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NUCLEAR-ACTIVE PARTICLES IN YOUNG AIR SHOWERS

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The total energy $E_{n.a}$ of nuclear-active particles in young air showers (YAS), in which the energy of the electron-photon component $\geq 1.7 \times 10^{12}$ eV, is measured. On the average $E_{n.a} \leq (3.3 \pm 6)\%$, the nucleon energy E_n comprising $(17 \pm 3)\%$ of the energy of the particle producing the young atmospheric shower. It is shown that YAS are produced in interactions with a mean inelasticity coefficient $\bar{K} \geq 0.83 \pm 0.03$ and a mean fraction of energy imparted to π^0 mesons in the interactions $\bar{K}_{\pi 0} \geq 0.67 \pm 0.96$. The probability W of such interactions is estimated. It is shown that almost 50% of all the energy imparted to the π^0 mesons is lost by the nuclear-active particles in processes with $\bar{K}_{\pi 0} \geq 0.7$.

INTRODUCTION

It is well known that the passage of high-energy nucleons through the atmosphere is accompanied by generation of pions. The decay of the π^0 mesons leads to the appearance of high-energy γ quanta, which initiate electromagnetic cascades that develop along the path of the nucleon. The higher the nucleon energy, the larger, in the mean, the total energy of the pions generated in each interaction, and the more intense the electromagnetic cascades accompanying the nucleon. This explains why the high-energy nuclear-active particles travel as a rule in an air accompaniment, the size of which increases with increasing particle energy [1]. The characteristics of this air accompaniment (the total energy flux of the electron-photon component, the degree of its lateral concentration, the energy spectrum of the particles forming the accompaniment) are determined essentially by the characteristics of the interaction between the nucleon and the atomic nuclei of the atmosphere.

A study of the electron-photon component of atmospheric showers with energy $\gtrsim 2 \times 10^{12}$ eV and with the main energy of the shower concentrated in a circle several dozen centimeters in radius has shown that such showers are produced as a result of interaction between a nuclear-active particle in a relatively thin layer of the atmosphere above the array. Therefore the showers that have a high lateral energy concentration have been called by us "young" atmospheric showers (YAS)[2].

In order to reconcile the observed frequency of the YAS with the measured flux of nuclear-active particles, it became necessary to assume that the YAS are generated in interactions in which a small number of neutral pions receive the greater part of the primary-particle energy [3].

The classification of the YAS and their registration are based on selecting the specific electron-photon cascades (selection by cascade energy E and its lateral concentration). Selection by these attributes may therefore single out, from among all the interactions possible in the presence of fluctuations of the angular and energy distributions of the generated π^0 mesons, interactions in which the produced π^0 mesons have an anomalously narrow angular distribution and an anomalously large average energy. Inasmuch as the secondary $\pi^{\pm}$ mesons produced in the same interaction take practically no part in the formation of the YAS, their angular and energy distributions are the parameters to which the selection requirements for the YAS do not apply directly. Therefore measurement of the nuclear-active component affords very important information on the characteristics of the interactions which serve as the basis for the formation of young air showers.

1. APPARATUS AND SELECTION OF YOUNG AIR SHOWERS

We studied young air showers at an altitude of 3,260 meters with the aid of an array with a working area 10 m^2, shown schematically and described in detail earlier[3,4]. The array contained six rows of ionization chambers separated by lead and graphite filters. The two upper rows of chambers (V and VI), which were under layers of lead 3 and 2 cm thick in one series of experiments and 4 and 3 cm in the other, served for the measurements of the energy of the electron-photon component of the YAS[3]. The chambers of the remaining four rows (I—IV), located under a combined filter made of graphite and lead, served to measure the energy transferred to the π^0 mesons in the filters of the array by the nuclear-active particles contained in the YAS.

We investigated showers in which m chambers ($m \leq 6$) of the row situated under the 3 cm layer of lead registered not less than 60% of the ionizations registered by all the chambers of the row. This selected the electron-photon showers in which not less than 60% of the entire energy incident on the 10 m^2 array is contained in a circle of radius $R \approx m \times 10$ cm[3]. Examples of the distribution of the ionization over the chambers of the different rows are given in [2,3].

In order to reduce the probability that the nuclear active particles incident on the upper surface of the array leave through the side surface, we retained for subsequent analysis only those YAS whose axes fell in the central part of the installation, not closer than 50 cm from the edges. (The position of the YAS axis was determined in one projection using the chamber with the maximum ionization in row V, and in the other projection using the chamber with maximum ionization in row VI.)

The energy E of the electron-photon component of the YAS was determined by us with the aid of the relation $E = 1.4 \times 10^8 J_{5,6}$ eV, where $J_{5,6}$ is the larger of the two values of the ionization in the entire row (V or VI), expressed in terms of the number of relativistic particles passing through the central chord of the chambers. The coefficient 1.4×10^8 was obtained from the ratio of the number of particles at the maximum of the cascade in lead to the energy of the "primary" γ quantum. It takes into account the correction (factor 1.4) for the absorption of the particles emerging from the lead filters in the chamber walls (2 mm of brass). The energy of the π^0 mesons generated by the nuclear-active particles in the filter over the chamber rows III and IV is determined by the value of the total ionization J_{3+4} registered by the chambers of these rows. In each individual case, the development of the electromagnetic cascade in the lead filters may fluctuate. Furthermore, additional generation of π^0 mesons is possible in the lead filters lying over the rows of chambers III or IV. All these processes make J_3 unequal to J_4. (The very same situation will be observed in the first and second rows of the chambers, as well as in the fifth and sixth.) Therefore, to determine the energy transferred to the π^0 mesons in the filters of the array, we have taken in each individual case the largest values of the ionizations in row III or IV ($J_{3,4}$) and in the second or first row ($J_{1,2}$), i.e., $E_{\pi^0 1} = kJ_{3,4}$ and $E_{\pi^0 2} = kJ_{1,2}$.

