

Cosmic Ray Energy Spectrum and Mass Composition from 10^{15} to 10^{17} eV by Data of the Tunka EAS Cherenkov Array

N. M. Budnev^b, D. V. Chernov^a, O. A. Gress^b, T. I. Gress^b, E. E. Korosteleva^a,
L. A. Kuzmichev^a, B. K. Lubsandorzhiiev^c, L. V. Pankov^b, Yu. V. Parfenov^b,
V.V. Prosin^a, Yu. V. Semenyev^b, Ch. Spiering^d, R. P. Wischniewski^d and I. V. Yashin^a

(a) Skobel'syn Institute of Nuclear Physics, Moscow State University, Russia

(b) Institute of Applied Physics, Irkutsk State University, Irkutsk, Russia

(c) Institute of Nuclear Research, Russian Academy of Science, Moscow, Russia

(d) DESY, Zeuthen, Germany

Presenter: V.V. Prosin (prosin@dec1.sinp.msu.ru), rus-prosin-VV-abs2-he12-oral

We present results of an improved analysis of the experimental data of the EAS Cherenkov array Tunka-25. A new function to fit the Cherenkov light lateral distribution LDF at core distances from 0 to 350 m has been developed on the base of CORSIKA simulations and applied to the analysis of Tunka data. Two methods to estimate the EAS maximum position have been used. The one is based on the pulse FWHM, the other on the light LDF. We present the primary energy spectrum in the energy range 10^{15} - 10^{17} eV. The use of the depth of the EAS maximum to determine the mean mass composition is discussed.

Tunka-25: Experiment and Simulations

The Tunka EAS Cherenkov array is located in Tunka Valley, at an altitude of 675 m a.s.l., and was described in Ref. [1].

Extensive air showers in an energy range $3 \cdot 10^{14}$ to $2 \cdot 10^{16}$ eV have been simulated with CORSIKA. The total amount of 600 CORSIKA events has been simulated for primary protons and iron nuclei and for three zenith angles 0° , 15° and 25° . The LDF consists of two branches: one almost exponential from the core to some distance R_{kn} , the other following a power law from R_{kn} up to 350 m:

$$Q(R) = \begin{cases} Q_{kn} \cdot \exp((R_{kn} - R) \cdot (1 + 3/(R + 3))/R_0), & \text{for } R < R_{kn} \\ Q_{kn} \cdot (R_{kn}/R)^b, & \text{for } R \geq R_{kn} \end{cases} \quad (1)$$

$$R_0 = 10^{2.95 - 0.245P}, m$$

$$R_{kn} = 155 - 13P, m$$

$$b = 1.19 + 0.23P$$

The main difference to the expression suggested in [2] is the use of variable power law index for the second branch. All three partial parameters defining the LDF shape, R_0 , R_{kn} and b , are strict functions of a single steepness parameter P , defined as the ratio of Cherenkov light fluxes at core distances 100 and 200 m: $P = Q(100)/Q(200)$.

Examples of fitting the simulated LDF with equation 1 for different parameters P are shown in fig.1. The parameter P and the light flux at a fixed core distance 175 m, Q_{175} , have been determined for every simulated event.

The essential correlations of parameter pairs E_0 and Q_{175} , E_0 and H_{max} , H_{max} and P , and the standard deviations of their distributions, separately for p and Fe , have been extracted from this CORSIKA simulation

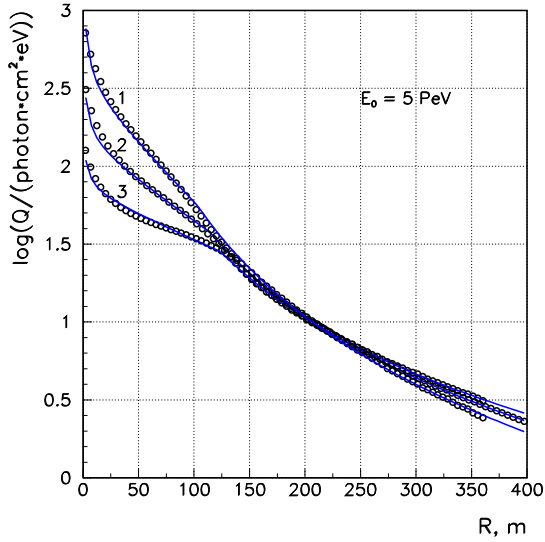


Figure 1. CORSIKA: EAS Cherenkov light LDFs and fitting functions. 1 - $P = 5$, 2 - $P = 4$, 3 - $P = 3$

