Giant air shower properties and the problem of primary particle energy estimation

M. I. Pravdin, A. V. Glushkov, A. A. Ivanov, V. A. Kolosov,
S. P. Knurenko, I. T. Makarov, Z. Ye. Petrov, A. V. Sabourov,
I. E. Sleptsov, G. G. Struchkov

Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 678980 Yakutsk, Russia

Abstract

This paper considers the problem of energy spectrum GZK-cutoff and disagreement in intensity estimated for ultra-high energy cosmic ray obtained in different experiments. Main errors in energy estimation for individual showers have been analyzed. At the Yakutsk EAS array it was experimentally discovered that in showers with energy $> 10^{19}$ eV muon portion is higher than following from lower energy approximation. This is possibly connected with the appearance of new processes in interaction of particles with such energies, which result in significant increase of energy potion from primary particle transferred into muon component. The influence of this effect on the energy estimation for giant showers in different experiments is discussed.

Introduction

Estimation of particle intensity for energies above the cut-off predicted by Greizen, Zatsepin and Kuzmin [1,2] (the GZK-cutoff) still remains one of the most important problems in search for the sources of cosmic rays with energies above 10^{19} eV. Inspite of long-term studies, the presence or absence of GZK-cutoff is yet not established definitively. There are 4 events registered at the Yakutsk EAS array [3] with energy above the cutoff level [4]. It indicates the absence of the spectrum cut-off, but due to poor statistics and uncertainties in energy determination, the reliability of conclusion made from only these data is low. There are evidence of spectrum cut-off absence in the data from AGASA where 11 showers with energy $> 10^{20}$ eV were registered [5]. But HiRes collaboration obtained opposite result — the spectrum is cut off above 3-5 $\cdot\, 10^{19}$ eV [6]. The exposition of new Auger experiment has already exceeded AGASA's [7]. No events with energy $> 10^{20}$ eV have been registered yet by the particle detector array.

Spectrum shapes obtained in these experiments correspond well up to 10^{20} eV but intensities substantively differ. The most likely explanation for such a controversial results is systematic inequality of energy estimation for individual showers in different experiments. This is why it is so important to investigate every possible systematic and random error in shower parameters determination and in final energy estimation.

1 Energy determination at the Yakutsk EAS array

In EAS experiments the energy of primary particle is estimated from the basic parameter determined in given experiment. For the Yakutsk EAS array such parameter is density at 600 m distance from the shower axis — S_{600}. Usually at arrays similar to Yakutsk a correlation between the basic parameter and primary energy E_0 at the atmospheric depth X_0 (corresponding to vertical shower with $\theta = 0°$) is calculated. To estimate E_0 for events with zenith angles $\theta > 0°$ the determined value of the parameter is recalculated to vertical level using zenith angular dependency. In most experiments this dependency is obtained using simulation results. At the Yakutsk EAS array three basic components are measured: charged particle flux, Čerenkov light and muon component. This allows using of calorimetric method for energy estimation and obtaining of correlation between S_{600} and E_0 [8] from experimental data with minimal shower development model dependence.

Calorimetric method

The base of this method is experimental estimation of energy dissipated by the shower at observation level using EAS Čerenkov radiation measurement. Showers with $\theta < 20°$ were divided into groups by different S_{600} values. The full energy E_0 in separate group is expressed as sum of several components:

$$E_0 = E_i + E_{\mathrm{el}} + E_\mu + E_{\mu\mathrm{i}} + E_\nu + E_{\mathrm{h}},$$

where:

E_i — energy loss of the shower at observation level, amounts about 70 % and is estimated using full Čerenkov radiation flux measurements;

E_{el} — energy transferred below the array level, estimated by charged particle absorption versus atmospheric depth;

$E_\mu + E_{\mu\mathrm{i}}$ — muon component energy is estimated by full muon number at observation level;

$E_\nu + E_{\mathrm{h}}$ — neutrino energy and nuclear reactions in the atmosphere are added upon the simulation results (5 %).

From the data obtained for vertical showers a relation between E_0 and S_0 (which corresponds to particle density at 600 m from the axis at atmospheric depth $X_0 = 1020\,\mathrm{g}\cdot\mathrm{cm}^2$ and $\theta = 0°$) was determined:

$$E_0 = (E_1 \pm \delta E_1) \cdot S_0^{k \pm \delta k}, \tag{1}$$

where $E_1 = 4.6 \times 10^{17}$ eV, $\delta E_1 = 1.2 \times 10^{17}$ eV, $k = 0.98$, $\delta k = 0.02$.

Experiment data are given on fig. 1. The line on the plot corresponds to equation (1).

Zenith angular dependence of S_{600}

To determine primary energy for individual events using equation (1) it is necessary to obtain S_0 value (recalculate to $\theta = 0°$) from S_{600} for given θ value using corresponding dependence. To determine zenith angular dependence a variation of S_{600} versus θ with fixed energy was studied. For this purpose we used two methods. In the first one an equal intensities in spectra for different zenith angle interval were fixed (equi-intensity method). In second one experimental parameter Q_{400} — Čerenkov radiation flux density at 400 m from the axis — was involved in energy determination. Q_{400} appears to be good equivalent of the primary energy being θ-independent if atmospheric light absorption is taken into account.

