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NECESSITY FOR A NEW HYPOTHESIS REGARDING ENERGY TRANSFER TO AN ELECTRON–PHOTON CASCADE BY NUCLEONS WITH ENERGIES EXCEEDING 10^{13} eV

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We have compared the results of calculations and the experimental data on extensive-air-shower distribution in number of electrons and muons and on the energy spectrum of nuclear-interacting particles, on the spectrum of showers accompanying high energy nuclear-interacting particles, and on the shower composition. It is shown that in order to explain the entire set of experimental data on superhigh-energy cosmic rays it is necessary to assume the existence of an additional mechanism for energy transfer from nucleons with energies above 4×10^{13} eV to the electron-photon component. The primary cosmic-ray spectrum also changes at the same energy at which the new process appears.

THE study of phenomena associated with cosmic rays with energy above 10^{13} eV is complicated by two circumstances. On the one hand, the high energy and low intensity of these particles prevents the setting up of unique, direct experiments. On the other hand, in interpreting the experimental results and describing the elementary processes in the energy region $> 10^{13}$ eV, it is necessary to take into account a large number of frequently undetermined parameters. These difficulties lead to arbitrariness in interpretation of the results of independently performed experiments and to pessimism in evaluating the use of cosmic rays in general and extensive air showers (EAS) in particular to clarify the situation relating to interaction of superhigh-energy particles with matter.

The only means of overcoming these difficulties is to analyze the largest possible set of experimental data. In this article we have attempted to show how such a set of "strange" results of the experiments of different investigators in the cosmic ray energy region $10^{12}-10^{18}$ eV leads to the necessity of assuming the existence of an additional process in which nucleons with energy $\gtrsim 4 \times 10^{13}$ eV, in addition to the inelastic nuclear interaction process observed in the low energy region, bypassing pionization,[1)] transfer a large part of their energy to the electron-photon component with a cross section $\Delta\sigma \approx 0.3\sigma_{\text{nuc}}$. Along with the increase in the total cross section for inelastic interaction in collisions of nucleons with energy $\gtrsim 4 \times 10^{13}$ eV, the exponent of the primary cosmic-ray energy spectrum also increases by an amount $\Delta\gamma = 0.5$.

Let us enumerate the "strange" results cited above, which do not agree with the idea of constancy of the basic nucleon interaction processes over the entire energy range $10^{10}-10^{18}$ eV and which require for their explanation additional assumptions involving a change in the nature of nucleon-nucleus collisions at energies of $10^{13}-10^{14}$ eV. The experimental results being enumerated were obtained by various workers several years ago, and have been published, reported, and discussed at the international and all-union conferences on the physics of cosmic rays. In this connection it is desirable to discuss here once more their degree of reliability.

1. The nonmonotonic nature of the dependence of the total number of nuclear-interacting particles on the number of electrons in EAS,[1, 2] which it is impossible to explain without introducing additional assumptions regarding the interaction of primary particles with energies of $\sim 10^{14}$ eV with nuclei in the atmosphere (Fig. 1).

2. The difference in the role of the nuclear-interacting component in large and small showers, which is evident also from the absorption in dense matter of showers with different numbers of particles at the level of observation[3] (Fig. 2).

[1)] For a definition of "pionization," see N. L. Grigorov and V. Ya. Shestoperov, Bull. Acad. Sci. USSR, Phys. Ser. 28, 1668 (1964) – Translator.

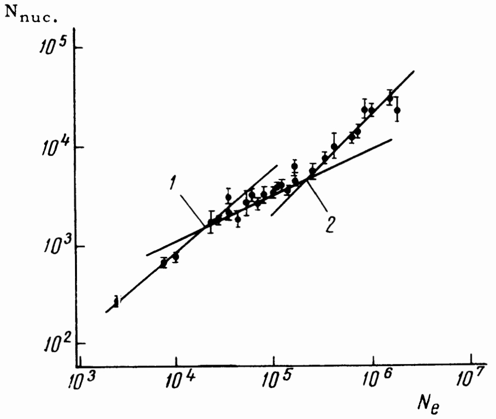

FIG. 1. Total number of nuclear-interacting particles in a shower (N_{nuc}) as a function of the number of electrons (N_e): 1 – primary protons with energy ~4 × 10^{13} eV, 2 – primary oxygen nuclei with energy ~4 × 10^{13} eV/nucleon (protons – 6 × 10^{14} eV).

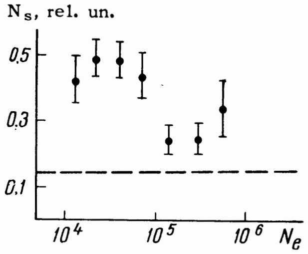

FIG. 2. Relative number of shower particles under an absorber of 230 g/cm², as a function of the number of electrons in the shower; dashed line – cascade theory.

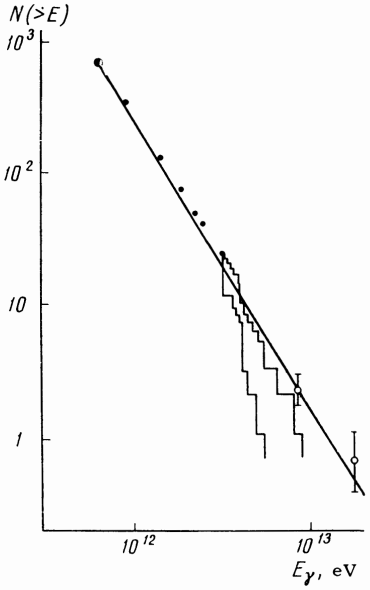

FIG. 3. Energy spectrum of γ rays in the stratosphere. Solid points and stepped lines – according to [14], straight line and hollow points – according to [5].

