Study of the energy spectrum and the composition of the primary cosmic radiation at ultra-high energies

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Abstract

The signals in both the surface and underground scintillation detectors of the Yakutsk array from particles of extensive air showers have been calculated in the energy range of $10^{17} - 10^{20}$ eV and compared with data. The new energy spectrum based on these calculations and data of the Yakutsk array had been obtained. The intensity of the calculated spectrum is by a factor of 5 lower than the one estimated experimentally. The reference spectrum has been suggested to compare data. The fall of the intensity of the primary particles relatively to the reference spectrum is not clearly noticeable. The variable sources of the primary ultra-high energy particles are suggested to understand differences in data observed at various arrays. The changes of the chemical composition from the heavy primaries to the proton primaries at energies $(1 - 2.6) \cdot 10^{18}$ eV and from the proton to the heavy primaries at energies above $1.3 \cdot 10^{19}$ eV are possibly observed. These conclusions may be understood if various sources of the primary particles are suggested to contribute to different intervals below and above $\sim 2.6 \cdot 10^{18}$ eV of the energy spectrum.

1 Introduction

The Yakutsk array includes the surface scintillation detectors and the underground scintillation detectors with the declared threshold energy ~ 1 GeV of muons and detectors of the Vavilov-Cherenkov radiation. The various particles of extensive air showers (EAS) hit detectors at the observation level and induce some signals sampled as detector readings. These detectors readings should be interpreted in terms of various models to find out the best estimates of energy E and the atomic number A of the primary particle which generate a shower. Fluctuations in both the longitudinal and lateral development of a shower should be taken into account. At last, the type of the model used for obtaining the best estimates should also be determined. Several methods may be used to carry out this program. The standard approach of energy estimation at the Yakutsk array uses the signal $s(600)$ which is the energy deposited by shower particles to the surface scintillation detector at 600 m from the shower axis for the vertical EAS. This signal is estimated from data by some experimental procedures. Then this signal $s(600)$ is calibrated with the help of the Vavilov-Cherenkov radiation to find out estimates of energy E of EAS. We carried out calculations of signals in both the surface and underground scintillation detectors of the Yakutsk array from EAS particles in terms of the models QGSJET2 [1], Gheisha 2002 [2] and SYBILL [3] with the help of the codes CORSIKA-6.616 [4] and GEANT4 [5] in the energy range of $10^{17} - 10^{20}$ eV. The simplest way to use these calculations is estimating a dependence of signal $s(600)$ on energy E for the vertical EAS. This method was used at the Aceno Giant

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Air Station Array (AGASA) [6]. The new method was realized for the most energetic shower observed at the Yakutsk array [7]. The new energy spectra based on these calculations and data of the Yakutsk array had been obtained. It is convenient to compare energy spectra observed at various arrays relatively to the one reference spectrum. Such spectrum based on the High Resolution Fly's Eye (HiRes) data [8] has been suggested. The observation of the Greisen-Zatsepin-Kuzmin (GZK) effect [9, 10] is not so obvious if this references spectrum is assumed. Usually the energy spectrum is considered as a result of contributions from many different sources of the primary particles uniformly distributed in space [11]. Measurements at the Pierre Auger Observatory (PAO) [12] differ from observations at other arrays. The variable sources of the primary particles have been suggested to understand differences in results of various observations.

The study of chemical composition of the primary radiation is of importance. The ratios of signals in the underground muon detectors to the total signals in the surface detectors at 600 m from shower axis have been used to study this composition in the energy range of $3 \cdot 10^{17} - 3 \cdot 10^{19}$ eV.

2 Estimates of an energy of the primary particles

The standard approach of energy estimation at the Yakutsk array uses the signal $s(600)$ and the following estimate of energy E of EAS is obtained:

$$E = 4.8 \cdot 10^{17} \cdot (s(600)/\Delta E), eV. \quad (1)$$

where signal $s(600)$ is expressed in MeV and $\Delta E = 10.5$ MeV (a signal from the one vertical muon). It is interesting to compare this estimate with the one obtained with the help of calculation like in the standard AGASA approach. Our calculations gave the following estimate [13]

