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ABSTRACT. Discussion of possible approaches to a study of interactions of high-energy cosmic-ray particles during extensive air showers. The significant role of inelastic collisions between nucleons and 10,000 to 100,000 GeV nuclei in extensive air showers produced by primary superhigh-energy cosmic-ray particles is pointed out. It is noted that new data obtained at the Tien Shan High Mountain Station of the USSR Academy of Sciences indicate that changes in the characteristics of these interactions take place during extensive air showers. The nature of extensive "multicare" air showers is also discussed. Their occurrence is linked to the nature of the primary particles involved and to the large transverse moments produced by secondary particles during inelastic superhigh-energy collisions.

In the study of the pattern of interaction among high-energy particles by /1501*
an investigation of extensive atmospheric showers, there can be three approaches: 1) successive transition from the region of relatively low energies ($\lesssim 10^{13}$ eV.), for which there is quite detailed data available concerning the processes of interaction among nucleons and pions and other particles, to the region of superhigh-energy; 2) comparison of the results of computations using the proposed model and experimental data on extensive atmospheric showers; 3) search for characteristic phenomena in extensive atmospheric showers for whose explanation, the quantative values of most parameters of an elementary event are unimportant.

The first approach is experimentally more applicable for mountain conditions; it gives unambiguous results with an increase in measurement accuracy and an increased accumulation of a wide range of data. The second approach, for the time being indispensable in studying extensive atmospheric showers at sea level, does not make it possible to obtain unambiguous results, and accumulation of experimental data, like an increase in their accuracy, only

*Numbers in the margin indicate pagination in the foreign text.

decreases the probability of a random coincidence between the results of computations and experimental observations. Moreover, an unambiguous negative result from comparison of computed and experimental data has only historical interest: some hypotheses, to be more correct, a combination of hypotheses, do not correspond to reality.

During recent years many computations based on a wide variety of assumptions have been made. The best agreement between the computed characteristics of a shower and experimental data is obtained using a model of two fireballs with an isobar or a model with a spectrum of secondary pions as proposed by Cocconi. Since the models are close to one another in their principal parameters, and the second is less schematic in structure, it will be adequate to characterize the second. According to this model, the paths for interaction of nucleons in the air (90 g × cm^{-2}) and pions (120 g × cm^{-2}) are not dependent on particle energy. The inelasticity coefficients are K = 0.5 for nucleons and K = 1 for pions and also are not dependent on the energy of the colliding particles. The multiplicity of secondary particles changes with an increase in the energy of the incidence particle $\sim E_0^{0.25}$, and their energy spectrum can be expressed as follows

$$\frac{dn}{dE} = \frac{A}{T} e^{-E/T}, \quad \text{where} \quad A = 1.35\, E_\theta^{0.25},\ TA = KE_0.$$

Figure 1, taken from [1], gives a comparison of the results of computations of the number of muons in a shower with a known number of electrons at sea level and the number of electrons for a stipulated number of muons with experimental data for this same observation level [2]. This same figure shows the sensitivity of computations to a change in a elasticity coefficient and the path length for an elastic collision. The situation is approximately the same for a number of other shower characteristics at sea level (see Table).

What is it that forces us to question the unambiguous correspondence /1502
between this model and reality? In particular, it is the results of a study of cosmic radiation in the energy range 10^{12} - 10^{14} eV. The model, matched with the characteristics of extensive showers, is based on the assumption of constant effective cross-sections, inelasticity coefficient and mechanism of

secondary particles during multiple generation events, remaining unchanged with an increase in the energy of colliding particles. Figure 1 shows that a change in the effective cross-section or inelasticity coefficient leads to a mismatch between the computed and experimental data and reveals the necessity for some additional changes in the model. Moreover, investigation of cosmic radiation in the energy range 10^{12}-10^{14} eV reveals that with an increase in the energy of incident nucleons from 10^{13} to 10^{14} eV the effective cross-section for inelastic collision between nucleons and nuclei or the inelasticity coefficient in such collision, or both together, increased by a factor of 1.3-1.5.

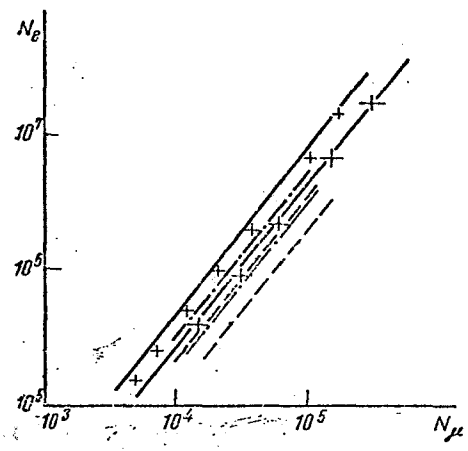

Figure 1. Computed and experimental ratio between number of muons and number of electrons in a shower at sea level. The upper lines represent the registered number of electrons; the lower lines represent the registered number of muons. The dot-dash lines represent computed data with an increase in the inelasticity coefficient by a factor of 1.5. The dashed lines represent the effective cross-section, increased by a factor of 1.t.

