The cosmic rays energy spectrum of the Yakutsk EAS Array

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***Abstract*. The energy spectrum obtained on the Yakutsk array for the parameter S_{600} is compared with the results obtained on the AGASA and HiRes arrays and the latest Pierre Auger Observatory data. The discrepancy in the intensity of the energy spectra obtained in different experiments can be explained by the presence of systematic errors in shower energy estimations.**

***Keywords*: Energy Spectrum, GZK - cutoff**

I. Introduction

Study of the cosmic ray (CR) energy spectrum and establishment of its cutoff, predicted by Greisen [1] and Zatsepin and Kuzmin [2] (GZK cutoff), remain to be the most important problems for detecting CR sources at energies above 10^{19} eV. Four extensive air showers (EASs) with energies above the cutoff threshold have been detected on the Yakutsk EAS array [3]. The data of AGASA array (where 11 showers with energies above 10^{20} eV were registered) indicate the absence of cutoff in the spectrum . In the new Auger experiment, a record exposure has been reached and a spectrum cutoff was evidenced [5], which is in agreement with the HiRes results [6]. The spectra below 10^{20} eV obtained in all these experiments have a similar shape but significantly different intensities. This contradiction is most likely to be caused by the systematic difference in the energy estimates for individual showers in different experiments.

II. Determination of EAS energy

On EAS arrays, the primary-particle energy E_0 is estimated from the experimentally determined basic parameter. Such a parameter for the Yakutsk array is the density S_{600} at a distance of 600 m from the shower core. On the arrays similar to the Yakutsk array, the relation between the basic parameter and primary energy E_0 at the atmospheric depth X_0 , corresponding to vertical showers ($\theta = 0°$), is generally found. To estimate E_0 in events with zenith angles $\theta > 0°$, the found parameter value is recalculated to the vertical level from the zenith angle dependence.

Three main components are measured on the Yakutsk EAS array: charged-particle flux, Cherenkov light, and muon component. This circumstance allowed us to estimate energy by the calorimetric method and obtain a relation between S_{600} at $\theta = 0°$ and E_0 [7] from the experimental data with a minimum dependence on the development model. This method is based on experimental estimation of the energy dissipated by a shower above the observation level from the measured EAS Cherenkov light. This energy fraction exceeds 70% of the total energy.

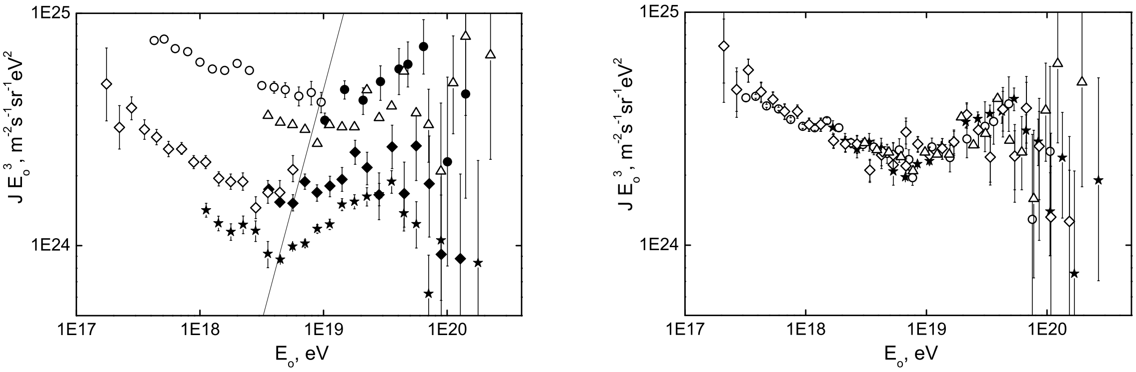
For the events recorded during operation of Cherenkov light detectors, the parameter Q_{400} (Cherenkov flux density at a distance of 400 m from the shower core) was used to parameterize showers.

The error in determining the energy in individual events is affected by many factors. Some of them are random; however, there are systematic errors, which significantly influence determination of the energy spectrum intensity and shape. It was found in [8] that the relative systematic error in estimating energy on the Yakutsk array for vertical showers above 10^{19} eV is 25-26%. For a zenith angle of $\approx 60°$, it reaches 30%. The dominant contribution is from the uncertainty in absolute calibration of the Cherenkov light detectors and the error in determining the average transparency of atmosphere. However, this contribution is the same for all showers and does not affect the spectral shape but only leads to an energy shift of the entire spectrum. This fact significantly affects the estimated intensity at a certain energy. Other factors may lead to some change in the spectral shape.