$$E = 3 \cdot 10^{17} \cdot (s(600)/\Delta E), eV. \quad (2)$$

New approach had been developed to find out the most accurate estimates of energy and other parameters for the EAS observed at the Yakutsk array [7]. The energy E and the type of the primary particle (the atomic number A), which induces the individual EAS, the type of model of hadron interactions at ultra-high energies and peculiar development of EAS in the atmosphere are not known. The goal is to find out the most accurate estimates of the energy E and atomic number A, the type of model of hadron interactions which fit data for each individual shower well taken into account the peculiar development of EAS in the atmosphere. It has been suggested for the each observed EAS to simulate all detector readings for many individual showers, induced by various primary particles with different energies in terms of various models. These detector readings for all simulated individual showers should be compared with detector readings of the one observed EAS. The best estimates of the energy E, the atomic number A, coordinates of the shower axis and the type of model are searched by the χ^2 method taken into account the peculiar features of the development of EAS in the atmosphere. The best estimates of the arrival direction are also searched by the χ^2 method. Simulations of the each individual shower development in the atmosphere have been carried out in terms of the models QGSJET2 [1] and Gheisha 2002 [2] and SYBILL [3] with the help of the code CORSIKA-6.616 [4].The very small value of the weight parameter $\varepsilon = 10^{-8}$ (thinning) had been used to decrease artificial fluctuation as much as possible. Many individual showers had been simulated for each observed event to take into account fluctuation in both the longitudinal and lateral development. The program GEANT4 [5] has been used to estimate signals in the scintillation detectors from electrons, positrons, gammas and muons in each individual shower. First, the surface detector model was developed. The signals $s_p(600)$ in these detectors have been calculated for various incoming particles with different energies and the arrival zenith angles. These signals have been used to estimate signals $s(600)$ in these detectors from shower particles which happened to hit detector. Readings of all scintillation detectors have been used to search for the minimum of the function χ^2 in the square with the width of 400 m and a center determined by data with a step of 1 m. The experimental readings have been compared with calculated signals for EAS with the energy $E_0 = 10^{20}$ eV multiplied by the coefficient C. This coefficient C was changed from 0.1 up to 4.5 with a step of 0.1. Thus, it was assumed, that the energy of a shower and signals in the scintillation detectors are proportional to each other in some small intervals. New estimates of energy of the giant air shower observed at the Yakutsk array have been calculated. These estimates are equal to $E \approx 2 \cdot 10^{20}$ eV for the proton primaries and $E \approx 1.7 \cdot 10^{20}$ eV for the primary iron nuclei. The energy spectra have been calculated using these methods of energy estimation.

3 The analysis of the energy spectrum

It is convenient to analyze the energy spectrum $J(E)$ using new variable $y = \lg E$ instead of an energy E. In three energy intervals of this variable y_i $(i = 1, 2, 3)$

$$17.20 < y_1 < 18.65,$$
$$18.65 < y_2 < 19.75,$$
$$19.75 < y_3$$

the HiRes Collaboration has been presented approximations of the data on the energy spectrum $J(E)$ by the following exponent functions [8]:

$$J_1(E) = A \cdot E^{-3.25},$$
$$J_2(E) = C \cdot E^{-2.81},$$
$$J_3(E) = D \cdot E^{-5.10},$$

where $A \approx 7.1 \cdot 10^{28}$ $\mathrm{m^{-2}s^{-1}sr^{-1}eV^{2.25}}$ and constants C and D may be expressed in terms of A using the boundary conditions. The change of the exponent from -2.81 to -5.1 and the strong fall of the intensity of the primary particles at $y > 19.75$ is considered as the observation of the GZK effect [9, 10]. The observations of gammas and neutrinos which will be generated due to the GZK effect would strongly support this conclusion. But now it is interesting to note that such strong fall of the intensity may not be observed relatively to the spectrum $J_1(E) = A \cdot E^{-3.25}$ extrapolated to higher energies. So we suggest that the approximation $J_3(E) = D \cdot E^{-5.10}$ is valid only to the point $y = 20.01$ where it intersects with the spectrum $J_1(E) = A \cdot E^{-3.25}$. Thus we suggest that the energy spectrum may be approximated as

$$J_4(E) = J_1(E) = A \cdot E^{-3.25}$$

at $y > 20.01$. It is convenient to compare data observed at various arrays relatively to the one reference spectrum. We assume this reference spectrum as follows

$$\lg z_i = \lg(J_i(E)/J_1(E)),$$

where $i = 1, 2, 3, 4$. This reference spectrum may be represented for four different intervals of variable y as follows