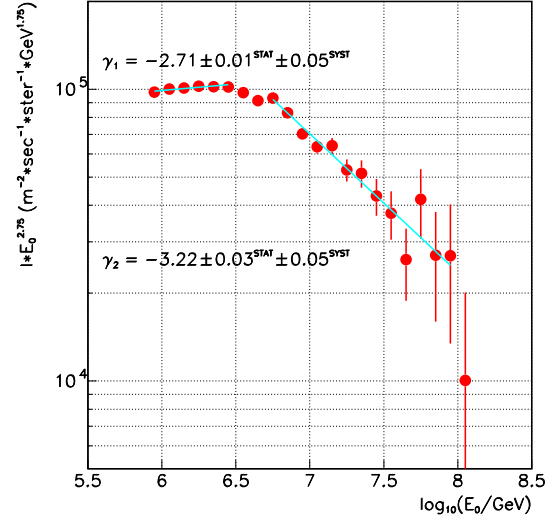


Figure 2. EXPERIMENT: Differential energy spectrum.

in order to use them in a special code called "model of experiment". Two intermediate nuclear groups, corresponding to primaries He and CNO have been added to the "model" using an interpolation of parameters, obtained for p and Fe . The real geometry of the array and the response of every detector and its fluctuations are taken into account in the model. The "model of experiment" permits a fast generation of $10^4 - 10^5$ artificial events, distributed with a realistic energy spectrum, for different assumptions concerning the primary mass composition. It allows to analyse the array response, including the analysis of details of the program of EAS parameter reconstruction, the efficiency of registration of EAS, the threshold of the total array, errors and possible distortions of the reconstructed energy E_0 , and the depth of the shower maximum X_{max} .

The "model of experiment", assuming a complex mass composition (p:He:CNO:Fe=0.25:0.25:0.25:0.25), has shown that for energies $> 3 \cdot 10^{15}$ eV, our procedures of relative calibration of the detectors and the EAS parameter reconstruction result in accuracies of primary energy determination of $\sim 15\%$, of the core position of ~ 5 m and of X_{max} of ~ 30 g/cm². For energies below $3 \cdot 10^{15}$ the errors are larger. The threshold of data acquisition with 100% (50%) efficiency is $8 \cdot 10^{14}$ eV ($5 \cdot 10^{14}$ eV). Some other conclusions of the "model" will be discussed later.

Primary Energy Spectrum

The primary energy E_0 [TeV] has been obtained from Q_{175} [photon \cdot cm⁻² \cdot eV⁻¹] with the relation:

$$E_0 = 400 \cdot Q_{175}^{0.95}.$$

The absolute energy calibration is based on the results obtained with the QUEST experiment [3].

Figure 2 presents the differential energy spectrum, derived from data taken in 300 hours, spread over about 50

clear, moonless nights, with a trigger rate above 1.8 Hz . To construct a spectrum, showers with zenith angles $\theta \leq 25^\circ$ and a core position inside the geometrical area of the array have been selected.

We note that particularly at the lowest and the highest energies, the new fit functions performs significantly better than that used in [4].

Depth of the EAS Maximum

The lateral and the time distributions of the Cherenkov light provide two independent methods to estimate the depth of the EAS maximum. The first is the measurement of the LDF steepness P , which is related to the distance to the shower maximum by the expression H_{max} (in [km]): $H_{max} = 17.63 - 0.0786 * (P + 8.916)^2$. This relation is almost independent of other details of the simulation: energy, sort of nucleus, zenith angle and model of hadron interaction. The distribution of H_{max} for a fixed P has a standard deviation of only 0.3 km.

The depth of the EAS maximum X_{max} is derived from H_{max} using the atmosphere parameters consistent with really observed (the mean temperature during the observations is -20°C). The "model of experiment" gives an error of 30 g/cm^2 for the experimental depth of the EAS maximum X_{max} .

The second method is measuring the Cherenkov pulse full width on half maximum (FWHM). In accordance with CORSIKA simulations as described above, the FWHM [ns] at distances larger than 200 m from the EAS axis is related to the relative position of the EAS maximum: $\Delta X = X_0 / \cos \theta - X_{max} [\text{g/cm}^2]$, – where X_0 is the total depth of the atmosphere and θ is the zenith angle of the shower. The relation between FWHM and ΔX depends only on the distance to the EAS axis, and is almost independent on the other details of the simulation: energy, sort of nucleus and model of hadron interaction. For example, for a distance of 250 m, one obtains $\Delta X = 1677 + 1006 \cdot \log_{10}(\text{FWHM})$. The underlying theoretical uncertainties for this method are smaller than for the first one.