The contribution to scintillation detectors response is made by electrons and muons. Electron component in the atmosphere dissipates faster than muon one. Therefore we proposed that real change of S_{600} versus atmospheric depth should be described by sum of soft and hard components with different exponential absorption length:

$$S_{600}(\theta) = S_0 \cdot \left((1 - \beta) \cdot \exp \frac{X_0 - X}{\lambda_{\mathrm{e}}} + \beta \cdot \exp \frac{X_0 - X}{\lambda_\mu} \right), \tag{2}$$

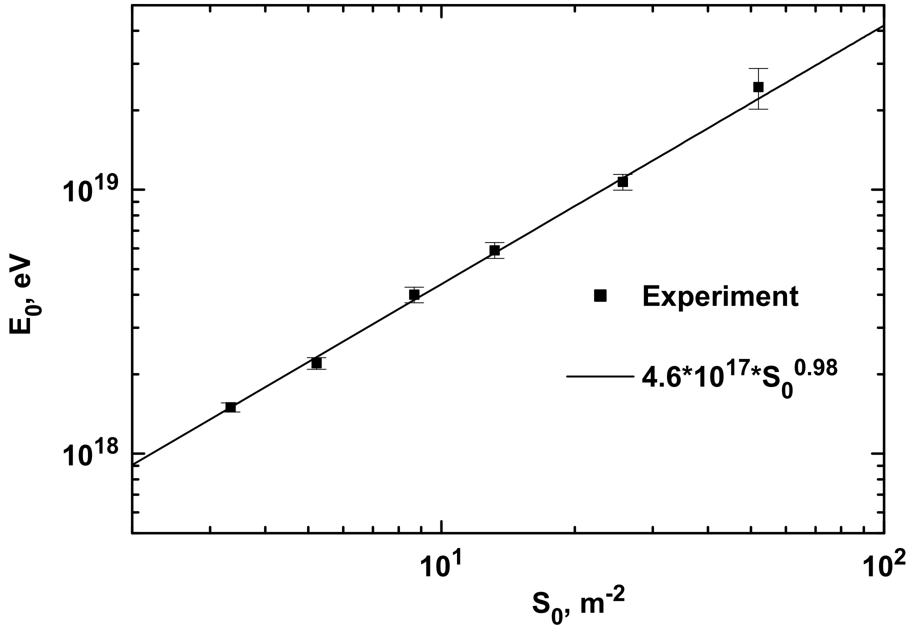

Figure 1: Relation between shower energy E_0 and parameter S_0 determined by the calorimetric method at Yakutsk array. The line corresponds to equation (1).

where $\lambda_e = 250\,\mathrm{g}\cdot\mathrm{cm}^2$ — soft component (electron) attenuation length, $\lambda_\mu = 2500\,\mathrm{g}\cdot\mathrm{cm}^2$ — hard component (associated with muons) attenuation length, β — portion of hard component in full response S_0 at depth $1020\,\mathrm{g}\cdot\mathrm{cm}^2$, $X = X_0/\cos\theta$. Values for λ_e and λ_μ were chosen on basis of QGS model calculations. Parameter β was determined from experimental data with different energies. On fig. 2 S_0-dependence of hard component β is shown. Line marks the dependence with fitted parameters:

$$\beta = (\beta_0 \pm \delta\beta_0)\cdot S_0^{p\pm\delta p}, \tag{3}$$

where $\beta_0 = 0.39$, $\delta\beta = 0.04$, $p = -0.12$, $\delta p = 0.03$.

On fig. 3 change of S_{600} versus atmospheric depth described by (2) with subject to hard component portion described by (3) is shown with solid lines. It is seen that curves describe experimental data well and correspond with points for depth $X > 2000\,\mathrm{g}\cdot\mathrm{cm}^2$ ($\theta > 60^\circ$) which did not participate in parameter selection procedure.

During energy determination in order to consider various atmospheric conditions, the parameter $S_{600}(\theta)$ is corrected to comply with Moliere radius $R_0 = 68\,\mathrm{m}$. This value fits in with atmospheric conditions at the beginning of Čerenkov light measurements season. The value of temperature correction may achieve 15 % by absolute value.

2 Errors in energy estimation for individual showers

There are many factors influencing upon the error of energy estimation in individual events. Some of them have sporadic nature and error of the mean value resulting from such uncertainties decreases with the growth of statistics in selection. But there are also systematic errors whose influence upon determination of intensity and spectrum shape may be significant.

The contribution to energy estimation in individual events is made by uncertainty in determination of $S_{600}(\theta)$ and in shower arrival direction. An error stipulated by inaccuracy in determination of axis coordinates and $S_{600}(\theta)$ have sporadic nature if correct lateral distribution of particle density is used and no systematic hardware distortion is presented during its measurements at operative range of axis distances. In the work [9] it is shown that for detectors