$$\lg z_1 = 0,$$
$$\lg z_2 = 0.44 \cdot (y - 18.65),$$

$$\lg z_3 = 0.484 - 1.85 \cdot (y - 19.75),$$

$$\lg z_4 = 0.$$

Data $J(E)$ observed at various arrays have been expressed as

$$\lg z = \lg(J(E)/J_1(E))$$

and are shown in Fig. 1 in comparison with the reference spectrum (solid line) as follows: (a) – HiRes2 (open circles), HiRes1 (solid squares) [8], (b) – PAO (solid circles) [12], (c) – AGASA (solid triangles) [6], (d) – Yakutsk (solid circles – data, open circles – the AGASA method, asterisk – the new method for the most energetic bin). The reference spectrum looks like a good fit for data observed at the HiRes array. Data observed at the PAO are lower by a factor of $\sim$ 1.5 but at energies above $\sim 10^{20}$ eV no deviations from the reference spectrum are seen due to large errors. The question may be put forward why the spectra observed by the same fluorescence method at the HiRes array and the PAO array differ so much? The answer may be given after calibration of the fluorescence method with the help of the electron beam from the linac which is planed at the Telescope Array (TA) [14]. The data observed at the AGASA array are nearly 2 times above the reference spectrum. But the most interesting three points at energies above $\sim 10^{20}$ eV exceed this approximation by factor of 10. Data observed at the Yakutsk array are nearly 3 times above the reference spectrum. Calculated estimates of energy of EAS happened to be nearly 1.6 times lower than the experimental ones obtained with the help of calibration signals $s(600)$ by the Vavilov-Cherenkov radiation. Thus, the intensity of the primary ultra-high energy particles has been decreased by nearly 5 times in comparison with the original spectrum. This intensity happened to be even $\sim$ 1.5 lower than the one observed at the HiRes array [8]. It should be noted that excess of the intensity is observed around the third interval of variable y at all arrays. Some relatively local sources of the primary particles might contribute to this energy interval. The intensity estimated for the most energetic bin at the Yakutsk array (asterisk) happened to be comparable with the one observed at the AGASA array for this bin. Of course, these results of calculations are model dependent. But it is possible now to suggest that some variable sources might contribute to the most energetic bins in the past to understand these results. Searching for the GZK photons and neutrinos are of very importance.

4 Study of the chemical composition

The chemical composition may be studied by comparing calculated ratios of the muon signal in the underground detectors to the total ones in the surface detectors at 600 m from the shower axis with data. In fact, the average density $\rho_\mu(600)$ of muons with the energy above some threshold E_t at 600 m from the shower axis depends on the energy E of the primary protons as follows:

$$\rho_\mu(600) = a \cdot E^b,$$

where a, b are constants and $b < 1$. This is due to decreasing of decay processes with increasing energy E of the primary particle. The threshold energy is declared to be $E_t = 1$ GeV. But its value should be tested. The muon density for the primary nuclei with atomic number A may be expressed according to the superposition hypothesis [15] as follows:

$$\rho_\mu(600) = a \cdot A^c \cdot E^b,$$

where $c = 1 - b > 0$. Calculations in terms of models QGSJET2 [1] and Gheisha 2002 [2] gave values of $b = 0.895$ and $c = 0.105$. For the iron nuclei we have $A^{0.105} = 1.53$. The signal $s(600)$ in the surface detector may be estimated from (2):

$$s(600) = \Delta E \cdot (E/3 \cdot 10^{17}, eV), MeV.$$

The signal $s_\mu(600)$ in the underground detector may expressed as follows:

$$s_\mu(600) = k \cdot \Delta E \cdot \rho_\mu(600), MeV,$$

where coefficient $k = 1.15$ takes into account the difference between the declared threshold energy and the one found with the help of calculations using the program GEANT4 and the cascades in the soil above detectors. The fact that calibration of the underground detector was carried out in the underground room should also be taken into account. The dependences of the average signal ΔE in the underground detector on the energy E of muons which come from the atmosphere to observation level at the various zenith angles (open circles – $0°$, stars – $45°$) are shown in Fig. 2. The depth h of soil above detector is equal to 2.5 m. The solid and dashed lines illustrate the expected values 10.5 eV and 14.85 eV accordingly. The differences between expected threshold energies and the calculated ones are clearly seen. Besides, values of the calculated signals are rather large in comparison with the expected ones. It is also important to note that fluctuations of this signal ΔE in the underground detectors are large. Fig. 3 illustrates distributions of the signal ΔE in the underground detector at depth $h = 3.2$ m for muons with energies $E_\mu = 1.05$ GeV (a), $E_\mu = 1.5$ GeV (b) and $E_\mu = 10$ GeV (c). In case of the small muon density these fluctuations may support misleading conclusions by imitation large muon density. Another possible source of imitation of large muon densities are gammas which can penetrate through the soil above the underground detector. There are many gammas in EAS. The dependences of the average signal ΔE in the underground detectors at depths 2.3 m (solid circles) and 3.2 m (open circles) on the energy E of gammas are shown in Fig. 4. If energy of gammas is above 0.5–1 GeV the signal may be rather large. Fig. 5 illustrates distributions of the signal from gammas with energies $E_\gamma = 5$ GeV (a) and $E_\gamma = 10$ GeV (b) in the underground detector at depth $h = 2.3$ m. The large tails up to 100–150 MeV are seen. So, if the shower axis happened to be near the muon detector interpretation of the signal in this underground detector meets serious problems. One should estimate the number of gammas which hit this detector.

