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Tunka-Grande array for high-energy gamma-ray astronomy and cosmic-ray physics: preliminary results.

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The Tunka-Grande scintillation array is a part of the TAIGA experimental complex designed for high-energy gamma-ray astronomy and cosmic-ray physics. In this work methods of reconstruction of primary particles parameters are presented, as well as the accuracy of reconstruction of the EAS core position, energy, and arrival direction, obtained by comparing the reconstruction results with the data of the Tunka-133 and TAIGA-HiSCORE Cherenkov arrays. The preliminary all-particle energy spectrum based on 3 operation seasons of the installation is presented.

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1. Introduction

The Tunka-Grande scintillation array is a part of the TAIGA hybrid experimental complex [1] designed for high-energy gamma-ray astronomy and cosmic-ray physics. It contains 19 scintillation stations located on the area of the Tunka-133 Cherenkov array [2] in the circle with a radius of about 400 meters. The total area of the Tunka-Grande is about 0.5 km^2. The altitude above sea level is about 670 meters. Each station is composed of two parts: one on the Earth's surface and one underground. The surface part, which consists of 12 counters, covers a total area of about 8 m^2 and detects EAS charged particles at the level of the array. The second part which consists of 8 counters with a total area of about 5 m^2, is under a layer of soil 1.5 meters deep and is designed to separate the EAS muon components. Both parts of the array are near to each other.

The main tasks of the Tunka-Grande array are:

- the study of the energy spectrum and mass composition of cosmic rays in the energy range from 10 PeV to 1 EeV;
- search for diffuse gamma rays with energy above 10 PeV.

It is, also, interesting to estimate the possibility of using the Tunka-Grande array to study the mass composition and search for gamma rays with energies below 10 PeV. To this task, the search for joint events was conducted using independent experimental data from Tunka-Grande and TAIGA-HiSCORE [3] arrays.

2.Data processing and reconstructing EAS parameters

During the three seasons from 2017 to 2020, there were 542 days of Tunka-Grande operation. The array trigger condition was a coincidence of any three surface detectors within 5 μs. During this period, about 2950000 triggering events were recorded on the Tunka-Grande area over 8080 h of operation. The scintillation array also operated using triggers of the Tunka-133 Cherenkov array. During the three seasons, there were 787 h of joint operations and about 252000 events were selected.

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

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 [4]: $T_i - T_{th} = a(1 + R_i/30)^b$, 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 [5].

To reconstruct the lateral distribution of charged particles, the LDF from the EAS MSU experiment [6,7] 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 [8]. The lateral distribution of muons is described using the Greysen function with fixed parameters a and R and variable parameter b [7].

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

As a measure of energy, we use the charged particles density at a core distance of 200 meters – ρ_{200}. The parameter ρ_{200} is rescaled to the vertical direction relative to the measured zenith angle as:

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

there x_0 = 960 g/sm^2 is the atmospheric depth from sea level for the Tunka Valley, λ = 206 g/sm^2 – obtained from experimental data average value of absorption path length.

The value of $\rho_{200}(0)$ relative to the energy can be rescaled as $E_0 = 10^b \cdot \left(\rho_{200}(0)\right)^a$, where $a = 0.87 \pm 0.01$, $b = 16.0 \pm 0.01$. Correlation $\rho_{200}(0)$ with the primary energy is determined using the experimental results of TAIGA-HiSCORE array. For this, the search for joint events from the independent experimental data of the Tunka-Grande and TAIGA-HiSCORE arrays was carried out. The energy value was taken from the TAIGA-HiSCORE experimental data and the $\rho_{200}(0)$ parameter value - from the Tunka-Grande experimental data (Fig.1).

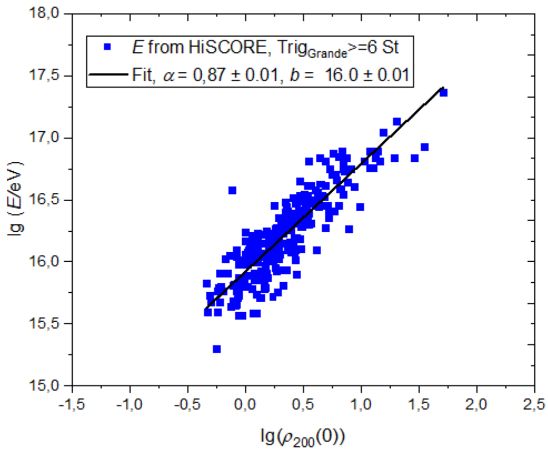

Fig.1. Correlation $\rho_{200}(0)$ with the primary energy from the TAIGA-HiSCORE experimental data

