Composition of cosmic radiation at energies $\sim 10^{15}$ eV and above

S. I. Nikol'skiĭ, Ĭ. N. Stamenov, and S. Z. Ushev

P. N. Lebedev Physics Institute, USSR Academy of Sciences

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Experimental data on relative fluctuations of the fluxes of electrons and muons in extensive air showers have been used to determine the nuclear composition of the primary cosmic radiation in the energy range 10^{15}–10^{17} eV. The analysis of the experimental data does not involve assumptions regarding hadron-multiple-production processes at ultrahigh energies, since any models which are consistent with the averaged dependence of the number of muons in an extensive shower on the number of electrons, which has been thoroughly investigated in many experiments, are acceptable for this purpose. On the basis of the present work and previously published results of other authors on the intensity of the fluxes of protons and various nuclei at the edge of the atmosphere, and also on the basis of data on the total flux of primary particles in the energy range 10^{14}–10^{18} eV, we have obtained approximations of the energy spectra of primary protons and heavier nuclei in the energy interval 10^{12}–10^{18} eV. Over this entire range the composition of the primary cosmic radiation with respect to the relative contribution of protons and various nuclei remains approximately constant.

There are two serious reasons for the unflagging interest in the nuclear composition of primary cosmic rays in the energy range 10^{15}–10^{16} eV. One of these reasons is related to problems of the origin of cosmic rays of this energy and their propagation in the Galaxy and outside it. On the other hand, in analysis of experimental data on the interaction of cosmic rays with the nuclei of the atmosphere at energies of 10^{15} eV or higher, we are faced in a number of cases with two alternative choices: either we must assume a change of hadron-multiple-production processes at this energy, or the composition of the primary cosmic radiation at energies above 10^{15} eV differs significantly from the composition at energies of about 10^{12} eV.

It is well known that a number of experiments have observed and confirmed a break in the energy spectrum of primary cosmic rays in the primary-particle energy region 10^{15}–10^{16} eV.[1–3] The simplest explanation of the increase of the exponent γ in the energy spectrum of primary cosmic-ray particles $F(>E_0) \propto E_0^{-\gamma}$ from a value $\gamma = 1.6$–1.7 at $E_0 \leqslant 10^{15}$ eV to a value $\gamma = 2.0$–2.3 at energies $E_0 \geqslant 10^{16}$ eV was the assumption of the influence of magnetic inhomogeneities on the diffusion of cosmic rays in the Galaxy and a dependence of the diffusion coefficient in the Galaxy on the energy of the particles.[1,2,4] However, in this case the location of the break in the energy spectrum would be determined by the magnetic rigidity, which corresponds to a substantial difference (two orders of magnitude) in the energies of protons and various nuclei, including iron, in primary cosmic rays. As a consequence it is difficult to interpret the break in the observed spectrum of the total flux of primary protons and nuclei, on the one hand, and on the other hand the composition of primary cosmic rays should change from primarily protons at low energies to primarily heavy nuclei at high energies. As a result it has been suggested many times that the change of the exponent of the energy spectrum is due not to diffusion of particles in magnetic fields, but to interaction of nuclei and protons in the cosmic-ray sources. Here one must take into account that the energy threshold for disintegration of nuclei is significantly lower than the loss of energy by a proton in photoproduction of pions. Hillas,[5] for example, proposed that the break in the primary particle spectrum is formed in cosmic-ray sources as the result of collisions of protons and nuclei with photons having an energy of about 70 eV.

As an illustration of an ambiguity in the experimental data on cosmic rays associated with the composition of the primary particles, when the data are used to study inelastic collisions of hadrons and nuclei, let us consider the height of the maximum of the development of extensive air showers of cosmic rays with initial energy $\gtrsim 10^{15}$ eV (Fig. 1). Beginning with the experiments of Antonov *et al.*[6] in 1964 it was noted that extensive air showers from primary particles with energy 10^{15}–10^{16} eV develop too rapidly in the upper part of the atmosphere. To explain this it was proposed that, in contrast to the energy region of $\sim 10^{12}$ eV, in multiple-production events at energies $\geqslant 10^{15}$ eV one does not have formation of energetically distinguished secondary hadrons, but the ener-

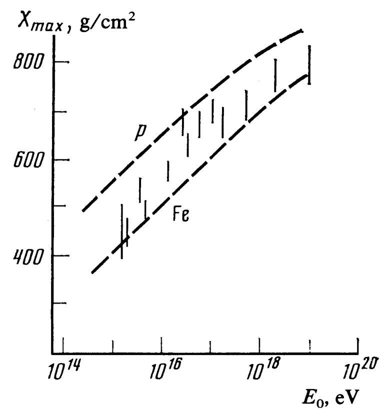

FIG. 1. Altitude of the maximum of development of extensive showers of various primary energies in the atmosphere on the basis of the review data from Ref. 7. The curves show the expected height of the maximum for primary protons p and for iron nuclei Fe on the assumption of scaling in the fragmentation region with a cross section for inelastic collisions which increases with energy.

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gy of the incident hadron is transferred to a large number of secondary particles. Recently investigations of the height of the maximum of the development of extensive air showers in a number of experiments have confirmed the high location of the maximum of the development of showers with primary energy 10^{15}–10^{16} eV.[7] However, in that same study[7] the authors conclude that on the assumption of scaling for the fragmentation (most energetic) part of the secondary hadrons, this height of the shower maximum corresponds to a dominant contribution of iron nuclei to the flux of primary particles with energy $\geqslant 10^{15}$ eV and it is not necessary to assume a change in the multiple-production event.

1. METHODS OF STUDY OF THE COMPOSITION OF PRIMARY COSMIC RAYS OF ULTRAHIGH ENERGY

As a result of the fact that the intensity of primary cosmic rays with energy $\geqslant 10^{15}$ eV amounts to about 10^{-2} particles per square meter per hour per steradian, and a square meter of spectrometric detectors for such energies weighs several tons, the entire range of methods of study of the primary-particle composition with apparatus taken outside the atmosphere is applicable only at lower energies. Detailed data of a number of experiments exist only in the energy region $\sim 10^{12}$ eV.[8–11] They are summarized in Table I for nuclei with various numbers of nucleons A. The flux of infrequent nuclei has been included in the flux of nuclei with the nearest A value. It can be seen from the table that the greatest relative contribution B to the total flux of primary particles with a total particle energy $\geqslant 10^{12}$ eV is from protons. The table also gives data in grouped form.

Study of the nuclear composition of primary cosmic rays at energies $> 10^{15}$ eV can be accomplished only by investigation of extensive air showers, with use of the sensitivity of certain characteristics of the showers to the nature of the primary particles. An example of a characteristic which is sensitive to the nature of the primary particle has already been given: the height of the maximum of shower development. Another example is the number of muons in a shower with a given number of electrons. Unfortunately these two characteristics depend in no small way on the parameters of the inelastic collision and of the multiple production of hadrons, which in turn frequently require study themselves. This leads to ambiguities in interpretation of the experimental data or to arbitrariness of the conclusions which are drawn.

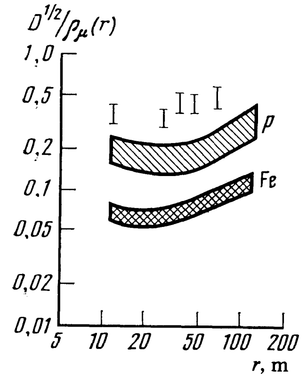


FIG. 2.

If we consider various possibilities of determining the composition of primary cosmic rays on the basis of studies of the properties of extensive air showers in the interior of the atmosphere, we must acknowledge that the most productive studies are those in which one analyzes not the average values of some characteristics of the shower, but the distributions of parameters observed for a given class of showers, measured in each individual shower. For example, in the early Refs. 3 and 12, fluctuations of the muon flux in showers with a given number of electrons at the observation level were utilized for analysis of the primary-particle composition.