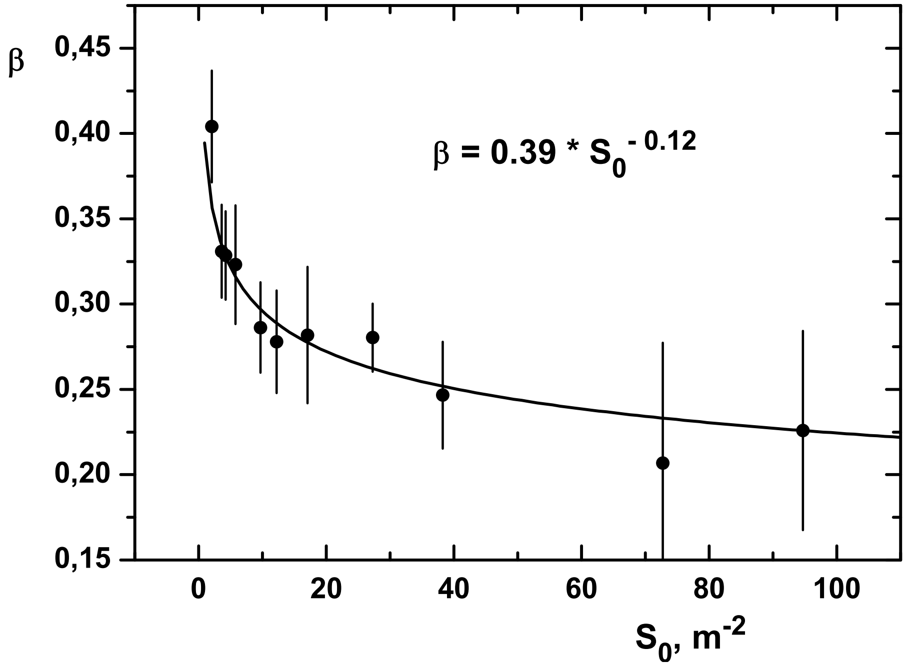

Figure 2: S_0-dependence of hard component portion β. Line corresponds to equation (3).

of the Yakutsk EAS array there are no significant systematic distortions of the estimated particle density at axis distances up to 2000 m ($< 10\,\%$). During shower selection in the effective area within the array borders (used for spectrum determination) the uncertainty of parameter $S_{600}(\theta)$ differs slowly versus the energy and amounts about 20 % near 10^{18} eV and 15 % above 10^{19} eV [10].

Error in arrival direction determination contributes uncertainty to atmospheric depth value X in equation (2). Since other systematic deviations from true direction in artificial showers are not detected, the contribution to energy estimation error caused by uncertainty of X value has sporadic nature [10]. But contribution to energy caused by uncertainty of parameter β is systematic and depends on shower arrival zenith angle. Errors in parameters of (1) make systematic contribution to shower energy estimation.

In the table 1 there are presented estimated contributions made by various factors to relative error of energy determination for different energies and zenith angles. In the row $\delta\theta$ errors in zenith angle determination are shown. In the next row for the same zenith angle the complete random error of energy determination is presented, which consists of relative $S_{600}(\theta)$ determination error and random error caused by $\delta\theta$. In the next row the complete systematic energy error is listed, and in the next row there is a contribution to complete systematic error from all factors except $\delta E_1/E_1$ — the main constant in equation (1).

It is seen from table 1 that prevailing contribution to systematic error is made by inaccuracy of the constant E_1 from equation (1). But it is equal for all showers and does not influence on the shape of the spectrum but results in the shift of whole spectrum along the energy scale. It influences significantly on intensity estimation at fixed energy. Other factors may lead to some mutilation of the very shape of the spectrum. Relative error $\delta E_1/E_1 = 25\,\%$ is mainly defined by accuracy of absolute calibration of Čerenkov radiation detectors and by error in determination of mean atmosphere transparency.

For intensity estimation at energies above $4 \cdot 10^{19}$ eV we use effective zone beyond the borders of the array. In this case during energy estimation random errors increase significantly and systematics practically does not change. For such shower, at the average, $\delta S/S(\theta) = 0.35\,\%$ and $\delta\theta = 3.5°$.

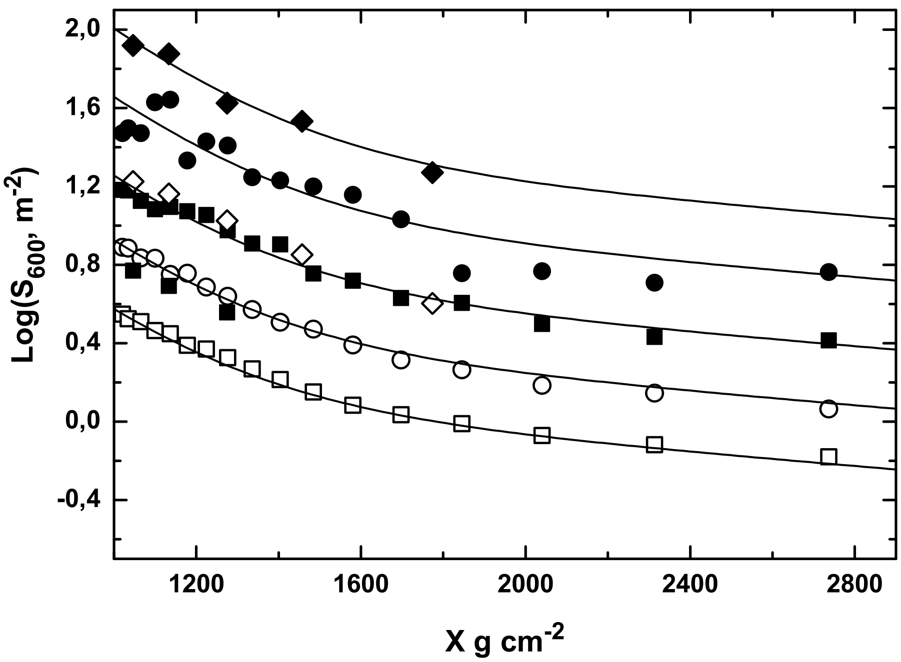

Figure 3: X-dependence for $S_{600}(\theta)$ for different energies. Lines indicate the change of S_{600} corresponding to absorption described by (2) and β described by (3).