3. The change[4] in the γ-ray spectrum at an energy of 2 × 10^{12} eV (Fig. 3).

4. The change[6] in the spectrum of nuclear-interacting particles at mountain altitude at (2–3) × 10^{13} eV (Fig. 4).

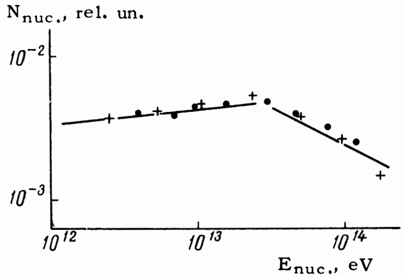

FIG. 4. Number of nuclear-interacting particles at 3860 m in the Pamirs, referred to the number of primary nucleons with energy above a given value, as a function of energy.

5. The simplest explanation of the breaks in the spectrum, due to items 3 and 4—assumption of a change in the primary-nucleon spectrum in the interval 10^{13}–10^{14} eV—is not sufficient to describe the passage of nucleons through the atmosphere,[7] according to the data on EAS accompanying high-energy nuclear-interacting particles.

The spectrum of EAS accompanying nuclear-interacting particles with energies of ~ 2 × 10^{12} eV at mountain altitude agrees with theoretical calculations based on interaction of nucleons with nuclei at 10^{11}–10^{12} eV. The spectrum of EAS accompanying 2 × 10^{13}-eV particles corresponds to an increase in the fraction of the primary-nucleon energy transferred to the electron-photon component (Fig. 5).

6. The shape of the EAS spectrum at sea level has led to the conclusion that there is a change in the primary cosmic-ray energy spectrum at ~ 5 × 10^{15} eV.[8] The sharp nature of the change in the shower spectrum for a complex composition of the primary cosmic rays greatly complicated the interpretation of the experimental data, but it

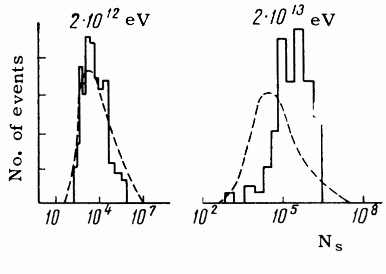

FIG. 5. Spectrum of EAS accompanying nuclear-interacting particles of a given energy at the level of observation (N_s is the number of particles in the shower for a fixed energy of the nuclear-interacting particles). The broken line shows the results of calculations in which the inelasticity coefficient is taken as $\overline{K} = 0.5$ and in which the complex composition of the primary cosmic radiation and the different fluctuations in the number of nucleon interactions and in the development of the shower have been taken into account.

is completely impossible to explain the shift in the break point of the shower spectrum to the region of smaller number of particles with increasing altitude of observation. Explanation of the break in the shower spectrum as a break in the primary energy spectrum without additional assumptions of a change in the nature of the elementary event unavoidably leads to a shift in the break point in the number-of-particle spectrum of the showers, on going from sea level to mountain altitude, toward the region of higher number of particles[9] (Fig. 6).

This list can be continued, for example, by the increase in the fraction of multicore EAS in the transition to showers with 10^5–10^6 particles at the observation altitude,[12, 15] the indication of the rapid development of showers in the upper part of the atmosphere,[16] and the contradiction between the varying exponent of the primary cosmic-ray spectrum and the constancy of the composition obtained from analysis of fluctuations in the muon flux and Cerenkov radiation in showers of a given energy.[17]

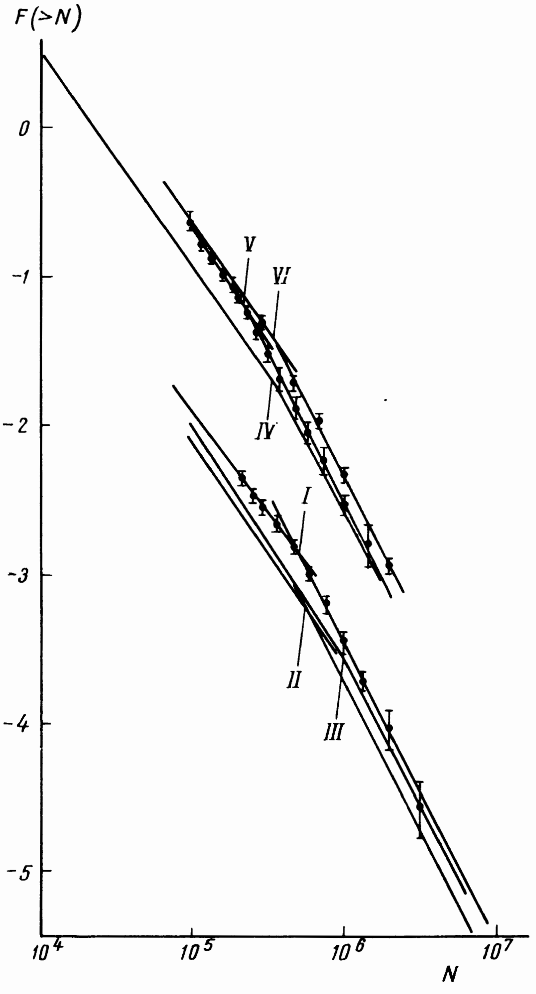

FIG. 6. Spectrum of EAS at different altitudes. At sea level: I – according to [10], II – according to [11], III – according to [12], at mountain altitude: IV – according to [2], V – according to [14], VI – according to [13].

