INVESTIGATION OF EXTENSIVE COSMIC RAY SHOWERS UNDER DENSE SUBSTANCES

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The absorption of extensive air shower particles in an absorber of low atomic number was investigated at the altitude of 3860 m above sea level. Analysis of the data shows that in the lower third part of the atmosphere about 60% of the energy of the nuclear-active component is transferred to μ mesons and neutrinos. Some of the data seem to indicate that the absorption of shower particles increases in showers with total number of particles $N > 10^5$.

INTRODUCTION

NUMEROUS experimental data on extensive air showers (EAS) of cosmic radiation, obtained at various altitudes, lead to the conclusion that the shower structure i.e., its lateral distribution and composition, is independent of the level of observation, within the limits of experimental errors, for altitudes from 0 to 5000 m above the sea level. On the other hand, the study of the dependence of EAS on the altitude shows that the variation of the recorded number of showers with altitude of observation depends only to a small extent on the total number of particles and, consequently, cannot be explained by the electromagnetic cascade theory. There are two possible ways of explaining these experimental facts:

1. An extensive atmospheric shower is produced by a nuclear cascade event[1] that takes place when ultra-high-energy primary cosmic ray particles pass through the atmosphere. The electron-photon component of the shower is in equilibrium with nuclear-active particles that constitute the foundation of the shower. The energy flux of these particles has the following absorption coefficient in the atmosphere

$$\mu \approx 1/200 \text{ cm}^2/\text{g}.$$

2. It is possible[2] that, because of the still-unknown value of the effective nucleon interaction cross-section, or of the fluctuations of energy distribution among secondary particles in interactions of ultra-high-energy nucleons, the mean free path of particles that initiate EAS is equal to or greater than ~ 120 g/cm^2, and that the flux of nucleons (and of other nuclear-active particles) of corresponding energies decreases with the altitude with an absorption coefficient $\sim 1/120$ cm^2/g. The shower characteristics are then independent of the observation level because of the biased detection of showers produced at a certain effective height above the place of observation.

There are still no sufficient data for a definite choice between the two alternatives. Two ways of solving the problem are possible. The first is to determine experimentally the effective cross-section for the transfer of a given energy fraction to secondary particles in nuclear interactions of nucleons and $\pi^{\pm}$ mesons of 10^{12} to 10^{15} ev. So far, such data are not available even for $\sim 10^{11}$ ev. The second way is to measure the particle absorption of an individual EAS. The absorption of an individual shower in the atmosphere can be studied by simultaneous measurement of Cerenkov-light pulses produced by the passage of shower particles through the atmosphere and of the number of particles at the observation level.[3] One can also measure the absorption of EAS of a given size in a dense medium. The results of such measurements, made with ionization counters and a counter hodoscope, are presented in this article. The measurements were carried out at 3860 m above sea level (Pamir) in the autumn of 1955.

EXPERIMENTAL SETUP

The results given below were obtained by means of a large and complex array described in reference 4. A general diagram of the part of the array essential for the present work is given in Fig. 1.

We recorded all EAS, the particles of which produced four-fold coincidences of counters placed around the center of the array in two groups 2 m apart. The area of the master counters in each channel amounted to 500 cm^2. Thirty-nine groups of hodoscoped counters, the position of which is shown in the diagram, were used for core location and determination of the number of charged particles. Thirty-three hodoscope-counter groups contained each 24 counters of 100 cm^2 area each, three groups placed 19 m from the array center consisted each of 36 counters, 330 cm^2 in area each; three other groups at 19 m from the array center consisted each of 24 counters 22 cm^2 in area each. The flux density of charged particles incident on a hodoscope-counter group was determined from the ratio of the number of counters struck to that of counters missed.

The method of core location was similar to that used in reference 5. The lateral distribution function of charged particles was taken from reference 6. Errors in axis location using such a method amounted to 5 or 6 m near the center of the array and increased to $\sim$15 to 20 m at distances of $\sim$60 m from the center. In case when the shower axis fell in the central part of the array where 33 counter groups were placed, the axis was located by our earlier method.[6] The accuracy increased then to 0.8 m.