A similar procedure for estimating the energy in showers is used on the AGASA array. The basic parameter is S_{600}. The experimental zenith angle dependence $S_{600}(\theta)$ is used for recalculation at a depth of $920 g{\cdot}cm^2 (\theta = 0°)$. The relation of the parameter $S_{600}(0°)$ with the primary energy was determined from model simulation. It was found in [9] that the systematic error in determining energy may amount to 18%.

At the HiRes array, the fluorescence from ionization of air atoms by EAS particles is measured with telescopes. These data are used to reconstruct the cascade curve of electrons and find the number of particles in the shower maximum. The measured signal is proportional to the ionization loss of shower electrons.The energy transferred to other components is estimated using model simulation. According to the HiRes collaboration estimates [6], the systematic error in determining energy is about 15%.

The Auger project uses both methods for recording showers. A ground-based array of thick water detectors occupies an area of $3000 km^2$. The distance between neighboring detectors is 1600 m and the area of each



(a) Original data

(b) after energy correction

Fig. 1: Differential energy spectrum according to the data of the (circles) Yakutsk [3], (triangles) AGASA [4], (asterisks) Auger [5], and (diamonds) HiRes [6] arrays. (b) Energy spectrum after the energy correction: $E_C = K \times E_0; K = 0.75$ (Yakutsk), 0.87 (AGASA), 1.2 (HiRes), and 1.5 (Auger).

detector is $10m^2$. The fluorescence produced by the showers falling in the ground-based array area is simultaneously measured with four telescopic systems. The energy is estimated from optical data in the same way as at the HiRes array.

The response in units of an equivalent vertical muon at a distance of 1000 m from the shower core, $S(1000)$, is used as the basic parameter for the data from ground-based detectors. An experimental zenith angle dependence of this parameter has been obtained. This dependence is used to derive from $S(1000)$ the parameter S_{38} in individual showers, which corresponds to the atmospheric depth for the zenith angle $\theta = 38°$ [5]. The relationship between S_{38} and the energy measured by fluorescence detectors is found from the common events. The systematic uncertainty of this energy scale is 22%.

III. Energy spectrum

Figure 1a shows the energy spectra registered on the Yakutsk [3], AGASA [4], Auger [5], and HiRes [6] arrays. The shapes of the energy spectra from different arrays are in good agreement; however their intensities significantly differ. The Auger and HiRes spectra are cut off for the most statistically provided data, a feature indicating the existence of the GZK cutoff. However, 11 events with energies above 10^{20} eV ($\theta < 45°$) have been detected on the AGASA array; i.e., the cutoff is absent. The Yakutsk array data are in better agreement with those of AGASA. Four events with energies above the cutoff threshold have been detected on the Yakutsk array.

It can be seen in Fig. 1a that the spectra of all arrays have characteristic features (dip and bump) and are in good agreement below 10^{20} eV. The oblique line shows the shift of a point on the plot in the coordinates used with a change in the estimated energy. It can be seen that dip position for all arrays only slightly deviates from this straight line. Figure 1b shows the spectra obtained by changing the energy estimates (multiplying the initial values by a coefficient K). The following values were used: K = 0.75 (Yakutsk), 0.87 (AGASA), 1.2 (HiRes), and 1.5 (Auger). The thus corrected results of the three experiments are in good agreement in the entire energy range, except for the AGASA data above 10^{20} eV. To put the intensities from all arrays into correspondence, a correction exceeding the specified systematic uncertainty by a factor of 2 was used for only the Auger data. The correction coefficients for other experiments were taken to be close to the systematic error in determining energy for each array.

According to the calculations of Berezinsky et al. [10], the observed features may arise in the energy spectrum if particles of extragalactic origin dominate in CRs above 10^{18} eV. Such a shape of the spectrum is explained by the energy loss on pion photoproduction and formation of electronpositron pairs on the relic radiation. In this case, protons should dominate in the spectrum. It was concluded in [10] that the most likely sources are active galactic nuclei.

IV. Conclusions

The discrepancy in the intensities of the energy spectra obtained in different experiments can be explained by the presence of systematic errors in the estimated shower energies. The HiRes and Auger data indicate the relic cutoff of the CR spectrum. This fact and the presence of a dip in all experiments suggest that protons from extragalactic sources dominate in the spectrum even at energies above 10^{18} eV. However, this suggestion is inconsistent with the Yakutsk array data on the muon component behavior in the showers above 10^{19} eV [8]. The muon fraction in this region increases with an increase in energy. In the most inclined showers at $E_0 > 2 \cdot 10^{19}$ eV, the responses of the muon the same as ground-based detectors in a wide range of distances. These results may indicate the occurrence of new processes upon interactions of particles with such energies. If this is true, the estimated energy of the most intense showers may be incorrect for all arrays. The contradictictory data from different arrays on the existence of particles above the GZK cutoff can be related to unknown features of development of EASs produced by such particles.

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