Many assumptions[16, 18–20] have been advanced to explain these peculiarities. Some of the assumptions advanced contradict each other in their details and explain only part of the experimental results. In the present discussion it is not expedient to make a critical-historical review of these hypotheses, but more useful to note the features of the assumptions currently being discussed of a change in the primary cosmic-ray energy spectrum together with appearance of a new additional process of energy transfer from nucleons to the electron-photon component.

A. The energy of $\sim 4\times10^{13}$ eV per nucleon, at which the new process of energy transfer to the electron-photon component is added to the inelastic nuclear interaction process well known for lower energies, is less than the threshold energy given in most of the previously published studies. However, these studies did not usually consider in detail the complex composition of the primary radiation, and evaluated the energy of the primary particles, not the primary protons or nucleons which constituted the complex nuclei.

Here we are considering the case of a sharp energy threshold of $\sim 4 \times 10^{13}$ eV for appearance of the new process. This sharpness is not a necessary condition for agreement of the theoretical calculations with the experimental data, but only facilitates the analysis, which is in effect a first approximation. However, the condition of a rapid change in the cross section in the energy interval 10^{13}–10^{14} eV from a value $\Delta\sigma \lesssim 0.03\,\sigma_{\text{nuc}}$ to a value $\Delta\sigma \approx 0.3\,\sigma_{\text{nuc}}$ is necessary for a consistent description of the entire set of data.

B. The rapid increase in the cross section and the preferential (~ 70%) energy transfer to the electron-photon component, on the one hand, and the necessity of assuming the preservation, with approximately the same parameters, of the processes of pionization and the isobar mechanism of pion generation in inelastic collisions at energies $\gtrsim 10^{14}$ eV, on the other hand, indicate uniqueness and novelty of the process, and not a change in the inelasticity coefficient. In order to emphasize the predominance of the energy transferred to the electron-photon component and to compare this new additional process to pionization, it is perhaps appropriate to call it "gamma-ization," without implying by this terminology any details of the mechanism or particles involved in this preferential energy transfer to the electron-photon component.

C. The energy of the primary cosmic-ray particles at which the exponent of the integral energy spectrum increases from $\gamma = 1.6$ to $\gamma = 2.1$ is $\sim 4 \times 10^{13}$ eV/nucleon, and not $\sim 5 \times 10^{15}$ eV/nucleon as has been suggested by Khristiansen.[10] The coincidence of the energy of the break in the primary-proton energy spectrum and the energy threshold for a change in the nature of the elementary event may indicate a direct connection between the shape of the primary energy spectrum and the nuclear lifetime of heavy cosmic-ray nuclei in the universe. If a preferential acceleration of heavy nuclei occurs, we might expect that the energy spectrum of the lighter nuclei and protons will be similar to the spectrum of heavy nuclei of an energy-per-nucleon scale. However, a quantitative connection between the rise in the interaction cross section and the change in the primary cosmic-ray energy spectrum exponent cannot be justified without additional assumptions regarding the acceleration mechanism and the propagation of cosmic rays in the universe, and corresponding calculations, all of which are beyond the scope of this work. Here we note the possibility of such a connection as some justification for the coinciding values of energy threshold for "gamma-ization" and for the change of the primary cosmic-ray energy spectrum exponent, although the assumption of sharpness of the energy threshold for change of the primary spectrum only simplifies the calculations and is not in any way required by experiment.

It is evident from Fig. 7 that even with the assumed sharp energy threshold of $\sim 4 \times 10^{13}$ eV/nucleon the spectrum of all primary cosmic-ray particles changes over a wide energy region from 4×10^{13} to 2×10^{15} eV. Therefore the theoretical results reported in this article would not be greatly changed if we assume that the smooth change in the primary cosmic-ray spectrum in the energy region 10^{13}–10^{16} eV due to diffusion of cosmic rays in the magnetic fields of the Galaxy accidentally coincides with the presence of the additional "gamma-ization" process at $E_0 \geq 4 \times 10^{13}$ eV.

D. The assumption of the "gamma-ization" process, even if with a low probability, at an energy $E_0 < 10^{13}$ eV can be compared with the conclusions of Grigorov[27] on the occurrence of π^0-meson production events in which the meson carries away nearly all of the primary-particle energy. In any case, the "gamma-ization" process should lead to appearance of individual events similar to so-called young atmospheric showers[28] at a primary-nucleon energy $E_0 \gtrsim 4 \times 10^{13}$ eV. In this connection we must emphasize the difference of the "gamma-ization" process from the assumptions of Grigorov and his co-workers.[27, 28] The probability of production of π^0 mesons carrying away 79–90% of the incident nucleon energy was assumed by these authors to be independent of the nucleon energy. The probability of "gamma-ization" rises sharply in a narrow energy interval. Grigorov et al. assumed equally probable production of pions with different charges. In the additional process being discussed here, a preferential energy transfer to the electron-photon component is accomplished on the average, which excludes the ordinary pionization process.