3 Energy spectrum

On fig. 4 the differential energy spectrum obtained in Yakutsk experiment at $\theta \geq 60^\circ$ is represented by rounds. There are also shown results from AGASA [5], HiRes [6] and preliminary Auger data [7]. Energy spectra obtained at various arrays correspond well with each other but differ in intensity. The Yakutsk array data near 10^{19} are $\sim$ 2.5 times higher than those from HiRes and $\sim$ 30 % higher then AGASA's.

At energies above the GZK-cutoff results are controversial. At HiRes there is only 1 event with $E_0 > 10^{20}$ eV and the spectrum is cut off. AGASA has registered 11 such events ($\theta < 45^\circ$), indicating the absence of the cutoff. Intensity obtained at Auger is lower than this obtained in other experiments and does not demonstrate drastic decrease at 3-5 $\times$ 10^{19} eV, therefore it is not possible yet to make unambiguous conclusion about the cutoff from these data.

Results from the Yakutsk array are in a better agreement with those from AGASA. There are 4 events with $E_0 > 10^{19.9}$ eV registered above the cutoff threshold. This fact indicates the absence of the GZK-cutoff. But the number of such events is small therefore with respect to errors in shower energy estimation it is impossible to make unambiguous choice. On fig. 5 the Yakutsk data are compared to results of spectrum shape calculations made under assumption that sources are active galactic nuclei (AGN) [11]. Sloped line at the point with energy above 10^{20} eV represents shifting range for this point caused by systematic error lying within 30 %. One can see from this plot that later point doesn't deflect much from calculated curve. The shape of energy spectrum corresponds to suggestion that main source of particles with energy $E_0 > 10^{19}$ eV are AGN.

Systematic errors in energy determination also exist in other experiments. HiRes collaboration estimates its error about 15 % [6]. If one tunes error of estimated energy for HiRes towards increasing (E_0 multiplied by 1.15) and and for Yakutsk — towards decreasing (E_0 multiplied by 0.73) then energy spectra from both experiments would be in agreement in all energy range. This is shown on fig. 6.

Table 1: Estimation of contribution from various factors to determined energy for different energy and zenith angle values

θ		$\lg E_0$ 19.5	19.0	18.5	18.0
10°	$\delta\theta^\circ$	3.0	2.5	2.5	2.5
	$\delta E/E$ random	0.15	0.16	0.18	0.2
	$\delta E/E$ syst.	0.26	0.26	0.255	0.251
	$\delta E/E$ syst., without $\delta E_1/E_1$	0.09	0.06	0.04	0.02
30°	$\delta\theta^\circ$	2.5	2.0	2.5	3.7
	$\delta E/E$ random	0.17	0.17	0.19	0.22
	$\delta E/E$ syst.	0.26	0.26	0.255	0.252
	$\delta E/E$ syst., without $\delta E_1/E_1$	0.07	0.07	0.045	0.03
45°	$\delta\theta^\circ$	1.5	1.7	3.0	4.7
	$\delta E/E$ random	0.16	0.17	0.21	0.26
	$\delta E/E$ syst.	0.27	0.27	0.26	0.26
	$\delta E/E$ syst., without $\delta E_1/E_1$	0.11	0.09	0.07	0.06
59°	$\delta\theta^\circ$	1.5	3.0	5.5	8.7
	$\delta E/E$ random	0.16	0.2	0.27	0.35
	$\delta E/E$ syst.	0.3	0.29	0.27	0.27
	$\delta E/E$ syst., without $\delta E_1/E_1$	0.17	0.14	0.11	0.1

4 Muon component in showers with energy above 10^{19} eV

Muon density measurements at the Yakutsk EAS array are carried out since the year 1976. Nowadays there are 5 operating muon detectors located withing the radius of 1 km around the center of array. For muon registration there are scintillation detectors installed in underground buildings similar to surface stations. Their total area in each point makes $20\,\mathrm{m}^2$. Threshold energy of registered muons is defined by their absorption in the soil and is $1.0/\cos\theta$ GeV.

Irregularities of muon component behaviour in EAS with energy above 10^{19} eV was discovered during studies of muon portion at large distances from shower axis [12]. It was discovered that muon content in inclined showers with such energies is much higher than that following from lower energy region approximation. In the works [13] this result was confirmed and conclusion was stated that observed EAS characteristics do not correspond QGS model at high energies.

According to recent data, near-vertical showers have similar behaviour [14]. On fig. 7 a ratio between muon number and total number of particles are shown as energy-dependence for events with $\cos\theta < 0.9$. Number of particles is determined in interval of 100-1000 m from shower axis, in which density is measured in real experiment. Lines represent expected values obtained for protons (solid) and iron (dashed) according to QGS model. Above 10^{19} eV muon portion increases with energy. Taken separately, this result could be interpreted as weighting of chemical composition and prevalence of heavy nuclei in primary flux at highest energies. But considering other data embarrasses the whole picture.

