiplier and 50 mm for an ElectronTube 9352KB photomultiplier. The averaged azimuth angular sensitivity of an optical station for the optimum PM position in a cone is given in the table. It roughly corresponds to the calculations for 47 and 54 mm.

Averaged azimuth angular station sensitivity (proportion of light incident at a given angle of the light flux detected by an optical station)

Angle, deg	Angular sensitivity (data analysis)	Angular sensitivity (stand)
0–2	0.88	0.99
2–4	0.92	0.99
4–6	0.97	1.00
6–8	0.96	1.00
8–10	0.97	1.00
10–12	1.00	1.00
12–14	0.99	1.00
14–16	1.00	0.99
16–18	1.00	0.96
18–20	0.94	0.92
20–22	0.89	0.88
22–24	0.85	0.85
24–26	0.76	0.81
26–28	0.67	0.75
28–30	0.57	0.62
30–32	0.44	0.47
32–34	0.29	0.33

By comparing the light fluxes from a single shower recorded simultaneously by the Tunka-133 and TAIGA-HiSCORE arrays, we can experimentally assess the averaged angular sensitivity of optical stations. This was done using the collaboration's data for winter 2013–2014, when the stations of the TAIGA-HiSCORE 9 array were oriented vertically as Tunka-133 sensors. The angular sensitivity can be reconstructed from general events, since the Tunka-133 array sensors cover much wider angles than those of the TAIGA-HiSCORE array, and their angular sensitivity up to 45° is well known. The averaged angular sensitivity obtained in this manner is also given in the table.

RECONSTRUCTING EVENTS AND 2015–2016 SEASON STATISTICS

During the winter of 2015–2016, around 10 million extensive air showers (EAS) with the simultaneous actuation of four or more stations were detected over 35 days with good weather (210 hours). EAS parameters were reconstructed using algorithms developed for the Tunka-133 array [5, 6]. The directions of arrival were determined by the relative delay of the Cherenkov light front at each station. Preliminary directions were reconstructed by assuming these were plane fronts. This direction was used for reconstructing the

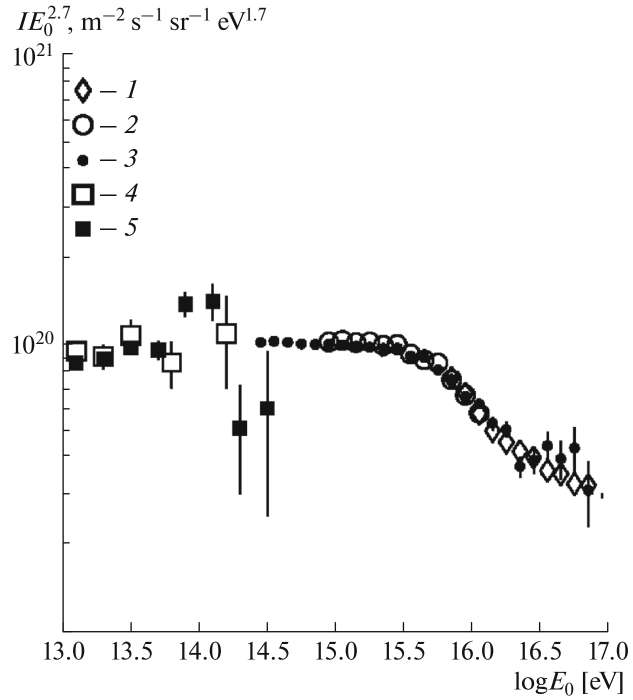

Fig. 1. Energy spectrum of primary cosmic rays according to the TAIGA HiSCORE array data, compared to the results from other experiments: (*1*) Tunka-133 [6], (*2*) Tunka-25 [7], (*3*) this work (preliminary results), (*4*) ATIC-2, and (*5*) NUCLEON (KLEM).

position of the EAS axis. Pulse amplitudes were fitted using the amplitude distance function (ADF) [6]. The final direction of EAS arrival was found for the determined axis position by assuming a curved front, the most likely form of which was derived from calculations using the CORSIKA software [6]. The primary particle energy was determined from the density of the Cherenkov radiation flux at a distance of 200 meters from EAS axis Q_{200} [6]:

$$E = AQ_{200}^{0.94}.$$

The absolute value of the energy was determined by normalizing the obtained energy spectrum to the Tunka-25 array spectrum [6] at an energy of 1 PeV.

In processing new data, it was found that the described algorithms did not work satisfactorily for too flat ADFs corresponding to low energies and large zenith angles, especially when we assumed that a gamma ray was the primary particle. Events with zenith angles smaller than 15° were thus used to reconstruct the primary spectrum of all charged particles for energies of less than 1 PeV, and the processing algorithm described below was used to search for gamma rays.

ENERGY SPECTRUM

Figure 1 shows the resulting combined energy spectrum. Events with zenith angles of 0 to 15 degrees are used in the energy range from the threshold to 10^{15} eV. At high energies, events with zenith angles of 0 to 40 degrees are included in the spectrum.