For the subsequent determination of the total number of shower particles we made use of many hodoscope points, obtaining an accuracy of 6 to 15% for showers with axes incident on the central part of the array. In that case, the error in axis location does not influence the measured number of particles in the shower, since the array is symmetric. In other cases the error of the determination of the shower size amounted to 40%. The showers recorded were divided into seven size groups. The distribution of showers in these groups, for showers with axes passing near the array center, is shown in Fig. 2. It should be noted that the distribution in Fig. 2 does not include showers with less than 10^4 and more than 10^6 particles, since the described hodoscope array was not suitable for detection of such showers. The relative number of showers of $> 10^6$ particles with axis near the array center was, however, small because of the energy spectrum of primary particles, and showers with $< 10^4$ particles practically did not produce four-fold coincidences in the master counter groups.

Twenty-four cylindrical ionization chambers* were used to measure the number of shower particles under the absorber. Twelve of these were 18.5 cm in diameter and had a working-volume length of 42 cm. The remaining chambers were 22.5 cm in diameter and a working-volume length of 96 cm. The chambers were filled with pure argon at 4 atmos. The chambers were calibrated

*The authors thank L. A. Razorenov who took part in the development and testing of the ionization chambers.

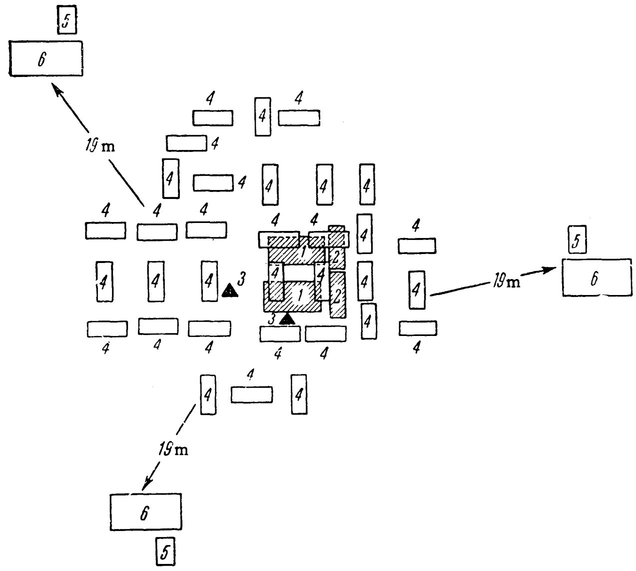

FIG. 1. General diagram of the array: 1) groups of large ionization chambers, 2) groups of small ionization chambers, 3) master counters, 4, 5, 6) hodoscope-counter group.

both by measuring the ionization produced by the passage of a μ meson along the chamber axis and by comparing the ionization burst in non-shielded chambers with the number of discharged hodoscope counters during the passage of an EAS. Allowing for the transition effect in chamber walls (2 g/cm^2 Cu) and for the angular distribution of shower electrons, both methods of calibration give practically identical results which are also in agreement with the calculated size of bursts.

An absorber made of aluminum and graphite was placed above the chambers for a measurement of the absorption of EAS in dense substances. The relative amounts of aluminum and graphite were chosen so that the absorber had absorption characteristics similar to air (neglecting the $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ decay). The thickness used was equal to 230 g/cm^2, which amounted to 7.7 cascade units and 3.5 nuclear units, or, assuming that the effective cross section for nuclear interactions is equal to the geometrical cross sec-

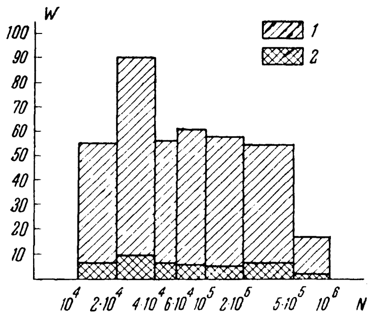

FIG. 2. Size distribution of EAS: 1) recorded near the array center 2) showers, the axis of which traversed ionization chambers.

tion, 3.45 nuclear units. A layer of air 230 g/cm^2 thick is equal to 7 cascade units and 3.5 nuclear units. Since the mean atomic numbers of the lower graphite layer and of the air are similar, the transition effect in walls of the chambers was practically identical in chamber calibration and in measurements of the number of particles under the absorber. An increase of the ionization per shower particle, caused by the scattering of shower particles, which leads to an increase of the "mean" chord of the chamber, was also independent of the fact whether the absorber was placed above the chamber. It is possible that the mean ionization per shower particle was somewhat lower under the absorber, in view of the zenith-angle distribution of shower axes. This effect, which could lead to a decrease of the number of particles observed under the absorber,