3. Energy spectrum

To plot the energy spectrum according to the results from processing the data collected by the Tunka-Grande facility, events with zenith angles $\theta \leq 45°$ and axial positions in a circle with radius R < 400 m were selected for energies $E_0 < 10^{17}$ eV, and in a circle with radius R < 600 m for showers with energies $E_0 \geq 10^{17}$ eV. A comparison of the spectra for the circle with radius R < 400 m and ring with inner radius R > 400 m and outer radius R < 600 m showed them to coincide within the limits of error, starting with the energy 10^{17} eV and up. The events with energy $E_0 > 10^{17}$ eV detected in the ring were naturally 1.25 times more numerous than in the circle. The efficiency of event selection was approximately 100% for energies E_0 > 20 PeV. The total number of events with energies higher than this was around 350000. Some 8070 events had energies over 10^{17} eV. The combined differential energy spectrum, reconstructed based on these results, for events with R < 400 m for $E_0 < 10^{17}$ eV and with R < 600 m for higher energies, is presented in Fig. 2. From energy of about 20 PeV to 300 PeV, the spectrum can be fitted by power law with index $\gamma = 2.99 \pm 0.01$. At high energies, the power-law index grows abruptly to γ = 3.33 ± 0.09 (a second knee). The spectrum is compared to results from Tunka-133

Cherenkov array [9]. The spectra of both experiments are practically indistinguishable at the energy range $2 \cdot 10^{16}$–$5 \cdot 10^{18}$ eV.

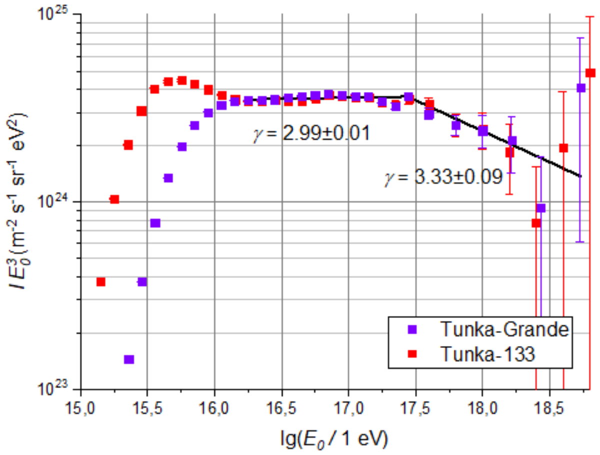

Fig.2. Differential primary cosmic-ray energy spectrum (multiplied by factor E^3) with a fit of power-law. Comparison with the Tunka-133 experimental data

A comparison of the Tunka-Grande spectrum with the results of other experiments is presented in Fig. 3.

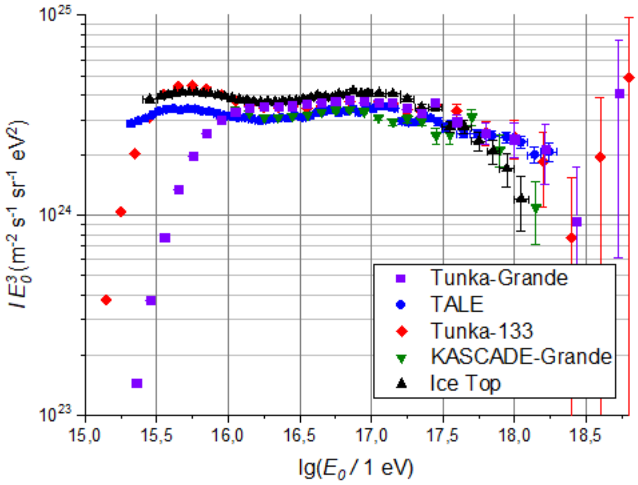

Fig.3. Primary energy spectrum: comparison with some other experimental data

The spectrum of this work in the range of 20 PeV–1EeV coincides with those collected by the KASCADE-Grande [10], TALE [11] and IceTop [12] facilities. The spectra reproduce the same structures. The difference between these spectra and one, acquired at the Tunka-Grande array, in the range of 20 – 100 PeV can be eliminated by raising the KASCADE-Grande and TALE energy estimate by 3% and reducing the IceTop estimate by the same amount. These changes are much lower than the absolute accuracy of the experiments.

