Technical Physics, 2024, Vol. 69, No. 12

Possibility estimation of hybrid approach application to the search of astrophysical gamma rays using data from the Cherenkov and scintillation installations of the TAIGA astrophysical complex

© V.S. Samoliga,[1,2] I.I. Astapov,[3] P.A. Bezyazeekov,[1] E.A. Bonvech,[4] A. Blinov,[5] A.N. Borodin,[5] N.M. Budnev,[1] A.V. Bulan,[4] P.V. Busygin,[1] P.V. Volkov,[6] P.A. Volchugov,[1,4] D.M. Voronin,[7] A.R. Gafarov,[1] A.Yu. Garmash,[2,8] V.M. Grebenyuk,[5,9] O.A. Gress,[1] T.I. Gress,[1] E.O. Gress,[1] A.A. Grinyuk,[5] O.G. Grishin,[1] A.N. Dyachok,[1] V.A. Erofeeva,[1] D.P. Zhurov,[1] A.V. Zagorodnikov,[1] V. Zirakashvili,[10] A.D. Ivanova,[1,11] A.L. Ivanova,[1,2] M.A. Iliushin,[1] I.A. Kabannik,[2] N.N. Kalmykov,[4] V.V. Kindin,[3] S.N. Kiryuhin,[1] V.A. Kozhin,[4] R.P. Kokoulin,[3] K.G. Kompaniets,[3] E.E. Korosteleva,[4] E.A. Kravchenko,[2,8] A.P. Kryukov,[4] L.A. Kuzmichev,[4] A. Chiavassa,[12] M.V. Lavrova,[5] A.A. Lagutin,[6] Yu.E. Lemeshev,[1] B.K. Lubsandorzhiev,[7] N.B. Lubsandorzhiev,[1,4] A. Lukanov,[7] S.D. Malakhov,[1] R.R. Mirgazov,[1] R.D. Monkhoev,[1,2] E.A. Okuneva,[1,4] E.A. Osipova,[4] A. Pan,[5] A.D. Panov,[4] L.V. Pankov,[1] A.L. Pakhorukov,[1] A.A. Petrukhin,[3] D.A. Podgrudkov,[4] I. Poddubny,[1] E.G. Popova,[4] E.B. Postnikov,[4] V.V. Prosin,[4] A.A. Pushnin,[1] R.I. Raikin,[6] A.V. Razumov,[1,4] G.I. Rubtsov,[7] E.V. Ryabov,[1] A.K. Sagdeeva,[1] I. Satyshev,[5] L.G. Sveshnikova,[4] A.Yu. Sidorenkov,[7] A.A. Silaev,[4] A.A. Silaev (junior),[4] A.V. Skurikhin,[4] A.V. Sokolov,[2,8] V.A. Tabolenko,[1] A.B. Tanaev,[1] M.Yu. Ternovoy,[1] L.G. Tkachev,[5,9] N.A. Ushakov,[7] D.V. Chernov,[4] A. Shaikovsky,[5] I.I. Yashin[3]

[1] Irkutsk State University,
664003 Irkutsk, Russia
[2] Novosibirsk State University,
630090 Novosibirsk, Russia
[3] National Research Nuclear University „MEPhI“,
105043 Moscow, Russia
[4] Skobeltsyn Institute of Nuclear Physics, Moscow State University,
119234 Moscow, Russia
[5] Joint Institute for Nuclear Research,
141980 Dubna, Moscow oblast, Russia
[6] Altai State University, 656049 Barnaul, Russia
[7] Institute for Nuclear Research, Russian Academy of Sciences, 117312 Troitsk, Moscow, Russia
[8] Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia
[9] Dubna State University,
141982 Dubna, Moscow region, Russia
[10] Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences,
142191 Moscow, Russia
[11] Moscow Institute of Physics and Technology (National Research University),
141701 Dolgoprudny, Moscow Region, Russia
[12] Dipartimento di Fisica Generale Universiteta di Torino and INFN,
Torino, Italy
e-mail: vladimir.samoliga@yandex.ru

Received May 2, 2024
Revised August 6, 2024
Accepted August 30, 2024

This paper presents the results of the analysis of experimental data from the Cherenkov and scintillation installations of the TAIGA astrophysical complex. Estimates are given for the number of cosmic gamma rays from the Crab Nebula with energies above 100 TeV, which can be recorded during the joint operation of the installations in one measurement season.