The ratio α of muon signal in the underground detector to the total one at 600 m from the shower axis may be expressed as follows:

$$\alpha = k \cdot \Delta E \cdot \rho_\mu(600)/s(600).$$

The dependences of this calculated ratios α on the total signal $s(600)$ are shown in Fig. 6 for the primary protons (solid line) and the primary iron nuclei (dashed line). The data observed at the Yakutsk array for the vertical EAS ($cos\Theta \geq 0.9$, where Θ is the zenith angle) are shown by points with the error bars [16]. The values of these points were increased on $\sim 3\%$ to take into account the calibration of muon detectors in the underground room (signals in underground detector are larger than the ones in the surface detector due to cascades developed in the soil). This Fig. 6 shows clearly that for signals $s(600)$ in the range of 90–450 MeV (which corresponds to the energy interval $2.6 \cdot 10^{18}$–$1.3 \cdot 10^{19}$ eV of the primary particles) data observed at the Yakutsk array may be interpreted well by the primary protons. The dashed line for the primary iron nuclei is placed ~ 1.5 times higher than points in this interval. The points on the left side from this interval (with the exception of the first one) should be interpreted in terms of the heavy composition of the primary particles. Thus, it is possible to conclude that the change of the chemical composition from the heavy nuclei to the protons had been observed in the range of 30–90 MeV of the signals $s(600)$ which corresponds to the energy interval $1 \cdot 10^{18}$–$2.6 \cdot 10^{18}$ eV of the primary particles. This conclusion agrees with observations at the HiRes array [8]. A special analysis is needed to interpret the most left points. If the signal $s(600)$ exceeds 450 MeV that corresponds to the energy $1.3 \cdot 10^{19}$ eV of the primary particles the composition becomes again heavier as was found in [17]. Results for the most energetic shower observed at the Yakutsk array are shown in Fig. 7 which illustrates a dependence of the function χ_1^2 per one degree of freedom on energy E of the primary particle for four showers generated by the primary protons (solid curves) and by the primary iron nuclei (dashed curves). It is clearly seen that both the proton primaries and the iron ones are possible in agreement with analysis [17]. Such changes of the chemical composition may be understood if various sources of the primary particles are suggested to contribute to different intervals below and above $\sim 2.6 \cdot 10^{18}$ eV of the energy spectrum.

5 Conclusion

The new energy spectra based on data of the Yakutsk array and calculations of signals $s(600)$ in terms of the models QGSJET2 [1] and Gheisha 2002 [2] with the help of the codes CORSIKA-6.616 [4] and GEANT4 [5] have been obtained. Calculated estimates of energy of EAS happened to be nearly 1.6 times lower than the experimental ones obtained with the help of calibration of signals $s(600)$ by the Vavilov-Cherenkov radiation. Thus, the intensity of the primary ultra-high energy particles has been decreased by nearly 5 times in comparison with the original spectrum. This intensity happened to be even ~ 1.5 lower than the one observed at the HiRes array [8]. The energy of the most energetic EAS observed at the Yakutsk array estimated by the new suggested method may be as high as $2 \cdot 10^{20}$ eV for the primary proton and $1.7 \cdot 10^{20}$ eV for the primary iron nucleus. The intensity estimated for the most energetic bin happened to be comparable with the one observed at the AGASA array. Of course, these results of calculations are model dependent. The possible existence of variable sources of the primary ultra-high energy particles is suggested to explain data observed at the AGASA and the Yakutsk arrays. The signals in the underground scintillation detectors have been calculated to study the chemical composition of the primary cosmic radiation through comparison of calculated ratios of these signals to the total signal $s(600)$ in the surface detectors with data. It was shown that the primary protons should dominate among the primary particles in energy interval of $2.6 \cdot 10^{18}$–$1.3 \cdot 10^{19}$ eV. The heavy nuclei are the most probable primary particles at energies below 10^{18} eV. Thus, the change of the chemical composition from the heavy primaries to the proton primaries has been observed at energies $1 \cdot 10^{18}$–$2.6 \cdot 10^{18}$ eV. The second change from the proton to the heavy primaries is possibly observed at energies above $1.3 \cdot 10^{19}$ eV as it was also found in [17]. These conclusions are also model dependent. The observed rapid changes of composition might be due to contributions of various sources of the primary particles to different intervals below and above $\sim 2.6 \cdot 10^{18}$ eV of the energy spectrum.