Since $E = kJ_{5,6}$,

$$E_{\pi^0 1}/E = J_{3,4}/J_{5,6}, \qquad E_{\pi^0 2}/E = J_{1,2}/J_{5,6}. \tag{1}$$

The experiment yields directly the ratios $J_{3,4}/J_{5,6}$ and $J_{1,2}/J_{5,6}$, i.e., $E_{\pi^0 1}/E$ and $E_{\pi^0 2}/E$. Knowing $E_{\pi^0 1} + E_{\pi^0 2}$, we can estimate the total energy of the nuclear-active component of the YAS (averaged over many showers), if we specify the average inelasticity coefficients for the interactions of these particles with the nuclei of lead and graphite.

2. EXPERIMENTAL RESULTS

For an analysis of the nuclear-active component we selected young air showers incident on the central part of the array, with different values of m and with different energies E. The number of registered YAS with different m is listed in Table I.

Table I

YAS energy E, 10^{12} eV	m = 1	2	3	4	5—6
$1.7 \leqslant E < 3.4$	11	20	28	32	42
$3.4 \leqslant E < 8.5$	1	8	4	5	31
$8.5 \leqslant E < 17$	—	2	1	1	3
$17 \leqslant E$	—	—	—	—	5

In determining the energy of the nuclear-active particles of the young showers from the ionization registered by the four lower rows of the chambers, we have introduced the following corrections to the experimental data.

1. Correction to $J_{3,4}/J_{5,6}$, due to the penetration of the electron-photon component of the YAS through the filters of the array. The determination of the energy of the π^0 mesons generated in the filter over the rows of chambers III and IV by using the value of the ionization $J_{3,4}$, presupposes that the entire ionization in the chambers of rows III—IV is determined by the development of the cascades from the quanta produced during the decay of π^0 mesons generated in the filters located over the chambers of these rows. This assumption would

Table II

YAS energy E, 10^{12} eV	m: 1	1÷2	3–4	5–6
$1.7 \leqslant E < 3.4$	1.90 ± 0.42	1.64 ± 0.34	1.39 ± 0.26	1.09 ± 0.15
$E \geqslant 1.7$	2.0 ± 0.43	1.77 ± 0.29	1.35 ± 0.19	1.27 ± 0.09
$E \geqslant 17$	—	—	—	1.82 ± 0.29

be satisfied were the electron-photon component of the YAS incident on the array from the atmosphere not to penetrate through the lead filters (total thickness 135 g/cm^2) and the graphite filter (60 g/cm^2). To ascertain whether such penetration does take place and to what degree it occurs for different YAS, we have proceeded as follows. If we select the cases when π^0 mesons are produced in filters over the rows III and IV by single nuclear-active particles, then we find that in this case we have in the mean $\overline{J_4/J_3} = 1.15$, where J_4 is the ionization in row IV and J_3 is the ionization in row III.

Therefore, if $\overline{J_4/J_3} = 1.15$ in the YAS, then we can state that the ionization in rows III and IV is produced by nuclear-active particles (via generation of π^0 mesons in the array filters). On the other hand, if $\overline{J_4/J_3} > 1.15$, then the ionization in rows III and IV is partially reduced by the penetration of the electron-photon component of the YAS. It is to be expected here that if the energy has a large lateral concentration (m is small) or when the YAS has a large energy (for a given value of m), the average γ-quantum (electron) energy in the YAS will be higher, and the penetration of the electron-photon component through all the filters over the rows of chambers III and IV will have a stronger influence. Experimental data on the value of $\overline{J_4/J_3}$ for different values of m and E are listed in Table II.

Analogous measurements of the ionization ratios J_2/J_1 have shown that $\overline{J_2/J_1} = 1.3 \pm 0.1$ and depends on neither m nor E.

It follows from Table II that the ionization in rows III—IV is greatly due to the penetration of the electron-photon component of the YAS incident on the array from the atmosphere through the filters, and that this penetration is particularly large for YAS with small m, i.e., for YAS with a small age parameter s [3]. The calculation of the correction for the penetration of the electron-photon component through the filters of the array is based on the fact that row III is under a layer of 14 cm of lead, while IV is under 12 cm of lead. The electromagnetic cascades from the electron-photon component of the YAS under such lead-filter thicknesses will be far from the maximum of their development, i.e., the number of particles in them will in the mean decrease like $\sim e^{-\mu t}$, where $\mu = 0.22$ (cascade unit)$^{-1}$. Since a lead filter 2 cm thick is situated between the rows of chambers III and IV (approximately four cascade units), the equality $(\overline{J_4/J_3})_{\text{ext}} = e^{0.88} = 2.4$ should be satisfied for particles due to the penetration of the electron photon component from the outside. On the other hand, for particles due to the generation of π^0 mesons by nuclear-active particles of the YAS we have $(\overline{J_4/J_3})_{\text{n.a}} = 1.15$.