Keywords: gamma-ray astronomy, cosmic rays, EAS, TAIGA-HiSCORE installation, Tunka-Grande array.

DOI: 10.61011/TP.2024.12.60408.348-24

Introduction

Study of gamma radiation with energy higher than 100 TeV is one of the key tasks of modern astrophysics. Such radiation is recorded by ground-based systems by detecting various extensive air shower (EAS) components. The very process of gamma quantum extraction from the charged cosmic particle background is quite nontrivial and requires various experimental approaches.

This study reviews experimental data from two TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) astrophysical installations [1] operated in

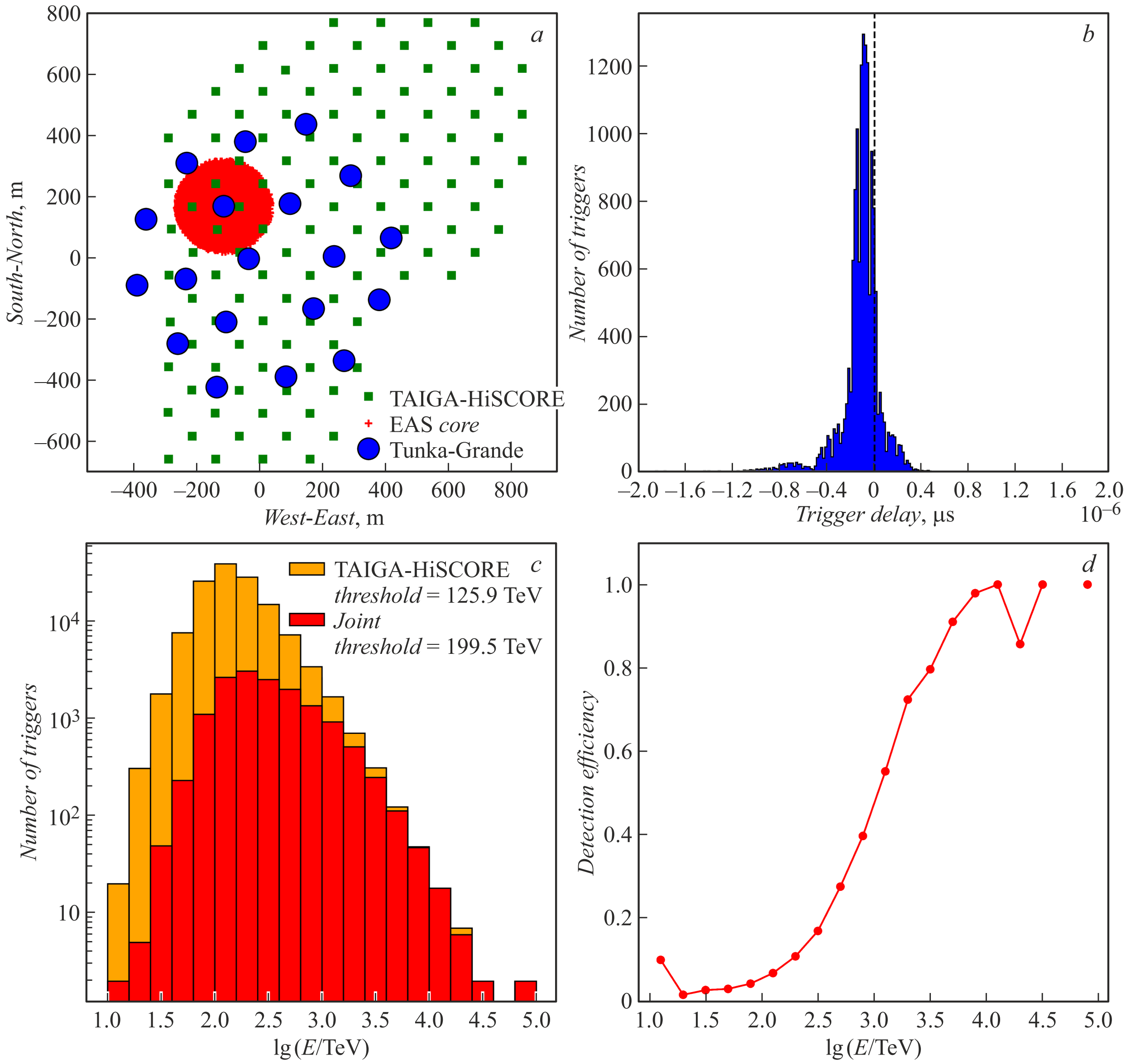

Figure 1. Example of joint events of one of the Tunka-Grande installations and TAIGA-HiSCORE optical detectors: *a* — layout of installations, optical detectors and EAS axes with event sampling radius $Rs = 150$ m; *b* — EAS detection time difference histogram; *c* — number of EAS's according to the TAIGA-HiSCORE data and joint events depending on the PCR energy; *d* — joint detection efficiency.