Figure 2 shows the energy spectrum of nuclearly active particles at an elevation of 3,330 m above sea level, obtained using the ionization calorimeter of the Tien Shan complex extensive atmospheric shower apparatus [3]. The "break" in the energy spectrum of nuclearly active particles observed in the mountains is difficult to attribute exclusively to a change in the spectrum of primary nucleons: even with a sharp threshold change in the index, both in the spectrum of primary protons and in the spectrum of nucleons entering into the primary nuclei[1], due to fluctuations in the number of collisions between nucleons and nuclei of air atoms during passage /1503 through the atmosphere, there is a smooth change in the nucleon spectrum in the mountains (Figure 3). A sharp

[1]The problem of the non-correspondence between this threshold energy and the threshold for change in the primary spectrum, determined from data on extensive atmospheric showers ($\gtrsim 10^{15}$ eV)[4], is not discussed here.

change in the energy spectrum of nucleons in the mountains can be obtained by postulating a sharp change in the path for interaction of nucleons or the inelasticity coefficient for a corresponding threshold energy (Figure 3).

N_e	Reference	$\bar{N}_\mu$	$\delta/\bar{N}_\mu$	$\bar{s}$	$\delta/\bar{s}$
$1{,}5\cdot10^5$	[1]	$4{,}02\cdot10^3$	0,62	1,22	0,08
	[2]	$(4{,}9\pm0{,}3)\cdot10^3$	$0{,}59\pm0{,}07$	$1{,}22\pm0{,}02$	$0{,}09\pm0{,}02$
$2\cdot10^6$	[1]	$3{,}25\cdot10^4$	0,56	1,19	0,073
	[2]	$(3{,}4\pm0{,}23)\cdot10^4$	$0{,}4\pm0{,}06$	$1{,}2\pm0{,}02$	$0{,}08\pm0{,}02$

Note. N_e is the registered number of electrons at sea level, $\bar{N}_\mu$ is the mean numb er of muons, $\delta/\bar{N}_\mu$ is the relative width of the distribution for number of muons, $\bar{s}$ is the mean age parameter, $\delta/\bar{s}$ is the relative width of the distribution for this parameter.

TRANSLATORS NOTE: Commas indicate decimal points in the above table.

Thus, one cannot help but thinking that the conclusion that there is an unambiguous selection of a model for the formation and development of extensive atmospheric showers with a primary energy greater than 10^{15} eV is premature without successive transition through the energy region 10^{13} - 10^{14} eV.

It was pointed out in [5, 6] that allowance for an additional process beginning with a threshold energy of $\sim 4\cdot10^{13}$ eV and arbritrarily called "gammanization" does not worsen the interpretation of experimental data on extensive atmospheric showers. Comparison of Figures 2 and 3 reveals that allowance for the "gammanization" process makes it possible to explain experimental data on the change of the spectral exponents for nuclearly active particles in the mountains. Unfortunately, this experimental result did not give information on the gammanization process, since both the increase in the effective cross-section and the increase in the total inelasticity coefficient for collisions of nucleons with energies greater than 10^{13} eV were postulated earlier in the gammanization hypothesis.

Taking this into account, new data on the energy of electron-photon cascades caused by muons in a system of ionization chambers like the ionization

calorimeter of the Tien Shan complex extensive atmospheric shower apparatus [7] (Figure 4), is more interesting. The observed excess of electrons-photon cascade in the energy region above $6 \cdot 10^{12}$ eV in the case either an increase in the probability of formation of such cascades by muons with energies greater than 10^{13} eV or an increase in the hardness of the muons energy spectrum in this energy range. The second hypothesis is more timely due to the gammanization hypothesis.