In Fig. 2 we have shown data on the dispersion D of the muon flux density $\rho_\mu(r)$ at various distances r from the shower axis in showers with a given number of electrons ($1.4 \cdot 10^6$) at a depth of about 700 g/cm^2 (the Tien Shan Observatory).

The calculated dispersion values for primary protons and iron nuclei are shown by the hatched bands labeled p and Fe. The widths of the bands characterize the total spread permissible at the present time in choice of the model of the inelastic collision of nucleons, pions, and iron nuclei with the nuclei of the atmosphere. It is clear that a mixture of protons and nuclei will have a dispersion no greater than a pure proton flux if the average values of the muon flux density in showers from different primary particles coincide. The significant excess of the experimentally observed dispersions tells us that the average values of the muon flux density in showers with a given number of electrons but with different primary particles do not coincide, as is illustrated in Fig. 3. This lack of agreement can be used[3,12] to determine the composition of primary cosmic rays in approximate form by

TABLE I.

Number of nucleons A in the nucleus	Flux of particles with energy $>10^{12}$ eV per nucleus, in m^{-2} sec^{-1} sr^{-1}	Fraction B	Groups of nuclei	Fraction B
1	$6.5 \cdot 10^{-2}$	0.40	p	0.40±0.03
4	$3.4 \cdot 10^{-2}$	0.21	α	0.21±0.03
12	$7.0 \cdot 10^{-3}$	0.044	M $\langle A\rangle=15$	0.14±0.03
14	$2.0 \cdot 10^{-3}$	0.012		
16	$1.4 \cdot 10^{-2}$	0.09		
20	$4.2 \cdot 10^{-3}$	0.03	H $\langle A\rangle=26$	0.13±0.03
24	$7.1 \cdot 10^{-3}$	0.044		
28	$6.6 \cdot 10^{-3}$	0.04		
32	$2.6 \cdot 10^{-3}$	0.016		
39	$1.8 \cdot 10^{-3}$	0.011	VH $\langle A\rangle=51$	0.12±0.04
40	$1.8 \cdot 10^{-3}$	0.011		
52	$8.4 \cdot 10^{-3}$	0.052		
56	$6.3 \cdot 10^{-3}$	0.04		

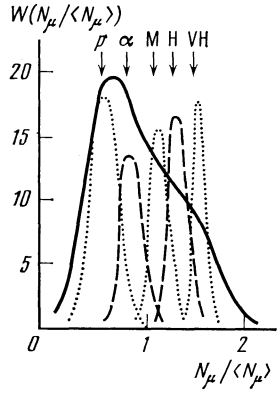


FIG. 3. Diagram of the causes of fluctuations of the number of muons in a shower with a given number of electrons. The dotted and dashed curves characterize the fluctuations of the number of muons in showers from primary protons p, α particles, and heavier groups of nuclei. The solid curve is the sum of the partial distributions, displaced with respect to each other, with inclusion of the experimental errors.

groups of nuclei which do not differ too greatly in the number of nucleons, as has been done in Table I and Fig. 3.

The experimental data on the fluctuations of the muon flux in extensive air showers with a given number of electrons at a depth ~ 700 g/cm^2 in the atmosphere—as shown in Fig. 2 and elsewhere below —were obtained in the Tien Shan comprehensive EAS installation[13] in the joint experiments of the P. N. Lebedev Physics Institute of the USSR Academy of Sciences and the Institute of Nuclear Research and Nuclear Power of the Bulgarian Academy of Sciences. The arrangement of the detecting portions of the Tien Shan installation which are important for the further discussion is shown in Fig. 4. In the center of the installation (the place of predominant passage of the axes of the detected showers) is an ionization calorimeter of dimensions 6×6 meters for measurement of the energy of the electron-photon and hadronic components of extensive air showers. The "carpet" of scintillation detectors above the calorimeter and four groups of scintillators at a distance of about 15 meters from the center of the installation provide high accuracy (~ 1 meter) in determination of the point of intersection of the shower axis and the plane of observation in a radius of about 7 meters around the center of the apparatus. The scintillation detectors at a distance of ~ 20 m from the center of the apparatus, in addition to determining the flux density of the electron-proton component of the shower, permitted determination of the angular coordinates of the shower axis on the basis of the relative delay of passage of the shower front through these scintillators. The error is $\sim 5°$ in the projections onto mutually perpendicular vertical planes passing through the scintillators mentioned and the center of the apparatus. The scintillation detectors and gas-discharge hodoscopic counters at a distance ~ 70 m from the center of the apparatus serve as a basis for classification of the detected event in the total number of electrons at the observation level. Discharge hodoscopic counters of total area ~ 50 m^2 were placed in an underground laboratory below the center of the apparatus and in a tunnel of length about 50 m leading into the underground laboratory. The earth layer of thickness ~ 20 mw.e. (meter water equivalent corresponded to an energy threshold ~ 5 GeV for the detected muons.

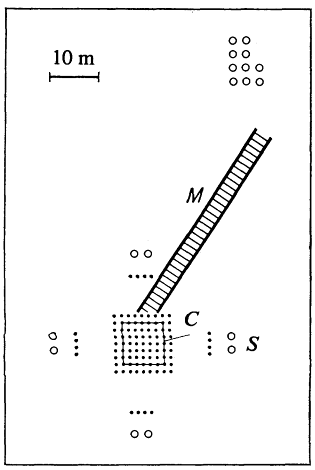


FIG. 4. Plan view of the Tien Shan comprehensive EAS installation. S are scintillation detectors for detection of electrons, C is an ionization calorimeter, and M are hodoscopic gas discharge counters under an earth layer $\sim 2 \cdot 10^3$ g/cm^2 for detection of muons.

2. RELATION BETWEEN THE NATURE OF THE PRIMARY COSMIC-RAY PARTICLES AND THE PROPERTIES OF EXTENSIVE AIR SHOWERS

The difference in the properties of extensive air showers produced by protons and by primary nuclei is the result of many factors. There are differences in the cross sections for inelastic collisions, the total multiplicities of secondary hadrons, the maximum energies of the secondary pions for the same total energy of the primary particle, and so forth.

The relation between the number of nucleons in the primary particle and the properties of the shower can easily be traced in the framework of the simplified superposition model.[14] The model is based on the single assumption that an extensive air shower produced by a primary nucleus with energy E_0 and with A nucleons can be considered as the superposition of A showers from primary electrons with energy E_0/A. Then, if the numbers of electrons and muons at the observation level is related to the energy of the primary protons as $E_{e,p} = kE_0^s$ and $N_{\mu,p} = k_1E_0^{s_1}$, the numbers of electrons and muons in the shower from a primary nucleus consisting of A nucleons can be written as

$$N_e = Ak(E_0/A)^s, \quad N_\mu = Ak_1(E_0/A)^{s_1}. \tag{1}$$

The relation between the number of electrons and the number of muons at the observation level will depend on the nature of the primary particles and in our discussion will be expressed as

$$N_\mu = k_1 k^{-s_1/s} A^{1-s_1/s} N_e^{s_1/s}. \tag{2}$$

In the maximum of development of the shower and below, $s \geqslant 1$ and $s_1 < 1$. In all experiments carried out to the present time $s_1/s = \alpha < 1$. Leaving aside for the moment all sources of fluctuations in the relative fluxes of electrons and muons other than the inhomogeneity of the composition of the primary cosmic radiation, we find that for a given number of electrons at the observation level the smallest number of muons is contained in showers from primary protons, and for a fixed number of muons the smallest flux of electrons is in showers from the heaviest nuclei,

$$N_\mu = A^{1-\alpha} N_{\mu,p}, \quad N_e = \text{const},$$
$$N_e = A^{1-1/\alpha} N_{e,p}, \quad N_\mu = \text{const}. \tag{3}$$

However, the fraction of showers from different primary particles for N_e = const and N_μ = const is not the same and does not correspond to the composition of the primary cosmic rays, since in the primary flux there are particles of different energies, and the relation between E_0, N_e, and N_μ depends on A.

