SOME CHARACTERISTICS OF EXTENSIVE AIR SHOWERS

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The hypothesis that a decreasing fraction of energy is transferred to pions as the primary-particle energy increases is shown to be inconsistent with experimental data on the altitude dependence of extensive air showers. It is also shown that the number of nuclear-active particles depends strongly on the relative number of baryons among all secondary particles produced in an elementary nuclear interaction.

EARLIER calculations by Nikol'skii and the present author[1,2] on the development of extensive air showers are here continued. The results obtained in[2] agreed with experimental findings regarding the altitude dependence of showers and the energy flux carried by the electron-photon component. The ratio of the mean energy of primary particles inducing showers with a given number of particles at the observation altitude, to the total number of shower particles, was consistent with the values usually assumed for the conversion coefficient from the number of particles to the primary-particle energy. However, some of the calculated quantities did not agree with experiment. Thus, too large a number of nuclear-active particles was computed in extensive showers of $N \geq 10^5$ particles at the given mountain altitude, compared with the experimental result.[3] There was also a discrepancy regarding the energy flux carried by nuclear-active particles (Table I). It was pointed out in[2] that the principal causes of disagreement are first, the hypothesis of a decreased elasticity coefficient of nucleon interaction as the nucleon energy diminishes to the 10^{11}—10^9 ev range, and, secondly, the large number of secondary particles, other than pions, identified as nucleons.

The foregoing conclusions were taken into account in the present calculation. Certain experimental results obtained in recent studies of elementary interactions at high energies,[4-7] were also considered. The nuclear emulsion results collected in the review by Koba and Takagi[8] were taken into consideration while selecting a model for the elementary nuclear interaction event. It was also considered that nucleons, antinucleons, and pions are produced in interactions between nuclear-active particles and the nuclei of air atoms. The principal assumptions on which the calculation is based can be summarized in the following manner.

A. Interaction of a Nucleon with the Nucleus of an Air Atom

1) All incoming nucleons retain 0.6 of the primary energy E_0.

2) The number of secondary pions as a function of E_0 is determined from the dashed line in Fig. 1. For $E_0 \leq 10^{10}$ ev the dependence of multiplicity on E_0 agrees with experiment[5,6] within error limits. For $E_0 > 10^{10}$ ev, $N \sim E_0^{1/4}$ was assumed, in agreement with experiment[4] and with contemporary theory.[9]

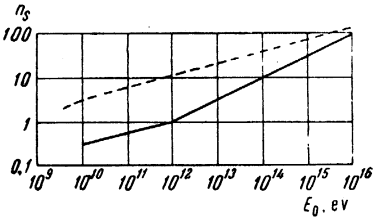

FIG. 1

3) The fraction of secondary nucleons and antinucleons in the incoming-particle energy range 10^{10} ev $\leq E_0 \leq 10^{12}$ ev was taken as ~10% of all secondary particles.* For $E_0 > 10^{12}$ ev the conclusions in[7] were taken into account, regarding the decreased fraction of energy transferred to the pion component with increasing primary-particle energy E_0. We assumed that for $E_0 > 10^{12}$ ev the fraction of nucleons and antinucleons increases monotonically, reaching 27% of the total number of

*We neglected the formation of secondary nucleons and antinucleons for $E_0 < 10^{10}$ ev.

secondary particles at $E_0 = 10^{15}$ ev (the continuous line in Fig. 1).

4) The fraction Δ of energy transferred to pions when $E_0 \leq 10^{10}$ ev was taken to be 0.4.* At high energies we assumed, following the Bristol group,[7] that the energy fraction transferred to the pion component diminishes monotonically as E_0 increases; but we assumed a slower rate of decrease compared with that in[7] (Fig. 2). It was assumed that 30% of Δ is carried away by a single pion (a π^0 meson, with probability $1/3$), and that 70% is divided equally among the remaining pions. When $E_0 < 10$ Bev the energy is divided equally among all pions.

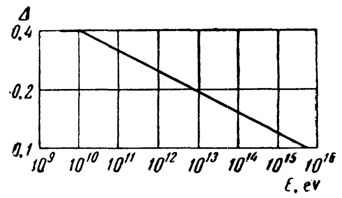

FIG. 2

5) Secondary nucleons and antinucleons carry away the energy $E_{n,\bar{n}} = (0.4-\Delta)E_0$, which is distributed equally among all particles of this type.

B. Interaction of $\pi^{\pm}$ Mesons with the Nuclei of Air Atoms

1) The inelasticity coefficient was taken to be unity, but energy spectra of the secondary particles were assumed harder than in nucleon-induced events. It was assumed that a $\pi^{\pm}$ meson, (in $2/3$ of the events) or a π^0 meson (in $1/3$ of the events) with energy $0.6\,E_0$ is produced.