4.Estimating the accuracy of the main EAS parameters experimentally

Since modeling an experiment to allow for all possible measurement errors is a very complicated task, it is of interest to estimate experimentally the errors in determining the EAS parameters. Simultaneous registration of showers by two independent arrays makes such estimates possible. The TAIGA-HiSCORE and Tunka-133 Cherenkov arrays demonstrate good performance and high reliability of equipment. Therefore, to determine the accuracy of the reconstruction of the EAS parameters measured with the Tunka-Grande array, the EAS parameters reconstructed from experimental data of both Cherenkov facilities are used.

The search for joint events was performed within the time range of minus plus 10 microseconds in showers, detected in a circle with $R < 400$ m.

The TAIGA-HiSCORE Cherenkov array energy threshold is 0.2 PeV, which is significantly lower than the energy threshold of Tunka-Grande array (20 PeV). But the search for joint events of the Tunka-Grande and TAIGA-HiSCORE arrays gave positive results in this energy range. The largest number of "Grande - HiSCORE" joint events is concentrated in the range of azimuth angles from minus 65 to 45 degrees and the zenith angles range from 15 to 35 degrees (Fig 4, *left*). This is since all HiSCORE Observation Stations are tilted southward by 25 degrees to increase the time of observation of the gamma-ray source in the Crab Nebula. The mean value of the time difference between Tunka-Grande and TAIGA-HiSCORE joint events is about 3.7 microseconds (Fig 4, *right*).

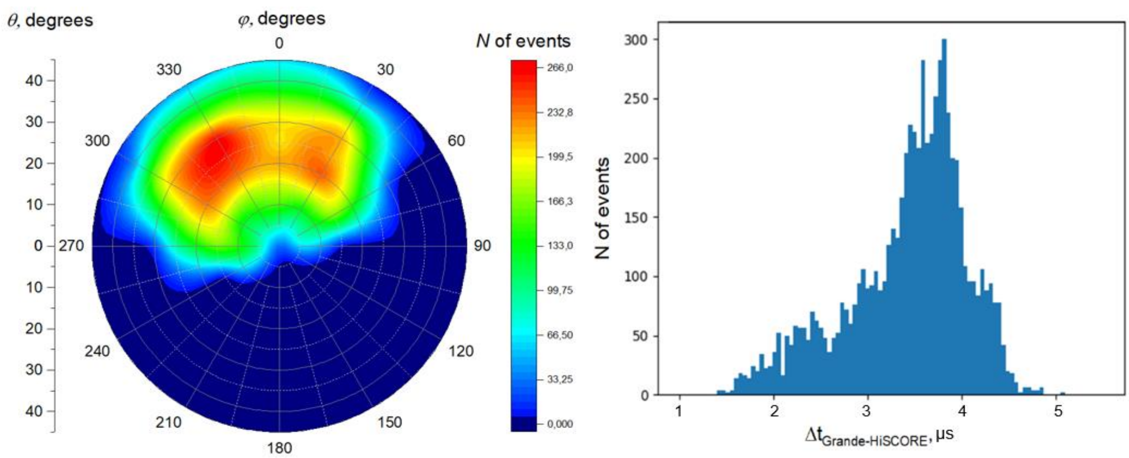

Fig 4. Tunka-Grande and TAIGA-HiSCORE joint events. Left: Angular joint events distribution. Right: time difference between joint events

The Figure 5 shows the accuracy of the reconstruction of zenith and azimuth angles measured with the Tunka-Grande array in comparison with data of TAIGA-HiSCORE facility. The standard deviation is 1.32° for the zenith angle and is 1.3° for the azimuth angle. The average angle value between EAS arrival directions reconstructed from Tunka-Grande and TAIGA-HiSCORE experimental data is 1.54°.

The standard deviation of the ratio between the shower energies, reconstructed from the data of the Tunka-Grande and TAIGA-HiSCORE arrays, is 20% for joint events with 3 and more Tunka-Grande triggered stations and 18% for joint events with 4 and more Tunka-Grande triggered stations.

The comparison of Tunka-Grande and Tunka-133 experimental data was made by events detected by Tunka-Grande array under the Tunka-133 array trigger. This allowed us to estimate the scintillation array errors at the reconstruction of EAS core position, arrival direction, and energy for events with energies above 20 PeV. The average differences between Tunka-Grande and Tunka-133 shower core coordinates are <X> = 2.5 m and <Y> = 5.39 m, the standard deviation is σ = 21.5 m for X-coordinate and is σ = 22.5 m for Y-coordinate (Fig. 6).