If $\bar{J}_{\text{n.a}}$ is the average ionization due to the nuclear-active particles in row III, while $\bar{J}_{\text{ext}}$ is the ionization due to the external electron-photon component of the YAS, then the ionization in row IV will be $\bar{J}_4 = 2.4\,\bar{J}_{\text{ext}} + 1.15\,\bar{J}_{\text{n.a}}$ and thus

$$\overline{J_4/J_3} = (2.4\bar{J}_{\text{ext}} + 1.15\bar{J}_{\text{na}})/(\bar{J}_{\text{ext}} + \bar{J}_{\text{na}}). \tag{2}$$

Using the experimental values of $\overline{J_4/J_3}$ for YAS with different m, with the aid of formula (2), we determined the ratio $J_{\text{n.a}}/J_{\text{ext}}$ and introduced a correction for the value of $\bar{J}_{\text{ext}}$ in the average values of $\overline{J_{3,4}/J_{5,6}}$. The value of $\overline{J_{3,4}/J_{5,6}}$ averaged over all the YAS without a correction is 0.10 ± 0.016, and the corrected value is 0.071 ± 0.018.

2. Correction to $\overline{J_{1,2}/J_{3,6}}$, due to the possible emergence of the nuclear-active particles through the side surfaces of the array. Starting from the absorption range of the YAS ($L_{\text{abs}} \approx 120$ g/cm^2), we calculated the angular distribution of the YAS at an altitude 3,260 meters above sea level. Taking into account the geometry of the array and the system for selecting the YAS (the requirement that the axes of the YAS be not closer than 50 cm to the edges of the array), we found that in 2% of the cases the nuclear active particles will leave through the side surface of the array between rows III—IV and V—VI, and in 28% of the cases they will leave between rows I and II or III and IV. The value of $\overline{J_{1,2}/J_{5,6}}$ averaged over all the YAS is 0.052 ± 0.009 without correction, and when corrected for the possible emergence of the nuclear-active particles through the side surfaces of the array the value is 0.072 ± 0.013.

Therefore

$$[\overline{(J_{1,2}+J_{3,4})/J_{5,6}}]_{\text{corr}} = 0.144 \pm 0.022.$$

To clarify the mechanism of YAS generation, it is important to know not only the relation between the energy of the nuclear-active particles $\overline{E}_{n.a}$ in the electron photon component $\overline{E}$ in the young air showers, but also the distribution of $E_{n.a}/E$. The combined filters which we used to estimate the energy of the nuclear-active particles do not give an exact value of $E_{n.a}$ for each individual case (since some of the particles can pass through the side surfaces of the array, the nuclear-active particles can leave through the lower base of the array, and part of the energy transferred to the π^0 mesons can be absorbed in the 210 g/cm^2 graphite layer and in the lead filters which are separated from the ionization chambers by thick layers of graphite). Therefore, in individual cases, the quantity $(J_{1,2} + J_{3,4})/J_{5,6}$ is not uniquely related to $E_{n.a}/E$. Nonetheless, it seems to us that the character of the distribution of $(J_{1,2} + J_{3,4})/J_{5,6}$ reflects essentially the character of the distribution of $E_{n.a}/E$. Figure 1 shows the experimentally observed distribution of the YAS relative to $(J_{1,2} + J_{3,4})/J_{5,6}$. It must be emphasized that for (38 ± 4.5)% of the YAS we have $J_{1,2} + J_{3,4} = 0$. (In Fig. 1 these YAS lie in the interval $0 \leq (J_{1,2} + J_{3,4})/J_{5,6} < 0.1$.) Attention is called to the fact that for 85% of the YAS we have $(J_{1,2} + J_{3,4})/J_{5,6} < 0.3$ and for these we have $[\overline{(J_{1,2} + J_{3,4})/J_{5,6}}]_{\text{corr}} = 0.060 \pm 0.009$.

In order to ascertain whether the small fraction of the energy contained in the nuclear-active component of the YAS is the result of the motion of some of the nuclear-active particles past the installation, we have constructed the distribution of the showers with energy $1.7 \times 10^{12} \leq E < 3.4 \times 10^{12}$ relative to the quantity $(J_{1,2} + J_{3,4})/J_{5,6}$ for different values of the parameter m, characterizing the "age" of the YAS (see Fig. 2). The smaller m, the less effective the layer of the atmosphere in which the YAS are generated[3], i.e., the smaller should be the divergence of the nuclear-active particles and the larger the energy flux of the nuclear-active component incident on the array.

Figure 3 shows the dependence of the average value $\overline{(J_{1,2} + J_{3,4})/J_{5,6}}$ on the "age" of the showers (on the parameter m). The figure shows that with increasing m the ratio $\overline{E_{n.a}/E}$ is more likely to grow than to decrease, as would be expected if an appreciable fraction of the energy of the nuclear-particle were to move past the array. It follows from these results that the nuclear-

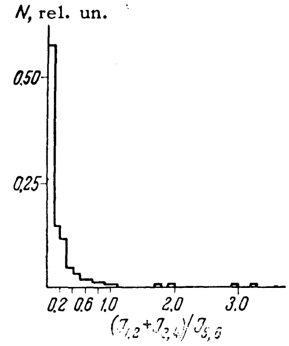

FIG. 1.