Representing the differential energy spectrum of the primary cosmic rays as $f(A,E_0) = \varphi(A) C E_0^{-\gamma-1}$ and taking into account the relations given above between E_0, N_e, and N_μ, we can obtain the observed spectra of showers in A, N_e, and N_μ (C is a normalization factor):

$$f(A, N_e) = C\varphi(A) A^{\gamma(1/s-1)} s^{-1} k^{\gamma/s} N_e^{-\gamma/s-1},$$
$$f(A, N_\mu) = C\varphi(A) A^{\gamma(1/s_1-1)} s_1^{-1} k_1^{\gamma/s_1} N^{-\gamma/s_1-1}. \tag{4}$$

These spectra permit us to evaluate the parameters s and s_1 introduced by us on the basis of experimental data on the spectra of showers in number of electrons and muons at the elevation of our measurements, 3330 m above sea level. Separating the dependences

$$f(N_e) \propto N_e^{-\gamma/s-1} = N_e^{-\varkappa_e-1}, \quad f(N_\mu) \propto N^{-\gamma/s_1-1} = N^{-\varkappa_\mu-1}$$

and using the experimental data from Kirov *et al.*[15] for a primary energy $E_0 \geqslant 2 \cdot 10^{15}$ eV: $\varkappa_e = 1.85 \pm 0.03$ and $\varkappa_\mu = 2.30 \pm 0.05$, we find for the exponent of the primary spectrum $\gamma = 2.0 \pm 0.05$ the values $s = 1.08 \pm 0.05$ and $s_1 = 0.87 \pm 0.05$. The parameter $\alpha = \varkappa_e / \varkappa_\mu = 0.80 \pm 0.03$ is evaluated without use of data on the energy spectrum of the primary cosmic rays. The relation between the number of muons and the flux of electrons in a shower at the measurement level has been studied experimentally with high accuracy over a wide range of the number of electrons in the shower.[16] The observed dependence (2) ($N_\mu \propto N_e^{s_1/s} = N_e^\alpha$ gives a value $\alpha = 0.80 \pm 0.01$.

The estimates made of the parameters s, s_1, and α on the basis of the experimental data are not directly related to the assumption of superposition, since they do not involve at all the question of the composition of the primary particles. However, this neglect of the complex composition of the primary cosmic rays in essence brings us somewhat closer to this assumption, since in not distinguishing the various components of the composition of the primary radiation we are assuming that the protons and the nuclei are similar in the dependences

$$N_\mu = f(E_0), \quad N_e = f(E_0), \quad N_\mu = f(N_e).$$

The assumption of superposition, which permits us to represent the shower from a primary nucleus as the sum of showers from the nucleons which make up this nucleus, is convenient but approximate, and it is the more erroneous, the closer we approach the first events of shower production. The first inelastic collision in a group of A nucleons occurs with a cross section $\sim A\sigma_0$, where σ_0 is the cross section for inelastic collision of a nucleon with a nucleus of the atmosphere. The cross section for a nucleus of A nucleons is proportional to $A^{2/3}\sigma_0$, and here complete breakup of the nucleus is unlikely. Among the secondary particles there very frequently turn out to be α particles and heavier fragments. Therefore the initial stage of a real shower from a primary nucleus does not correspond to the sum of the showers from the nucleons of this nucleus. However, with development of the shower and its penetration into the depth of the atmosphere, the difference between a shower calculated on the assumption of superposition and a shower calculated with allowance for fragmentation of the primary particle is smoothed out.[17] Qualitatively this is explained by the fact that the parameters s, s_1, and α characterize the properties of the cascade, which are sensitive primarily to the initial number of particles with the highest energies. The energy spectrum of the fragmentation portion of the secondary hadrons in a collision of nuclei is determined to a substantial degree by the Lorentz factor of the nucleus, i.e., by the energy per nucleon, and not by the total energy of the nucleus, since cumulative effects are small.

Calculations show that taking into account the fragmentation of the primary nucleus actually does not appreciably change the relative fluxes of muons and electrons in showers. If the relation (3) $N_\mu = A^{1-\alpha} N_{\mu,p}$ is rewritten as $N_\mu = \eta(A) N_{\mu,p}$, then the difference in $\eta(A)$ calculated with inclusion of fragmentation of the primary nucleus and $\eta(A) = A^{1-\alpha}$ calculated with assumption of the superposition of showers from A nucleons is practically unobservable (Fig. 5). In the same figure we have shown how the dispersion of N_μ for a fixed value N_e = const changes in the transition from showers produced by primary protons to showers from primary nuclei. On the assumption of superposition, the relation between these dispersions $D_A^{1/2} = \Delta D_p^{1/2}$ is determined simply. For a given number of electrons at the measurement level $\Delta_\mu = A^{0.5-\alpha}$. Taking into account the fragmentation greatly increases the dispersion of the relative fluxes of electrons and muons in showers from primary nuclei (Fig. 5).

3. NUCLEAR COMPOSITION OF PRIMARY COSMIC RAYS WITH ENERGY 10^{15}–10^{16} eV.

Fluctuations of the relative fluxes of electrons and muons in extensive air showers with primary energy 10^{15}–

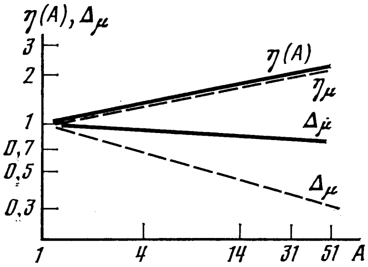
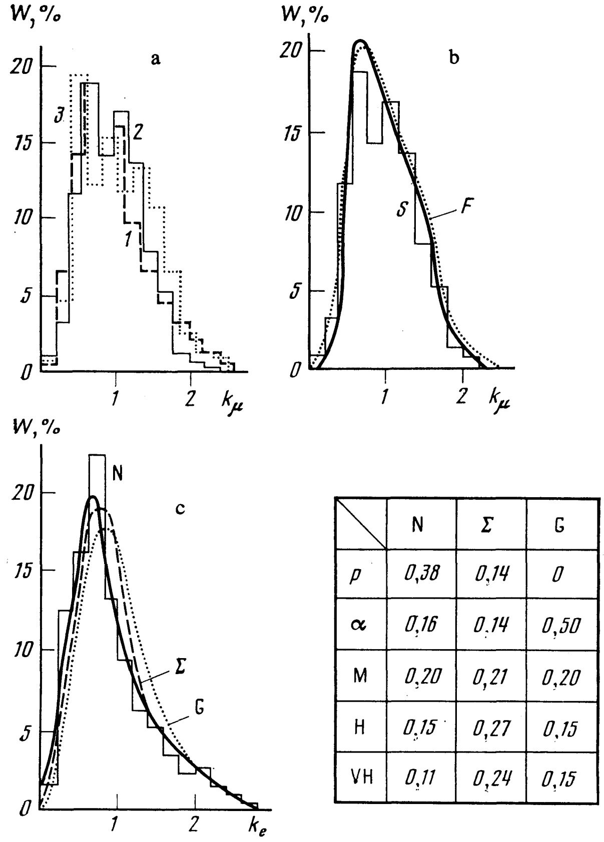


FIG. 5. Average number of muons $\eta(A)$ and the width of the fluctuation distribution Δ_μ, as functions of the number of nucleons in the primary nucleus. The solid lines were calculated with inclusion of fragmentation of the primary nuclei, and the dashed lines—on the assumption of superposition of A showers from the nucleons of the nucleus.