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References

[1] S. S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.) **151**, 143 (2006).

[2] H. Fesefeldt, Report PITHA-85/02 RWTA, Aachen (1985).

[3] R. S. Fletcher, T. K. Gaisser, P. Lipari and T. Stanev, Phys. Rev. D **50**, 5710 (1994); R. Engel, T. K. Gaisser, P. Lipari and T. Stanev, Proc. of the 26th ICRC, Salt Lake City, USA, **1**, 415 (1999).

[4] D. Heck, J. Knapp, J.-N. Capdevielle et al., Forschungszentrum Karlsruhe Thechnical Report No. 6019, Karlsruhe (1998).

[5] The GEANT4 Collaboration, http://www.info.cern.ch/asd/geant4.html.

[6] N. Hayashida, K. Honda, M. Honda et al., Phys. Rev. Lett. **73**, 3491 (1994).

[7] L. G. Dedenko, A. V. Glushkov, S. P. Knurenko et al., JETP Lett. **90**, 691 (2009).

[8] R. U. Abbasi, T. Abu-Zayyad, M. Allen et al. (High Resolution Fly's Eye Collab.), Phys. Rev. Lett. **100**, 101101 (2008).

[9] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966).

[10] G. T. Zatsepin and V. A. Kuzmin, Sov. Phys. JETP. Lett. **4**, 78 (1966).

[11] V. Berezinsky, A. Gazizov, S. Grigorieva, Phys. Rev. D. **74**, 043005 (2006).

[12] The Pierre Auger Collaboration, Phys. Rev. Lett. **101**, 061101 (2008).

[13] L.G. Dedenko, D.A. Podgrudkov, T.M. Roganova et al.,

[14] T. Shibata et al. for the Telescope Array Collaboration, icrc2009.uni.lodz.pl/proc/pdf/icrc0857.pdf

[15] L. G. Dedenko, G. T. Zatsepin, Proc. of the 6th ICRC, Moscow, Russia, **2**, 201 (1960).

[16] A. V. Glushkov and M. I. Pravdin, JETP **84** no 6, 831 (2006).

[17] A. V. Glushkov, I. T. Makarov, M. I. Pravdin et al., Jetp. Lett. **87** no 4, 190 (2008).