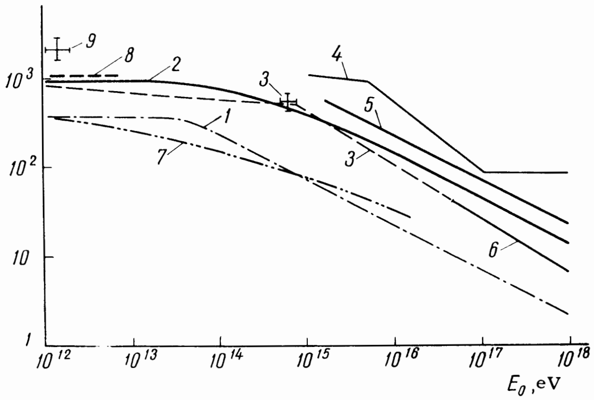

FIG. 7. Integral energy spectrum of primary cosmic radiation $F(>E_0)(E_0/10^{12})^{1.6}$: 1 – primary-proton spectrum proposed in the present work, 2 – combined spectrum of all primary particles, 3 – spectrum from [21], 4 – spectrum of Khristiansen,[10] 5 – spectrum of Clark, [22] 6 – spectrum of Linsley, [23] 7 – primary-proton spectrum according to Smorodin's approximation, [24] 8 – spectrum of Wolfendale, [25] 9 – photo-emulsion data.[26]

Let us compare the assumed primary-particle spectrum with a sharp change of exponent from $\gamma = 1.6$ to $\gamma = 2.1$ at an energy $E_0 = 4 \times 10^{13}$ eV/nucleon with the conclusions of other investigators (Fig. 7). At an energy $E_0 \approx 10^{12}$ eV the primary particle intensity a particle intensity according to the assumed spectrum agrees with the intensity obtained by Smorodin and co-workers[24] from analysis of the variations of the nuclear component of cosmic rays at airplane altitudes, and is somewhat less than the intensity estimated by Wolfendale[25] from the high-energy muon flux at sea level. The primary-particle intensity determined by means of photoemulsions in the stratosphere[26] is considerably higher than follows from the spectrum being discussed. Although the primary-nucleon spectrum has a sharp break at a nucleon energy of 4×10^{13} eV (in contrast to the approximation given by Yu. A. Smorodin), the primary-particle spectrum varies smoothly in the interval 4×10^{13}–2.5×10^{15} eV.

At an energy of 6×10^{14} eV the assumed spectrum agrees with the primary-particle intensity determined experimentally from the energy balance in EAS.[21] In the energy region above 10^{15} eV the assumed spectrum differs sharply from the spectrum obtained from the intensity of EAS at sea level by Khristiansen[10] and lies between the spectra of Linsley[23] and Clark[22] at energies above 10^{17} eV. Here it is necessary to have in mind that errors are more probable which bring the last two spectra together, and in the absolute primary cosmic-ray intensity determined on the basis of the intensity of showers with a given number of electrons at sea level; in the opinion of Khristiansen[10] a three-fold error is not excluded.

For a particle energy of $\sim 10^{20}$ eV the spectrum corresponds to the intensity given by Greisen in his review at the London conference. However, the spectrum shown in Fig. 7 is more than fifteen times greater than the intensity of the primary cosmic-ray flux with energies $\gtrsim 6 \times 10^{14}$ eV which follows from the extrapolation given by Grigorov in his report on the preliminary results of studies with the satellite Proton 1.[29] A substantial error in the intensity value for showers with a given number of particles at the level of observation is impossible; this intensity has been studied by many authors by different methods. If we assume that the spectrum reported by Grigorov[29] is correct, then the primary-particle energy is related to the number of electrons at the level of observation by the relation $E_0 = 0.42$ N [BeV]. The extent to which the coefficient 0.42 is too small can be seen from the fact that the energy dissipated by a shower at the level of observation is determined from the Cerenkov radiation to be more than two times greater, and the combined energy of all particles in the shower at the level of observation is 1.5 times greater than given by this coefficient.

Finally, we can pose this question: How can we obtain N electrons at the observation altitude from a primary nucleus or nucleon with energy $\sim 10^{14}$ eV in such a way that the relation $E_0 = 0.42$N [BeV] is satisfied? Without using anything except rather well tested cascade theory, we can deduce that, in order for this relation to be satisfied, the primary nucleons and nuclei must transfer all of their energy to γ rays or electrons with energies of $\sim 4 \times 10^9$ eV at an elevation of 1–2 km above the level of observation. This is an incomparably more extreme assumption than that discussed in the present work. Therefore the primary cosmic-ray energy spectrum given in Fig. 7 is a better approximation to reality than the spectrum based on the preliminary measurements in the satellite Proton 1.

A smooth variation of the exponent of the EAS spectrum follows, at first, glance, from the smooth variation of the exponent of the total primary-particle energy spectrum. This is confirmed by calculations. We calculated the expected number of EAS at a depth of ~ 700 g/cm^2 in the atmosphere for the primary particle energy spectrum given above, taking into account fluctuations in the height of production of the showers and the complex composition, varying with energy, of the primary radiation. The so-called two-fireball model calculated by Dedenko[30] was used as a model for the production and development of the shower. This shower-development model gives good agreement of the theoretical and observed shower parameters. However, in this case the choice of the model affects only the absolute intensity and not the width of the region of variation of the shower-spectrum exponent. We can see from Fig. 8 (lower curve) that the number-of-particle spectrum of the showers has an exponent $\varkappa$ varying smoothly from 1.44 to 1.75 in the hundredfold interval of N from 10^4 to 10^6.