Fig. 8 presents the dependence of parameter b_μ, that characterizes the slope of lateral density distribution of muons ρ_μ in approximation:

$$\rho_\mu(R) \sim \left(\frac{R}{280}\right)^{-0.75} \cdot \left(1+\frac{R}{280}\right)^{0.75-b_\mu} \cdot \left(1+\frac{R}{2000}\right)^{-6.5}, \qquad (4)$$

Values determined from experiment significantly differ from model predictions. On fig. 9 from the work [13] a dependence of parameter b_μ for different intervals of zenith angle is presented. Depending on energy this parameter changes differently in different angular ranges. For

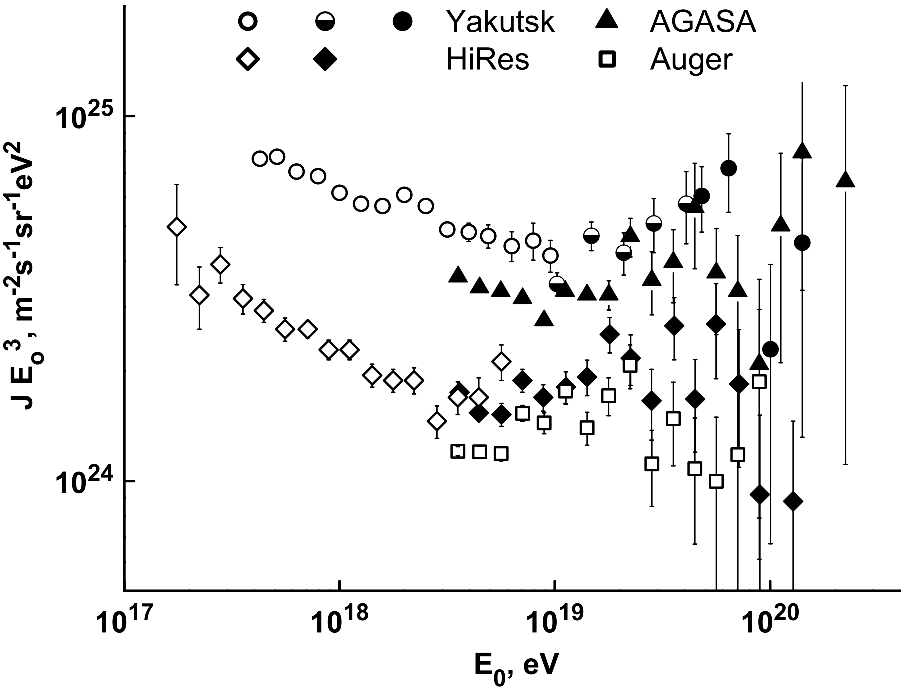

Figure 4: Differential energy spectrum based on the data from different experiments. Circles: Yakutsk [4]; triangles: AGASA [5]; diamonds: HiRes [6]; squares: Auger [7].

showers with energy above 10^{19} eV it practically does not depend on zenith angle. This fact contradicts the simple conjecture about changing of chemical composition for such energies.

In the most inclined showers at $E_0 > 10^{19}$ eV the responses in muon and surface detectors coincide between each other in wide distance range though at lower energy it is clear that muon density is lower than density of all particles measured by surface detectors. Graphically it can be seen from comparison of results shown on fig. 10. Fig. 10*a* presents the lateral distribution of all particles and muons for averaged shower with the energy $2 \cdot 10^{18}$ eV and zenith angle 55°. Fig. 10*b* shows averaged shower with same zenith angle and energy $2 \cdot 10^{19}$ eV. On fig. 10*a* muon density is lower than density of all particles and on fig. 10*b* they coincide, though decrease of muon portion with energy growth is expected. In individual showers of maximum energy (above 10^{20} eV) the response of muon detectors completely coincides with one of surface detectors.

These results possibly indicate that there are new processes in particle interaction at such energies, which result in significant increasing of muon component transferred from energy of primary particle.

5 Conclusion

The divergence in intensities of energy spectra obtained in different experiments can be explained with the presence of systematic errors in shower energy estimation. In order to decrease systematic errors in energy estimated at the Yakutsk array, a more accurate calibration of Čerenkov radiation detectors is required.

As it was indicated in results obtained at the Yakutsk array for muon portion in showers, at energies higher than 10^{19} eV new processes may appear which increase portion of primary energy transferred into muons. If this hypothesis is correct then energy estimated for the largest showers may be incorrect in all experiments. Considering Yakutsk and AGASA, it is difficult to say how exactly these distortions will affect, towards decreasing or increasing, since muons contribute to response of scintillation detectors. In HiRes and Auger experiments where energy

