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Technique for reconstructing the parameters of EAS and primary cosmic rays based on experimental data of the Tunka-Grande scintillation array

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Abstract. The Tunka-Grande scintillation array is a part of a single TAIGA experimental complex located in the Tunka Valley, 50 km from the Lake Baikal. It consists of 19 observation stations deployed on an area of about 0.5 km^2. The main aim of the Tunka-Grande facility is a detailed study of the energy spectrum and mass composition of cosmic rays in the energy range from 10 PeV to 1 EeV by detecting the charged and muon component of EAS. The article presents a method for reconstructing the parameters of the EAS and primary cosmic rays, the cosmic rays energy spectrum based on 4 measurement seasons, and compares the results obtained with the data of the Tunka-133 and TAIGA-HiSCORE Cherenkov arrays.

Keywords: Primary Cosmic Rays, EAS, scintillation detectors, Tunka-Grande scintillation array

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Материалы конференции
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Методика реконструкции параметров шал и первичного космического излучения по экспериментальным данным сцинтилляционной установки Tunka-Grande

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Аннотация. Сцинтилляционная установка Tunka-Grande является частью единого экспериментального комплекса TAIGA, расположенного в Тункинской долине, в 50 км от оз. Байкал. Она состоит из 19 станций наблюдения, развернутых на площади около 0.5 км^2. Основной целью установки является детальное исследование энергетического спектра и массового состава космических лучей в диапазоне энергий от 10 ПэВ до 1 ЭэВ методом регистрации заряженного и мюонного компонента ШАЛ.

В докладе представлены методика реконструкции параметров, зарегистрированных ШАЛ и первичного космического излучения, энергетический спектр космических лучей, набранный за первые 4 сезона измерений, а также приводится сравнение полученных результатов с данными черенковских установок Тунка133- и TAIGA-HiSCORE.

Ключевые слова: первичные космические лучи, ШАЛ, сцинтилляционные детекторы, сцинтилляционная установка Tunka-Grande

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Introduction

The study of energy spectrum and mass composition of primary cosmic ray particles in the energy range of 10^{16}–10^{18} eV is of crucial importance for the understanding of the origin of cosmic rays and their propagation in the Galaxy. It seems the maximum energy of cosmic rays accelerated in SN remnants to be in this energy domain [1]. As it was pointed out in [2], in this energy range the transition from Galactic to extragalactic cosmic rays occur.

One of the cosmic ray studies methods in the energy range of 10^{16}–10^{18} eV is the detection of charged particles from Extensive Air Showers (EAS). It is based on the property of primary particles to generate a cascade of secondary particles in the Earth's atmosphere. To realization (implementation) of this method, scintillation detectors or water Cherenkov detectors of charged particles are usually used.

Tunka-Grande scintillation array

The cosmic ray's studies by detecting of the EAS charged and muon component began in the Tunka Valley in 2015, when the Tunka-Grande scintillation array was put into operation.

The Tunka-Grande scintillation array contains 19 scintillation stations located on the area of the Cherenkov Tunka-133 array in a circle with a radius of ~ 400 m. The total area of the Tunka-Grande is about 0.5 sq.km.

Each scintillation station consists of surface and underground detector. The first detects all EAS charged particles at the level of array and consists of 12 counters united in 2 parts, 6 counters in each. The second, located under a layer of soil ~1.5 m thick and designed to detect muon component of EAS, consist of 8 counters, united into 4 pairs. The surface detector total area is about 8 m^2, the underground detector total area is about 5 m^2. A detailed description of the Tunka-Grande array is presented in [3, 4]. The energy and time resolution of the scintillators and description of the employed electronics are provided in [5, 6].

Data processing and reconstructing EAS parameters

During the four seasons from 2017 to 2021, there were 691 days of Tunka-Grande operation. The array trigger condition was a coincidence of any three surface detectors within 5 µs. During this period, about 3 409 000 triggering events were detected on the Tunka-Grande area over 8900 h of operation. The scintillation array also operated using triggers of the Tunka-133 Cherenkov array [7]. There were 850 h of joint operations and about 250 000 events were selected.

The first step of reconstruction from the primary data is extraction of pulse amplitude A, front delay t, and pulse area Q. The measured values of Q are used to determine a particle density in detectors and a shower core position.

The particles density in surface and underground detectors of each station is defined by the formulas:

$$\rho_e = \frac{1}{S_e} \cdot \sum_{i=1}^{2} \frac{Q_i}{Q_{MPV_i}}, \ \rho_\mu = \frac{1}{S_\mu} \cdot \sum_{i=1}^{4} \frac{Q_i}{Q_{MPV_i}}, \quad (1)$$

where i is the number of the surface detector part or number of a counter pair of the underground detector, Q_i is the pulse area, Q_{MPV_i} is the most probable value of the pulse area corresponding to the one particle level, S_i is the total area of the counters of the surface detector, S_μ is the total area of the counters of the underground detector.