A different result is obtained if we take into account an additional process of primary-nucleon energy transfer to the electron-photon component of the shower. In accordance with the assumptions stated above, it was assumed that 70% of the primary nucleon energy is transferred to ten γ rays in a single event with a cross section of $0.3\sigma_{\text{nuc}}$. The result of the calculation is characterized by a sharp break in the number-of-particle spectrum of the showers: The exponent $\varkappa$ varies from 1.44 to 1.75 for threefold variation of the number of particles in the shower—from $N = 2 \times 10^5$ to $N = 6 \times 10^5$ (upper curve of the figure). It is easy to understand

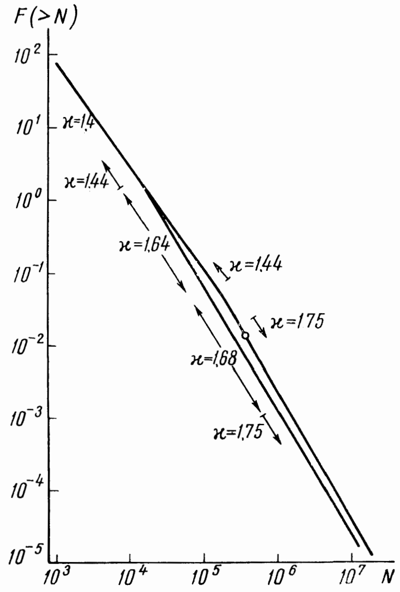

FIG. 8. Integral spectrum of EAS at 3400 m altitude above sea level (o – experimental data of [2]).

why inclusion of the new process raises and corrects the number-of-particle spectrum of the showers. Experimental determination of the relation between the number of particles per EAS at mountain altitude and the primary-particle energy gives the expression $E_0 = AN$, where $A = 1.7 \times 10^9$ eV for $N = 3.5 \times 10^5$, while calculations of the nuclear cascades for the same showers give $A = 2.4 \times 10^9$ eV, and for an electron-photon shower beyond the peak in the development ($s = 1.2$)—$A \approx 1.1 \times 10^9$ eV.

Thus, production of the same number of electrons at the level of observation in the case of transfer of a large fraction of the energy to the electron-photon component requires a considerably smaller primary-particle energy than in the case of the ordinary nuclear-cascade scheme of development. This calculation of the shower spectrum at mountain altitude is not very sensitive to the multiplicity of production of the particles by means of which the primary-particle energy is transferred to the electron-photon component, and reflects mainly the fraction of the energy transferred by the primary particle to the electron-photon component.

A similar situation exists in interpretation of the dependence of the number of nuclear-interacting particles per EAS on the number of electrons. Calculations of this dependence, based on a constant or weakly varying pattern of the elementary event, yield an approximate proportionality between the number of nuclear-interacting particles and the primary-particle energy. Consequently a relation of the type $N_{\text{nuc}} \sim N^{0.8}$ should exist between the number of electrons and the number of nuclear-interacting particles. It is evident in Fig. 1 that, beginning with showers of $\sim 2 \times 10^4$ particles, a deviation is observed from the $N^{0.8}$ dependence. If we use a rough conversion coefficient from the number of electrons at mountain altitude to the primary-particle energy, we obtain a primary-particle energy of just $\sim 4 \times 10^{13}$ eV. Starting at this energy, first the primary protons and then also the heavier nuclei transfer an ever increasing fraction of their energy to the electron-photon component, bypassing pionization. Correspondingly, the relation between the number of electrons and the number of nuclear-interacting particles varies in favor of the electrons up to the point where the effect of the new process is felt on the development of a large fraction of the showers. The second break in the dependence is associated with showers produced by primary particles of which more than 60% have an energy greater than 4×10^{13} eV/nucleon.

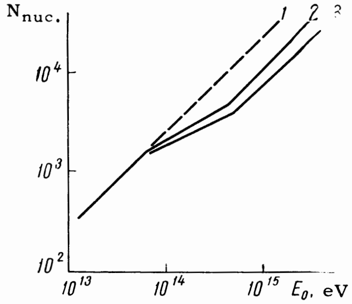

FIG. 9. Diagrammatic representation of the number of nuclear-interacting particles in a shower as a function of the primary-particle energy. Curves 1–3 are explained in the text.

The dependence of the number of nuclear-interacting particles in EAS on the primary energy can be considered from the point of view of energy balance. The conversion from the number of electrons at the level of observation to the primary-particle energy can be accomplished, on the average, by comparison of the primary particle spectrum with the intensity of showers with more than the given number of particles at the level of observation. A diagrammatic representation of the number of nuclear-interacting particles in a shower as a function of the primary-particle energy is shown in Fig. 9: The straight line 1 is the expected dependence, normalized at an energy $E_0 \approx 4 \times 10^{13}$ eV; curve 2 is the experimentally observed dependence, with the change in the nature of the primary particle interaction taken into account in the conversion from the number of electrons to the primary-particle energy; curve 3 is the experimentally observed dependence, but with conversion from the number of electrons to the primary-particle energy by means of the two-fireball model of shower development.[30] The difference in energy for curves 2 and 3 for a number of nuclear-interacting particles $N_{\text{nuc}} \approx 10^4$ is $\sim 30\%$.