	N	Σ	G
p	0,38	0,14	0
α	0,16	0.14	0,50
M	0,20	0,21	0,20
H	0,15	0,27	0,15
VH	0,11	0,24	0,15

FIG. 6. a) Experimentally observed fluctuations of k_μ for N_e in the intervals 10^6–$1.78 \cdot 10^6$ (1), $1.78 \cdot 10^6$–$3.16 \cdot 10^6$ (2), and $3.16 \cdot 10^6$–$5.6 \cdot 10^6$ (3); b) the histogram is the experimental distributions of k_μ for $1.78 \cdot 10^6 \leqslant N_e < 3.16 \cdot 10^6$; the curves are the expected distributions for a nuclear composition N in the table on the assumption of superposition (S) and with allowance for systematic fragmentation of the nuclei (F); c) observed (the histogram) and expected (the curves) fluctuations for various compositions of the primary particles, as shown in the table.

10^{16} eV were investigated by means of the Tien Shan comprehensive EAS installation (Fig. 4). Experimental data on the number of extensive air showers with various relative numbers of muons $k_\mu = N_\mu / \langle N_\mu \rangle$ with energy $\geqslant 5$ GeV for a given number of electrons

$$10^6 \leqslant N_e < 1{,}78 \cdot 10^6,$$

$$1{,}78 \cdot 10^6 \leqslant N_e < 3{,}16 \cdot 10^6 \text{ and } 3{,}16 \leqslant N_e < 5{,}6 \cdot 10^6$$

are given in Figs. 6a and b in the form of histograms. A histogram of the distribution of the relative number of electrons in shower for a fixed number of muons $1.6 \cdot 10^4 \leqslant N_\mu < 3 \cdot 10^4$ is shown in Fig. 6c.

We shall leave for subsequent discussion the question of the differences in the histograms of Fig. 6a and note their similarity in good representation of showers with a relative number of muons $k_\mu = N_\mu / \langle N_\mu \rangle$ in the interval 0.4–0.8, which characterizes the presence in the primary radiation of a significant fraction of protons. The curves in Fig. 6b characterize the expected distribution for a nuclear composition similar to the composition at 10^{12} eV (Table I). The calculation was carried out in the Cocconi-Koester-Perkins model, which gives the observed average number of muons $\langle N_\mu \rangle$ and the dependence of this number on the number of electrons in the shower. As can be seen, the assumption of superposition leads to the same distribution as allowance for fragmentation of the primary nuclei. In Fig. 6c we compare the observed and expected distributions of the relative number of electrons for a fixed number of muons in a shower with various assumptions regarding the nuclear composition of the primary cosmic rays. The calculation was performed on the assumption of superposition according to the same CKP model. The "normal" composition N corresponds to the histogram with a χ^2 probability $P(\chi^2) = 0.20$, and the nuclear compositions Σ and G have values $P(\chi^2) < 0.02$ and $P(\chi^2) < 0.01$. The identical nature of the nuclear composition obtained from comparison with experiment on selection of showers on the basis of the number of electrons (N_e = const) and on the basis of the number of muons (N_μ = const) indicates correct allowance for the efficiency in sampling of showers produced by different nuclei, the fraction of which is determined for an equal energy of the primary particles.

However, an approach by a method of selection to the analysis of the primary cosmic radiation with characteristics of the multiple production event and the four independent parameters characterizing the composition unknown in their details cannot give either a final result or estimates of its accuracy. It is always possible to propose another model of multiple production of hadrons for calculation and comparison with experiment. A more effective approach to analysis of experimental data in this case has turned out to be the statistical method of solution of the inverse problem proposed by V. P. Pavlyuchenko (see Ref. 18).

The experimentally observed distribution of fluctuations in the relative fluxes of electrons and muons F_i in showers and the nuclear composition of the primary cosmic radiation f_j are related as follows:

$$F_i = \sum_{j=1}^{n} A_{ij} f_j.$$

The matrix A_{ij} depends on the measurement errors and the fluctuations of the relative fluxes of electrons and muons in showers produced by various primary nuclei and can be determined for each specified model of hadron multiple production if the parameters of the apparatus are known. Here we again encounter an uncertainty in choice of the model of hadron interactions, but, as we mentioned in the previous section, as the result of the averaging in the hadronic cascade of a large number of multiple-production events the influence of the large number of parameters characterizing the inelastic collisions of hadrons with nuclei reduces to dependences on the nature of the primary particles of the average ratios of the fluxes of muons and electrons and the dispersions of these ratios. Furthermore the effect of errors in the measurements and in the analysis of the experimental data is reflected in the overall dispersion of the experiment. This permits determination of a class of models for which the solution of the inverse problem by a statistical method will lead to some definite results.

Since it has been shown by a sampling method that allowance for the fragmentation of the primary nuclei in collisions with the nuclei of the atmosphere does not lead to an appreciable difference of the fluctuations of $k_\mu = N_\mu / \langle N_\mu \rangle$ from the superposition model, the analysis of the experimental data by a statistical method of solution of the inverse problem will be illustrated in the framework of the superposition model. In this case the average numbers of muons in showers with a fixed number of electrons at the observation level produced by primary nuclei with various numbers of nucleons A will differ in accordance with $A^{1-\alpha}$. The same parameter α characterizes the relation between the averaged electron and muon fluxes in the shower $\langle N_\mu \rangle \propto \langle N_e \rangle^\alpha$. The dispersions of the calculated distributions of showers in the number of muons D_A for a given number of electrons at the observation level and a number of nucleons in the primary nucleus A are determined in terms of the dispersion of showers from primary protons as $D_A^{1/2} = A^{0.5-1} D_p^{1/2}$. In this way all details of the assumed model of hadron-nucleus interactions reduce in our analysis to two parameters: $D_p^{1/2}$ and α. Here, since the dependence $\langle N_\mu \rangle \propto \langle N_e \rangle^\alpha$ has been reliably studied experimentally and $\alpha = 0.80 \pm 0.01$, inconsistency of the calculated α value with experiment is a criterion for exclusion of models which are not acceptable for description of the development of extensive air showers.

Figure 7 gives the results of solution of the inverse problem by a statistical method with arbitrary values of the parameters α and $D_p^{1/2}$ and also of the measurement errors in a complete modeling of the experiment by computer.

Figures 7a and b show how the result of the experiment is influenced by our lack of knowledge of the true value of the parameter α characterizing the dependence of the relative number of muons on the number of nucleons in the primary cosmic-ray particle. In our mathematical model of showers $\langle N_\mu \rangle \propto \langle N_e \rangle^{0.8}$, which completely corresponds to $\alpha = 0.80 \pm 0.01$. In solution of the inverse problem we used various values of α. As can be seen both from the χ^2 test and from the reproduction of the given percentage of protons in

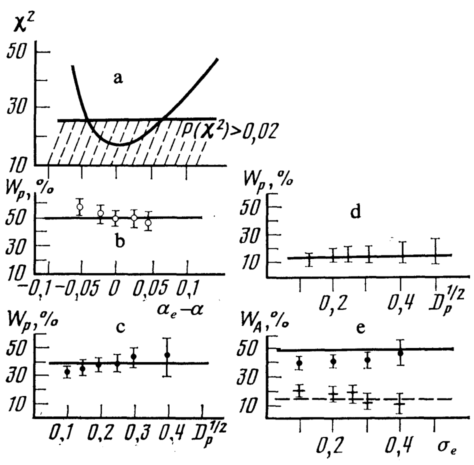


FIG. 7. Accuracy of solutions of the inverse problem by statistical means as a function of the cascade parameters of the shower and the accuracy of the experiment. W_p is the fraction of protons in the primary radiation. The horizontal straight lines are the specified fraction in the mathematical model of the experiment; W_A is the fraction of protons and iron nuclei (dashes) established from experimental data for various values of the experimental error σ_e and the parameters α and $D_p^{1/2}$.

the primary radiation, a deviation of the parameter α from its true value by 0.05 does not prevent determination of the nuclear composition of the primary radiation.

