Conference materials
UDC 524.1
DOI: https://doi.org/10.18721/JPM.161.273

Method for gamma-hadron separation according to the experimental data of The Tunka-Grande array

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Abstract. The Tunka-Grande array is a part of unified experimental complex, which also includes Tunka-133 and TAIGA-HiSCORE (High Sensitivity COsmic Rays and gamma Explorer) wide-angle Cherenkov arrays, TAIGA-IACT array (Imaging Atmospheric Cherenkov Telescope) and TAIGA-Muon scintillation array. This complex is located in the Tunka Valley (Buryatia Republic, Russia), 50 km from Lake Baikal. It is designed to study the energy spectrum and the mass composition of charged cosmic rays in the energy range 100 TeV—1000 PeV, to search for diffuse gamma rays above 100 TeV and to study local sources of gamma rays with energies above 30 TeV. This report outlines 3 key points. The first is the description of the Tunka-Grande scintillation array. The second one presents the strategy of the search for diffuse gamma rays based on a computer simulation of the Tunka-Grande array. The third one is devoted to the prospects for future research in the field of gamma-ray astronomy using simulation results.

Keywords: cosmic rays, extensive air showers, Tunka-Grande array.

Funding: The work was performed at the UNU «Astrophysical Complex of MSU-ISU» (agreements EB-075-15-2021-675). The work is supported by the Russian Science Foundation (grant 23-72-00054), the Russian Federation Ministry of Science and High Education (projects FZZE-2023-0004, FZZE-2020-0024, FSUS-2020-0039, FSUS-2022-0015).

Citation: Monkhoev R.D., TAIGA collaboration, Method for gamma-hadron separation according to the experimental data of the Tunka-Grande array, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.2) (2023) 480—484. DOI: https://doi.org/10.18721/JPM.161.273

Материалы конференции
УДК 524.1
DOI: https://doi.org/10.18721/JPM.161.273

Метод гамма-адронного разделения по экспериментальным данным сцинтилляционной установки Tunka-Grande

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Аннотация. Сцинтилляционная установка Tunka-Grande входит в состав астрофизического комплекса TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy), который также включает в себя широкоугольные черенковские установки Тунка-133 и TAIGA-HiSCORE (High Sensitivity COsmic Rays and gamma Explorer), сеть атмосферных черенковских телескопов TAIGA-IACT (Imaging Atmospheric Cherenkov Telescope) и сцинтилляционную установку TAIGA-Muon. Данный комплекс располагается в Тункинской долине (республика Бурятия, Россия) в 50 км от озера

Байкал и нацелен на изучение энергетического спектра и массового состава космических лучей в диапазоне энергий 100 ТэВ - 1000 ПэВ, поиск диффузного гамма-излучения с энергией выше 100 ТэВ и исследование локальных источников гамма-квантов с энергиями более 30 ТэВ. В работе приведено описание сцинтилляционной установки Tunka-Grande и метода поиска диффузного гамма-излучения на основе проведенного компьютерного моделирования. Также указаны перспективы будущих исследований с использованием результатов этого моделирования.

Ключевые слова: Космические лучи, широкие атмосферные ливни, установка Tunka-Grande

Финансирование: Работа выполнена на УНУ «Астрофизический комплекс МГУ-ИГУ», поддержана Минобрнауки России (соглашение EB675-2021-15-075-), в рамках тем государственного задания (проекты FZZE0004-2023-, FZZE0024-2020-, FSUS-2020-0039, FSUS0015-2022-), а также при поддержке Российского научного фонда (грант 00054-72-23).