As we have already noted, the effect of the additional process for energy transfer to the electron-photon component reduces, in the first approximation, to a redistribution of the energy between the electron-photon component and the remaining components of the shower. If there were no such additional transfer, then, as we can see from Fig. 9, the energy carried at the level of observation by nuclear-interacting particles, muons, and neutrinos would be increased by $0.3E_0$. Analysis of the experimental data[31] on the energy flux in EAS produced by particles with an energy of $\sim 10^{15}$ eV has also led to a value of $\sim 0.3E_0$ for the energy flux carried by muons, neutrinos, and nuclear-interacting particles. Thus, in the absence of an additional transfer of energy to the electron-photon component, the energy flux carried by the remaining components of the shower would be doubled, which would lead to doubling of the number of particles. The expected (line 1) and observed (curve 2) numbers of nuclear-interacting particles also differ by just a factor of two. The energy of the nuclear-interacting component of a shower, estimated from the absorption of the shower in a graphite-aluminum absorber, also differs by a factor of two for showers with $N \lesssim 10^5$ and $N \gtrsim 10^5$ particles.

Explanation of the energy spectrum of nuclear-interacting particles observed at mountain altitudes also does not require detailed description of the additional process for energy transfer to the electron-photon component. In addition, the accuracy of the experimental data is not very great and allows the simplest explanation relating the change in the exponent of the nuclear-interacting particle spectrum at mountain altitude to the change in the exponent of the primary-nucleon spectrum. Figure 10 compares the calculated nucleon spectrum at the altitude of the Pamirs with the observed spectrum of nuclear-interacting particles. Both of the spectra refer to an arbitrary primary-nucleon spectrum with a constant exponent γ over the entire region being considered. In comparison of theory and experiment it is necessary to have in mind that the experiment detects not only nucleons but also pions. A characteristic result of the theory is the small shift in the location of the break (less than a factor of three). Allowance for the increase in the cross section is complicated by the fact that in addition to the greater absorption of nucleons in the atmosphere it is necessary to take into account the increase in the efficiency for their detection in the apparatus, both because of the increased cross section and because of the change in the energy transfer to the electric-photon component. The experimental data are still too poor at the present time for analysis of different versions of the theory.

As we noted at the beginning of the article, the possibility of a very simple interpretation of the break in the nuclear-interacting particle spectrum as the result of a corresponding break in the primary-nucleon spectrum was the occasion for comparative analysis of the spectrum of EAS accompanying nuclear-interacting particles of various energies at mountain altitude. The observed spectrum for showers accompanying nuclear-interacting particles with energies of $\sim 10^{13}$ eV at the altitude of observation turned out not to agree with the calculated spectrum, if the pattern of an inelastic collision event is assumed identical for all energies. This can be seen in Fig. 11 where the experimental data for nuclear-interacting particles with energies of $\sim 0.7 \times 10^{13}$ eV are compared with theoretical calculations made previously.[7] Also shown in that figure is a theoretical result assuming an additional transfer of 25% of the nucleon energy to the electron-photon component, bypassing pionization. A tendency towards improved agreement is visible, but it should be noted that the calculations made in [7] assumed transfer of a smaller fraction of the energy to the electron-photon component than in the hypotheses considered here.

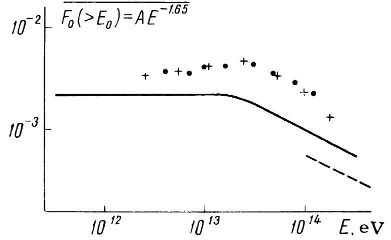

FIG. 10. Comparison of calculated nucleon spectrum with the nucleon and pion spectrum observed at altitude 3860 m. The broken line shows the estimate of the effect of the change in the combined cross section.

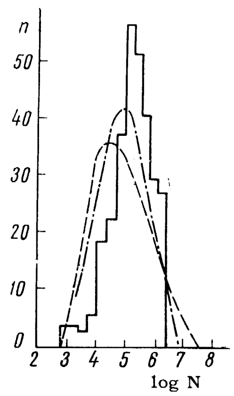

FIG. 11. Comparison of observed spectrum of EAS accompanying nuclear-interacting particles for an energy $E = (0.5-1) \times 10^{13}$ eV at the level of observation, with calculations assuming similarity of the interactions of nucleons and nuclei over the entire energy interval of interest (dashed line) and assuming additional energy transfer to the electron-photon component (dot-dash line).

Like the case of the nuclear-interacting particle energy spectrum, the experimental data on the increase of the γ-ray spectrum exponent can be explained by a single assumption of appropriate change in the primary cosmic-ray spectrum. However, if, simultaneously with the change in the primary-nucleon energy spectrum, we assume an increase of the energy transfer to the electron-photon component, then the explanation of the increase in the exponent of the spectrum of individual γ rays requires a large dissipation of energy, and not transfer of this energy to one particle. This is an essential detail of the additional process for energy transfer to the electron-photon component. If this process could be traced to transfer of a large fraction of energy to several γ rays, this would mean that everything could be explained by one or two pions. In this case the unequal probability of appearance of π^+, π^-, and π^0 mesons would not be surprising, and in general the entire question would reduce to the probability of production of mesons with energies comparable with the primary-nucleon energy.