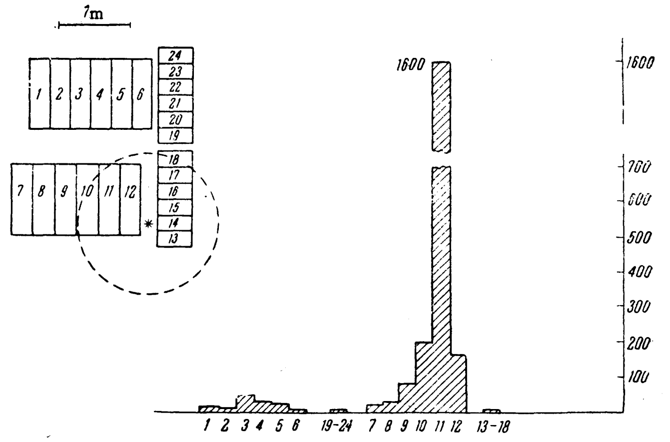

FIG. 3. A single-core shower with $\bar{N} = 4.2 \times 10^4$. Position of ionization chambers appear in the diagram (upper left). The position of the axis is indicated by a star. The numbers of the ionization chambers are indicated on the x axis. The y axis represents the number of particles.

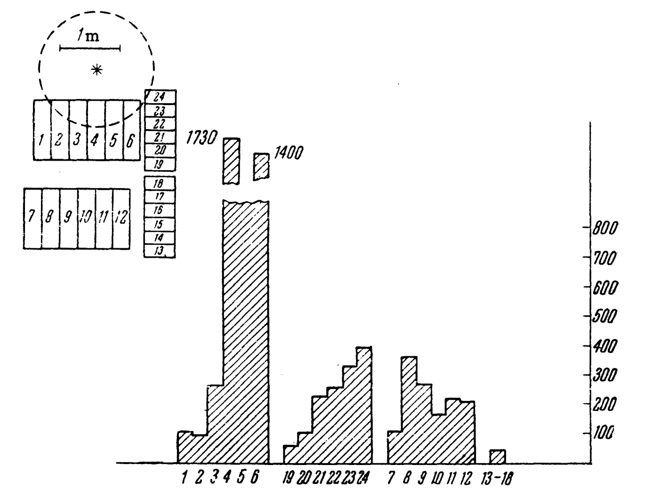

FIG. 4. A multicore shower, with $\bar{N} = 4.7 \times 10^5$. Notation as in Fig. 3.

has been neglected, but its magnitude is clearly small. In view of the fact that the $\pi^{\pm}$ decay mean free path is much larger than the nuclear interaction mean free path in a dense medium, the fraction of nuclear-active particles in a shower is larger under a dense absorber than at a corresponding altitude in air. The contribution of ionization due to heavily ionizing particles to the total ionization measured under a dense substance increases proportionally to the flux of nuclear-active particles. However, the uncertainty about the composition of ionizing particles under a dense absorber does not influence the determination of the energy flux carried by shower particles, since it is immaterial in which way the energy of the shower is dissipated on ionization.

OBSERVATION OF THE CORES OF EXTENSIVE AIR SHOWERS

It was already mentioned that the error in shower-axis location by means of the hodoscope was 0.8 m when the axis passed near ionization chambers. Since the ionization chambers and the counters were placed in different horizontal planes, and the shower-arrival angle was measured in a few cases only, the error in finding the point of intersection of the axis with the ionization-chamber plane increased to ~ 1 m. It was therefore impossible to tell, on the basis of the hodoscope data only, through which of the chambers the core passed.

The distribution of pulse heights of the ionization chambers was analyzed for each case in order to increase the accuracy in core location. It was found from the pulse-height distribution that the number of cores passing through the chambers is approximately equal to that expected from statistical considerations. The size distribution of showers given in Fig. 2 consists of all events in which the axis fell not further than 3.5 m from the geometrical center of the ionization-chamber positions. The collecting area was equal to ~ 37 m^2. Out of 400 showers, the axes of which fell in that area, 43 axes passed through the chambers, the total area of which amounted to ~ 3.5 m^2. The shower size distribution of these events is shown in Fig. 2. It can be seen that the distribution is analogous to that of all 400 showers. One cannot, however, attribute much weight to this fact in view both of the existence of multicore showers and of the diffuseness of the core.