If the excess of muons with an energy greater than 10^{13} eV is the result of direct muon generation in nucleon collisions, in no case would this contradict the gammanization process. On the contrary, the fact of muon formation during the collision of nucleons would make it possible to relate the gammanization process with the direct generation of nucleon and γ-quanta in interaction events for nucleons with energies greater than 10^{13}-$4 \cdot 10^{13}$ eV. The process of additional generation of muons with energies greater than 10^{13} eV /1504 could be related to gammanization also in a case if the formation of both muons and electrons for γ-quanta transpires through the disintegration of some particles which disintegrate considerably more rapidly than charged pions and kaons. Only attempts to explain the excess of high-energy muons ($>10^{13}$ eV) on the basis of an increase in the inelasticity coefficient for the ionization process or an increase in the effective cross-section for this process would contradict the gammanization hypothesis and the experimental results which led to this hypothesis. For further progress in this field, as in the interpretation of experimental data on superhigh-energy extensive atmospheric showers it is necessary to have detailed data on interactions of nucleons, pions and nuclei in the energy region 10^{13}-10^{14} eV.

An example of characteristic phenomena in extensive atmospheric showers for whose interpretation it is not essential to know the total picture of inelastic collisions among nucleons and nuclei is the phenomenon of "multicore" showers. This is an old problem. Data on the first observations of multicore showers were published 15 years ago [8]. In complex investigations of extensive atmospheric showers in the Pamirs, multicore showers were observed using ionization chambers. It was noted at such times that the percentage of multicore showers increases with an increase in the number of particles in the

shower at the observation level [9]. This was also demonstrated in subsequent measurements at sea level and was attributed to the increasing role of multiply charged nuclei in primary cosmic radiation with a transition from energies of $\gtrsim 10^{15}$ eV to energies > 10^{16} eV [10]. In analyzing the data on multicore /1505 showers, the authors of the report [11] even mentioned a flux of deuterium nuclei with energies greater than 10^{15} eV. On the other hand, the divergence of subcores can be related to transverse impulses imparted to secondary particles in inelastic collision events, [12]. Experimental data on the divergence between subcores apparently indicate an increase in the magnitude of the transverse impulse for superhigh energies (tens of GeV) of interacting particles.

It should be noted that the question has recently arisen as to the very fact of existence of multicore showers and the number of multicore showers. The fact is that in experiments with a neon photoscope the observed number of multicore showers remained extremely low (~ 1%) [13]. According to data obtained using scintillation detectors at the Tien Shan extensive atmospheric shower apparatus, among showers with a number of particles > 10^5 at the observation level the percentage of multicore showers is ~ 15%. These measurements gave only the lower limit of the percentage of such showers, because cases of two or more cores, separated by a distance of less than a meter, cannot be distinguished by the apparatus from single-core showers. It is important to note that the percentage of multicore showers is highly dependent on selection criteria for showers whose axis passes through a particularly area. For example, if in the search for showers among all the registered events one selects only those showers whose spatial distribution in the range of distances of 1-6 m from the axis corresponds to the mean (or more closely than the mean), the percentage of multicore showers is reduced by more than a factor of 10. It is not impossible that the difference in data for different experiments is associated with this circumstance.

Now we will return to an interpretation of multicore showers. The relationship between multicore extensive atmospheric showers and multiply charged nuclei of primary cosmic radiation appears entirely natural [14]. However, it would erroneous to identify the number of observed subcores with the number

of nucleons in a primary nucleus. Only the probability of a different number of collisions of nucleons during passage through the atmosphere without allowance for fluctuations in the inelasticity coefficient will mean that only half the nucleons of the nucleus disintegrating at the boundary of the atmosphere will differ in their energy by a factor greater than 30 at sea level. At an altitude of ~ 5 km above sea level ~ 60% of the nucleons in the nucleus will be within this factor -- of -- 30 energy range. At the same time, the experiment can discriminate "subcores" differing by not more than a factor of 10 in intensity. However, it is usual to discriminate subcores which differ by only a few times in the particle flux.

Accordingly, for identification of the observed subcores in multicore extensive showers with nucleons of the primary nucleus it is necessary to make additional assumptions: 1) quite large transverse impulses, imparted to the nucleons during disintegration of the nucleus at the boundary of the atmosphere; 2) small fluctuations between the subcore energy and the energy of nucleons at the atmospheric boundary. The latter can occur either by a single event transfer of the energy of primary nucleons to a cascade shower near the atmospheric boundary or due to the "calorimetric" accumulation of the electron-photon core component of the shower in the entire thickness of the atmosphere, but neglecting deviations in the electron-photon shower from the direction of each of the nucleons of the primary nucleus in comparison with the divergence of nucleons from one another.

If the second assumption is satisfied by some mean, it follows from the distances between subcores observed at sea level that the transverse impulses imparted to the nucleons in the first interactions constitute ~ 10^{10} eV. This /1506 estimate was made on the assumption that the energy of the subcore corresponds to the energy of a nucleon forming part of the primary nucleus that is, each subcore corresponds to the axis of a partial shower forming part of an extensive shower from a primary nucleus.