2) The number and energy distribution of other secondary particles is the same as in nucleon-induced events.

C. Antinucleon Collision Events assumed Similar to Events Induced by $\pi^{\pm}$ Mesons

The calculation was performed by the method of successive generations. The different parameters of extensive air showers were derived in exactly the same manner as in[2]. The mean free interaction path of nuclear-active particles was taken as $\lambda_0 = 75$ g/cm^2; we considered nuclear interactions with $E_{na} \geq 3.7 \times 10^9$ ev. The results are given in Tables I and II, where all quantities pertain to showers with the given numbers of particles at the altitude of the Pamir (3860 m). We

Table I

No. of particles	10^4			10^5			10^6		
Shower parameters	Present work	Данные [2]	Experimental	Present work	Data of[2]	Experimental	Present work	Data of[2]	Experimental
Conversion coefficient from N to E_0	$3.3\cdot10^9$	$2.6\cdot10^9$	—	$2.9\cdot10^9$	2.10^9	—	$2.4\cdot10^9$	$1.6\cdot10^9$	—
I_m/I_s	7	16	14±3	4,7	16	14±3	3,7	16	14±3
Energy flux carried by nuclear-active particles, ev	$6.4\cdot10^{12}$	$6\cdot10^{12}$	$(4.4\pm1.3)\cdot10^{12}$	$6.3\cdot10^{13}$	$4.6\cdot10^{13}$	$\leq1.1\cdot10^{14}$	$5.6\cdot10^{14}$	$4\cdot10^{14}$	$(2.3\pm0.8)\cdot10^{14}$

Table II

No. of particles	10^4				10^5				10^6			
Kind of nuclear-active particles	Present work	Data of[2]	Checking calculation	Experimental	Present work	Data of[2]	Checking calculation	Experimental	Present work	Data of[2]	Checking calculation	Experimental
Nucleons	46	228	—	—	357	1480	—	—	2780	11300	—	—
Antinucleons	22	—	—	—	183	—	—	—	1830	—	—	—
$\pi^{\pm}$ mesons	27	36	—	—	230	210	—	—	1960	1000	—	—
All nuclear-active particles	95	264	32	250±50	770	1690	237	400±100	6570	12300	1740	1650±400

*This is close to the value $\Delta = 0.44$ given in[6] for E = 9 Bev.

took into account the fluctuations in the depth of the first nuclear interaction participated in by the primary particles.

Table I gives the intensity ratio I_m/I_s of showers of a given number of particles at the mountain altitude (3860 m) and at sea level. The ratios obtained in the present calculation differ from experimental results regarding the altitude dependence of showers (as between the Pamir and Moscow),[10] whereas in[2] there was approximate agreement. The discrepancy is especially marked for showers having large numbers of particles. The anomalously small difference noted in the present work between shower intensity in the Pamir and Moscow, especially for showers with large numbers of particles, is associated with the weak absorption of cascades formed by high-energy particles.

Electron-photon cascades calculated according to the nuclear-cascade scheme are shown in Fig. 3, compared with those in[2]. With increasing primary-particle energy cascade absorption is slower in the present work than in[2]. This results from the hypothesis, adopted in agreement with the Bristol group,[7] that the energy fraction transferred to the pion component decreases as the incident-nucleon energy increases while the energy fraction retained by the nucleon remains constant at 0.6 E_0.

It was assumed in our calculations that an incoming nucleon always retains the fraction 0.6 of its initial energy E_0, while the remaining fraction 0.4 E_0 is distributed among secondary nucleons, antinucleons, and pions. We also accepted the conclusion arrived at in[7] that the energy fraction transferred to pions (and therefore to π^0 mesons) decreases as E_0 increases. This leads to a slower absorption of nuclear-active cascades and of the accompanying electron-photon component. In[2] it was calculated that the fraction of incident-nucleon energy transferred to pions remains practically unchanged beginning with $E_0 \geq 10^{13}$ ev. The energy expended by the nuclear-active cascade to produce γ rays therefore depended only slightly on primary-particle energy.

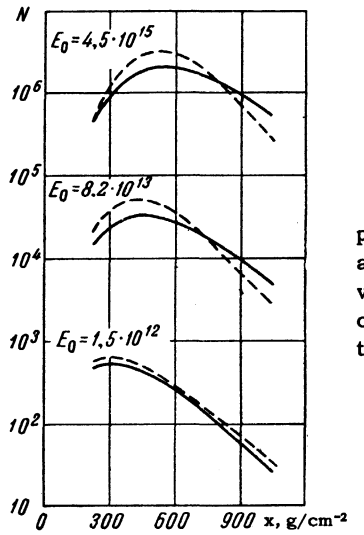

FIG. 3. No. of shower particles as a function of atmospheric depth for three values of E_0. Continuous curves – present calculation; dashed curves – from [2].