Typical histograms of the ionization-burst size distributions for showers incident on an area covered by ionization chambers are shown in Figs. 3

and 4. Since there is no sharp limit between the record of showers with single cores and those having multiple ones, we classify as multicore showers all events in which the largest pulses, differing by no more than a factor of two, were observed at least in two non-adjacent or any three ionization chambers. We analyzed all events in which the shower axis passed through ionization chambers, using this criterion for multicore showers. The results are given in Table I.

TABLE I

Total number of particles in showers of the group	Number of axes observed	Number of axes with two or more cores
$1.5 \cdot 10^4$	7	2
$2.9 \cdot 10^4$	10	3
$5 \cdot 10^4$	8	2
$8 \cdot 10^4$	6	2
$1.5 \cdot 10^5$	5	2
$3.5 \cdot 10^5$	6	5
$5.8 \cdot 10^5$	1	1

It can be seen that the relative number of multicore showers amounts to $\sim 30\%$ of showers with total number of particles $N \leq 10^5$. Multicore showers are more frequent among EAS with $N > 10^5$, their fraction being $\sim 70\%$.

MEASUREMENT OF THE SHOWER PARTICLE FLUX UNDER AN ABSORBER

To determine the shower particle flux under an absorber in EAS with a given number of particles $\overline{N}$ at a given distance $\overline{r}$ from shower axis, we measured the mean ionization produced in ionization chambers by showers with mean number of particles between N_1 and N_2 $(N_1 < \overline{N} < N_2)$ the axes of which fell in the ring $r_1 < \overline{r} < r_2$. The chosen intervals of the total number of shower particles are shown in the histogram in Fig. 2.

The mean number of particles in EAS of a given group was defined as $\overline{N_0} = (1/n) \sum_i^n N_{0i}$, where N_{0i} is the total number of particles in the i-th shower, and n is the number of showers in the group. The mean distance was defined for a given ring as $\overline{r} = (1/n) \sum_i^n r_i$. The corresponding particle flux density under an absorber can be defined as $\rho(\overline{r}, \overline{N}_0) = \frac{i}{n\sigma} \sum_i^n J_i$, where σ is the area of the ionization chambers and J_i is the sum of ionization bursts in chambers under the absorber, expressed in numbers of shower particles. The results are given in Table II. It should be noted that all said above is correct for distances larger than 2 or 3 m, where we can neglect the dimensions of the ionization chamber array and the error in axis location. For smaller distances, the axis location was found more accurately by comparing the ionization bursts in various chambers and taking the chamber position into account. In addition, for distances in the 0 to 0.3 m range, when the dimensions of separate chambers were larger than the region under consideration, the number of particles

TABLE II. Mean ionization, expressed as the number of relativistic particles per m^2 for shower groups with different number of particles $\overline{N}_0$

Distance from axis, $\overline{r}$	$1.5 \cdot 10^4$	$2.9 \cdot 10^4$	$5 \cdot 10^4$	$8 \cdot 10^4$	$1.5 \cdot 10^5$	$3.5 \cdot 10^5$	$5.8 \cdot 10^5$
0.03	1750 ±650	3000 ±1000	5300 ±1600	6300 ±500	6700 ±400	18000 ±7000	58000
0.3—1	230 ±120	360 ±60	630 ±130	1000 ±250	1400 ±600	5000 ±2200	11000
1—2	25 ±13	125 ±25	200 ±60	500 ±230	540 ±220	1150 ±450	2500
2—3	23 ±5	79 ±16	126 ±24	260 ±70	320 ±80	470 ±120	630 ±160
3—5	18 ±7	37 ±15	44 ±19	71 ±16	89 ±21	120 ±30	400 ±120
5—8	6.3 ±2.3	12.5 ±4.5	23 ±10	45 ±10	37 ±9	90 ±25	250 ±70
8—20	—	3.1 ±0.9	6.3 ±1.7	7.4 ±2.5	9.1 ±2.6	8.3 ±2.2	—
20—40	—	—	0.83 ±0.27	2 ±0.6	2.9 ±1.1	2.5 ±0.8	8 ±1.5
40—70	—	—	—	—	—	1 ±0.25	1.75 ±0.3
Number of particles within the radius of 0.3 m	500 ±180	850 ±280	1500 ±450	1800 ±140	1900 ±110	5100 ±2000	16000