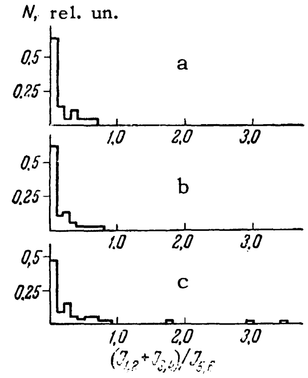

FIG. 2.

FIG. 1. Distribution of YAS with energy $E_{ep} > 1.7 \times 10^{12}$ eV with respect to the quantity $(J_{1,2} + J_{3,4})/J_{5,6}$.

FIG. 2. Distribution of YAS with energy $1.7 \times 10^{12} \leqslant E_{ep} < 3.4 \times 10^{12}$ eV with respect to the quantity $(J_{1,2} + J_{3,4})/J_{5,6}$ for different values of m: a) m = 1 – 2; b) m = 3 – 4; c) m = 5 – 6.

active particles moving past the array contain a small fraction of the energy registered by the apparatus. The same conclusion is arrived at from the experimentally observed fact that $\overline{(J_{1,2} + J_{3,4})/J_{5,6}}$ is independent of the YAS energy.

In many cases the ionization in rows III, IV, and I, II was produced not by one but by several nuclear-active particles. This was seen from the distribution of the ionization among the chambers, which had several sharp maxima, similar to what takes place in the registration of "structural" bursts[1]. We have therefore attempted to estimate the contribution made to the total ionization by the particle with maximum energy (we identified it with the largest maximum of the ionization if the distribution of the ionization among the chambers had more than one maximum, or with the entire registered ionization if the distribution had a single maximum). In order not to introduce into this estimate the error connected with the penetration of the electron photon component of the YAS from the atmosphere, we based the entire analysis on the data from the second row of chambers, in which 50% of the ionization is produced (in the mean) by the most powerful maximum (or by the single maximum), and 50% is produced by all the remaining nuclear-active particles. (It is possible

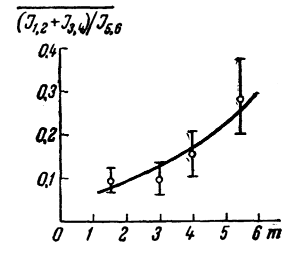

FIG. 3. Dependence of the average value of $(J_{1,2} + J_{3,4})/J_{5,6}$ on m.

that not one but several nuclear-active particles are concentrated in the region of the largest maximum. Therefore by attributing 50% of $\overline{J_{1,2}/J_{5,6}}$ to one particle, we merely overestimate its energy.)

3. DISCUSSION OF RESULTS

Energy of nuclear-particles in young air showers. In order to convert from the ionizations $J_{1,2}$ and $J_{3,4}$ to the energies of the nuclear-active particles incident on the array, we must make definite assumptions concerning the average characteristics of the interaction between the nuclear active particles and the atomic nuclei of the array filters (graphite and lead). We have assumed that the ranges for the interaction of the nuclear-active particles, regardless of their nature, are 85 and 200 g/cm^2 in graphite and lead, respectively. We have assumed further that in the mean the pions transfer during the interaction ⅓ of their total energy to the π^0 mesons, while the nucleons transfer $K_n/3$ (K_n is the average inelasticity coefficient of the nucleons). Calculations were made for the cases when the inelasticity coefficients K_n^C and K_n^{Pb} of the interaction of the nucleons in the graphite and in the lead were equal to 0.5 or 1.

It was assumed further that the entire energy transferred to the π^0 mesons in the lead filters was not registered. The results of different calculation variants are listed in Table III.

In the fourth and fifth columns are given the fractions of the nuclear-active particle energy $E_{n.a}$ transferred to the π^0 mesons in graphite layers 60 and 210 g/cm^2 thick. The last column lists the coefficient a, by which the sum $E_{\pi^0}(60) + E_{\pi^0}(210)$ must be multiplied in order to obtain the average value $\overline{E}_{n.a}$.

As can be seen from Table III, different assumptions concerning the nature of the nuclear-active particles (more accurately, concerning the characteristics of the interactions from the point of view of the transfer of energy to the π^0 mesons) change little the value of the coefficient of conversion from the measured ionization $\overline{J_{1,2} + J_{3,4}} \sim E_{\pi^0}(60) + E_{\pi^0}(210)$ to the energy $E_{n.a}$.