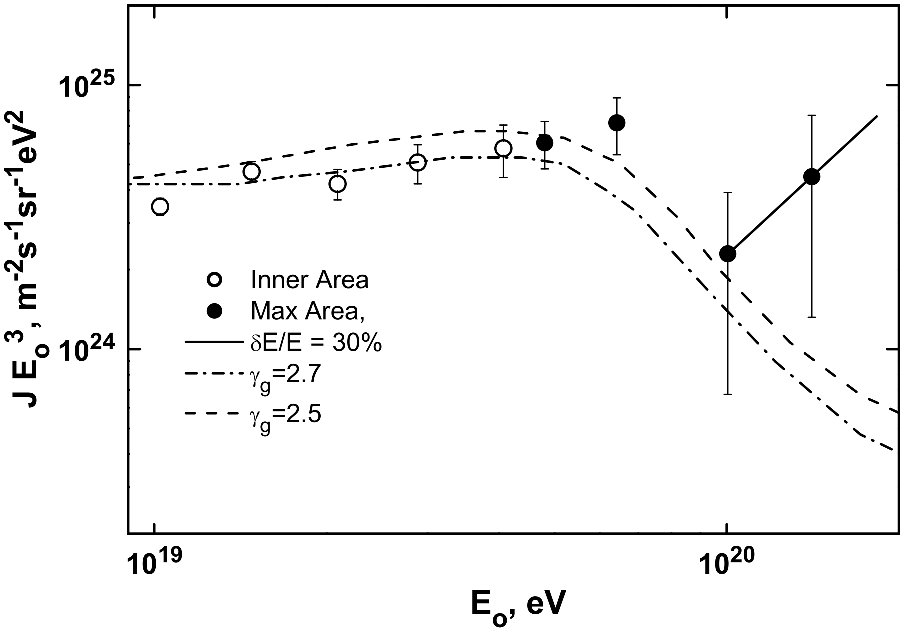

Figure 5: Comparison of spectrum obtained at the Yakutsk array to model calculations where the main source of particles with energies above 10^{19} eV are AGN [11]. Sloped line indicates the shift of last point for the case when estimated energy changes in the range of 30 %.

estimation is based on fluorescent light measurements, the energy will be decreased, since muons lose insignificant part of their energy during ionization process. The disagreement in results concerning existence of super-GZK particles from different arrays is possibly connected with undiscovered peculiarities in development of EAS generated by such particles. In order to solve this problem correctly it is vital to investigate muon component in energy domain above 10^{19} eV.

Acknowledgment

This work was supported by President RF grant No. Nsh–7514.2006.2 an INTAS grant No. 03–51–5112.

References

[1] K. Greisen // Phys. Rev. Lett., 1966, v. 16, p. 748.

[2] G. T. Zatsepin. and V. A. Kuzmin // JETP Lett., 1966, v. 4, p. 144.

[3] V. P. Egorova et al.// Proc. 13 Inter. Seminar Quarks-2004, 2005, v. 2, p. 390.

[4] V. P. Egorova, et al. // Nuclear Physics B (Proc. Suppl.), 2004, v. 136C, p. 3.

[5] N. Sakaki et al. // Proc. 27th ICRC, Hamburg. 2001, v. 1, p. 333.

[6] R. U. Abbasi et al. // Preprint, 2005, astro-ph/0501317.

[7] P. Sommers at al. // Proc. 29th ICRC, Pune 2005, v. 7, p. 387.

[8] A. V. Glushkov et al. // Proc. 28th ICRC, Tsukuba. 2003, v. 1, p. 393.

[9] V. P. Egorova et al. // Inter. Journal of Modern Physics, 2005, v. 20, No. 29, p. 6878.

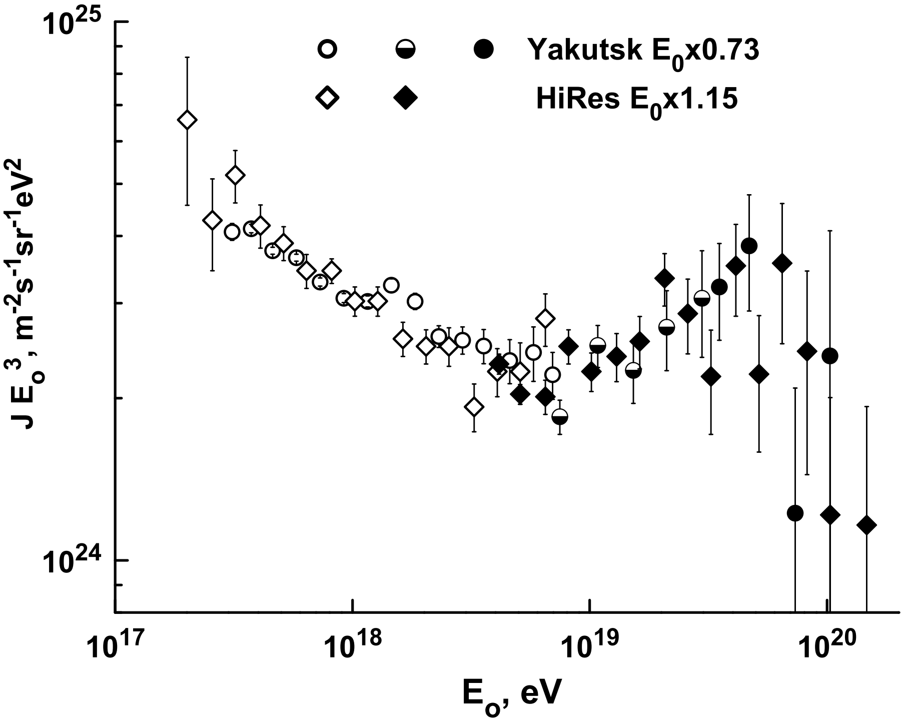

Figure 6: Comparison of spectra obtained at Yakutsk and HiRes if one tunes adopted energy estimation by one standard deviation. Circles — Yakutsk result multiplied by 0.73, diamonds — HiRes energy multiplied by 1.15.

[10] N. N. Efimov et al. // Proc. ICRR Int. Symp. — Astrophysical Aspects of the Most Energetic Cosmic Rays. — Kofu, Japan, 1990, World Scientific Singapore 1991, p. 20.