The shower arrival direction parametrized by the shower axis's zenith and azimuth angles is determined by fitting the measured pulse front delay using a curved shower front formula, which is obtained in a KASCADE-Grande experiment [8]:

$$T_i - T_{th} = a \cdot \left(1 + \frac{R_i}{30}\right)^b, \quad (2)$$

where T_{th} is the theoretical delay time for a flat shower front, R_i is the perpendicular distance from the shower axis in meters. The values of the variable parameters a and b were obtained by analyzing artificial showers generated by the CORSIKA program [9]. The zenith and azimuthal angles are determined using the triangle method by the trigger times of 3 surface detectors with highest detected particle density and optimal geometry.

To reconstruct the lateral distribution of charged particles, the LDF from the EAS MSU experiment [10, 11] is used. This function takes into consideration experimental data on the distribution of particles over the distance from the EAS core position, obtained with the EAS MSU array [12]. The lateral distribution of muons is described using the Greisen function [11].

The shower core coordinates, number of muons and charged particles, and slope of the LDF are calculated in minimizing the functional using independent variables.

An effective method for estimating the energy of primary particles for an array of detectors spaced over longer distances is based on a measure of the density of charged particles at distance form EAS core close to distance between nearby measure stations. Since the typical distance between the Tunka-Grande observation stations is about 200 m as a measure of energy we use the charged particles density at a core distance of 200 meters $-\rho_{200}(\theta)$. The parameter $\rho_{200}(\theta)$ is rescaled relative to the measured zenith angle as:

$$\rho_{200}(0) = \rho_{200}(\theta) \cdot \exp\left(\frac{x_0}{\lambda} \cdot (\sec\theta - 1)\right), \quad (3)$$

where $x_0 = 960$ g/sm^2 is the atmospheric depth from sea level for the Tunka Valley, $\lambda = 260$ g/sm^2 is the average value of absorption path length obtained from experimental data.

The value of $\rho_{200}(0)$ relative to the energy can be rescaled as:

$$E_0 = 10^b \cdot (\rho_{200}(0))^a, \quad (4)$$

where $a = 0.84 \pm 0.01$, $b = 15.99 \pm 0.01$. Correlation $\rho_{200}(0)$ with the primary energy is determined using the experimental results of Tunka-133 [7] and TAIGA-HiSCORE [3] Cherenkov arrays (Fig. 1, *a*, *b*).

Comparison of the Tunka-Grande and Cherenkov facilities experimental data

The accuracy of the reconstructed shower parameters can be estimated using analysis of joint events with Tunka-133 and TAIGA-HiSCORE Cherenkov facilities (Fig. 2, *a*, *b*).

The search for joint events was performed within the time range of [–10 μs; +10 μs] in showers, detected in a circle with $R < 350$ m and the zenith angles range from 0 to 35 degrees.

a) *b*)

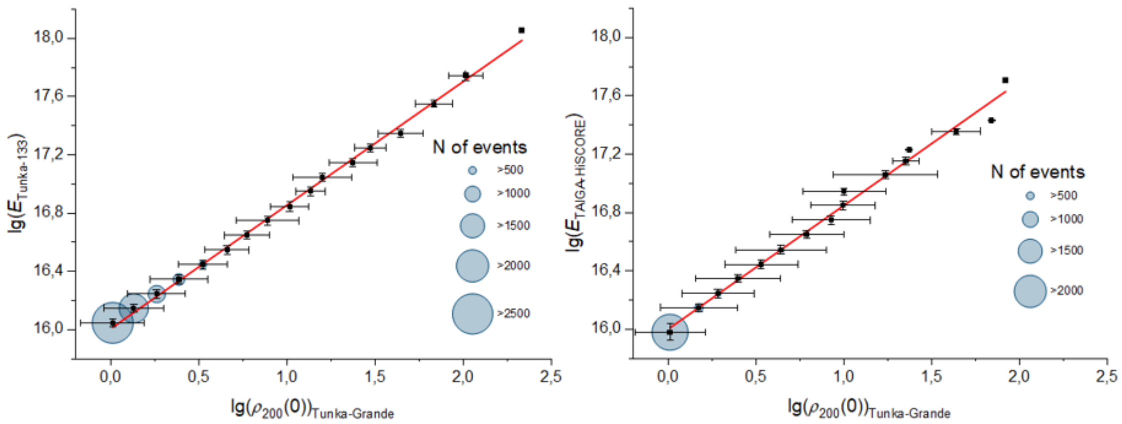

Fig. 1. Correlation $\rho_{200}(0)$ with the primary energy from the Tunka-133 (*a*) and TAIGA-HiSCORE (*b*) experimental data

The mean value of angle between EAS arrival directions reconstructed from Tunka-Grande and TAIGA-HiSCORE experimental data is about 2.5 degrees. The median value is 1.65 degrees, the most probably value of angle is 1.15 degrees (Fig. 2,*a*). The angle resolution of the Tunka-Grande array can be obtained from the distribution of the angle ψ between reconstructed by Tunka-Grande and TAIGA-HiSCORE EAS arrival directions, being defined by 68% of the events having deviations less than it does. It is 2.25 degrees.

A detailed analysis of the Tunka-Grande and Cherenkov facilities joint events is presented in [13].