According to (1)

$$\overline{[E_{\pi^0}(60) + E_{\pi^0}(210)]/E} = \overline{(J_{1,2} + J_{3,4})/J_{5,6}},$$

Therefore the ratio of the average energy of the nuclear-active particles $\overline{E}_{n.a}$ to the energy E of the electron-photon component of YAS will be

$$\overline{E_{na}/E} = a\,\overline{[E_{\pi^0}(60) + E_{\pi^0}(210)]/J_{5,6}}.$$

Taking for a a value 2.3, we get $\overline{E_{n.a}/E} = 2.3 \times (0.144 \pm 0.022) = 0.33 \pm 0.05$. However, it is possible that this quantity calls for the introduction of still another correction, for the absorption of the electron-photon component in the thick layer of graphite (210 g/cm^2). Calculations show that if the effective energy of the γ quanta produced via decay of the π^0 mesons generated in the thick graphite filter were 10^9 eV, then the row of chambers II would register 50% of $E_{\pi^0}(210)$. The possibility of appreciable energy absorption in 210 g/cm^2 of graphite is indicated also by the fact that, according to Table III, the ratio $\overline{E_{\pi^0}(210)/E_{\pi^0}(60)} = \overline{J_{1,2}/J_{3,4}}$ should lie in the interval 1.7—2.7, whereas experiment yields for this ratio 1.0 ± 0.31.

Taking into account the possible 50% energy absorption in 210 g/cm^2 of graphite, we find that $\overline{(J_{1,2} + J_{3,4})/J_{5,6}} \le 0.214 \pm 0.39$ and $\overline{E_{n.a}/E} \le 0.050 \pm 0.09$. Thus, the nuclear active particles contained in the young air showers have in the mean an energy not more than 33 ± 6% of E_0 — the energy of that "primary" particle whose interaction in air caused the YAS.

Since the average energy of any nuclear-active particle does not exceed 0.5 $\overline{E}_{n.a}$, we can state, by identifying the particle of highest energy with the nucleon, that the average energy of the nucleon in the registered YAS does not exceed 0.5 × (0.33 ± 0.06) E_0, i.e., $\overline{E_n/E_0} \le 0.17 \pm 0.03$.

In the selected young air showers ($m \le 6$) the energy flux of the electron-photon component has a high lateral concentration, which can be ensured only if the YAS is the result of the generation of a small number of γ quanta of sufficiently high energy ($E_\gamma \gtrsim 4 \times 10^{11}$ eV). Then the transverse lateral distribution of the energy flux density of the electron-photon component will be determined essentially by the scattering of the particles in the

Table III

Nature of nuclear-active particles	K^C	K^{Pb}	$\frac{E_{\pi^0}(60)}{E_{na}}$	$\frac{E_{\pi^0}(210)}{E_{na}}$	$\frac{E_{\pi^0}(210)}{E_{\pi^0}(60)}$	a
$\pi^{\pm}$-mesons	1	1	0.180	0.310	1.72	2.04
nucleons	0.5	1	0.125	0.308	2.46	2.30
	0.5	0,5	0.125	0.337	2.70	2.17

cascade shower, and the effective layer in which the YAS is generated, i.e., the layer of the atmosphere in which the main part of the showers is generated, will be $X \leq 130$ g/cm^2[3]. It is easy to calculate the expected average value $\overline{E_{n.a}/E}$ under the assumption that the YAS is generated by a nucleon that experiences within the limits of this effective layer not less than one interaction, losing 50% of its energy in each interaction, viz., 17% to the production of π^0 mesons and 34% to the production of $\pi^\pm$ mesons. The latter transfer during the interactions one-third of their energy to the π^0 mesons. Such calculations show that in young air showers we should have $\overline{E_{n.a}/E} = 1.8$, and this is more than 3.5 times larger than the experimental value for $\overline{E_{n.a}/E}$. Consequently, interactions characterized by an average inelasticity coefficient $\overline{K} = 0.5$ cannot serve as the basis for the formation of YAS.

Mechanism of formation of young air showers. The fact that an appreciable role is played in the formation of YAS by processes with much more than average interaction inelasticity can be seen from the following. First, in 38% of the cases we have $J_{1,2} + J_{3,4} = 0$. Even assuming that the entire energy of the nuclear-active component is concentrated in one particle, the fraction of the YAS with $J_{1,2} + J_{3,4} = 0$ should be 16%. Consequently, at least in 20% of the YAS there are no nuclear active particles whose energy exceeds 0.06 E. (This quantity is arrived at from the minimum value of the registered ionization of 300 particles, and from the mean value $\overline{J}_{5,6} \approx 24{,}000$ particles). Thus, in $\sim 20\%$ of the showers the nucleon has lost not less than 94% of its energy as a result of interactions within the limits of the effective layer.

Second, we have in the mean, over all showers, $\overline{E_n/E_0} < 0.17 \pm 0.03$. Consequently, the nucleon loses in the effective layer during the generation of the YAS not less than $(83 \pm 3)\%$ of its energy. From the fact that $\overline{E_n/E_0} < 0.17 \pm 0.03$ it follows that hyperon or isobar decay to a high-energy π^0 meson and nucleon does not play any appreciable role. If the interaction of the high-energy nucleon results in an isobar that carries away a considerable fraction ($\sim 70\%$) of the primary-nucleon energy, then its decay can give rise to the high-energy π^0 meson that initiates the YAS. A steeply decreasing nuclear-active particle spectrum will then lead (when the YAS is registered) to unique selection of decays in which the π^0 meson receives more than the average energy, and the remaining nucleon gets less.

It is easy to calculate the average ratio of the nucleon energy due to isobar decay to the π^0-meson energy (the energy E of the electron-photon component of the YAS), with account of the energy spectrum of the generated particles. For an isobar with spin and isospin $S = T = 3/2$, we have $\overline{E_n/E} = 2.5$, whereas experiment yields $\overline{E_n/E} \leq 0.25 \pm 0.045$.