Ссылка при цитировании: Монхоев Р.Д., TAIGA collaboration, Метод гамма-адронного разделения по экспериментальным данным сцинтилляционной установки Tunka-Grande // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.2. С. 480–484. DOI: https://doi.org/10.18721/JPM.161.273

Introduction

The study of the charged cosmic rays and cosmic gamma rays of high and ultrahigh energies has a great interest for understanding the mechanisms and nature of their origin, which is the most important task of modern astrophysics. The investigation of such radiation is carried out using method, based on the property of primary particles to generate a cascade of secondary particles in the Earth's atmosphere, the so-called extensive air shower (EAS). When an EAS develops, a large number of components arise in it. The electron-photon, hadron, and muon components, as well as the accompanying Cherenkov, ionization, and radio emission reach the observation level within the Earth's atmosphere. All of these components can be used to reconstruct the properties of primary cosmic radiation. Nowadays, the simultaneous detection and the study of many parameters of an EAS with the help of the ground base hybrid systems similar to the experimental complex located in the Tunka Valley, is of major importance.

Astrophysical research in the Tunka Valley has begun in 1993 and for many years was aimed at the study of charged cosmic rays, which continues to this day on the Tunka-133 array [1]. It is known that primary charged particles are deflected by galactic and intergalactic magnetic fields, which lead to the loss of any information about direction to the origin. In many ways, this reason has contributed to the rapid development of experimental gamma-ray astronomy in recent years. Indeed, since gamma rays are electrically neutral, they can be used as a pointer to the astrophysical objects in which they were produced. However, since the gamma-ray flux is low compared to the cosmic-ray flux, the problem arises, how to separate gamma quanta from the background events caused by high-energy charged particles. To solve this non-trivial task, the work has begun on the creation of the TAIGA-HiSCORE [2, 3], Tunka-Grande [4], TAIGA-IACT [5] and TAIGA-Muon [6] arrays in 2012, 2013, 2017 and 2019 respectively.

Experimental set-up

The Tunka-Grande is designed to detect the charged component of an EAS and is presented as an array of scintillation counters combined in 19 stations on an area of 0.5 km^2. Each of them consists of two parts: surface and underground. The first detects all an EAS charged particles at the level of the array and consists of 12 counters covering an area of about 8 m^2, while the second, consisting of 8 counters with a total area of about 5 m^2, is located under a layer of soil ~1.5 m thick and is designed to detect the muon EAS component. Both parts are near to each other. The scintillation counter [7] has the form of a truncated pyramid whose inner surface is covered by a thin diffusely reflecting layer of white enamel. Inside the case there is the NE102A plastic scintillator in the form of a flat plate 800 mm × 800 mm × 40 mm in size and the Philips XP-3462 photomultiplier tube (PMT). Two counters at each station have additional PMTs whose amplification factor is 10 times lower than the standard one, ensuring a wide range of linearity in the measured signals. It should be noted that this type of counters is also currently used in the NEVOD-EAS [8] experiment and has previously been successfully used in the KASCADE-Grande [9] and EAS-TOP [10] experiments.

The electronics of the Tunka-Grande array [11] largely coincide with the electronics of the Tunka-133 array. The stations can send experimental information to central data acquisition system when both the external trigger signal arrives from the nearest cluster of the Tunka-133 array and when the signal arrives from the local trigger of the surface part. The local trigger generation condition of each station is the signal from two relativistic particles at the input of measuring channels of electronics. The count rate of one station in the external trigger mode is about 0.1 Hz and in the local trigger mode is about 10 Hz.

The aim of the Tunka-Grande array is the studying of the energy spectrum and mass composition of charged cosmic rays in the energy range of 10 - 1000 PeV, as well as to search for diffuse gamma rays about in the same energy range.

Strategy of the search for diffuse gamma rays

Despite more than half a century of work on the search for high-energy diffuse gamma rays, no astrophysical photons with energies above 10 PeV have been detected, and at present only upper limits on their fluxes have been established experimentally. A great contribution to such research in the energy range 10–1000 PeV was made by the EAS-MSU [12] and KASCADE-Grande [13] arrays. According to the experimental data of the Tunka-Grande array, preliminary results were also obtained [14].