hybrid mode. TAIGA-HiSCORE system [2] is a network of 120 optical detectors placed in the area of 1 km^2 with spacing ~ 106 m. Tunka-Grande system [3] is a set of scintillation counters combined into 19 installations with spacing ~ 200 m in the area of 0.5 km^2 (Figure 1, *a*). The former installation is designed for investigation of primary cosmic radiation (PCR) by detecting Cherenkov radiation, the latter detects electron-photon and muon components of EAS.

1. Hybrid approach to the extraction of primary gamma quanta

The main idea of the hybrid approach is in using the scintillation counter data for gamma-hadronic separation of PCR on the basis of EAS muon component analysis. High accuracy of PCR parameter reconstruction according to the TAIGA-HiSCORE data allows event mapping in the equatorial and galactic coordinate systems to associate these events with known gamma sources and to estimate the significance of a signal from them.

PCR detection energy threshold for the TAIGA-HiSCORE system with minimum required triggering of four optical detectors is 100 TeV. Provided that EAS is registered by three and more Tunka-Grande installations, its threshold is 10 PeV. To reduce the Tunka-Grande threshold by a factor of ~ 2, it was proposed to use the operation mode of individual installations. Thus, Figure 1, *c* shows that the threshold in such mode is ~ 200 TeV. In our case, the Tunka-Grande installations are supposed to be

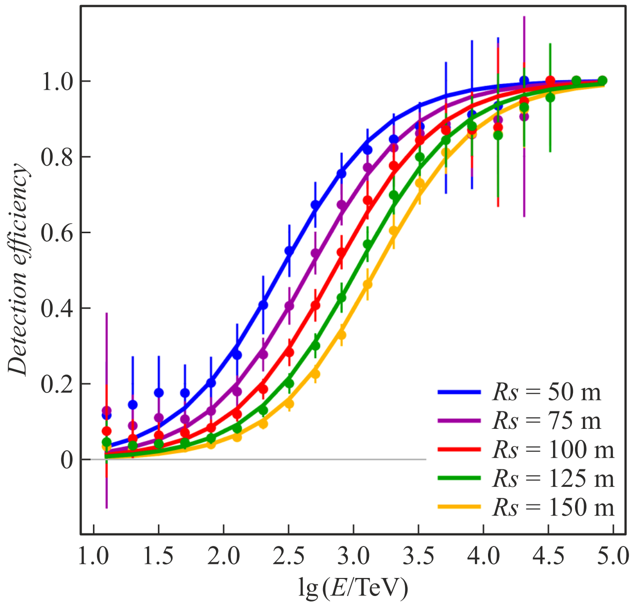

Figure 2. Mean efficiency of joint EAS detection by individual Tunka-Grande installations with different Rs.

treated as additional detectors included in the TAIGA-HiSCORE system to extract gamma candidates among all detected events. Other parameters such as EAS axis position, angles of arrival and energy of primary particles can be reconstructed with experimentally confirmed high accuracy [4,5] using the TAIGA-HiSCORE detector data.

2. Search and analysis of Tunka-Grande and TAIGA-HiSCORE joint events

To search for joint events using the experimental data of Tunka-Grande's individual installations, EAS's that coincide in detection time with the TAIGA-HiSCORE system within $\pm 10\,\mu$s were first chosen. A session with a duration of 7.5 h on December 17, 2022 was chosen for this analysis. Figure 1, b shows the histogram of time difference of EAS arrival to an individually addressed installation and optical detectors within $\pm 2\,\mu$s. The mean value in this case was $-0.11\,\mu$s. Then, a restriction was put to the distance from the installations to the EAS axes reconstructed using the TAIGA-HiSCORE system (Figure 1, a). On the one hand, this avoids random coincidences with EAS that are separated from the installations at distances of about several interstation steps. On the other hand, this provides a ratio of the number of joint events to the number of EAS detected by TAIGA-HiSCORE at various event sampling radii Rs. Dependence of this ratio on the reconstructed EAS energy is a joint EAS detection efficiency curve (Figure 1, d).