Thus, if some part of the YAS is produced as a result of the decay of an isobar with $S = T = 3/2$ into a π^0 meson and a nucleon, the fraction of such YAS does not exceed $0.25/2.5 \approx 10\%$.

If we assume that the YAS are produced as the result of decay of isobars with higher excitation energies—with rest mass $M_{is} = 2M_n$, then in the YAS produced in this manner $\overline{E_n/E} = 1.01$, i.e., in this case the fraction of the YAS due to the isobar decay would not exceed 25% of the observed number of young air showers. We have seen already that in the course of production of the YAS the generating particle loses within the effective generation layer ($X \gtrsim 130$ g/cm^2) on the average $(83 \pm 3)\%$ of its energy. This raises the very important question: to what degree is this average energy loss due to one interaction act, and what role is played by the successive interactions within the layer X.

In order to clarify the role of the successive interactions of the nucleon within the layer X during the generation of the YAS, we have considered the following model for their generation. Within the layer X the nucleon, which is the "primary" particle generating the YAS, can experience n interactions. During each interaction it can transfer, with probability W, a fraction $\overline{K}_{\pi^0}$ of its energy to the π^0 mesons and a fraction $\overline{K}_{\pi^\pm}$ to the $\pi^\pm$ mesons.

The produced $\pi^\pm$ mesons transfer $1/3$ of their energy to the π^0 mesons in each interaction. (The transfer of energy to the π^0 mesons from the $\pi^\pm$ mesons in the layer X is calculated from the average characteristics without account of the fluctuations.) The total energy transferred to the π^0 mesons, $E_{\pi^0} = \alpha_{\pi^0}(n)E_0$, was assumed to equal the energy E of the electron-photon component of the YAS.

Assuming that X does not depend on E, and choosing the energy spectrum of the nuclear-active particles generating the YAS in the form $F(E_0)dE_0 = B\,dE_0/E_0$, we obtain

$$N_{\mathrm{YAS}}(E)\,dE = \frac{B\,dE}{E^{\gamma}} e^{X/L_{\mathrm{abs}}} \sum_{n=1}^{\infty} \alpha_{\pi^0}^{\gamma-1}(n) P_n, \qquad (3)$$

$$\alpha_{\pi^0}(n) = \frac{\bar{K}_{\pi^0} + \beta \bar{K}_{\pi^\pm}}{\bar{K}_{\pi^0} + \bar{K}_{\pi^\pm}} [1 - \{1 - (\bar{K}_{\pi^0} + \bar{K}_{\pi^\pm})\}^n], \qquad (4)$$

$$\alpha_{\pi^\pm}(n) = \frac{(1-\beta)\bar{K}_{\pi^\pm}}{\bar{K}_{\pi^0} + \bar{K}_{\pi^\pm}} [1 - \{1 - (\bar{K}_{\pi^0} + \bar{K}_{\pi^\pm})\}^n], \qquad (5)$$

$$\frac{E_n(n)}{E_0} = [1 - (\bar{K}_{\pi^0} + \bar{K}_{\pi^\pm})]^n, \quad (6)$$

$$P_n = W^n \frac{(\bar{n})^n}{n!} e^{-\bar{n}}, \qquad \bar{n} = \frac{X}{L_{\text{int}}} \quad (7)$$

Here α_{π^0} and $\alpha_{\pi^\pm}$ are the fractions of the energy acquired ultimately by the π^0 and $\pi^\pm$ mesons; β is the average fraction of the energy transferred to the π^0 mesons by the $\pi^\pm$ mesons in the layer X ($\beta = 0.25$ when $X = 130$ g/cm^2 and $L_{\text{int}} = 85$ g/cm^2).

From (3)—(7) we calculated the relative probabilities for the production of YAS with a given energy E, E+dE due to 1, 2, . . . , n nucleon interactions within an effective layer $X = 130$ g/cm^2. Knowing the relative contribution of events with different n to the production of the YAS, we can calculate the average value

$$\frac{\overline{E_n}}{E_0} = \sum_{n=1}^{\infty} \frac{E_n(n)}{E_0} \alpha_{\pi^0}^{\gamma-1}(n) P_n \Big/ \sum_{n=1}^{\infty} \alpha_{\pi^0}^{\gamma-1}(n) P_n$$

and the average value

$$\frac{\overline{E_{na}}}{E_0} = \overline{\alpha_{\pi^\pm}(n) + \frac{E_n(n)}{E_0}} = \frac{\overline{E_n}}{E_0} + \frac{\sum \alpha_{\pi^\pm}(n)\, \alpha_{\pi^0}^{\gamma-1}(n) P_n}{\sum \alpha_{\pi^0}^{\gamma-1}(n) P_n}.$$

Calculations of $\overline{E_n/E_0}$ and $\overline{E_{n.a}/E_0}$ were made for different values of $\bar{K}_{\pi^0}$, $\bar{K}_{\pi^\pm}$, and W. The results of the calculations are shown in Figs. 4 and 5. It is seen from Fig. 4 that in order for a nucleon to retain a fraction of the energy $\overline{E_n/E_0} \le 0.17 \pm 0.03$ as a result of the production of a young air shower, it is necessary that the interaction generating the YAS have an inelasticity coefficient $\bar{K} = \bar{K}_{\pi^0} + \bar{K}_{\pi^\pm} \ge 0.8$.