Thus, if we assume a decreasing transfer of energy to pions as the primary-nucleon energy increases while a constant fraction (> 0.5) of the energy is retained by the nucleon, without admitting any other important channels for energy transfer to the electron-photon component, our results disagree with the experimental altitude dependence of showers. The same conclusion was reached in[11].

Reference[1] presents one possible version of variation in the elementary event, which, while admitting a decrease of energy transfer to pions, brings the calculation into closer agreement with the experimental altitude dependence. It was there postulated that at primary energies $\geq 10^{14}$ ev an electron-photon component is produced, to which the fraction 0.63 of the primary-particle energy is transferred, without involving pions. For the sake of simplicity[1] direct energy transfer to the electron-photon component was considered, although the same result can obviously be achieved by introducing any rapidly decaying particles (see[12], for example).

The large energy fraction retained by the primary nucleon up to the very highest energies results in an increased number of high-energy nuclear-active particles in showers (compare the present work with[2]). This can be seen from the integral spectra of nuclear-active particles in Fig. 4. It must be noted that the increasing fraction of high-energy nuclear-active particles is accompanied by an increased flux of energy carried by the nuclear-active particles. This augments the discrepancy between the calculated and experimental energy flux given in Table I (as compared with[2]).

The last line of Table II gives the numbers of nuclear-active particles in showers having different total numbers of particles. Our calculated number of nuclear-active particles is considerably smaller than that given in[2]. In order to account for this reduction we checked the composition of the nuclear-active component at mountain altitude, i.e., we calculated separately the number of nucleons and the number of $\pi^{\pm}$ mesons included among all nuclear-active particles in extensive air showers (Table II).

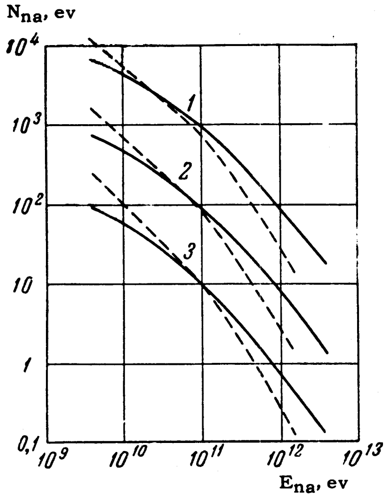

FIG. 4. Integral spectra of nuclear-active particles in extensive air showers with different total numbers of particles: $1-10^6$, $2-10^5$, $3-10^4$ particles. Continuous curves – present calculation; dashed curves – from [2].

Table II shows that nuclear-active particles at the mountain altitude are mainly nucleons,* and their number at the given altitude is apparently determined by the relative number of nucleons among all secondary particles created in an elementary event. This is evident from a comparison with[2], where the relative number of nucleons was taken to be constant at 0.27. The relative combined number of nucleons and antinucleons in the important energy range was 0.1 in the present work.

Two additional calculations were performed as a check. In the first of these the model differed from that in[2] only by taking 0.08 instead of 0.27 as the constant relative number of nucleons among all secondary particles produced in an elementary event. Table II gives the results of this check.

The second checking calculation was based on postulates differing from those formulated at the beginning of the present article. All secondary nucleons and antinucleons were replaced with charged pions having the multiplicity and energy distribution that had been taken for the secondary nucleons and antinucleons. Thus in nucleon-induced events the secondary particles will include only one ("primary") nucleon, while in events induced by $\pi^\pm$ mesons no nucleons will be formed. Recoil nucleons have energy $E \ll 3.7$ Bev and were disregarded in our calculations. For a shower observed at the mountain altitude and induced by a primary particle having energy 8×10^{13} ev, the relative number of nuclear-active particles ($\pi^\pm$ mesons) was found to be 0.002 instead of 0.0095 according to Table I.

The total number of nuclear-active particles at the given altitude therefore depends strongly on the relative number of nucleons (and hyperons) among the secondary particles produced in elementary events of nuclear interaction between nucleons, or $\pi^\pm$ mesons, and the nuclei of air atoms. We conclude from the foregoing that when reliable data are available for the number of nuclear-active particles in an extensive air shower, it becomes possible to derive a mean value for the relative number of baryons among the secondary particles produced in elementary events when the energy of the colliding particles is 10^{10}—10^{12} ev.

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*These results are also valid at sea level.

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