under an absorber in a circle of 0.3 m radius, given in the lowest row of Table II, was actually measured instead of the mean density $\rho(\bar{r}, \bar{N}_0)$. This number was assumed to be equal to $N'(r) = (1/n)\sum_{i=1}^{n} J'_i$, where J'_i is the measure of ionization in the chamber with the largest burst or the sum of ionizations in two adjacent chambers with the largest bursts. In part of the events, the value of $N'(r)$ was slightly higher in view of the fact that particles not belonging to the core passed through the chambers. However, by extrapolating the lateral distribution of shower particles under a dense absorber (Fig. 5) for the smallest distances, we can see that the increase is not larger than 25% of the value measured. The errors given in Table II are standard deviations of the arithmetic mean for the given shower group.

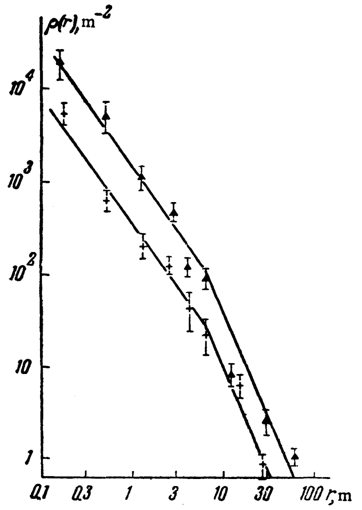

FIG. 5. Lateral distribution of the particle density of charged particles under an absorber in EAS of different size. Δ – showers with $\bar{N} = 3.5 \times 10^5$ particles, × – with $\bar{N} = 5 \times 10^4$. Solid curves represent an analytical approximation.

The data of Table II can be regarded as the result of measurements of the mean particle flux density at various distances from the axis of the EAS under an infinitely extended absorber. Consequently, one can talk about the lateral distribution function of the effective particle flux under an absorber. An analysis of Table II shows that, within the limits of experimental errors, the function is independent of shower size in the region from 0 to 6.5 m and can be written in the form

$$f(r) \sim r^{-(1.37\pm0.04)}.$$

The lack of experimental data on the flux of particles at large distances form the axis for showers with $N < 10^5$ does not permit us to determine the dependence of the lateral distribution function on shower size at distances above 6.5 m. However, the fact that function does not change at small distances from the axis gives grounds for expecting that the lateral distribution of particle flux under dense substances is independent of shower size also at large distances from the axis. For showers with $N > 10^5$, the lateral distribution function in the 6.5 to 70 m region can be written in the form

$$f(r) = r^{-(2.3\pm0.1)}.$$

Figure 5 illustrates the fit between this approximate expression and the observed lateral distribution of particle flux in EAS under a dense substance.

ABSORPTION OF EXTENSIVE AIR SHOWERS IN A DENSE SUBSTANCE

The data on particle flux density under a dense substance obtained by us made it possible to calculate the total number of particles in EAS under an absorber 230 g/cm^2 in thickness. The number of particles was directly measured in the 0 to 0.3 m region, while for larger distances we used the approximations discussed above.

An estimate of the ionization produced by shower μ mesons and electrons in equilibrium with each other shows that the ionization measured under the absorber can be explained by μ mesons traversing the absorbers only at distances > 1000 m from shower axis, i.e., at distances where the particle-density observed in air coincides with the density of the μ-meson component. We limited ourselves therefore to distances < 1000 m from shower axis in calculating the number of particles in a shower under the absorber. Results of the calculation are given in Table III.