Figure 3 presents the mean depth of the EAS maximum, derived with the two methods described above, as a function of primary energy. The "model of experiment" shows that there is no influence of the array threshold on the obtained X_{max} , starting from an energy $1.5 \cdot 10^{15} \text{ eV}$. It is seen from fig.3 that the threshold of the FWHM method is higher than that of the LDF steepness method, but the mean depths, obtained with the two different methods are in good agreement. Both methods result in large fluctuations of mean points at low statistics (high energy), as expected for a very asymmetric distribution like that of X_{max} .

Experimental X_{max} distributions for EAS in the energy range 3 – 10 PeV are shown in fig 4. All the values of X_{max} are re-normalized to a fixed energy of $5 \cdot 10^{15} \text{ eV}$, using an experimental elongation rate of $(97 \pm 3) \text{ g/cm}^2$. The experimental distribution is compared to distributions simulated with the "model of experiment", for different assumptions on primary composition, and re-normalized in the same way as the experimental one. The agreement with experimental data is better for the complex composition (p:He:CNO:Fe=0.25:0.25:0.25:0.25), than for pure p or Fe . So the intermediate mass composition is more probable, but it should be noticed that the difference between simulated and experimental standard deviation is significant only for pure p or Fe . For a wide range of intermediate compositions, mixtures of mass components lead to standard deviations similar to those marked as "complex" in the figure.

The mean value of the simulated distribution depends on hadron interaction model. In fig. 3, X_{max} vs. energy is displayed for two models QGSJET-01 [5] and QGSJET-II [6]. All other models used in CORSIKA yield lines between these borders [7].

One sees, that a conclusion about the mean mass composition strongly depends on the chosen hadron interaction model. To solve the problem with the model the measurement of energy dependence of X_{max} in much

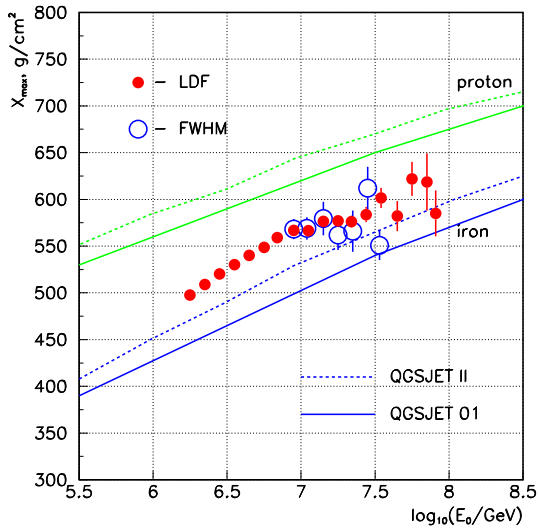


Figure 3. Mean depth of EAS maximum vs energy.

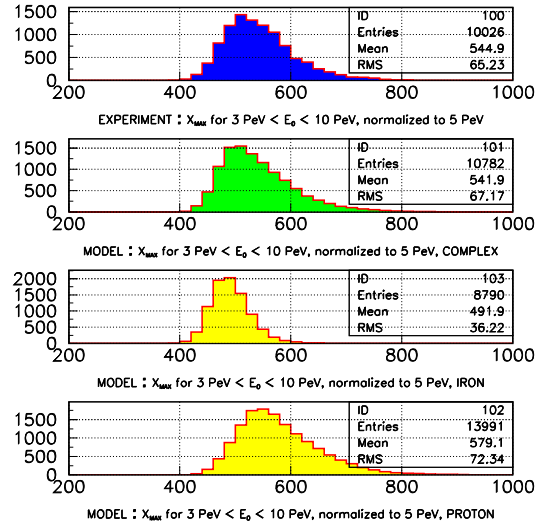


Figure 4. X_{max} distribution.

wider energy range is very essential. This is one of the reasons of our decision to spread our measurement to lower energy with the new version of Tunka-25 Cherenkov light detectors supplied with spheric mirrors of 1 m diameter. To the other hand the new experiment Tunka-133 [8] with effective area 10 times higher than that of Tunka-25 is under construction in Tunka valley.

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