ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
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УДК 537.591

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In the paper the survey of a set of experimental data obtained at four various arrays, which indicate appearance of different types of irregularities and anomalies in energy characteristics of cosmic rays of very high energies, is done. A possibility of explaining these peculiarities due to influence of long-flying component of cosmic rays, evidences of its existence were obtained at Tien-Shan calorimeter, is discussed. The role of this long-flying component in the interpretation of seeming absence of cosmic-ray energy spectrum cutoff because of Greisen–Zatsepin–Kuzmin effect is analyzed.

Дан обзор совокупности экспериментальных данных, которые свидетельствуют о появлении разного сорта нерегулярностей и аномалий в энергетических характеристиках космических лучей, полученных на четырех различных установках. Рассматривается возможность объяснения этих особенностей за счет влияния длиннопробежной компоненты, указания на существование которой были получены в экспериментах на калориметрах Тянь-Шаньской высокогорной научной станции. Оценивается роль длиннопробежной компоненты при интерпретации отсутствия обрезания энергетического спектра космических лучей предельно высоких энергий за счет эффекта Грейзена–Зацепина–Кузьмина.

INTRODUCTION

Recent studies of cosmic-ray energy spectrum in the region above $5 \cdot 10^{19}$ eV, did not confirm the existence of the predicted cutoff associated with the GZK effect. The explanation of this contradiction has generated a number of rather exotic assumptions.

Below, we present the results obtained with different experimental arrays, which show that a possible reason for the appearance of events with an energy exceeding $5 \cdot 10^{19}$ eV can be the long-flying hadronic component formed in interactions of high-energy particles in the atmosphere. The experimental results under discussion were obtained, basically, at the Tien-Shan high-mountain laboratory and on Pamir mountains (3340 and 4300 m above sea level, respectively), as well as by a Yakutsk group.

1. LONG-FLYING COMPONENT IN DENSE MATTER

First data concerning registration in the ionization calorimeter of long-flying component in EAS cores were published in 1974 [1]. In 1975, Feinberg [2] had assumed that charmed particles can be responsible for the delay of the energy flux absorption in EAS cores. However, data available in that time on lifetimes of these particles could not be compared with experimental data related to the long-flying component. After charmed particles parameters had been specified, Dremin et al. [3, 4] showed that the experimental data for the hadronic component in EAS cores, which had been obtained at an energy above 30 TeV (Fig. 1), could be explained under the assumption that the generation cross section of charmed particles attains $\sim 30\%$ of the inelastic proton–nucleus cross section. In addition, these particles could carry away a significant fraction of primary-particle energy. To distinguish the new component from the penetrating muon component, it was called by us the long-flying component (LFC).

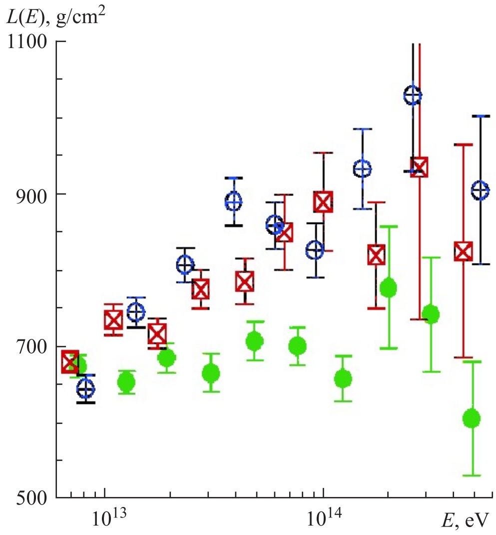

Fig. 1. Attenuation length $L(E)$ of hadronic component in EAS cores: crossed circles — experiment; solid circles — Monte Carlo without charm, $P(\chi^2) < 10^{-4}$; crossed squares — Monte Carlo with charm, $P(\chi^2) = 0.16$

Later on, Boreskov and Kaidalov [5] showed that in the case of an associative production of a Λ_c baryon and a $\bar{D}_c$ meson, they carry away the overwhelming fraction of the interacting-particle energy. Because charmed particles are composed of heavy quarks, they practically preserve their momentum up to decay, and thus carry away the energy deeply into the cascade produced.