Figures 7c and d show the influence of the dispersion in the relative fluxes of muons and electrons in showers on the value and the accuracy in determination of the fraction of primary protons by the method discussed. Thus, for any models of the processes of inelastic collision and multiple production which satisfy the observed dependence of the average number of muons and electrons in the shower $\langle N_\mu \rangle \propto \langle N_e \rangle^\alpha$ with $\alpha = 0.80 \pm 0.01$ and which give a dispersion in the ratio of the fluxes of muons and electrons in the shower $D_p^{1/2} < 0.4$, it is possible to obtain information on the nuclear composition of the primary cosmic radiation, making use of the fluctuations in the relative magnitudes of the fluxes of electrons and muons in the shower.

The influence of the errors in measurement and analysis of the experimental data on the extensive air showers under study on the establishment of the composition of the primary radiation on the basis of fluctuations of the observed characteristics of the showers is shown in Fig. 7e.

The complete modeling which we have carried out of the experiment and the analysis of the experimental data by computer have enabled us not only to convince ourselves of the possibilities of the analysis, but also to bring to light for subsequent quantitative consideration systematic distortions of the results of the analysis.

Application of a statistical method of solution of the inverse problem to the experimental data obtained in the Tien Shan comprehensive EAS installation permits us to obtain the nuclear composition of the primary cosmic radiation in the range of primary-particle energies 10^{15}–10^{16} eV. In lines 1–5 of Table II we have given the results of analysis of the fluctuations of the muon flux in showers with a given number of electrons at the observation level for five values of the primary-particle energy. In the values given we have taken into account all known systematic distortions. When we select showers with a given number of electrons, we record showers with a greater energy of the primary particle, the more nucleons are contained in it. The question of the efficiency for detection of showers produced by various primary particles was discussed in the previous section. In order to verify the correctness of taking into account the detection efficiency, in the next two lines of Table II we have given a comparison of the nuclear composition determined from a sample of showers with a given number of electrons and from a sample of showers with a given number of muons.

The primary cosmic-ray composition obtained for the energy range 10^{15}–10^{16} eV does not differ within experimental error from the nuclear composition at primary particle energies $\sim 10^{12}$ eV (Table I). The large fraction of protons in the composition of the primary cosmic rays is preserved also with further increase of the primary-particle energy. Fluctuations of the ratio of the number of electrons and the number of muons in extensive air showers with primary energies 10^{16}–10^{17} eV have been studied in the Akeno installation located at 900 m above sea level in Japan.[19] The last three lines of Table II were obtained by application of the statisti-

TABLE II.

E_0, eV	B_A, %				
	p	α	M	H	VH
$1{,}5\cdot10^{15}$	39±4	11±7	16±5	16±5	18±5
$2{,}5\cdot10^{15}$	42±3	10±5	16±5	17±5	15±4
$4{,}5\cdot10^{15}$	38±4	14±6	17±4	17±5	14±5
$7{,}6\cdot10^{15}$	40±4	13±7	16±6	16±5	15±5
$1{,}2\cdot10^{16}$	43±5	15±8	15±6	13±4	14±6
10^{15}–10^{16} (N_e=const)	40±3	13±4	16±4	16±4	15±4
10^{15}–10^{16} (N_η=const)	40±6	17±8	10±8	15±6	18±6
$9\cdot10^{15}$	46±5	8±4	9±3	18±5	19±6
$3\cdot10^{16}$	47±5	10±6	13±6	10±3	20±4
$9\cdot10^{16}$	50±6	12±6	13±4	13±4	12±3

cal method of solution of the inverse problem to the experimental data[20] obtained in the Akeno installation.

Note the approximate nature of the estimates of the fraction of the various nuclei in the composition of the primary cosmic rays in Table II (relative error 30–50%). The higher accuracy in estimation of the fraction of primary protons is explained by the asymmetry of the experimentally obtained distributions (Fig. 6a).

4. DISCUSSION OF THE RESULTS ON COMPOSITION OF PRIMARY COSMIC RAYS WITH $E_0 > 10^{15}$ eV

Analysis of fluctuations in the relative number of muons and electrons in a shower permits us to state that the composition of primary cosmic rays in the energy range 10^{15}–10^{17} eV does not greatly differ from the nuclear composition of the primary particles at energies near 10^{12} eV. As was shown in the previous section, this conclusion does not depend on the details of the processes of inelastic collisions and multiple production, if only the assumed model provides the dependence of the averaged fluxes long established experimentally for extensive air showers $\langle N_\mu \rangle \propto \langle N_e \rangle^\alpha$.

On the other hand, data on the altitude of the maximum of development of extensive air showers with primary energy 10^{15}–10^{16} eV have served as the basis for the conclusion of the authors of Ref. 7 that the nuclear composition of the primary radiation at these energies becomes significantly heavier. However, this conclusion rests on the assumption of scaling in the fragmentation region of the inclusive spectrum of secondary hadrons. The rapid lowering of the altitude of the maximum of development of showers in the atmosphere with increase of the primary-particle energy in the energy region above 10^{16} eV, on the basis of these assumptions, signifies again an increase of the fraction of primary protons.

Thus, there are two opposite conclusions regarding the fraction of protons in the composition of primary cosmic rays in the energy region 10^{15}–10^{16} eV. Our conclusion of a fraction of protons $40 \pm 4\%$ on the basis of analysis of fluctuations is not greatly sensitive to the choice of the model of hadronic interactions. It is valid both for a model with preservation of scaling only in the fragmentation region (see for example Ref. 21) and for a model with strong violation of scaling. The opposite conclusion that there is a small fraction of primary protons and a dominance of heavy muclei at energy 10^{15}–10^{16} eV, which is obtained from data on the height of the maximum of development of the extensive shower, is closely related to the assumption of preservation of scaling in the fragmentation region of hadron multiple production.[1)] Experimental studies of this process at energies 10^{15}–10^{16} eV by means of x-ray emulsion chambers[23] indicate the absence of scaling, both in the pionization and in the fragmentation region of the secondary particles. It has been shown that this result does not depend on assumptions regarding the nature of the primary cosmic rays. This limitation of the conclusions of Ref. 7 to the assumptions of a definite model of the elementary event, including a model which is inconsistent with the experiment of Ref. 23, provides a basis for assigning a preference to the conclusion that the fraction of protons in the primary cosmic radiation is approximately constant ($\sim 40\%$).

The observed lack of correspondence of the height of the maximum of shower development in the atmosphere to the calculation with assumption of scaling must be explained not by a change of the composition of the primary particles, but by a violation of scaling both in the pionization region[21] and in the fragmentation region.[23] The dependence of the height of the maximum of shower development on the energy of the primary particle is complicated in the energy region 10^{16}–10^{7} eV, where the maximum drops into the depth of the atmosphere more rapidly than could be expected even for scaling with a constant value of the cross section for inelastic hadron-nucleus collisions. This complicated and changing pattern of inelastic collisions in the energy region 10^{14}–10^{17} eV cannot yet be expressed quantitatively, which is necessary in analysis of the experimental data. The influence of the assumed changes in hadronic interactions and hadronic cascades on the fluctuations of the relative fluxes of muons and electrons in showers can be seen qualitatively in comparison of the experimental data of Fig. 6a, which refer to showers with various energies. The histograms of the fluctuations for different primary energies are not completely similar, although they lead to primary cosmic-ray compositions which are identical within experimental error.