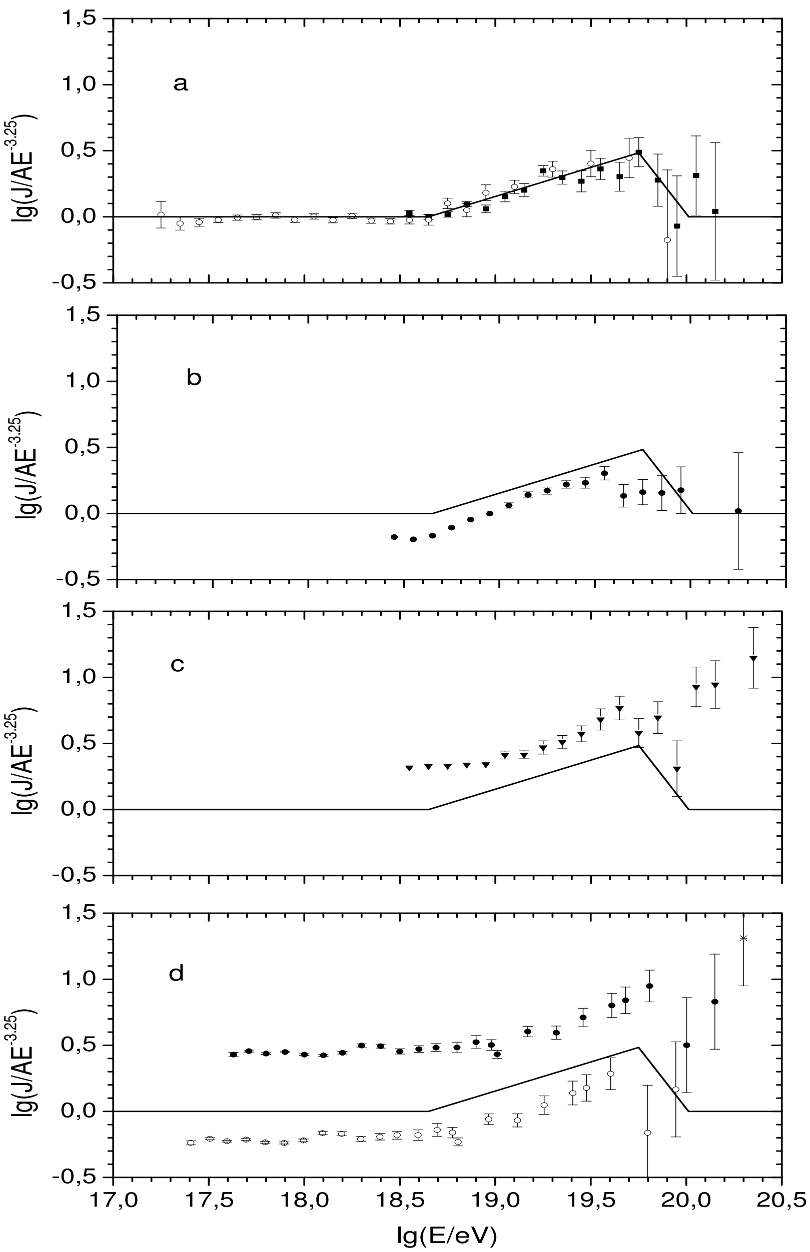

Figure 1: Energy spectra $\lg z = \lg(J(E)/J_1(E))$ vs. the reference spectrum (solid line). *a*–[8] (•–HiRes1, ○–HiRes2), *b*–[12], *c*–[6], *d*–(•–the Yakutsk array data, ○–calculations by AGASA method, *–[7]).

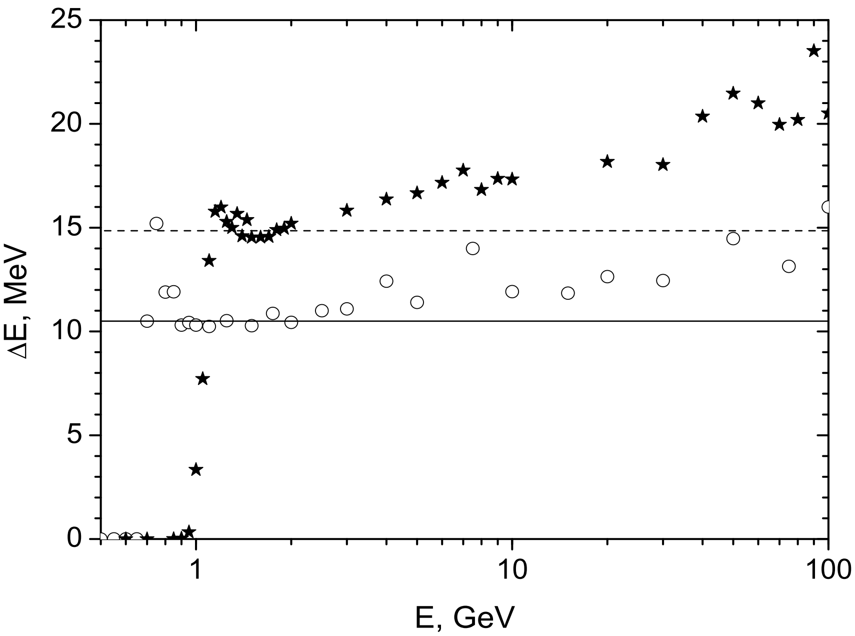

Figure 2: Signals ΔE in the underground detectors at depth $h = 2.5$ m vs. energy E of muons for various zenith angles ($\circ$–0°, $\star$–45°).