In [6], we showed that cascades initiated by protons in an ionization calorimeter with a lead absorber rapidly change their shape with increasing the energy from 5 to 20 TeV: the lower energy being allocated at the cascade onset. The energy released decreases by factors of 3.3 and 2.2 at cascade depths of $\leqslant 110$ and $\leqslant 150$ g/cm^2; respectively, but increases at deeper depths (Fig. 2). This can also be explained by the important role of charmed particles.

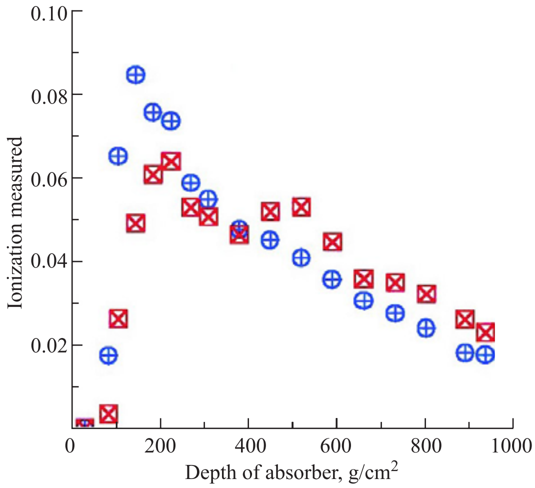

Fig. 2. Cascades initiated by single protons in calorimeter: circles — $E = 4.3$ TeV; squares — $E = 17.3$ TeV

In 1987, the PAMIR collaboration presented the data [7] on the abundance of cascades observed at large depths of lead in X-ray emulsion chambers. These results were also explained by the noticeable role of charmed particles.

2. LONG-FLYING COMPONENT IN AIR

If the role of charmed particles is significant, then at high energies they should manifest themselves deeply in the atmosphere. This idea was formulated for the first time by Stodolsky and McLerran [8].

In experiments performed at the Tien-Shan high-mountain laboratory of the Lebedev Institute, new experimental data had been collected [9–12], which indicated a rapid appearance of the shower maximum at the observation level. At an energy of $\sim (1{-}3) \cdot 10^{16}$ eV, the maximum of shower development falls through the mountain level, and the most energetic component of showers escapes registration.

In Fig. 3, the EAS size spectra are shown [9] for all showers (squares) and for young showers ($S < 0.7$) (circles). As is seen, the fraction of young

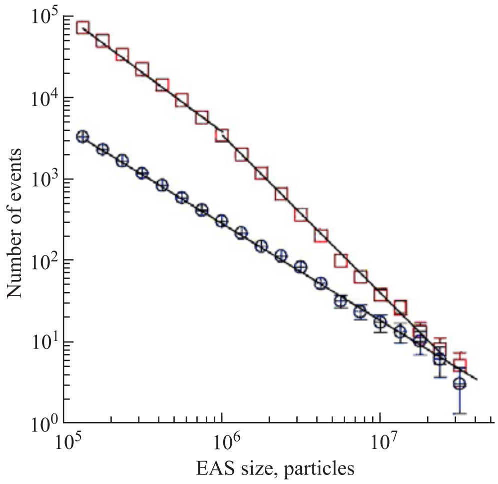

Fig. 3. EAS size spectra: squares — all showers; circles — young showers

showers rapidly grows with the EAS size, and for the number of particles $N \sim 10^7$, this fraction attains $\sim 80\%$. Such a fact testifies to a rapid shift of EAS maximum to the observation level. Escaping of the most energetic component from the observation level is accompanied by the spasmodic behavior of energy dependences of certain EAS parameters.

In [10], the dependence of the γ-ray energy on the EAS size was investigated. At the EAS size $N > 10^7$ particles (which corresponds to the energy $E > 10^{16}$ eV of a particle that initiated EAS), the jump (Fig. 4) indicating sudden drop in the energy transferred to γ rays was observed.