We have stated before that it follows from the inequality $\overline{E_n/E_0} \le 0.17 \pm 0.03$ that the generating particle loses on the average $\gtrsim (83 \pm 3)\%$ of its energy in the effective layer. On the other hand, during the generation of YAS there are realized interactions in which $\bar{K} \gtrsim 0.8$ in one act. Consequently, the overwhelming number of YAS are formed as a result of one interaction. For a specified $\bar{K} = 0.8$, the choice of $\bar{K}_{\pi^0}$ determines $\bar{K}_{\pi^\pm}$ and consequently also the value of $\overline{E_{n.a}/E_0}$. As can be seen from Fig. 5, in order to have $\overline{E_{n.a}/E_0} \le 0.50 \pm 0.09$, it is necessary to have $\bar{K}_{\pi^0} \ge 0.6$.

Direct calculations show that if $\bar{K}_{\pi^0} = 0.6$, $W = 0.3$, and $\bar{K}_{\pi^\pm} = 0.3$, then 76% of the YAS are formed as a result of one interaction of the generating particle in a layer $X = 130$ g/cm^2. Actually $W < 0.3$, since $W\bar{K}_{\pi^0} < 0.17$. Therefore the fraction of YAS generated in one interaction will exceed 76%. Consequently, the previously obtained value $\overline{E_{n.a}/E_0} \le 0.33 \pm 0.06$ pertains essentially to one act of interaction, i.e., $\bar{K}_{\pi^0} \ge 0.67 \pm 0.06$. This estimate, of the average fraction of the energy transferred to the π^0 mesons in the interactions responsible for the production of YAS obtained from the average energy flux of the nuclear active component of the YAS, is in good agreement with the estimate of the quantity $\bar{K}_{\pi^0} \ge 0.65$, obtained from an analysis of the characteristics of the electron photon component of the YAS[3].

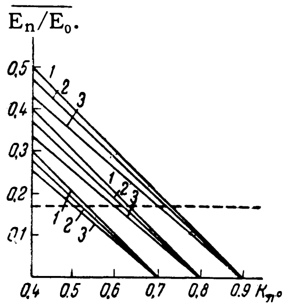

FIG. 4.

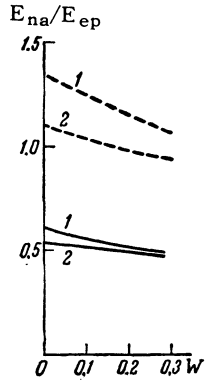

FIG. 5.

FIG. 4. Results of calculation of $\overline{E_n/E_0}$. Lower family of lines—$\bar{K}_{\pi^\pm} = 0.3$; middle family $\bar{K}_{\pi^\pm} = 0.2$; upper family $\bar{K}_{\pi^\pm} = 0.1$. 1—W = 0.01; 2—W = 0.1; 3—W = 0.2. Dashed line—experiment.

FIG. 5. Results of calculation of $\overline{E_{na}/E_{ep}}$. Dashed lines $\bar{K}_{\pi^0} = 0.4$, solid lines $\bar{K}_{\pi^0} = 0.6$. 1—$\bar{K}_{\pi^\pm} = 0.1$; 2—$\bar{K}_{\pi^\pm} = 0.3$.

Role of processes with large energy losses. Let us consider the contribution of the processes responsible for the production of YAS to the total energy lost by the nucleons to the production of π^0 mesons.

The number of YAS with an electron-photon energy component $\ge$ E incident in a vertical direction in a unit solid angle is[3]

$$N_{\text{YAS}}\ (\geqslant E) = (3.6 \pm 0.23) \cdot 10^{-9} (10^{12}/E)^{1.69 \pm 0.08}\ \text{cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}.$$

Consequently the total energy of the electron-photon component of all the YAS with $E \ge 1.7 \times 10^{12}$ eV is

$$\bar{E}_{\text{YAS}} = \int_{1.7 \cdot 10^{12}}^{\infty} N_{\text{YAS}}(E)\, E dE = (6.3 \pm 0.9) \cdot 10^3\ \text{eV} \cdot \text{cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}.$$

This energy is released in an effective layer of air of thickness X.

To determine the contribution made to the total energy losses by the processes responsible for the formation of the YAS, let us compare the quantity $\bar{E}_{\text{YAS}}$ with the total energy $\overline{\Delta E_{\pi^0}}$ transferred to the π^0 mesons by all the nuclear active particles with energy $\ge 1.7 \times 10^{12}$ eV in all the interaction processes in the same effective layer X. If the energy flux of the nucleon component carried by the particles with energy $\geq 1.7 \times 10^{12}$ eV at the observation level is denoted by E_n^0, then $E_n^0 = \int_{1.7\times10^{12}}^{\infty} EN_n(E)\,dE$. The energy flux of the same component incident on the effective layer X will be $\exp(X/L_{abs})$ times larger, i.e., $E_n(X) = E_n^0 \exp(X/L_{abs})$. The difference $E_n(X) - E_n^0$ gives the energy lost by the nucleon component to the production of pions in the layer X. Consequently, the nucleon component transfers in this layer the following energy to the π^0 mesons:

$$(\overline{\Delta E}_{\pi_0})_n = \tfrac{1}{3}\,[E_n(X) - E_n^0] = \tfrac{1}{3}E_n^0\,(e^{X/L_{abs}} - 1). \quad (8)$$