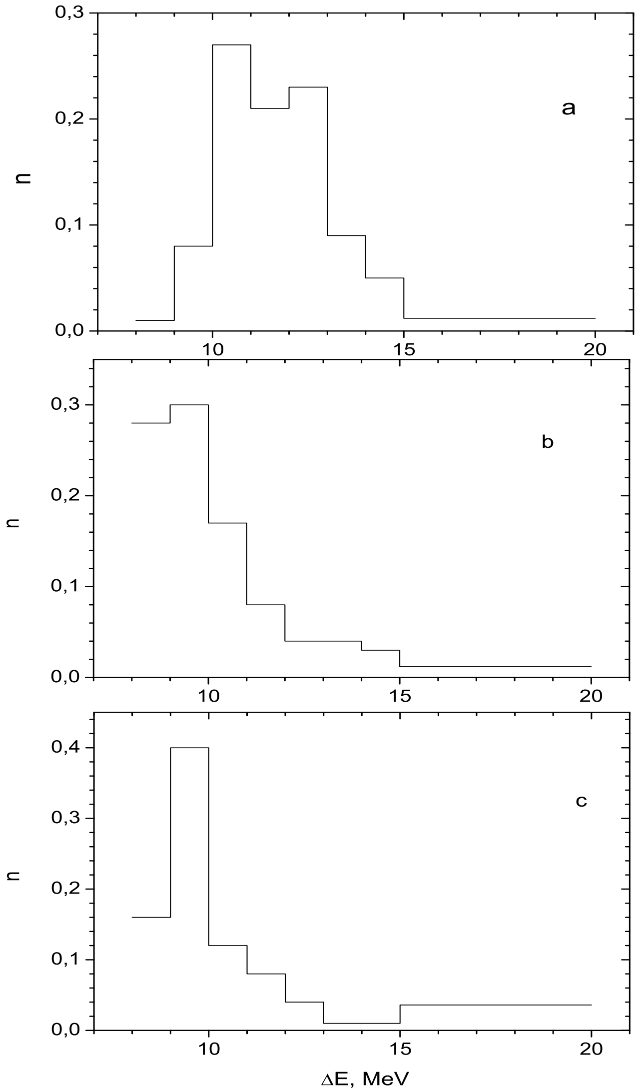

Figure 3: Distributions of signals ΔE in the underground detectors at depth $h = 3.2$ m for muons with different energies (a–1.05 GeV, b–1.5 GeV, c–10 GeV).

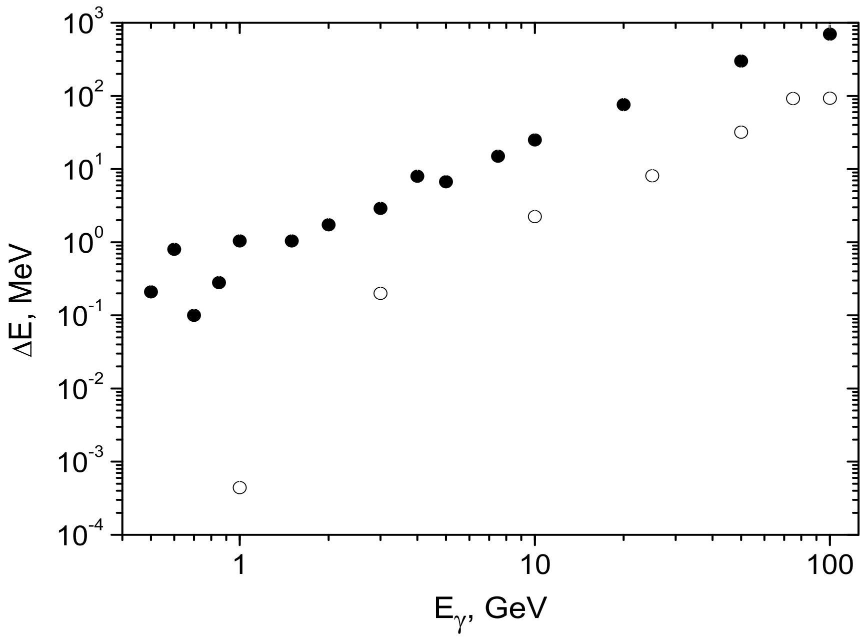

Figure 4: Signals ΔE in the underground detectors at different depth h m vs. energy E of gammas ($\bullet$–$h = 2.3$ m, $\circ$–$h = 3.2$ m).