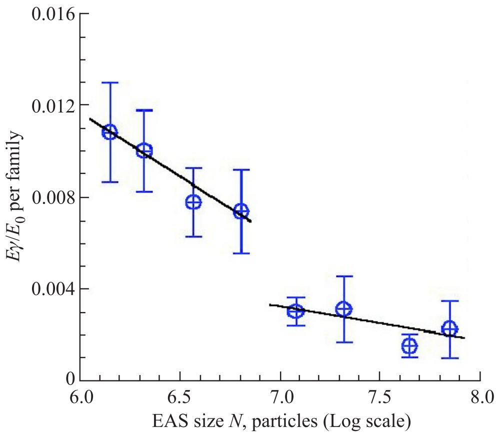

Fig. 4. Dependence of gamma-family energy on EAS size

In [11], electron–hadron cascades (normalized to one shower particle) formed in the EAS core were measured using an ionization calorimeter containing a thick lead absorber. Cascades practically preserve their shape, while changing the initial energy by approximately a factor of 30. However, at an energy of $\sim 10^{16}$ eV, the energy of the cascade jump-like decreased (Fig. 5).

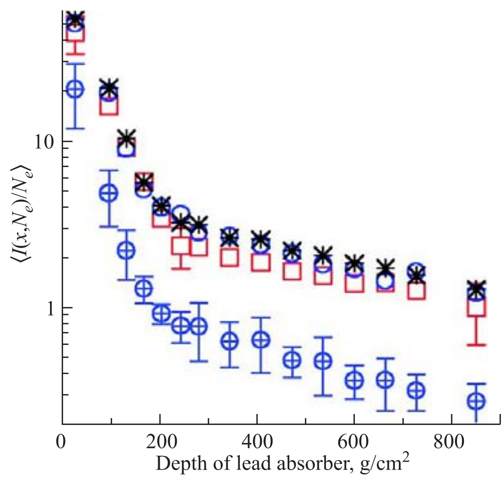

Fig. 5. Electron–hadron cascades in calorimeter normalized to EAS size: $*$ — $N = (1.8-3.2) \cdot 10^5$; $\bigcirc$ — $N = (1.8-3.2) \cdot 10^6$; $\square$ — $N = (3.2-5.6) \cdot 10^6$; $\oplus$ — $N = (5.6-10) \cdot 10^6$

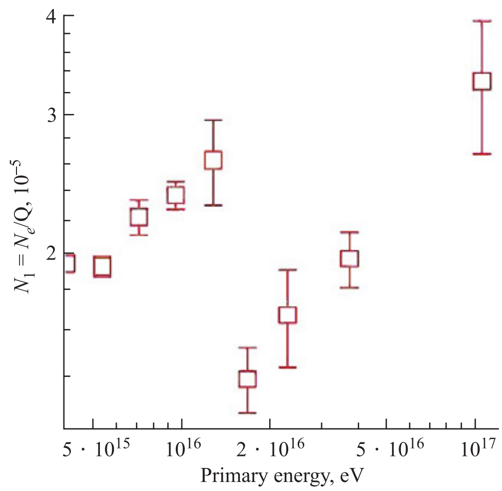

Fig. 6. Ratio: EAS size to the flux of Cherenkov light flux measured at Tien-Shan

In [12], the energy dependence for the ratio of a number of shower particles to the Vavilov–Cherenkov light flux, i.e., to the primary energy was investigated. This dependence also has a jump at an energy of $\sim 1.5 \cdot 10^{16}$ eV (Fig. 6).

All the listed results [9–12] can be explained by a sudden and rather sharp change in the mass composition of primary cosmic radiation or a threshold change in characteristics of particle interactions at energies above 10^{16} eV [13]. However, such a sharp change in the mass composition (lack of protons) is hardly consistent with the diffusion model of cosmic-ray propagation in the Universe [14].

We believe that the listed results can be explained under the assumption of the important role of charmed particles produced as a result of interactions of primary cosmic-ray particles in the atmosphere.