For several values of Rs (50, 75, 100, 125 and 150 m), mean detection efficiency of the Tunka-Grande installations was approximated using the following function:

$$f(E) = \left(1 + \exp\left(\frac{a - \log_{10}(E/\mathrm{TeV})}{b}\right)\right)^{-1}, \qquad (1)$$

where a and b are selected for each Rs. When Rs decreases, the joint detection efficiency increases (Figure 2). However, the total system event sampling area decreases, which reduces the probability of gamma quanta detection. With increasing Rs, the event sampling areas of individual installations start overlapping (at $Rs > 100$ m), and at $Rs \approx 150$ m, they cover the whole Tunka-Grande area. In this case, maximum detection efficiency among neighboring installations shall be considered for each EAS. It was determined that at $Rs > 100$ m the Tunka-Grande detection efficiency was equal to the mean detection efficiency of individual installations at $Rs = 100$ m.

The obtained characteristics are used to estimate the detected gamma quantum flux. The Crab Nebula, a „standard candle" of gamma-astronomy, is used in this work as a cosmic gamma quantum source. In [6], it was shown that the observation time of this source using TAIGA-HiSCORE was equal to 204 h during 2 measurement seasons (2019–2022). This is because optical detectors are active only at clear moonless nights. The following expression was taken as the Crab Nebula energy spectrum according to [7]:

$$\frac{dN}{dE} = (8.2 \pm 0.2) \cdot 10^{-14} (E/10\,\mathrm{TeV})^{-\Gamma}\,\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{TeV}^{-1},$$

$$\Gamma = (2.90 \pm 0.01) + (0.19 \pm 0.02) \log_{10}(E/10\,\mathrm{TeV}). \qquad (2)$$

The density of gamma flux from the Crab Nebula with energies higher than 100 TeV is $0.1\,\mathrm{km}^{-2} \cdot \mathrm{h}^{-1}$, which gives 10.2 gamma quanta per measurement season at TAIGA-HiSCORE. Expressions (1) and (2) were used to estimate the gamma flux density Fg and the number of gamma quanta Ng that can be detected with energy higher than 100 TeV when the systems run together during one measurement season (~ 100 h) with different Rs (see the table).

Conclusion

With current configuration of the Tunka-Grande system, detection of 2.6 gamma quanta is available during the measurement season (~ 100 h) in the area of $0.88\,\mathrm{km}^2$ when working together with TAIGA-HiSCORE. This number is 29.1% of that available for TAIGA-HiSCORE in the same area. To increase the detection frequency, closer spacing of installations is required. Thus, to observe the flux$Fg = 5.23 \cdot 10^{-2}\,\mathrm{km}^{-2} \cdot \mathrm{h}^{-1}$, an interstation spacing of about 100 m is necessary.

In addition to Tunka-Grande, deployment of the TAIGA-Muon scintillation system [8] with the PCR energy detection threshold lower than 1 PeV was started in 2019. The first construction phase includes detectors of electron-photon and muon components of EAS with the total area of $\sim 200\,\mathrm{m}^2$. Interstation spacing is ~ 100 m. Introduction of a new system into the TAIGA astrophysical complex is expected to increase the gamma quantum detection efficiency in hybrid operation mode and will allow proceeding

Flux density and number of gamma quanta available for joint detection by the TAIGA-HiSCORE and Tunka-Grande systems during 1 observation season

Station event sampling radius Tunka-Grande Rs, m	System event sampling area Tunka-Grande S, km^2	Gamma quantum flux density Fg, km$^{-2}\cdot$h^{-1}	Number of gamma quanta Ng
50	0.15	$5.23\cdot10^{-2}$	0.8
75	0.34	$3.92\cdot10^{-2}$	1.3
100	0.6	$2.91\cdot10^{-2}$	1.8
125	0.8	$2.91\cdot10^{-2}$	2.3
150	0.88	$2.91\cdot10^{-2}$	2.6

to detail study of local high and ultrahigh energy gamma radiation sources.

Funding

The work was carried out at the unique scientific installation „Astrophysical Complex MSU-ISU". The study was supported by the Russian Federation Ministry of Science and Higher Education (projects FZZE-2024-0005, FZZE-2023-0004, FSUS-2022-0015) and Russian Science Foundation (projects 23-72-00019 (section 2), 23-72-00054 (section 3)).

Conflict of interest

The authors declare no conflict of interest.

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Translated by E.Ilinskaya