TABLE III

Total number of shower particles above the absorber	Total number of shower particles underneath the absorber	Number of particles underneath the absorber within the radius of 40 m
$1.5\cdot10^4$	$(7.8\pm1.4)\cdot10^3$	—
$2.9\cdot10^4$	$(1.7\pm0.23)\cdot10^4$	—
$5\cdot10^4$	$(2.8\pm0.43)\cdot10^4$	$(2.2\pm0.3)\cdot10^4$
$8\cdot10^4$	$(4.3\pm0.54)\cdot10^4$	$(3.9\pm0.46)\cdot10^4$
$1.5\cdot10^5$	$(4.6\pm0.6)\cdot10^4$	$(4.5\pm0.6)\cdot10^4$
$3.5\cdot10^5$	$(1.1\pm0.17)\cdot10^5$	$(7.3\pm0.9)\cdot10^4$
$5.8\cdot10^5$	$(2.5\pm0.6)\cdot10^5$	

The result of a straightforward summation of the number of particles in rings at distances 0 to 40 m from the shower axis is given in column 3 for several shower groups. It can be seen that particles at distances larger than 40 m contribute little to the total number of particles.

The ratio of the number of particles observed under the absorber N to the total number of charged particles of the same showers at the observation level in air N_0 is given in Fig. 6. The values of that ratio calculated for an electron-photon cascade with age parameter $s = 1.2$, neglecting the nuclear-active shower component, are also shown in the figure. This value of s follows from the altitude dependence and from the electron lateral distribution function of EAS at 3860 m altitude.[7] The marked discrepancy between experimental data and cascade theory calculations indicates a substantial contribution of the electron-photon component, produced in the absorber by nuclear-active particles to the total flux of shower particles under the absorber.

It is of interest to compare the absorption of shower particles in the dense substance used as the absorber with the absorption of EAS particles in air. The ratio of shower particles at an altitude corresponding to the pressure of 880 g/cm² to the number of particles at our observation level (650 g/cm²) is also shown in Fig. 6. The absorption of shower particles in air is calculated from the longitudinal development of EAS[8] and the data on the barometer effect.[9] The discrepancy between the values of the absorption coefficient of EAS with $N_0 > 10^5$ at sea level given by references 8 and 9 is shown in Fig. 6 by the shaded area.

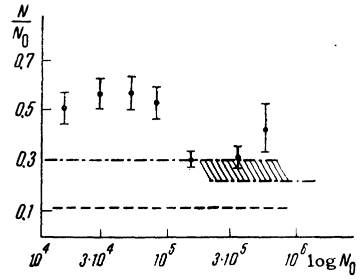

FIG. 6. Dashed line represents the ratio N/N_0 calculated for an electron-photon cascade with $s = 1.2$; dot-dash – N/N_0 calculated from the altitude dependence of showers. The points represent the values of N/N_0 measured in the experiment.

DISCUSSION OF RESULTS

A striking feature of Fig. 6 is the observed difference in the absorption of EAS of various size. For showers with $N_0 < 10^5$ the ratio of particles under the absorber N to the number above the absorber N_0 is equal to 0.55 ± 0.035. For showers with $N_0 > 10^5$ that ratio is 0.33 ± 0.032. The deviations from the mean $\overline{N/N_0} = 0.47 \pm 0.025$ are large enough to be significant. The question arises whether the observed absorption variation is limited to a narrow range of primary energies which follows directly from Fig. 6, or whether shower absorption varies all over the investigated range, increasing monotonically with shower size. It must be mentioned that the increase of the shower absorption coefficient with the primary energy contradicts both the electromagnetic cascade theory and any nuclear cascade theory of development of EAS, which assumes that the character of elementary nuclear interactions is independent of the energy of interacting particles.

We shall write the dependence of N/N_0 on N_0 as

$$N/N_0 = \log (\alpha / N_0^{\beta}).$$

The values of α and β can be determined by the least-squares method. At the statistical accuracy of the experimental data, the proposed relation cannot be rejected, although the probability that it is correct is less than 25%. The fit between the experiment and the proposed relation $N/N_0 = f(N_0)$ is especially bad near $N_0 \approx 10^5$. The spread of the values N/N_0 observed over the range $N_0 = 5 \times 10^4$ to $N_0 = 1.5 \times 10^5$ at the seven measured points would be expected to occur with a probability of 6%, the proximity of the values N_0 indicating that the problem lies not in a successful choice of the relation $N/N_0 = f(N_0)$, but in the validity of that relation on the whole range of N_0 from 1.5×10^4 to 5.8×10^5. It is therefore very probable that the experimentally-observed variation of the absorption of EAS in dense substances for showers of $N_0 \geq 1.5 \times 10^5$ and $N_0 \leq 8 \times 10^4$ actually exists. This variation could be due to a variation of the character of the elementary act of nuclear interaction for particles with energy corresponding to EAS with $N_0 \sim 10^5$ at 3860 m altitude.