Then, the observable spasmodic changes in EAS parameters can be explained by rapidly increasing the disintegration length with the energy of unstable particles. At a sufficiently high energy, they slip a level of observation and avoid registration, demonstrating a *seeming* sudden increase in the fraction of heavy-mass primaries in cosmic radiation.

In this case, these particles should manifest themselves at large depths of observation, in particular, as abundance of showers registered at large zenith angles.

The excess of showers was really found out by us in [15]. Unfortunately, our experimental array had insufficient angular resolution. Later on, similar abundance was also found out in [16, 17]. However, the authors of [16] could not explain the nature of surplus, and authors of [17] were interested only in horizontal showers, i.e., showers practically consisting of only muons or showers produced by muons.

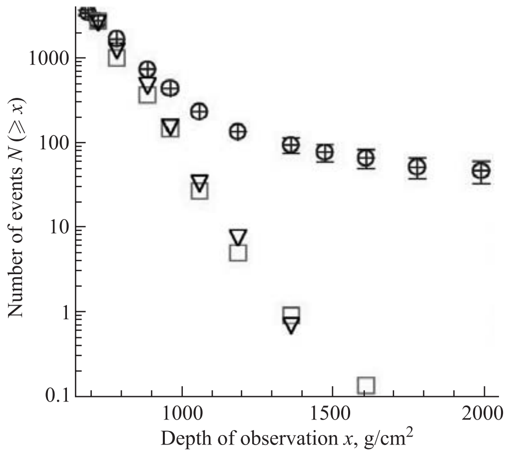

Fig. 7. Angular distribution of EAS at $N > 10^7$ particles: circles — experiment; calculations: squares — proton initiated EAS; triangles — iron initiated EAS

Recently, we put into operation an array having a good angular resolution and recording showers with $N > 10^7$ particles. The preliminary experimental results [18] also confirmed the existence of a slowly attenuating component as is seen from Fig. 7. Monte-Carlo calculations of the angular distribution for EAS initiated by protons and iron nuclei have not revealed any excess of showers detected at large zenith angles [18].

The slowly attenuating component also manifests itself at large depths of observation in the atmosphere in the case of higher energies as jumps found out by the Yakutsk group. In Fig. 8, data of [19] are shown related to the energy dependence of the ratio of the number of shower particles to the Vavilov–Cherenkov radiation intensity, i.e., to the primary energy. Here, in contrast to the data presented in Fig. 6, the jump occurs in the inverse direction: the number of particles increases at an energy of $\sim (2{-}3) \cdot 10^{17}$ eV. Apparently, this testifies to an increase of the fraction of showers initiated by protons.

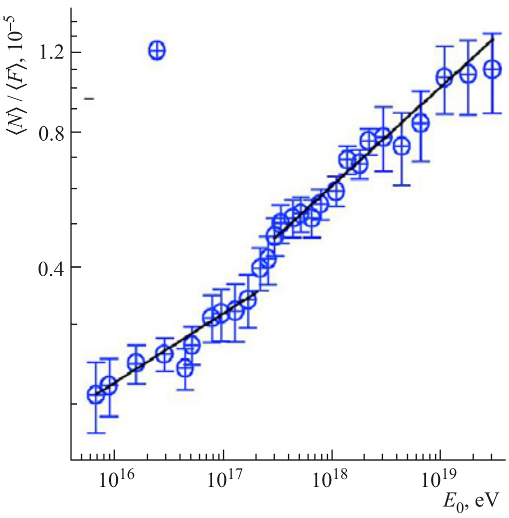

Fig. 8. Ratio: EAS size to the flux of Cherenkov light flux measured in Yakutsk

Even sharper jump at the same energy is demonstrated by the dependence of secondary-particle multiplicity as a function of primary energy [20], which is shown in Fig. 9. Here, the jump-like multiplicity decrease takes place, which can also testify to a sudden increase in a fraction of showers initiated by protons.