However, available data do not make it possible to exclude that at least some subcores are associated with nuclear cascade showers during the initial stage of development, formed near the observation level by pions and nucleons,

whose energy is tens of times less than the energy of nucleons near the atmospheric boundary. In this case the observed structure of the shower core can be explained in the case of transverse impulses of ~ 1 GeV. If the magnitude of the transverse impulse does not increase with an increase in the energy of the interacting nucleon (or forming pion), the dimensions of the core region are determined by the last interaction event. For example, 0.8 of the mean deviation of the "guiding" nucleon from the direction of the primary particle is determined by the last three collisions, assuming a mean inelasticity coefficient of 0.5 and a distribution of transverse impulses of the type $p_{\perp}$ esp $(-p_{\perp}/p_0)$. Thus, neither present-day concept concerning the development of an extensive atmospheric shower nor available experimental data make it possible with any adequate degree of realiability to determine the role of primary nuclei and the presence of anomalously great transverse impulses in the formation of a multicore structure of a shower. The nature of a primary particle, naturally, is reflected in the core structure. In showers formed by primary nuclei the role of a single guiding particle is reduced. In the case of a primary proton the energy release of such a particle among secondary pions in any computation is obtained with an inelasticity coefficient 0.5.

Accordingly, experimental data [10] on the disappearance of single-core showers when the number of particles in the shower is > 10^6 at sea level means that there is either a substantial decrease in the percentage of protons in the primary force of super high energy or a disappearance of energetically released nucleons in events of a corresponding energy. On the other hand, even in an interpretation of multicore showers as showers caused by primary nuclei, we meet with some difficulties if it is assumed that the magnitude of the transverse impulse remains constant. More detailed experimental data are necessary on the structure and energy composition of the shower core. The timeliness of such investigations is illustrated by an interesting case of observation of an extensive atmospheric shower core with the scintillation detectors, ionization calorimeter and X-ray films at the Tien Shan complex extensive atmospheric shower apparatus [15].

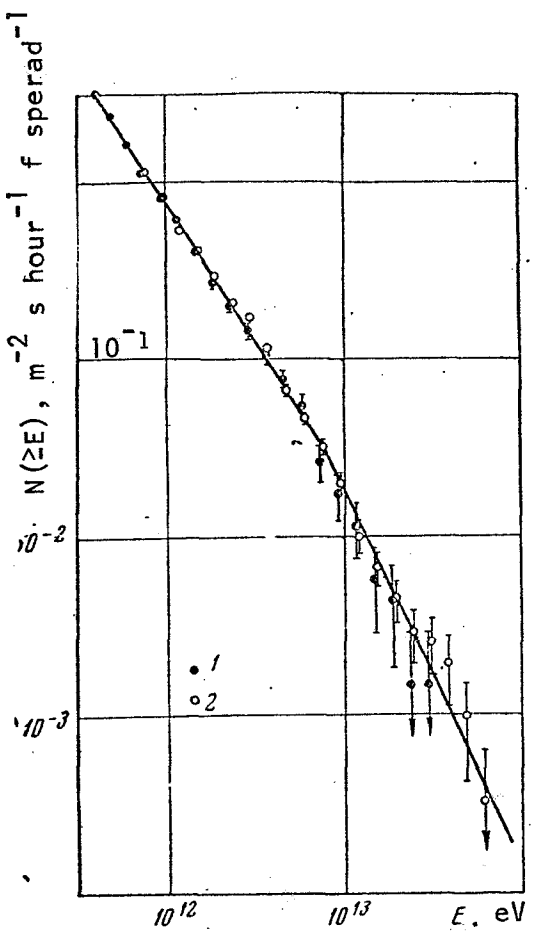

Figure 2. Energy spectrum of nuclearly active particles at an elevation of 3,330 m above sea level: 1) measurements by the ionization calorimeter method, 2) measurements by the ionization bursts method.

The spatial distribution of electrons in the registered shower makes it possible to assert that the shower was formed by a particle with an energy of $\gtrsim 10^{15}$ eV at an altitude of ~ 7 km above the observation level. This estimate of the formation altitude was made on the assumption of shower generation by an individual γ-quantum with an excessive shower age and is therefore the upper limit. Shower generation at an atmospheric depth of ~ 200 $g \cdot cm^{-2}$ means with a high degree of probability that the primary particle was a proton, since the probability of passage of a primary α-particle to such a depth without experiencing interaction is less than 1%.