For comparison, the same figure shows the results from direct experiments, i.e., the ATIC-2 balloon experiment and the KLEM version of the NUCLEON satellite experiment. The data set from the last experiment is ongoing, and it is expected that the number of statistics will grow at least 5 times by the end of the satellite's operation. So far, extrapolation of our spectrum does not contradict the results from direct experiments within their statistical errors.

SEARCHING FOR GAMMA RAYS FROM THE CRAB NEBULA

The Crab Nebula with a pulsar at the center (or simply The Crab) is the most prominent and thoroughly studied source of TeV gamma ray astronomy. It is therefore used as a standard source for calibrating gamma ray telescopes. In addition, it is one of the few sources from which radiation has been detected in the range of 10 to 80 TeV, although the scatter of data in this field is still quite large. The source can be observed in the array's aperture from October to March for as long as 3.5 h per night. Full potential source observation time for the described array is about 230 h per year. The actual observation time is usually half this figure because of bad weather. In the winter of 2015–2016, the actual observation time was around 60 h.

Until atmospheric telescopes with EAS image analysis are put into operation, it remains impossible to distinguish between events from gamma rays and events from cosmic rays using EAS characteristics, and the only way to detect gamma rays is to find a statistically significant excess of events in the direction of a source. Events in a cone with an angular field of 3° relative to the direction to The Crab were thus selected to search for gamma rays. In the Earth's coordinate system, this corresponds to zenith angles of 28° to 39°. Events with the threshold energy for the described array are of the greatest interest in the search for gamma rays.

The axis position for these events was determined from the center of gravity of the amplitude readings at the stations. The direction of EAS arrival was reconstructed for this axis position by assuming the same curve front as for charged particles. The average value of the Cherenkov light flux at the four stations closest to the axis was used to reconstruct the energy. This flux was converted to the primary energy using the CORSIKA software.

The distribution according to the reconstructed energy is shown in Fig. 2. The distributions for October 2015 and January 2016 are shown separately. In these two months, the array's count rates (i.e., the count rate for events with four or more triggered stations) were different: 17 Hz in October and 11 Hz in

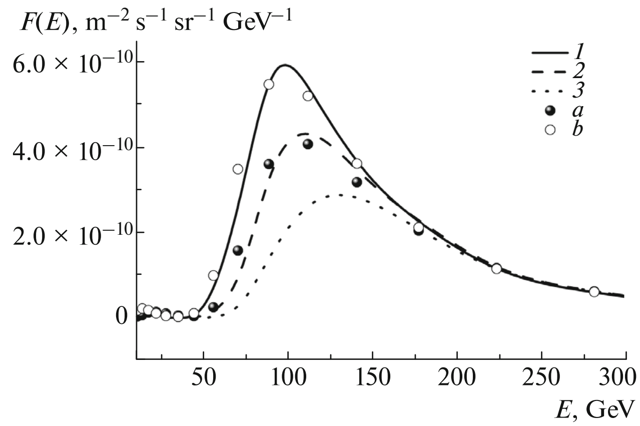

Fig. 2. Spectrum of cosmic rays in a cone of 3 degrees relative to the direction to the Crab. Symbols represent experimental data for (*a*) January and (*b*) October. The lines indicate calculations corresponding to different array count rates in different months: (*1*) 17, (*2*) 14, and (*3*) 11 Hz.

January. This change in the count rate was due to the different thresholds for the activation of local triggers at the stations in October and January. The array count rate is associated with the energy detection threshold for EASes from cosmic rays and allows us to estimate it. The energy distributions for different array count rates, calculated using the CORSIKA software, are shown by the lines in Fig. 2. The peak energy values range from 80 to 110 TeV. As can be seen from Fig. 2, the experimental distributions have a peak energy close to the one calculated. Since the energy for gamma rays is on average 1.6 times lower than for the charged particles of cosmic rays under the same Cherenkov light flux, the peak energy for a gamma ray flux with an energy spectrum of 2.7 will lie in the range 50–70 TeV.

At this peak energy, the expected number of gamma rays from The Crab during an observation is 10–25 events, depending on the extrapolation of the spectrum at low energies.

The excess of events above the background number of events is approximately 20 in an angle of 0.4 degrees, which is in good agreement with the expected number of events at the specified threshold.

CONCLUSIONS

The first season of the operation of the TAIGA HiSCORE array prototype consisting of 28 optical stations was quite successful in terms of both results and equipment reliability. Thirty-two new stations and the first atmospheric Cherenkov telescope with image analysis will be deployed in 2016–2017. By the start of winter observations in 2017–2018, the prototype will include 60 wide-angle stations positioned over an area of 0.6 km^2 and one telescope. The expected integral sensitivity of the prototype at 200 h of source observation (about two seasons of the array's operation) in the range of 30–200 TeV is around 10^{-12} erg cm^{-2} s^{-1}, which roughly corresponds to the integral sensitivity of the HAWC array [8] in this energy range over five years of operation.

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