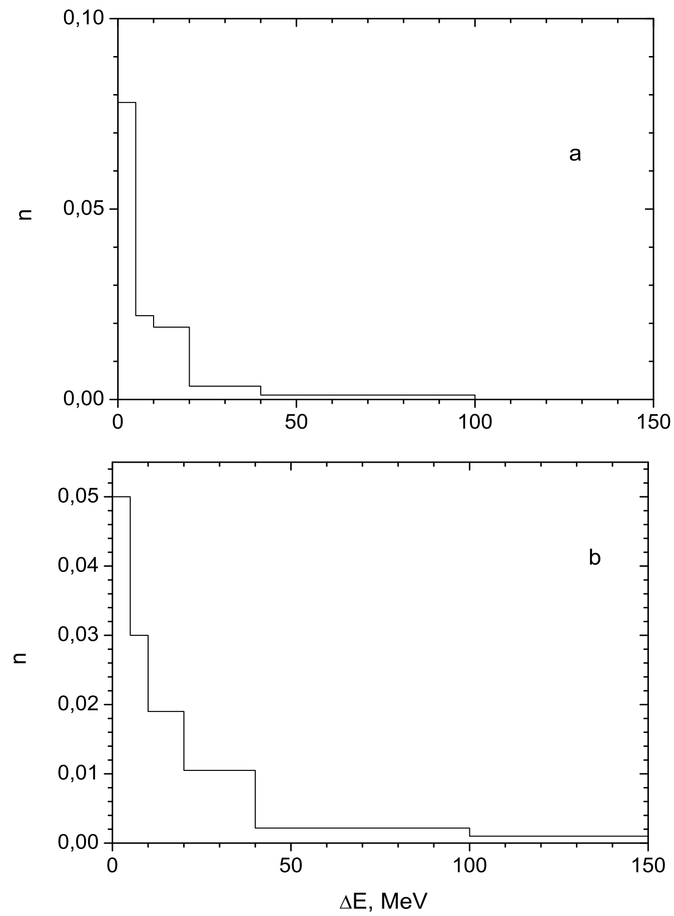

Figure 5: Distributions of signals ΔE in the underground detectors at depth $h = 2.3$ m for gammas with different energies (a–5 GeV, b–10 GeV).

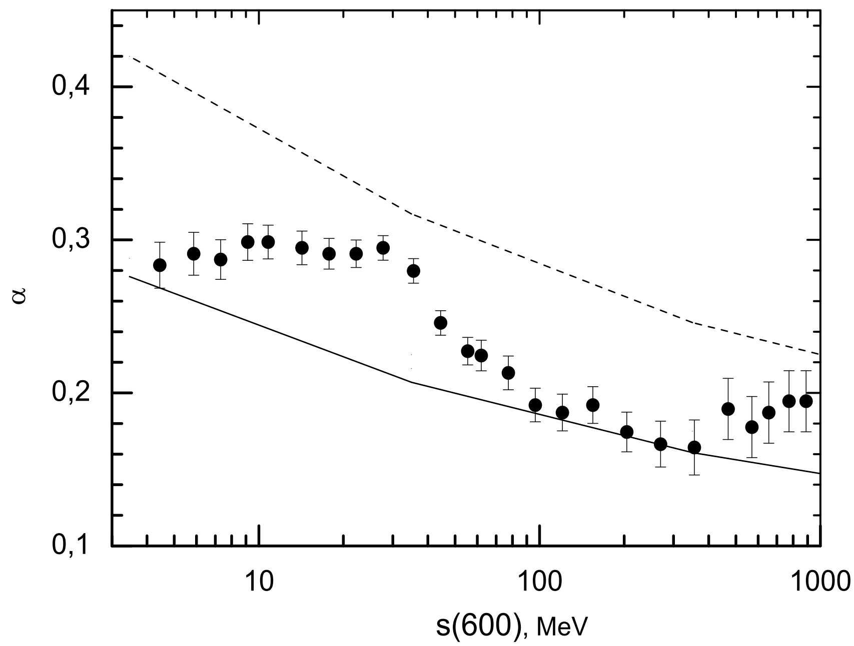

Figure 6: Ratios α of signals in the underground detectors to the total signals in the surface detectors at 600 m from shower axis vs. total signals $s(600)$ for various primary particles (solid line–p, dashed line–Fe). Points with error bars–[16].

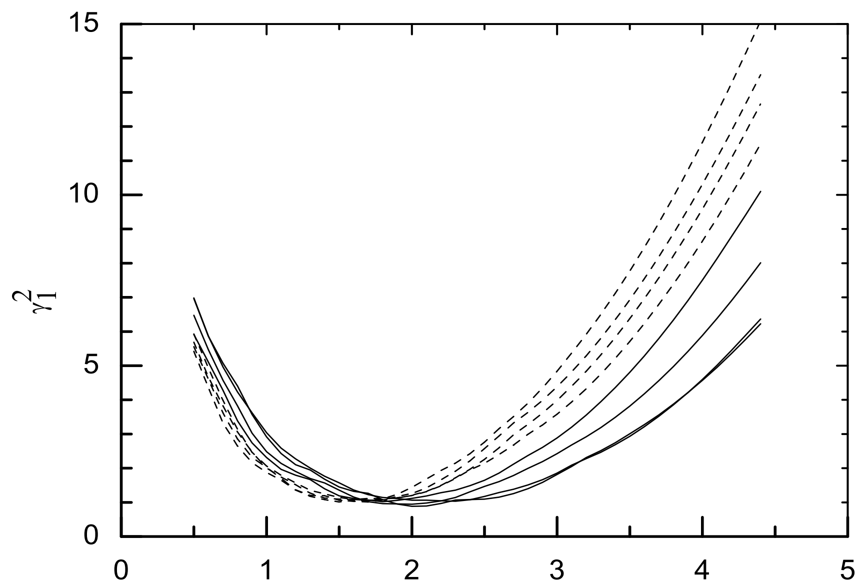

Figure 7: Functions χ_1^2 per one degree of freedom vs. energy E of EAS (solid lines–p, dashed lines–Fe).