The ratio of the EAS sizes at sea level to those in shower maximum as a function of the primary energy was investigated in [21, 22]. This ratio steeply increases starting from the shower energy $E > 10^{17}$ eV, which indicates the rapid shift of the shower maximum toward the sea level. At the same time, the

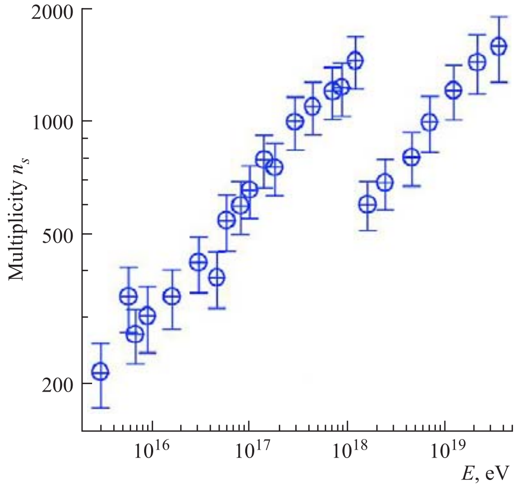

Fig. 9. Energy dependence of multiplicity of secondaries measured in Yakutsk

experimental data of [23] show that the attenuation of particle fluxes in EAS with primary energies above 10^{19} eV occurs much slower ($\lambda_{\rm att} = 226 \pm 16$ g/cm^2) than it is predicted by Monte-Carlo calculations based on the QGSJET model: $\lambda_{\rm att} = 178$ g/cm^2. This difference can result in overestimating the shower size at an observation level.

The results of [24] obtained with the AGASA array also confirm the assumption on the important role of the LFC at higher energies. It follows from this fact that statistics of events at $E > 10^{19}$ eV increases by a factor of 1.5 [24] if the analysis is restricted by zenith angles of 60° rather than 45°. In this case, the number of showers at a fixed energy decreases with the atmosphere depth in accordance with the attenuation length $\Lambda = 429$ g/cm^2 as it follows from the expression

$$N(x \leqslant 920/\cos 60°)/N(x \leqslant 920/\cos 45°) = 1.5.$$

Here, $x = 920$ g/cm^2 is the observation depth in the atmosphere; $N(x \leqslant 920/\cos 60°) = N_0[1 - \exp(-920/\Lambda \cos 60°)]$ is the number of events detected within the limits of 60°; and $N(x \leqslant 920/\cos 45°) = N_0(1 - \exp(-920/\Lambda \cos 45°))$ is the number of events detected within the limits of 45°, where $N_0 = N(x = 920$ g/cm$^2)$.

3. DISCUSSION

It is difficult to assume that in primary cosmic radiation at energies of $\sim 2 \cdot 10^{16}$ eV and $\sim (2\text{–}3) \cdot 10^{17}$ eV, the fractions of heavy nuclei and of protons, respectively, increase jump-like. The assumption on the important role of the long-flying component removes this difficulty.

It is clear that the rapid displacement of the shower maximum to sea level at standard assumptions on the high-energy shower development results in overestimation of the energy of a primary particle forming this shower. This statement concerns arrays used for estimating primary energy according to the shower size, or to the parameter ρ_{600}, i.e., the density of particles at a distance of 600 m from the shower axis.

At the same time, arrays recording the Vavilov–Cherenkov radiation or luminescence light in the atmosphere can underestimate the shower energy. This is associated with the fact that in the case of rapid displacement of the shower maximum to the observation level, the thickness of the atmosphere, in which this radiation is produced, decreases.

The allowance for the long-flying component can make consistent to each other the data of AGASA and of FLY's EYE.

Of course, the true nature of the long-flying component is still under question.

CONCLUSION

The set of results obtained with various experimental arrays shows that *the seeming absence* of the cosmic-ray energy spectrum cutoff in super-high energy region because of the GZK effect can be explained in natural way by the important role of the long-flying component produced while passing high-energy particles through the atmosphere.

Acknowledgements. This work was supported in part by the Russian Foundation for Basic Research, project No. 03-02-16272.

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