In the ionization calorimeter there are two regions of concentration of the energy of the electron-photon components of a shower. One of these regions corresponds to the axis of the electron-photon components of the shower, determined from the scintillation detectors with an accuracy to ~ 1 m. The second region corresponds to a family of γ-quanta detected in the X-ray films placed in the calorimeter. In the nuclear layers of the ionization calorimeter there is a clearly distinguishable passage of a single high-energy nuclearly active particle through the entire calorimeter, together with a considerable number of nuclearly active particles of relatively low energy, whose number could /1507 not be determined. According to the total energy flux, the electron-photon

component, energetically released nuclearly active particle and family of γ-quanta, the shower axes are 20-30 cm distant from one another and create a complex structure of the shower core. The energetically released nuclearly active particle has an energy of $\simeq 5 \times 10^{13}$ eV and can be identified with the "guiding" nucleon, since its energy approximately corresponds to the energy of a primary proton after passing through half the atmosphere and no other particles of comparable energy are observed in a radius of 1-1.5 m from the shower axis.

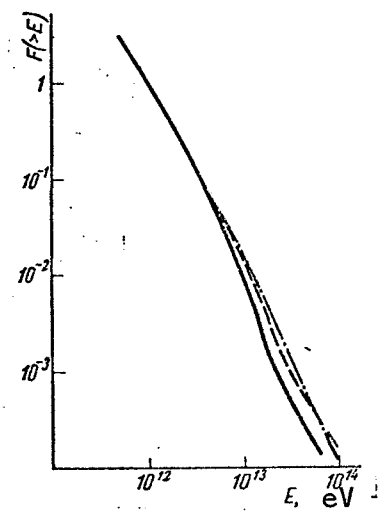

Figure 3. Computed energy spectra for nucleons in the mountains in relative units. The solid curve represents the results of computations on the assumption of an increase by a factor of 1.3 for the effective cross-section for the interaction between nucleons and nuclei for a nucleon energy greater than $4 \cdot 10^{13}$ eV; the dashed curve represents computations based on the assumption of an increase by a factor of 1.3 for the inelasticity coefficient for this same nucleon energy; the dash-dot curve represents the results of computations with constant parameters for the event but with variable exponents for the energy spectrum of primary nucleons ($\gamma = 1.7$ for an energy below $4 \cdot 10^{13}$ eV and $\gamma = 2.1$ for an energy greater than $4 \cdot 10^{13}$ eV).

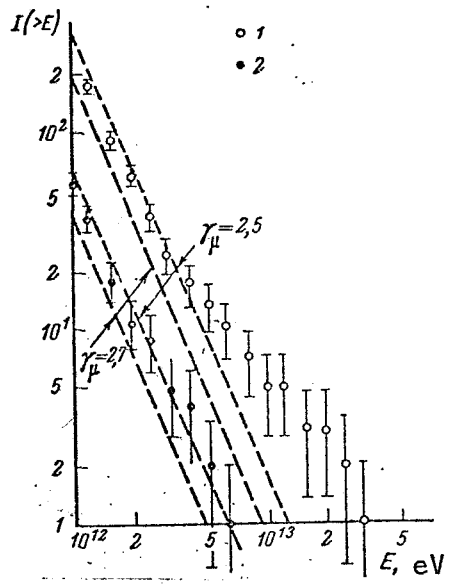

Figure 4. Spectrum of electrons-photon cascades in lead, caused by global flux muons (1) and muons with zenith angles less than 50° (2). The curves represent the computed spectra for 2 values of the muon spectron exponent (2.5 and 2.7).

A family of 20 γ-quanta was analyzed for finding the altitude of disintegration for π^0-mesons which yielded the observed combination of γ-quanta in pairs. This altitude was 1 km above the observation level. The absence of electrons-photon cascades from the atmosphere around γ-quanta

of maximum energy confirms the low altitude of their generation above the observation level. The total energy of the family of γ-quanta is $5 \cdot 10^{13}$ eV. If it is assumed that it was formed at an altitude of $\sim$ 1 km above the observation level by a guiding nucleon, it follows from their energies and divergence at the observation level that the transverse impulse was > 10 GeV. On the extreme assumption that a particle generating a family of γ-quanta at an altitude $\sim$ 1 km above the observation level was formed in the first shower generation event, its divergence with the guiding nucleon in the observation plane gives an estimate of the transverse impulse of $\gtrsim$ 2 GeV.

The individual case described here cannot serve as a basis for drawing serious physical conclusions. It only illustrates the presence and absence of the problem of multicore extensive atmospheric showers and the possibility of its investigation using complex apparatus.

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