Similar events are observed in photoemulsion. It is sufficient to mention the case quoted by Schein at the Moscow International Conference,[32] in which an electron-photon cascade with an energy of 2.4×10^{13} eV was observed after a primary-proton interaction with a low multiplicity (16), while the energy of the secondary interaction of one of the particles of the narrow cone was estimated as only 5×10^{11} eV and, aside from the angular distribution, nothing indicated the high energy of the primary proton. However, many experimental data on the properties and structure of EAS unambiguously indicate the softness of the energy spectrum of the particles responsible for energy transfer from the nuclear-interacting component to the electron-photon component. The data obtained by the group led by Yu. A. Smorodin on the high intensity of vertical EAS in the stratosphere[16] are a striking experimental result showing large dissipation of energy in the first interactions of primary cosmic-ray particles with energy $> 10^{15}$ eV. Interpretation of these data without assumptions of a large energy dissipation by the interacting particles is simply impossible.

The EAS intensity observed at 12 km altitude is greater by factors of ten than the value expected if the primary cosmic-ray spectrum and the model of the elementary interaction are consistent with the experimental data on shower intensity and the relative fraction of muons contained in showers in the lower part of the atmosphere. To increase the expected shower intensity in the stratosphere it is necessary to increase substantially the multiplicity in the elementary event (the Heisenberg model), to increase the fraction of heavy nuclei in the primary radiation, and to increase the flux of primary particles. However, each of these changes by itself, as well as the entire set, leads to contradiction between theory and experiment in the lower part of the atmosphere.

Thus, assumption of an enrichment of the primary spectrum by heavy nuclei, even for the multifireball model[33] which gives a minimum number of muons in the pionization process, leads to a discrepancy of a factor of two between the experimental and theoretical numbers of muons in showers with a total number of particles $> 10^5$. Interpretation of EAS by an elementary interaction model with pionization corresponding to formation of a single fireball (Heisenberg) leads to exaggeration by a factor of three of the number of muons in showers at mountain altitude and at sea level.[33]

The assumption of higher intensity of the primary radiation encounters contradictions with the intensity of EAS at mountain altitudes. The conversion from the number of particles in a shower at mountain altitude to the energy of the primary particle is practically independent of the shower-development model assumed. With very extreme assumptions, for example, assumption of a passive state of the nucleon after the first interaction,[34] the estimate of the energy of the primary particles producing a shower of a given energy at an altitude of 3–5 km above sea level cannot be increased by more than a factor of two.

The monotonic variation of the total energy spectrum of the primary cosmic radiation and the assumption of a single model of inelastic nucleon collisions over a wide energy interval should lead to a monotonic variation of the number-of-electron spectrum of EAS at sea level. Figure 12 shows the number-of-electron spectrum of showers at sea level calculated with assumption of a multifireball model.[30] The smooth variation obtained for the spectrum is difficult to reconcile with the experimental data.[9]

The result of taking into account the additional process of energy transfer to the electron-photon component, bypassing pionization, depends on the degree of subdivision of the energy. The greater the subdivision, the lower the intensity of EAS with $N = 10^4 - 10^5$ at sea level and the more the break in the number-of-particle spectrum of the showers (broken line in Fig. 12) is displaced to the right.

The existence of a large number of low-energy muons in EAS is the result of pionization processes in collisions of pions and nucleons with nuclei. The large penetrating ability of muons results in the total number of muons beyond the peak in a nuclear-cascade shower being almost proportional to the energy transferred to all charged pions in the initial stage of shower development. Therefore, the numbers of muons in a shower at sea level differ, for example, by a factor of 1.7 for calculations according to the one-fireball model and according to a multifireball model of the event, although the multiplicity of pion production in the first interaction differs by more than fifty times[30] for these models. This feature of the muon flux in a shower is favorable for analysis of the primary cosmic-ray energy spectrum and the fraction of

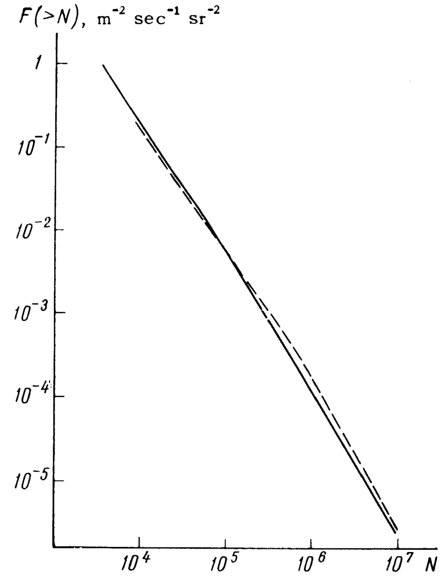

FIG. 12. Theoretical spectra of EAS.

primary-particle energy transferred to charged pions.

A calculation of the EAS number-of-muon spectrum for muons of energies above 10 BeV was made in three different versions.