Nowadays one of the most promising approaches to separate events from primary gamma rays from the charged cosmic rays background is the studying the muon EAS component, since the number of muons in a shower generated by a gamma quantum is an order of magnitude less than in the hadronic shower. This in turn requires Monte Carlo simulation of EASes, along with selecting and comparing experimental data. For more accurately assess the promise of the Tunka-Grande array in this direction compared to earlier investigating [14], a new two-step computer simulation of the detectors operation was done. At first, the development of an EAS is simulated, second, the detectors response to passage of elementary particles is simulated as well. To solve these tasks, the CORSIKA (Version 7.7401) [15] and Geant4 [16, 17] packages were chosen as the software. EASes were generated from various primary particles (gamma quanta, protons, and iron nuclei) for the energy range $16.5 < lg(E/\text{eV}) < 17.5$ and for an interval of the zenith angle 0–45°. Hadron interactions at low energies were calculated using the GHEISHA model [18], high-energy interactions were processed with the QGSJET-II-04 model [19]. Simulation of the detectors response using the Geant4 package is described in the report [20].

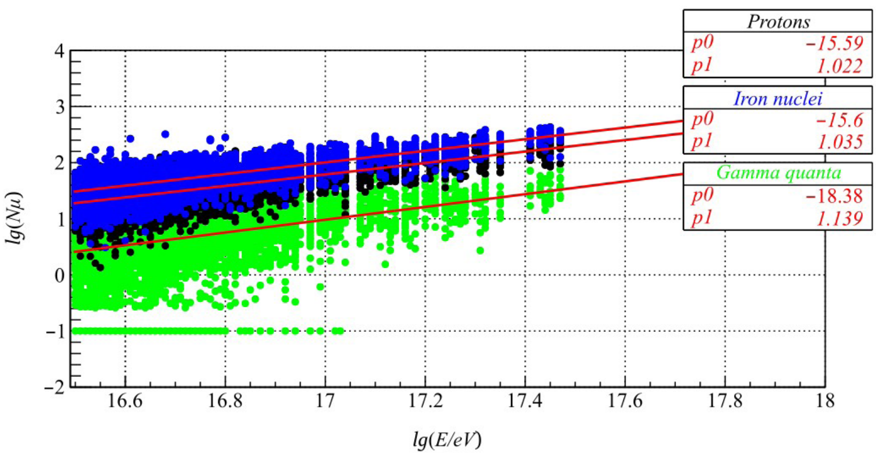

Fig. 1. Simulated distributions of the muon number

The distributions of the muon number versus the energy of primary particles are shown in Fig. 1. The figure presents the sum of detected particles for underground parts of all 19 stations for each EAS initiated by a gamma quantum (green points), proton (black points) and iron nucleus (blue points). The events without any detected muons are plotted with $lg(N\mu) = -1$ to be visible at the logarithmic axis. The distributions are approximated by function:

$$lg(N\mu) = p0 + p1 \cdot lg(E/\text{eV}). \quad (1)$$

It follows from Fig. 1 that, according to the Tunka-Grande experimental data, it is possible to separate gamma-ray candidates from the charged cosmic rays background with an efficiency of no worse than 50%.

Prospects for the search for diffuse gamma rays

The EAS-MSU and KASCADE-Grande arrays are completed experiments. The Tunka-Grande array is an active experiment and operates around the clock in the data collection regime for almost the entire calendar year over a relatively large total area. Currently, ~240000 EASes with energies of primary particles above 10 PeV and ~2000 EASes with energies above 100 PeV have been detected over ~8900 hours (5 years of operation). The potential of the experiment based on these data will make it possible to detect gamma quanta or to set upper limits no worse than existing in the world.

Conclusion

The Tunka-Grande array has great prospects for investigating diffuse gamma rays with energies above 10 PeV. Currently, there are experimental data for 5 years of operation of the array. This, together with the use of new computer simulation, will improve existing knowledge in the field of gamma-ray astronomy in the near future

Acknowledgments

The authors would like to thank Irkutsk Supercomputer Center of SB RAS for providing the access to HPC-cluster "Akademik V.M. Matrosov" (Irkutsk Supercomputer Center of SB RAS, Irkutsk: ISDCT SB RAS; http://hpc.icc.ru).

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Received 29.10.2022. Approved after reviewing 08.11.2022. Accepted 09.11.2022.