Let us consider our results on the absorption of EAS with $N_0 \leq 10^5$ in connection with two possible interpretations of experimental data on EAS. If we assume that the showers recorded at any observation level are initiated at different heights above that level by primary cosmic ray particles as the result of nuclear interactions accompanied by a transfer of the whole energy of the primary to secondary particles (π mesons), and that the variation of the recorded number of showers with the altitude of observation is associated with the absorption of primary cosmic ray particles, then the age of the electron-photon component of EAS $s = 1.2$ to 1.3, observed in measurements, is an average characteristic of the showers selected by the array.

Under such assumptions, secondary nuclear-active particles are not an important component of EAS. To estimate the further absorption of the group of showers recorded by the array, we consider the absorption of the electron-photon shower, which is a superposition of all showers recorded* and which can, therefore, be assigned the value $s \sim 1.2$. It can be seen from Fig. 6 that the absorption of a shower with $s \sim 1.2$ is markedly different from the absorption measured, which shows that one cannot neglect the nuclear-active component. Production of the electron-photon component by nuclear-active particles lengthens the range of the cascade.

If the range increase is such that the cascade absorption corresponds in the mean to the altitude dependence then, on the average, an equilibrium is reached between the electron-photon and the nuclear-active shower components. This fact rules out nuclear interactions with full energy transfer to secondary particles, since such events cannot lead to equilibrium cascades, absorbed with a mean free path of ~ 180 to 200 g/cm^2.

We shall consider now our results from the point of view of an equilibrium between the electron-photon component and the nuclear-active shower particles. In that case the observed altitude dependence of EAS corresponds to the absorption of the particles in an individual shower. It can be seen from Fig. 6 that the absorption of showers with $N_0 < 10^5$ in a dense substance, measured in our experiments, is much less than the absorption in an equivalent layer of air. This result can be explained by the transition effect, in view of the fact that no decay of 10^9 to 10^{10}-ev $\pi^{\pm}$ mesons occurs in dense substances.

We shall now analyze quantitatively the energy balance in EAS with $N_0 = 10^5$. The energy E_e dissipated by the shower electrons, from the observation level (3860 m altitude) until the shower is totally absorbed, is derived from the energy carried by the electron-photon component at the observation level E_{e-p} and from the energy E_{π^0} transferred to π^0 mesons in nuclear interactions below the observation level. E_{e-p} can be determined from the electromagnetic cascade theory under the assumption that $s = 1.2$.[7] For a shower with $N_0 = 10^5$, E_{e-p} equals $\sim 2.6 \times 10^{13}$ ev.

Furthermore,

$$E_e = \int_0^{\infty} N_0 \beta \exp\{-x/200\}\, dx = 4.2 \cdot 10^{13} \text{ ev}.$$

where β is the ionization-energy loss of a relativistic particle traversing 1 g/cm^2 of air, and x is the thickness of air in g/cm^2 traversed. We have, therefore,

$$E_{\pi^0} = E_e - E_{e-p} = 1.6 \cdot 10^{13} \text{ ev}.$$

Since the absorption of a nuclear cascade in dense substances, as well as in air, is determined essentially by the absorption of particles having the highest energy we can expect that, after the transition processes have ended, the absorption of EAS particles in a dense substance follows the same law as in air (cf. Fig. 7). However, in a dense substance the total energy of the nuclear-active component is transferred to the electron-photon component, $E_e = E_{e-p} + E_{n-a}$. We shall now determine E'_e. According to Fig. 7 we have

$$E'_e = \int_0^{\infty} N_e \beta f(x)\, dx = 1.1 N_0 \beta 120 + \int_{120}^{\infty} \beta \cdot 5.5 N_0 \exp\{-x/200\}\, dx \approx 7 \cdot 10^{13} \text{ ev}.$$

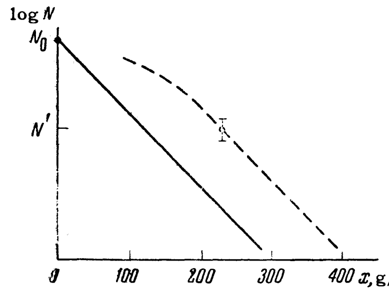

FIG. 7. Absorption of shower particles in the lower third of the atmosphere (solid line) and in an equivalent dense substance (dashed).