While at an incident-nucleon energy $\sim 4 \cdot 10^{13}$ eV there is an increase in the inelasticity coefficient and the fraction of the energy of the incident nucleon transferred to the electron-photon component,[24] on the other hand, in the distribution with $E_0 \sim 2.5 \cdot 10^{15}$ eV in Fig. 6a, showers produced by very heavy nuclei ($A = 50$) should have an increased number of muons not only because for them E_0/A is smaller, but also because $E_0/A < 4 \cdot 10^{13}$ eV. In addition, if the increase of the inelasticity coefficient and of the energy transfer to the electron-photon component occurs by production and decay of some new particles,[25] then the accelerated dropping of the maximum of the development of extensive air showers at primary energies $E_0 > 10^{16}$ eV can be associated with an increase of the Lorentz factor of the decaying particles and accordingly of the transport by them of energy into the depth of the atmosphere. This will be reflected in an increase of the primary energy at the beginning in development of showers produced by protons. The relative number of muons in showers with a given number of electrons at the observation level decreases in this case, which apparently is manifested in a shift to the left of the proton peak of the observed distribution $N_\mu/\langle N_\mu\rangle$ for $E_0 \sim 8 \cdot 10^{15}$ eV. The absence of the influence of these distortions in the distributions of the relative fluxes of electrons and muons on the result of establishment from these data of the nuclear composition of the primary particles is explained by the fact that the changes in the parameter α, which are responsible for the observed shifts, in the first case of heavy nuclei and in the second case of protons, do not exceed values $\Delta\alpha = 0.05$. As can be seen in Fig. 7b, such changes in the value of the parameter α do not distort the results of solution of the inverse problem.

What must be assumed regarding the interactions of the primary cosmic-ray nuclei with the nuclei of the atmosphere in order to imitate showers from protons? Just large fluctuations in showers from primary nuclei, which give a distribution with one maximum and a large distribution, cannot give an excess of showers with a relatively small number of muons, which is necessary for imitation of showers from primary protons. It is necessary that sometimes in addition to showers which originate in fragmentation of the primary nucleus there be formed showers from nuclei of another type in which in the first collision of the primary nucleus with the nucleus of an atom of the atmosphere the fraction of the energy of the primary nucleus $\Delta E_0/E_0 = A^{1-\alpha}-1$ is transferred by means of some kind of hadrons to the electron-photon component.

The property of the second type of nucleus-nucleus collisions consists not only of dominance of hadrons which decay into γ rays, but also of the concentration of a large fraction of the energy in these single hadrons. A concentration $\sim A^{1-\alpha}-1$ already for nuclei with $A = 20$ reaches $0.5E_0$ with an energy of the nucleons in the nucleus $\sim 0.05E_0$. These are collisions of a special type with a clearly expressed cumulative nature, but with a large cross section, which follows from the relative number of showers which imitate primary protons. Thus, in order to obtain, with a primary radiation containing in equal fraction protons and the four groups of nuclei α, M, H, and VH, the observed fluctuations in the number of muons in showers with a given number of electrons (Fig. 6a), it is necessary to assume that the cross section for nucleus-nucleus collisions with a transfer of a fraction $A^{1-\alpha}-1$ of the energy of the incident nucleus into the electron-photon component reaches 25% of the total cross section for inelastic collision. From this example it is evident how weakly the determination of the nuclear composition of the primary radiation on the basis of fluctuations of the muon and electron fluxes in the showers will depend on assumptions regarding the hadron-nucleus interactions.

The early work by Khristiansen and his colleages[1,2] demonstrated the change in the exponent of the energy spectrum of the primary cosmic radiation in the energy region $E_0 \gtrsim 10^{15}$ eV. If the change of the energy spectrum is related to the nature of the diffusion of cosmic rays in the Galaxy, then the energy spectrum of primary protons and nuclei should change for particles with different numbers of nucleons in the nucleus for identical radii of curvature in the interstellar magnetic fields (identical magnetic rigidity). If inelastic collisions of particles of cosmic radiation near the sources or in the Galaxy are responsible for the break in the primary spectrum, then the influence of these processes should appear at given values of the energy per nucleon, i.e., at identical Lorentz factors. However, as the result of the difference in the inelastic collision processes of protons and nuclei, which lead to knockout of particles of a given energy from the flux, the critical value of the Lorentz factor for protons should be 10–20 times higher than for nuclei. For protons this is due to pion production, and for nuclei it is sufficient that the inelastic collision result in disintegration of the nucleus.

Approximations of the energy spectrum, corresponding to this schematic approach, with an exponent changing in the energy region $\gtrsim 10^{15}$ eV, can be represented in the form

$$F(\geqslant E_0)=0{,}16E_0^{-\gamma}\Big[B_p(1+3\cdot 10^{-3}E_0)^{-0{,}4} + \sum_A B_A(1+6\cdot 10^{-3}A^{-1}E_0)^{-0{,}4}\Big], \quad (5)$$

$$F(\geqslant E_0)=0{,}16E_0^{-\gamma}\Big[B_p(1+6\cdot 10^{-4}E_0)^{-0{,}4} + \sum_A B_A(1+10^{-2}A^{-1}E_0)^{-0{,}4}\Big]. \quad (6)$$

Here E_0 is the primary-particle energy in TeV in the interval $1 \leqslant E_0 < 10^7$ TeV, B_p and B_A are the fractions of protons and the corresponding nuclei in the total flux of primary particles at $E_0 = 1$ TeV (Table I), $F(\geqslant E_0)$ is the flux of particles in units of $\mathrm{m}^{-2}\cdot\mathrm{sec}^{-1}\cdot\mathrm{sr}^{-1}$, and $\gamma = 1.62 \pm 0.03$.

Equations (5) and (6), as the sums of the partial spectra of primary protons and various nuclei, coincide in the behavior of $F(\geqslant E_0)$ and correspond to data on absolute intensities at energies $E_0 \geqslant 10^{12}$ eV,[8,10] $E_0 \geqslant 10^{15}$ eV,[26] and $E_0 \geqslant 10^{18}$ eV,[27,28] and also to data on the form of the energy spectrum in the vicinity of the break.[15] Equation (5) reflects the change of the energy spectrum of primary particles for a given magnetic rigidity. The characteristic size of the inhomogeneities of the magnetic fields in the Galaxy has been discussed in Refs. 1, 2, and 4 as the possible cause of the behavior of the cosmic-ray spectrum in the energy region $> 10^{15}$ eV. Equation (6) corresponds to the hypothesis of Hillas,[5] which relates the change of the energy spectrum of primary particles at energy $> 10^{15}$ eV to photodisintegration of nuclei with photoproduction of pions near sources of cosmic rays by photons with energy ~ 70 eV.