1. The energy spectrum and composition of primary cosmic radiation are taken in accordance with the assumptions of the present work. The so-called two-fireball model[30] was used as a model of the shower development, but the multiplicity of pion production in pion-nucleus events was decreased by 1.5 times.[33] This change in the model reduces the number of muons in the shower and is evidently an extreme case, if we take into account only the number of secondary charged particles observed experimentally in photoemulsions and cloud chambers in investigation of interactions in the energy region 10^{11}–10^{13} eV. The theoretical result is shown in Fig. 13 by the broken line.

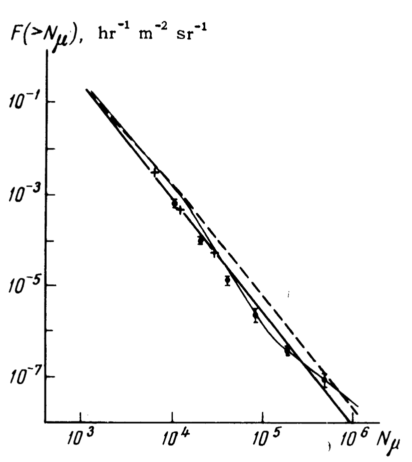

FIG. 13. Comparison of theoretical and observed [35] spectra of EAS as a function of number of muons.

2. This version of the calculation is identical with the preceding one except that we have included energy transfer from the primary protons and nuclei to the electron-photon component of the shower by the "gamma-ization" process (heavy solid line in Fig. 13).

3. The energy spectrum and composition of the primary cosmic radiation are taken in accordance with the conclusions of Khristiansen,[10] and the relation $N_\mu = 0.2A^{0.2}(E_0/10^{10})^{0.8}$ was used in determining the number of muons from a primary particle with energy E_0 and a number of nucleons A. This relation was used for analysis of the number-of-muon spectrum of showers in the work of Vernov et al.,[35] although in the deduction of this relation[36] the multiplicity of pion production in the interaction of pions and nucleons with nuclei was clearly underestimated. Thus, for example, for an incident-nucleon energy of 2×10^{13} eV, according to the assumptions of Dedenko[36] 5.5 charged pions are produced in the interaction instead of the 20 observed in experiments with emulsion stacks. The spectrum calculated for this version of the theory is shown in Fig. 13 by the thin line.

Direct measurements of the number-of-muon spectrum of showers, for muon energies > 10 BeV, have been made by the group of workers at Moscow State University.[35] In the first series of measurements in 1960–1962, the number-of-muon spectrum of showers for $N_\mu > 10^5$ was studied without determination of the zenith and azimuthal angles of the shower axis. In the more recent measurements with determination of the zenith and azimuthal angles of the axis of each shower, the range of values of muon flux studied was $10^4 \leq N_\mu < 10^5$. The two series of measurements are shown in Fig. 13 by the points. The number-of-muon spectrum of the showers in the region $N_\mu \leq 10^4$ can be obtained by conversion from the number-of-electron spectrum of the showers.[10] This conversion is possible as the result of detailed measurements of the distribution of the number of muons in a shower for a fixed number of electrons.[37] The dispersion of this distribution in the showers which interest us does not vary with the number of electrons. The result of the conversion is shown by the crosses in Fig. 13, as a function of the average number of muons for a fixed number of electrons. It can be seen from the figure that the experimental data on the number-of-muon spectrum of the showers is in good agreement with the main assumptions of this article (the second version of the calculation).

Thus, to explain from a single point of view a large aggregate of experimental data on the passage of cosmic rays with energy above 10^{13} eV through the atmosphere, it is necessary to make two assumptions.

A. In the collision of nucleons and nuclei of superhigh energy, in addition to the multiple pion production process well known in the energy region $10^{10}-10^{12}$ eV, a process exists for transfer of a large fraction ($\geq 70\%$) of the nucleon energy to the electron photon component, bypassing pionization. The cross section for this process is $\sigma < 1$ mb/nucleon for an incident-nucleon energy of $E < 10^{13}$ eV and $\sigma \sim 15$ mb/nucleon for an energy of $\sim 10^{14}$ eV.

B. The exponent of the primary cosmic-ray energy spectrum changes by an amount $\Delta\gamma = 0.5$ in roughly the same energy interval $10^{13}-10^{14}$ eV/nucleon.

Unfortunately only a few characteristic features of the new process are apparent as yet: a sharp energy threshold, preferential transfer of energy to the electron-photon component, and dissipation of energy. The information on the transverse momenta are contradictory. An estimate of the transverse momenta of the γ rays in a series gives a value $\lesssim 10^8$ eV/c, while an estimate of the transverse momentum on the basis of multicore EAS leads to a value certainly greater than 10^9 eV/c.

With such poor information on the nature of the process, it is difficult to say anything about its physical nature. The rise of the combined inelastic-interaction cross section in the energy interval $10^{13}-10^{14}$ eV evidently cannot be associated with the theory of complex orbital momenta, since it is not characterized by ordinary pionization. If we associate the sharp energy threshold with a new particle, its mass must be $\sim 10^{11}$ eV/c^2 and its lifetime $< 10^{-11}$ sec, but the absence in the decay of a noticeable number of $\pi^{\pm}$ mesons distinguishes this anomalously heavy particle from the already known baryons. We may note in addition that an energy $\gtrsim 4 \times 10^{13}$ eV corresponds to a length $\lesssim 10^{-15}$ cm, which is interesting both from the point of view of weak interactions and from the point of view of nucleon structure.

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