[11] V. S. Berezinsky, A. Z. Gazizov and S. I. Grigorieva // Phys. Rev. D, 2006, v. 74, 043005.

[12] N. N. Efimov et al. // Proc. ICRR Int. Symp. — Astrophysical Aspects of the Most Energetic Cosmic Rays. — Kofu, Japan, 1990 World Scientific Singapore 1991, p. 434.

[13] A. V. Glushkov et al. // Astroparticle Physics 1995, v. 4, p. 15;
A. V. Glushkov et al. // Physics of Atomic Nuclei, 2000, v. 63, No. 8, p. 1477.

[14] A. V. Glushkov, M. I. Pravdin // JETP, 2006, v. 103, No. 12.

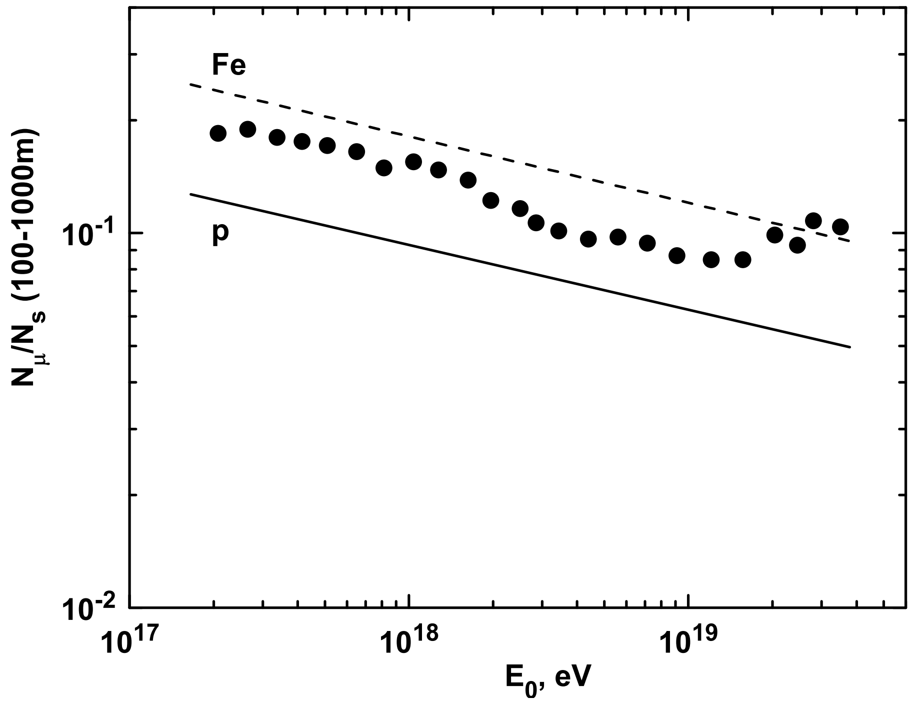

Figure 7: Ratio between muon number N_μ and total number of particles N_s in the range of 100-1000 m axis distance. Solid line (p) corresponds to predictions from QGSJet for protons, dashed line — for iron (Fe). Experimental data were obtained from showers with $\cos\theta > 0.9$.

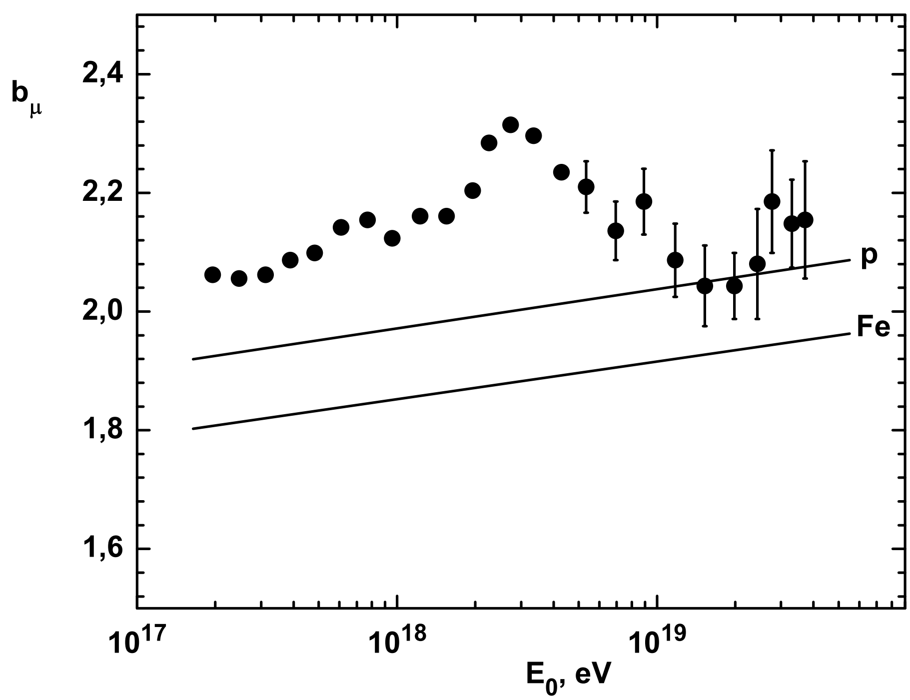

Figure 8: Dependence of parameter b_μ from approximation (4) for muon lateral distribution in showers with $\theta > 0.9$. Line (p) represents predictions from QGSJet for protons, Line (Fe) — for iron.