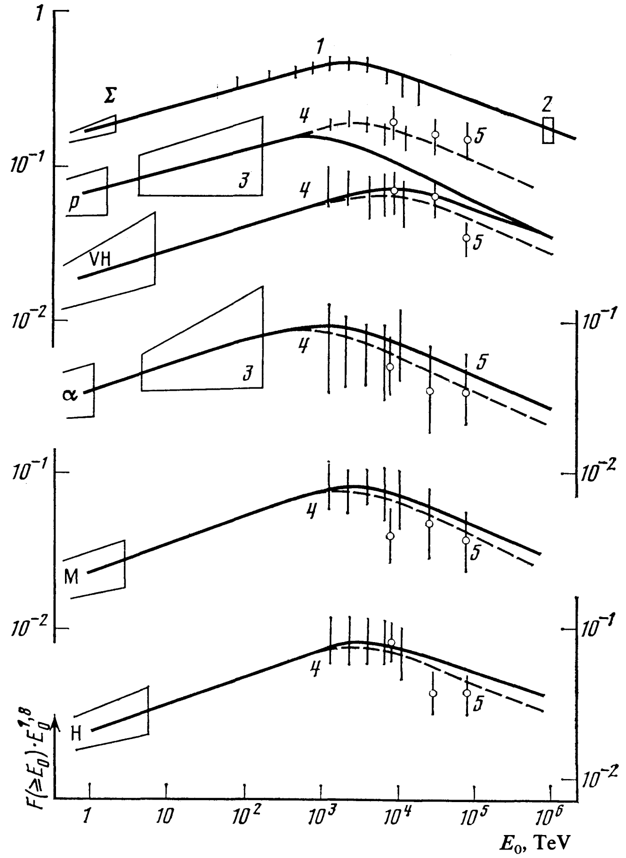


FIG. 8. Energy spectra of the total flux of primary cosmic radiation (Σ) and its components protons (p), α particles, and the groups of nuclei M, H, and VH. The ordinate gives the flux with energy above a given value in $m^{-2} \cdot sec^{-1} \cdot sr^{-1}$, multiplied by the energy in TeV to the power 1.8. The solid curves are the approximation (5), and the dashed curves are the approximation (6). The experimental data are from the following sources: the regions labeled p, VH, α, M, and H correspond to Table I, the data labeled 1 are from Ref. 15, the data 2 are from Refs. 27 and 28, the regions 3 are shown in accordance with Ref. 11, the data 4 correspond to Table II, and the data 5 correspond to the last three lines of Table II.

Comparison of the partial energy spectra in Fig. 8 with the experimental data of Table II shows that the approximation (6) best describes the set of experimental data on the energy spectrum and the composition of the primary cosmic radiation in the energy region 10^{14}–10^{17} eV. The spectrum of primary protons, in comparison with the spectrum of the combined flux of primary particles, is inconsistent with the hypothesis of a change in the exponent of the spectrum of all particles at the same value of magnetic rigidity.

Yodh *et al.*[29] have recently used the Monte Carlo method to analyze our approach to analysis of the nuclear composition of the primary cosmic radiation by analysis of the fluctuations of the fluxes of muons and electrons in an extensive air shower. The hadron-interaction model used, so-called radial scaling, gives the correct behavior of the number of muons as a function of the number of electrons with $\alpha = 0.8$ and is close to the models used by us. The conclusion drawn by the authors of Ref. 29 that there is a weak sensitivity of the muon-flux fluctuations for a fixed number of electrons to the details of the primary-particle composition is due to the large value obtained by them for fluctuations in the development of showers, $\sigma_p = 0.34$. As can be seen from Figs. 7c and d, with this value of σ_p the accuracy in determination of the fraction of protons becomes substantially poorer. However, the value $\sigma_p = 0.34$ obtained in Ref. 29 appears to us to be exaggerated for the following reason. The relative fluctuations in the muon flux $N_\mu / \langle N_\mu \rangle$ actually are fluctuations for $N_e = \text{const}$ in the case of limiting small intervals N_e or in the case in which by N_μ for $N_e = \langle N_e \rangle$ (where $\langle N_e \rangle$ is the average value for a fixed interval N_e'–N_e'') we understand $N_\mu (N_e / \langle N_e \rangle)^\alpha$. Otherwise σ_p will contain a dispersion associated with the width of the interval N_e'–N_e'', both experimentally and in the Monte Carlo calculations. Specifically in Ref. 29 the double interval N_e'–$2N_e'$ is used. This leads to a dispersion $D = 0.045$. Exclusion of this dispersion decreases the value $\sigma_p = 0.34$ to a value $\sigma_p = 0.26$, which agrees with the values of σ_p used by us and leads to a satisfactory resolution of the various components of the nuclear composition of the primary cosmic rays.

5. ULTRA-HIGH-ENERGY γ RAYS

If the shaping of the energy spectrum of the primary protons and nuclei in the energy region above 10^{15} eV occurs with participation of hadron photoproduction and photodisintegration of nuclei, then the regions of space where this occurs, or the sources of cosmic rays with $E_0 > 10^{15}$ eV, should manifest themselves in fluxes of γ rays with energy $\geqslant 10^{14}$ eV. In order to search for such γ rays we examined the experimental data on extensive air showers for the total time of operation of the Tien Shan comprehensive installation—17 950 hours. We selected for analysis showers in two intervals of number of electrons N_e: $3.2 \cdot 10^5$–$5.6 \cdot 10^5$ and $5.6 \cdot 10^5$–10^6. The cross section for photoproduction of pions and muons is much less than the cross section for production of pions by hadrons. A method, based on this, of searching for primary γ rays as a manifestation of extensive air showers deficient in muons was used more than twenty years ago.[30]

Figure 9a shows distributions in the relative number of muons for showers with a specified number of electrons. The arrow shows the permissible number of muons in showers from primary γ rays as the result of hadron photoproduction with consideration of the possibilities of the Tien Shan EAS installation. As can be seen from the figure, this method does not provide sufficient resolution for the unambiguous selection of showers from primary γ rays.

In contrast to muons, pions are accumulated to a smaller degree in the development of cascades in the atmosphere. In Fig. 9b we have shown the distribution of the ratio of the energies of the hadronic and electron-photon components in the cores of extensive air showers in the cases of passage of the shower axis through the ionization calorimeter. The arrow in the figure shows the limiting permissible value of the relative energy flux in the hadronic component for electron-photon cascades from primary γ rays. The value of the energy flux in the hadronic component of the core of a shower more reliably distinguishes showers from primary γ rays than does the relative number of muons. Only six of the twenty-one showers in which in a counter area of about 50

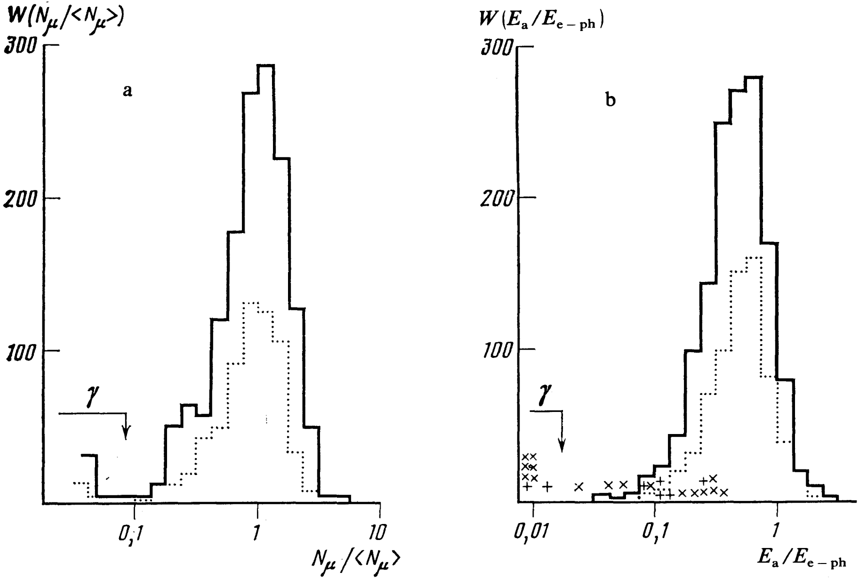


FIG. 9. Distributions in the relative flux of muons in a shower (a) and in the ratio of the energy flux of the hadronic component E_a and the electron-photon component E_{e-ph} of the core of the shower (b). The arrows show the permissible values of these ratios in showers from primary γ rays. The solid line and the oblique crosses correspond to $3.2\cdot10^5\leqslant N_e\leqslant5.6\cdot10^5$, and the dashed line and the upright crosses correspond to $5.6\cdot10^5\leqslant N_e\leqslant10^6$. The crosses in Fig. 9b are the muon-free showers on the basis of Fig. 9a.

m^2 there was no muon, did not also have hadrons in the shower core. On the other hand, we found two showers which did not have hadrons in the core but which were not included in the number of muon-free showers as the result of operation of one of the counters of the muon hodoscope, which could be assigned to accidental coincidences. The energy of the primary γ rays which produced these eight showers turned out to be in the range $(5–8.5)\cdot10^{14}$ eV with an average value $6.7\cdot10^{14}$ eV.

