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Status and latest results of the experiments on detection of charged particles from EAS in the Tunka Valley

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Experiments on detection of charged particles from EAS in the Tunka Valley are the part of the TAIGA astrophysical complex and consists of two arrays: the operating Tunka-Grande facility and TAIGA-Muon array under construction. In report we present description of arrays, methods of EAS parameters reconstruction, scientific programs and the main results of Tunka-Grande array based on 6 seasons of operation: CR energy spectrum in the energy range 10 PeV - 1000 PeV and limit on the flux of the diffuse gamma rays in the same energy range. In addition, we provide prospects for studying primary cosmic radiation in the energy range 1 PeV - 1000 PeV.

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1. Introduction

The experiment on detection of charged particles from EAS in the Tunka Valley consists of the operating Tunka-Grande facility [1] and TAIGA-Muon array under construction [2], which are the part of the TAIGA astrophysical complex [3]. This complex is located in the Tunka Valley, 50 km from Lake Baikal and is aimed at solving fundamental problems of cosmic ray physics and gamma-ray astronomy in the energy range from a few TeV to 1 EeV.

The deployment of the scintillation experiment as part of the TAIGA Observatory began in 2013, when the scintillation counters used before in the KASCADE-Grande [4] scintillation experiment ar- rived in the Tunka Valley.

The priority tasks of the scintillation experiment are to study the energy spectrum and mass composition of cosmic rays, as well as to search for diffuse gamma rays in the energy range from 1 PeV to 1 EeV by detecting the electron-photon and muon components of EAS.

2. Tunka-Grande scintillation array

The Tunka-Grande scintillation array [1] is a network of 19 observation stations, located on the area of the Cherenkov Tunka-133 array. Each station consists of the surface and underground detector. The surface detector contains 12 scintillation counters with a total area about 8 m^2 that detect charged EAS particles. The underground detector located under a layer of soil ~1.5 m thick and designed to detect muon component of EAS consists of 8 similar counters with a total area ~5 m^2. The scintillation station electronics is analogous to the electronics of the Tunka-133 Cherenkov facility.

The main tasks of the Tunka-Grande array are to study of the energy spectrum and mass composition of cosmic rays in the energy range from 10 PeV to 1 EeV and to search for diffuse gamma rays with energy above 10 PeV.

2.1 EAS and CR parameters reconstruction

Our methods of EAS and CR parameter reconstruction are presented in several papers [1, 5, 6]. Recall that during the reconstruction, in each EAS event, the core position and arrival direction of EAS, the total number of charged particles and muons, particles density at a core distance of 200 m, the shower age parameter, and energy of the primary particle are restored.

As a measure of energy, we use the charged particles density at a core distance of 200 m – ρ_{200} parameter [1] rescaled relative to the measured zenith angle for atmospheric depth from sea level for the Tunka Valley x_0 = 960 g/sm^2 and obtained from experimental data average value of absorption path length λ = 260 g/sm^2.

The ρ200 conversion to energy is carried out according to formula:

$$E_0 = 10^b \cdot (\rho_{200}(0))^a \qquad (1)$$

where $a = 0.84 \pm 0.01$, $b = 15.99 \pm 0.01$.

The values of the coefficients in Formula 1 were obtained from the joint events analysis of the Tunka-Grande and Tunka-133 facilities [1].

For an independent assessment of the quality of the EAS and CR parameters' reconstruction according to the Tunka-Grande installation, a search and analysis of joint events of the Tunka-Grande array and the TAIGA-HiSCORE Cherenkov facility were performed [1]. The obtained values practically coincided with the results of the analysis of joint events with the Tunka-133

Cherenkov facility [5]: for events with energy $E \geq 10$ PeV the angular resolution of the Tunka-Grande is no worse than 2.0°, the accuracy of the core position reconstruction is 26 m, the energy resolution is 36%. In addition, the analysis made it possible to correct the values of the coefficients in Formula 1.