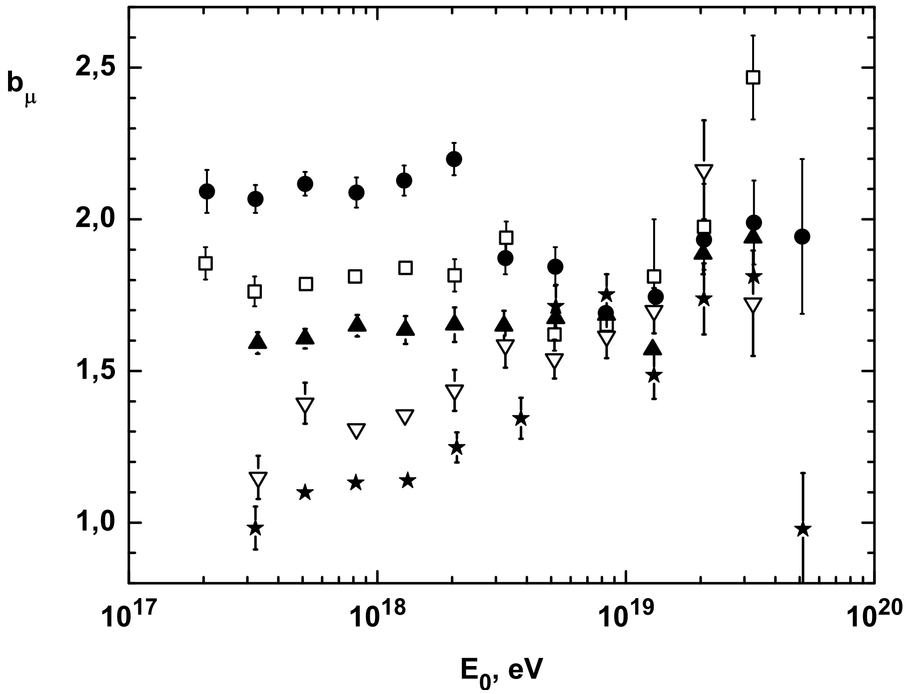

Figure 9: Dependence of parameter b_μ from approximation (4) for muon lateral distribution in different zenith angle (θ) intervals. Closed circles: $<\cos\theta>= 0.95$; open squares: $<\cos\theta>= 0.85$; closed triangles: $<\cos\theta>= 0.75$; open triangles: $<\cos\theta>= 0.65$; stars — $<\cos\theta>= 0.55$.

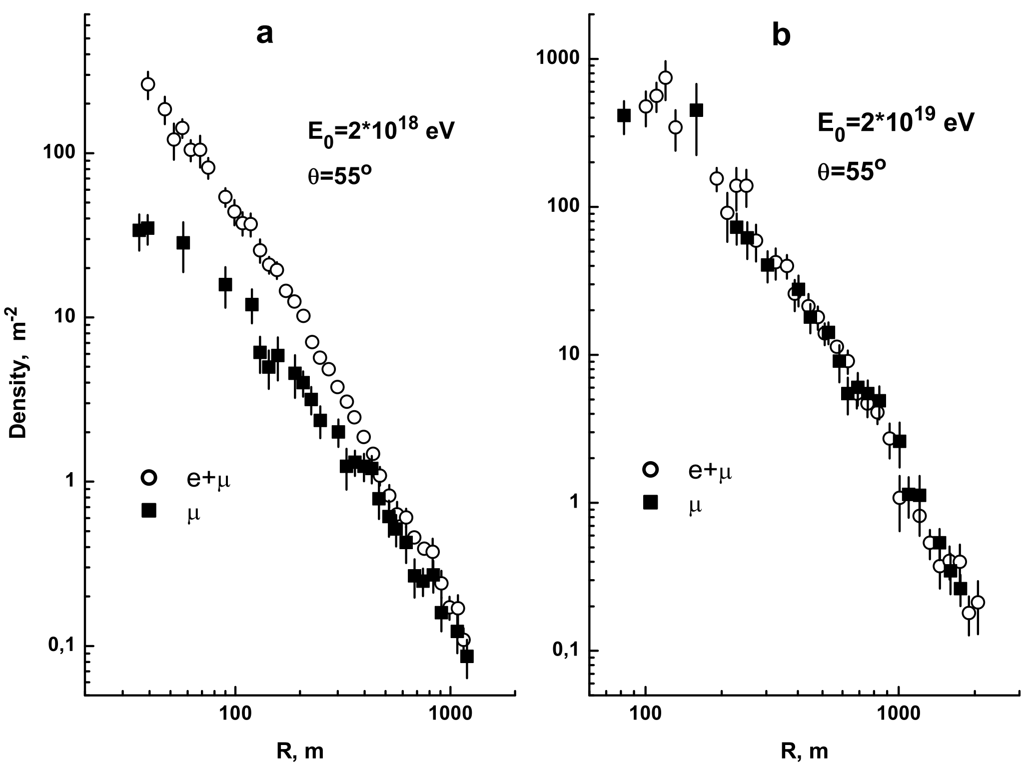

Figure 10: Lateral distribution for charged particles (white circles) and for muons (black squares) in two showers with equal zenith angles $\theta = 55°$ and with different energies: *a)* $E_0 = 2 \cdot 10^{18}$ eV; *b)* $E_0 = 2 \cdot 10^{19}$ eV.