In Fig. 10 we have shown the directions in which the γ rays were observed. All the γ rays turned out to be concentrated in roughly half the field of view of the Tien Shan EAS installation. The diffuse flux of γ rays with energy $6.7\cdot10^{14}$ eV assigned to the entire visible region of the celestrial sphere is $(4.8\pm1.6)\cdot10^{-13}$ cm$^{-2}\cdot$sec$^{-1}\cdot$sr^{-1}, or $\sim10^{-3}$ of the flux of primary protons and cosmic-ray nuclei of the same energy. This diffuse flux agrees with the results of Ref. 31.

The absence of γ rays from local x-ray and γ sources from the Crab Nebula and Cygnus X3 falling into the field of view of the Tien Shan comprehensive installation is consistent with the data of Refs. 32–35 on the fluxes of ultrahigh-energy γ rays from these sources. The flux of γ rays with energy $3\cdot10^{14}–10^{17}$ eV observed by Dzikowsky *et al.*[36] from the region of the Crab Nebula exceeds the upper limits estimated from the absence of γ rays both in our measurements and in Refs. 32–34. Allowance for the nonuniformity of the distribution of γ rays in different directions approximately doubles the flux from the region around the north pole of the Galaxy, bounded by galactic latitude $b=30$°. If this flux is considered as a diffuse flux from the region outside the galactic disk and is compared with the flux of γ rays at energies $\geqslant10^8$ eV, then the energy spectrum of γ rays turns out to be significantly more energetic than the spectrum of cosmic rays, which indicates an enhanced pumping of energy from nucleons and cosmic-ray nuclei into γ rays at energies $>10^{15}$ eV, as should be the case if the break in the cosmic-ray spectrum at $E_0\geqslant10^{15}$ eV is due to interactions.

It is possible to consider the observed γ rays as γ rays from unknown sources located outside the galactic disk. However, none of our γ rays coincides in its coordinates with the assumed six sources of γ rays with energy above 10^{15} eV identified on the basis of an excess of extensive air showers in narrow solid angles[35] (Fig. 10), or with the region outlined in Ref. 37 on the basis of an excess flux of extensive air showers with primary energy $\sim10^{17}$ eV.

6. CONCLUSIONS

The results of the experiments in the Tien Shan comprehensive EAS installation unambiguously correspond to a nuclear composition of the primary radiation with energy $10^{15}–10^{16}$ eV close to the composition at 10^{12} eV (protons $40\pm4\%$). This result essentially does not depend on assumptions regarding the inelastic collision and hadron mul-

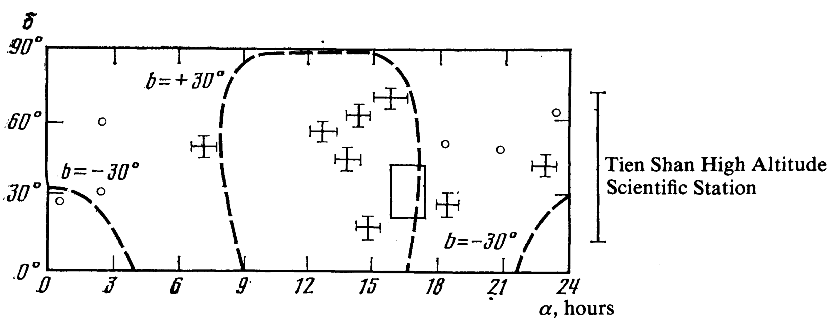


FIG. 10. Distribution of recorded γ rays over the visible part of the sky. The size of the crosses corresponds to the accuracy in determination of the coordinates. The dashed lines separate regions of galactic latitude b: $|b|\geqslant30$° and $-30°\leqslant b\leqslant30$°. The rectangle denotes the region of excess flux of showers with $E_0\sim10^{17}$ eV according to Ref. 37, and the circles show the coordinates of the γ-ray sources with energy $\gtrsim10^{15}$ eV suggested in Ref. 35.

tiple production processes. The alternative point of view regarding the large fraction of heavy nuclei at primary energies $\sim 10^{15}$ eV is closely associated with definite assumptions regarding these processes and cannot be considered to be justified experimentally.

The approximation of the spectrum in the extended energy range from 1 to 10^7 TeV taking into account a change of the energy spectrum of the primary radiation in the energy region 10^6–10^7 TeV:

$$F(\geqslant E_0, \mathrm{TeV}) = 0.16 E_0^{-1.62\pm0.03}\Big[B_p(1+6\cdot10^{-4}E_0)^{-0.4} + \sum_A B_A(1+10^{-2}A^{-1}E_0)^{-0.4}\Big]\ \mathrm{m^{-2}sec^{-1}sr^{-1}}$$

contains also the energy spectra of the principal components of the primary cosmic radiation at energies 1–10^5 TeV. Here for the coefficients B_p and B_A we are taking the rather well known relative fluxes of protons B_p and of nuclei with various numbers of nucleons A, B_A, at an energy 1 TeV per particle. For protons and for the groups of nuclei with $A = 4$ $\langle A \rangle = 15$, $\langle A \rangle = 26$, and $\langle A \rangle = 51$ these coefficients are given in Table I ($B_p = 0.40 \pm 0.03$, $B_4 = 0.21 \pm 0.03$, $B_{15} = 0.14 \pm 0.03$, $B_{26} = 0.13 \pm 0.03$, and $B_{51} = 0.12 \pm 0.04$). This approximation is still meaningful with a more detailed representation of the nuclear composition of the primary cosmic radiation.

The change of the exponent of the energy spectrum of the primary protons at a significantly higher value of magnetic rigidity than for nuclei signifies the inapplicability of simple explanations of the break in the cosmic-ray spectrum at energy $\gtrsim 10^{15}$ eV by the influence of the distribution of magnetic fields in the Galaxy. Explanations which relate the increase of the exponent of the cosmic-ray energy spectrum at energies $\gtrsim 10^{15}$ eV with the loss of energy by protons to photoproduction of pions and to the photodisintegration of nuclei are becoming more probable.

The possible relation of pion production to the formation of the cosmic-ray energy spectrum in the energy region $> 10^{15}$ eV would permit association of the region of production of γ rays with energy $\gtrsim 10^{14}$ eV with the regions of formation of the energy spectrum of cosmic rays, and with sources of particles of ultrahigh energy. The dominant arrival of γ rays with energy (5–9) $\cdot 10^{14}$ eV from outside the galactic disk, on the one hand, and the significantly smaller diffuse flux of γ rays of this energy from the central regions of the galactic disk,[38] on the other hand, could be an indication of the extragalactic origin of cosmic rays of ultrahigh energy, if we do not consider the absorption of γ rays in the relict radiation. However, cosmic-ray charged particles with energy $\gtrsim 3 \cdot 10^{19}$ eV, which are not entwined by the magnetic fields of the Galaxy,[39] also arrive preferentially from high northern latitudes of the Galaxy, but in regions close to the galactic disk, from the side opposite the center. In order to overcome the difficulties in interpretation of data on primary cosmic rays of ultrahigh energy at the present time, it appears that the following steps are both very important and experimentally realizable: 1) study of the energy spectrum of γ rays in the energy region 10^{13}–10^{16} eV; 2) answering the question of whether the observed γ-ray flux is actually diffuse or does it reflect numerous local sources; 3) increase of the reliability of the conclusions that cosmic rays with energy $\geqslant 10^{19}$ eV are anisotropic.

[1)]Estimates of the composition of the primary particles on the basis of the delay of hadrons in extensive air showers[22] also involve certain model assumptions.

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