2.2Current results obtained by the Tunka-Grande array

Regular observations by the Tunka-Grande scintillation array have been started since October 2016. Data from the first observation season of 2016-2017 were used to analyze the joint events of the Tunka-Grande and the Tunka-133 arrays. Here we present the data of 5 seasons of the Tunka-Grande array operation from 2017 to 2022. The total time of data acquisition was about 11800 hrs. To plot the energy spectrum by the Tunka-Grande experimental data about 1 226 500 events with a zenith angle of $\theta \leq 35^{\circ}$ and an core position in a circle with a radius of 350 m were selected. Of these, ~312200 events have energy $E \geq 10$ PeV and ~2500 events have energy $E \geq 100$ PeV.

The differential energy spectrum obtained by Tunka-Grande facility is shown in Fig. 1 along with the spectra of Tunka-133 [7], TAIGA-HiSCORE [7], TALE [8], Ice Top [9] and KASCADE-Grande [10] arrays. The spectrum of Tunka-Grande shows a few features which indicate deviations from the power law. One can interpret the picture as a multiply broken power law. At an energy of about 20 PeV the power law index changes from $\gamma = 3.18 \pm 0.01$ to $\gamma = 3.00 \pm 0.01$. Points of the spectrum are consistent with such an index value till $E_0 = 100$ PeV. Above this energy the spectrum becomes much steeper with $\gamma = 3.26 \pm 0.03$ (the second “knee”).

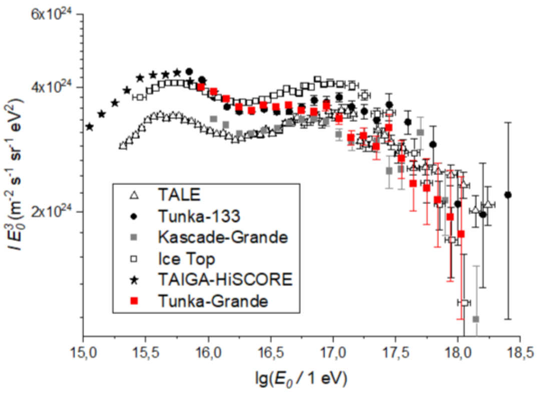

Figure 1: Primary energy spectrum: comparison with some other experimental data (red squares – this work, black circles - Tunka-133 [7], black stars – TAIGA-HiSCORE 7], unpainted triangles - TALE [8], unpainted squares - Ice Top [9], gray squares - KASCADE-Grande [10]).

The next important result obtained by Tunka-Grande array is a gamma–hadron discrimination.

To search for diffuse gamma quanta with an energy above 10 PeV, an analysis of muon-poor events was carried out. For this Tunka-Grande experimental data from 4 observation seasons (2017 – 2021) were used. The total time of data acquisition from this period was about 8900 hrs. The number of recorded events with energies above 10 PeV, zenith angle of $\theta \leq 35^{\circ}$ and an core position in a circle with a radius of 350 m was about 240000. Approximately 2000 events from them had energies above 100 PeV.

To evaluate the efficiency of discrimination of candidates for photon EASs, a Monte-Carlo simulation of the Tunka-Grande array was performed in 2 steps. At the first step, EASs were generated, at the second, the response of scintillation counters and stations was determined when particles of artificial showers passed through them. The CORSICA [11] packages (version 7.7401) and Geant4 [12] were used as software.

Figure 2 shows the results of measurements of the share of gamma quanta depending on the energy, including this work, for the energy range from 10 PeV to 100 PeV. It should be emphasized that all the presented limits are based on the EAS simulation and largely depend on the hadron interaction models used. An additional contribution to the systematic measurement errors is made by the error of energy reconstruction and the existing uncertainty of the PCRs mass composition.