The energy spectrum

To plot the spectrum events with zenith angle $\theta \le 35$ degrees and core position in a circle with radius $R < 350$ m were selected. The number of recorded events with energies above 10 PeV was about 260 000. Approximately 2100 events from them had energies above 100 PeV. The best quality of recovery of the EAS parameters and the primary energy is achieved for events inside the geometrical area of the array. The volume of statistics accumulated over 4 seasons allowed us to limit events inside the Tunka-Grande facility and exclude events whose core position was on the border and outside the array The threshold energy of 100% registration efficiency for chosen area and zenith angles is 10 PeV.

a) *b*)

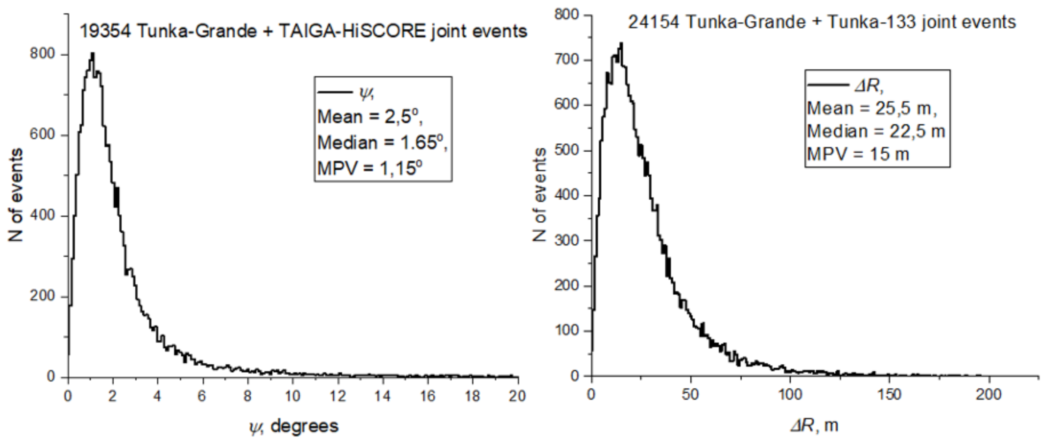

Fig. 2. The accuracy of the EAS arrival direction reconstruction by the Tunka-Grande array in comparison with data of TAIGA-HiSCORE array (*a*) and the accuracy of the EAS core position reconstruction by the Tunka-Grande array in comparison with data of Tunka-133 facility (*b*)

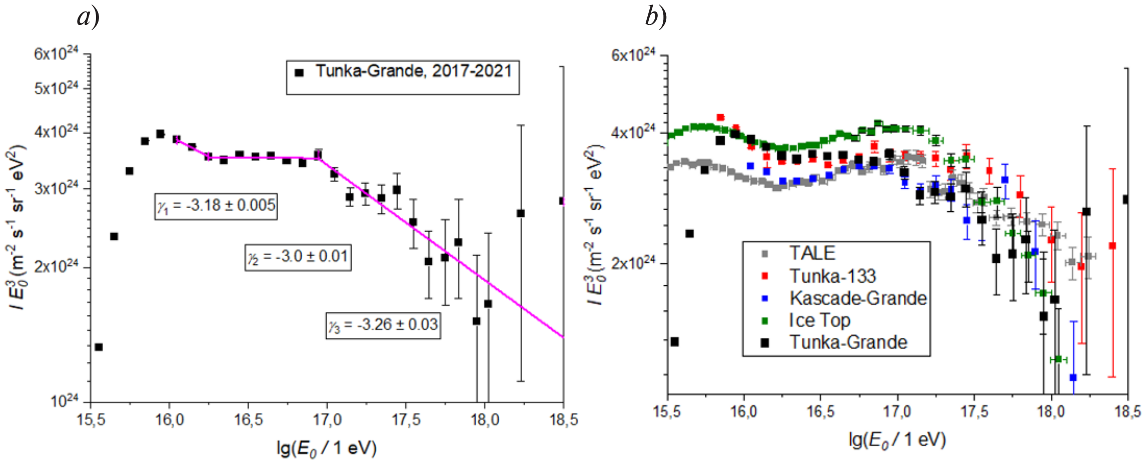

Fig. 3. Differential primary cosmic-ray energy spectrum with a fit of a doubly broken power law (*a*) and comparison of energy spectrum obtained at Tunka-Grande with some other experimental results (TALE [14], Tunka-133 [7], Kascade-Grande [15], Ice Top [16]) (*b*)

The energy spectrum beyond the first “knee” looks rather complicated. One can see that the spectrum can be fitted by power laws with three different power law indexes (Fig. 3,*a*). The value of power law index below 2 PeV is $\gamma_1 = -3.18 \pm 0.005$ and above this energy is $\gamma_2 = -3.0 \pm 0.01$. The spectrum becomes much steeper with $\gamma_3 = -3.26 \pm 0.03$ above 100 PeV (the second “knee”).

Fig. 3,*b* compiles the energy spectra obtained by different experiments. Tunka-Grande all-particle energy spectrum are compatible with the findings of most of the other experiments.

Conclusion

Applying above reconstruction method to the Tunka-Grande data, we obtained the all-particle energy spectrum based on 4 measurement seasons. The energy spectrum 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.

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