It follows that $E_{n-a} = 4.4 \times 10^{13}$ ev. In the atmosphere a larger part of this energy ($E_{n-a} - E_{\pi^0} \sim 2.8 \times 10^{13}$ ev) is carried away by μ mesons and neutrinos in the $\pi^{\pm} \to \mu^{\pm} + \nu$ decay. If that fact were neglected, the energy of the nuclear-active component would be underestimated. The energy distribution among the various components of a shower with $N_0 = 10^5$ at 3860 m altitude is as follows:

Energy of the electron-photon component	2.6×10^{13} ev
Energy of the nuclear-active component:	
carried by π^0 mesons	1.6×10^{13} ev
carried by $\mu^{\pm}$ mesons and neutrinos	2.8×10^{13} ev
Energy of μ mesons	4×10^{13} ev

It can be seen from the above that the energy fraction of the nuclear-active component, transferred to the electron-photon component in the passage of EAS with $N_0 < 10^5$ through the lower part of the atmosphere, is practically identical to the number of π^0 mesons relative to that of all the mesons produced in nuclear interactions. This means that most nuclear-active particles in EAS

*Such a procedure is permissible when the number of showers with $s < 1$ amounts to not more than 20 to 25% of the total number of showers in the group.

with $N_0 < 10^5$ are nucleons, owing to the instability of $\pi^{\pm}$ mesons. In fact, according to Ref. 4, the most energetic nuclear-active particle in EAS with $N_0 = 10^5$ has an energy of 2 to 4×10^{12} ev and transfers in a nuclear interaction about 4×10^{12} ev per secondary π meson, which is close to the energy at which the decay of $\pi^{\pm}$ mesons at 3860 m in air becomes predominant over secondary nuclear interactions. The main flux of nuclear-active particles in EAS with $N_0 = 10^5$ has an even lower energy. Calculations* carried out by us using the consecutive-generation method[12] lead to the same result: 60% of the energy of the nuclear-active component is carried away by μ mesons. The calculations were based upon the following assumptions: (1) The energy spectrum of nucleons of the depth of 500 g/cm^2 is of the form $\sim dE/E^{1.8}$ for $E \leq 10^{13}$ ev, high-energy particles are absent; (2) in nuclear interactions a nucleon carries away 0.6 of the primary nucleon energy; (3) such a particle is not produced in nuclear interactions of π mesons; (4) 0.25 of the secondary π mesons carry away 75% of the energy transferred to π mesons; the remaining π mesons carry away the remaining energy fraction, the assumed total number of π mesons being $\sim 4(E_0/2Mc^2)^{1/4}$, where E_0 is the primary-particle energy and M the nucleonic mass. The mean free path for nuclear interactions was taken as 70 g/cm^2. It should be noted that the conclusion about the predominantly nucleonic composition of the nuclear-active component of EAS is in agreement with the observed ratio between the neutral and charged nuclear-active particles.[13]

CONCLUSION

1. The measurements indicate that in EAS with total number of particles $10^4 < N < 10^5$ an equilibrium is attained, at least in the mean, between the nuclear-active and electron-photon components. This fact contradicts the hypothesis that EAS are produced in the depths of the atmosphere as the result of nuclear interactions in which the total energy of the primary particle is dissipated. It indicates also that fluctuations play a comparatively unimportant part in the development of EAS of the above size.

2. The energy carried by the nuclear-active component in EAS with $N < 10^5$ in the lower third of the atmosphere is 1.7 times that carried by the electron-photon component. However, a larger part ($\sim 60\%$) of this energy is dissipated in μ-meson production.

3. The variation of the absorption coefficient of EAS, as well as the change in the core structure observed in the passage from showers with $N < 10^5$ to showers with $N > 10^5$, is consistent with the assumption, proposed earlier,[14] that the character of the nuclear interaction changes at the energy $E_0 \approx 3 \times 10^{14}$ ev.

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*The energy carried away by μ mesons was estimated according to references 10 and 11. In view of the lack of experimental data on the energy region above 10^{10} ev and on their lateral distribution at distances > 1000 m from the shower axis, these estimates are very rough.

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