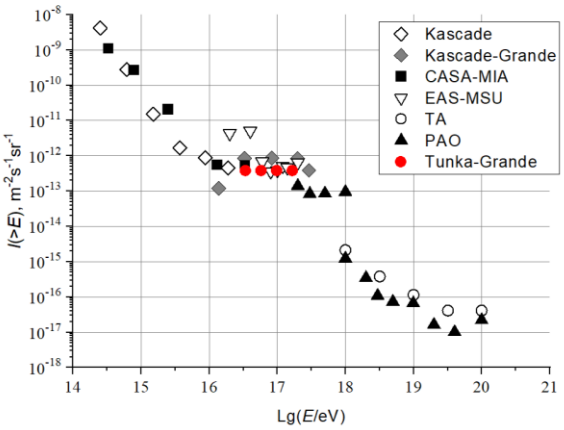

Figure 2: Limit on the integral flux of diffuse gamma quanta according to the experimental data of the Tunka-Grande array (90% C.L., QGSJET-II 04) and its comparison with similar measurements of EAS-MSU (90% C.L., QGSJET-II-04) [13], Kascade, Kascade-Grande (90% C.L., QGSJET-II-02) [14], Pierre Auger Observatory (95% C.L., EPOS LHS) [15], TelescopeArray (95% C.L., QGSJET-II-03) [16] and CASA-MIA experiments.

3. TAIGA-Muon scintillation array

The TAIGA-Muon scintillation array [2, 17, 18] is an extension of the Tunka-Grande array into th e energy range below 10 PeV. The need to deploy additional scintillation detectors is since the energy range below the detection threshold of the existing Tunka-Grande scintillation facility (10 PeV) is more promising for searching for high-energy astrophysical gamma quanta. The TAIGA-Muon array will reduce the energy threshold of the scintillation experiment to 1 PeV and improve the accuracy of the recovery of the EAS and CR parameters by increasing the density of detectors on area of experiment.

It is assumed that the first stage of the TAIGA-Muon array will consist of 10 clusters located in the centers of triangles formed by Tunka-Grande observation stations. The total area of the detectors will be 2000 m^2. Currently, three clusters of the TAIGA-Muon array are deployed and putted into operation. Each of the first two clusters consists of 8 surface and 8 underground

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scintillation counters. Surface and underground counters are in pairs, surface ones strictly above the underground ones, along the perimeter of a square with a side of 5 m.

Each TAIGA-Muon counter [19] consists of a duralumin case, inside of which there are 4 triangular scintillation plates with a variable thickness of 10 - 20 mm based on polystyrenewith the addition of 1.5% p-Terphenyl and 0.01% POPOP, shifter with a cross section of 5 mm×20mm (acrylic glass with BBQ dye), diffuse reflectors and PMT FEU-85. An increase in the thicknessof the scintillation plates to the periphery of the counters and the using of optical fiber plates make itpossible to achieve acceptable uniformity of signal amplitudes from different parts of the counters.The total area of the counter is 1 m^2.

The third TAIGA-Muon cluster is deployed in a new configuration — 4 surface and 16 underground detectors. After first two clusters of the TAIGA-Muon array were putted into operation, it was found that the stainless casings of the scintillation counters were insufficiently sealed. To protect against the negative effects of atmospheric phenomena and groundwater the scintillation counters of the third cluster were placed in sealed plastic boxes. Each box is made of polypropylene capable of withstanding changes in ambient temperature from -25 to +85◦C. To protect against significant loads from the soil, the boxes with underground counters were additionally placed in wooden casings.

4. Conclusion

Applying above reconstruction method, we processed the experimental data of the Tunka-Grande array for 5 measurement seasons. The energy spectrum and upper limits on the gamma-ray fraction demonstrates the good agreement with data of large terrestrial facilities. Comparison of the Tunka-Grande array data with the data of the Cherenkov facilities confirmed the sufficient quality of the reconstructed events for their further use in joint analysis for the gamma-hadron separation.

The extension of the scintillation experiment by the TAIGA-Muon array will increase the accuracy of determining the energy spectrum and mass composition of cosmic rays, as well as become part of a hybrid system with Cherenkov facilities for the separation of gamma quanta.

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