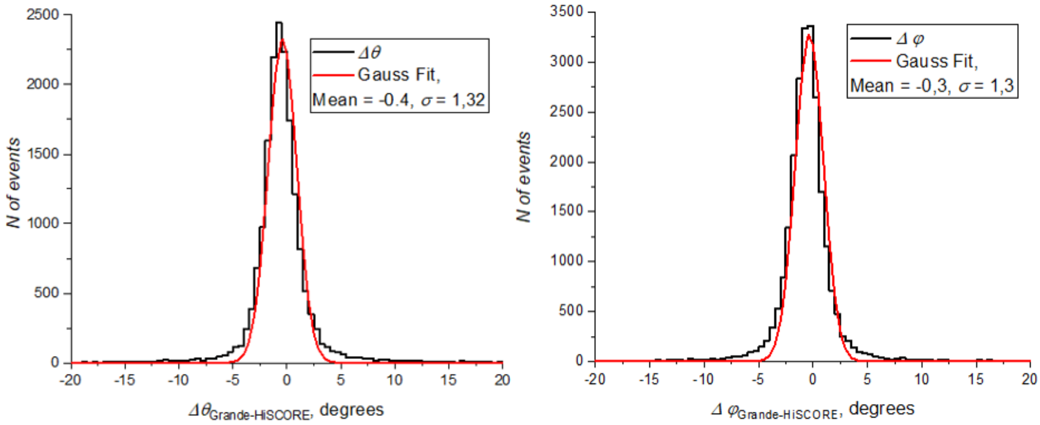

Fig 5. The accuracy of the arrival direction reconstruction by the Tunka-Grande array in comparison with data of TAIGA-HiSCORE array

The average angle value between EAS arrival directions reconstructed from Tunka-Grande and Tunka-133 experimental data is 1.5°, the square deviation is 1.3° for the zenith angle and is 1.3° for the azimuth angle.

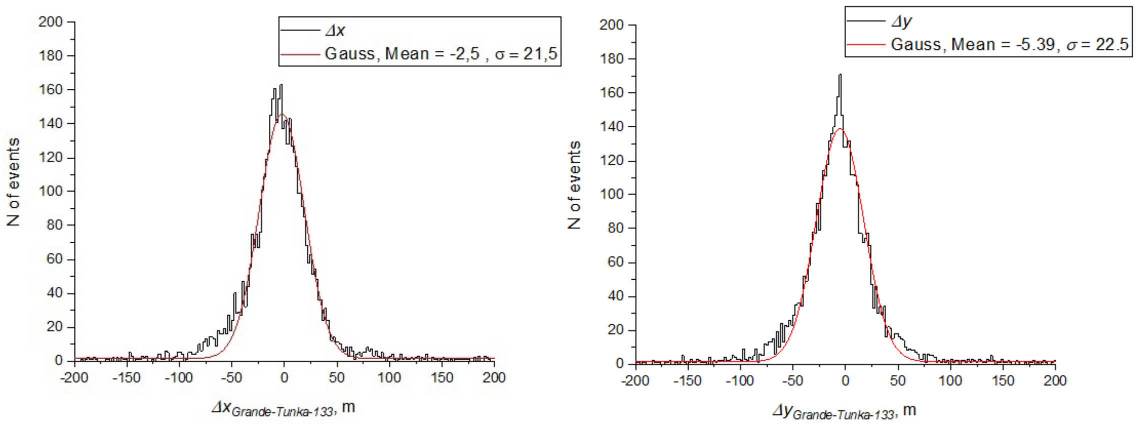

Fig 6. The accuracy of the EAS core position reconstruction by the Tunka-Grande array in comparison with data of Tunka-133 array

The standard deviation of the ratio between the shower energies, reconstructed from the data of the Tunka-Grande and Tunka-133 arrays, is 18% for joint events with 3 and more Tunka-Grande triggered stations and 12 % for joint events with 6 and more Tunka-Grande triggered stations.

5.Conclusion

The primary cosmic-ray energy spectrum based on 3 Tunka-Grande operation seasons was reconstructed. The spectrum in the energy range of 2×10^{16}–10^{18} does not obey the unified power law but has a number of characteristic features: at the energy range 2×10^{16} - 3×10^{17} eV, the value of the power spectrum index is $\gamma = 2.99 \pm 0.01$. At higher energies, the spectral index rises sharply to $\gamma = 3.33 \pm 0.09$ (the second knee). In the energy range of 10^{16}–10^{17} eV, the agreement is observed between the results of this work and the spectra obtained by the Kaskade Grande [10], TALE [11] andIce TOP [12] arrays.

The search for joint events of the Tunka-Grande and TAIGA-HiSCORE arrays gave positive results. The presence of such events indicates the possibility of joint analysis of the data of the scintillation experiment and the Cherenkov facilities for the study of mass composition and gamma-hadron separation at energies below 10 PeV.

6.Acknowledgments

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