At mountain altitudes, as shown by calculation [5], the pion spectrum in the particle energy region $E \geq 10^{12}$ eV does not differ from the nucleon spectrum, i.e., $N_\pi(E, x)\,dE = bN_n(E, x)\,dE$. Therefore the energy flux of the pions (with $E \geq 1.7 \times 10^{12}$ eV) incident on the effective layer is $\overline{E}_{\pi^\pm} = bE_n(X) = bE_n^0 \exp(X/L_{abs})$. Assuming that the pions transfer to the π^0 mesons, in the mean, $1/3$ of their energy in the interaction with light nuclei, we find that in the layer X they transfer to the π^0 mesons, in all the interactions, an energy

$$(\overline{\Delta E}_{\pi^0})_{abs} = \int_{1.7\cdot10^{12}}^{\infty} dE \int_0^X \frac{1}{3} EN_\pi(E, x)\,\frac{dx}{L_{int}}$$

$$= \frac{1}{3}\int_0^X \frac{dx}{L_{int}} \int_{1.7\cdot10^{12}}^{\infty} EN_\pi(E, x)\,dE = \frac{b}{3}\int_0^X \frac{dx}{L_{int}}\overline{E}_n(x);$$

but

$$\overline{E}_n(x) = E_n^0 e^{X/L_{abs}},$$

i.e.,

$$(\overline{\Delta E}_{\pi^0})_{abs} = \frac{b}{3}E_n^0\,\frac{L_{abs}}{L_{int}}\,[e^{X/L_{abs}} - 1]. \quad (9)$$

Thus

$$\overline{\Delta E}_{\pi^0} = (\overline{\Delta E}_{\pi^0})_n + (\overline{\Delta E}_{\pi^0})_{abs}$$

$$= \frac{E_n^0}{3}\,[e^{X/L_{abs}} - 1]\left[b\,\frac{L_{abs}}{L_{int}} + 1\right]. \quad (10)$$

The energy flux of the nucleon component amounts to the following fraction of the energy flux of the entire nuclear active component $\overline{E_{n.a}^0}$ at the observation level

$$\overline{E_{na}^0} = (1 + b)\,\overline{E_n^0},\ \text{i.e.}\ \overline{E_n^0} = \overline{E_{na}}\,/(1 + b).$$

Inasmuch as the spectrum of the nuclear-active particles at mountain altitudes is of the form [6]

$$N_{na}(\geqslant E) = 1.4\cdot10^{-8}\,(10^{12}/E)^{1.9}\ \text{cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}$$

we get

$$\overline{E_{na}^0} = \int_{1.7\cdot10^{12}}^{\infty} E\,\frac{dN_{na}}{dE}\,dE = 1.8\cdot10^4\ \text{eV}\cdot\text{cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}$$

i.e.,

$$\overline{\Delta E}_{\pi^0} = \frac{1.8\cdot10^4}{3}\,(e^{X/L_{abs}} - 1) \times\left(\frac{\frac{L_{abs}}{L_{int}}b + 1}{1 + b}\right)\text{eV cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1} \quad (11)$$

When $L_{abs} = 120$ g/cm^2, $L_{int} = 85$ g/cm^2, and $X \approx 130$ g/cm^2 we get

$$\overline{\Delta E}_{\pi^0} = 1.2\cdot10^4\left(\frac{1.4b + 1}{1 + b}\right)\text{eV}\cdot\text{cm}^{-2}\text{-sec}^{-1}\text{-sr}^{-1}$$

Calculations show [5], that when $E > 10^{12}$ eV we get $b \approx 0.5-0.3$; assuming $b = 0.5$, we get $\overline{\Delta E}_{\pi^0} = 1.36 \times 10^4$ eV-cm^{-2} sec^{-1} sr^{-1}. Comparing this quantity with $\overline{E}_{YAS} = (6.3 \pm 0.9) \times 10^3$ eV-cm^{-2} sec^{-1} sr^{-1} we see that in the processes responsible for the production of the YAS, approximately 50% of all the energy consumed in the formation of the π^0 mesons in all the interactions is transferred to the π^0 mesons.

If the average energy lost by the nucleons in interactions with the air nuclei is $\overline{K}_n$, then the fraction of the energy lost by the nucleons to the production of π^0 mesons is in the mean $\overline{K}_n/3$. In processes similar to the generation of YAS, the nucleons lose in the mean a fraction $\overline{K}_{\pi^0}$ of their energy to the formation of π^0 mesons, and such interactions have a probability W. Since the contribution of these processes to the total energy lost in the production of π^0 mesons is $\sim 50\%$, we get $\overline{WK_{\pi^0 1}} \cong 0.5 \times (1/3)\,\overline{K}_n = 0.16\,\overline{K}_n$. We have previously found that $\overline{K}_{\pi^0 1} \cong 0.7$. Therefore for $\overline{K}_n = 0.5-0.6$ we have $W \cong 0.11-0.14$. From the frequency of generation of YAS [3] we have obtained $W < 0.25$. Consequently, $0.10 \approx W < 0.25$.

An analysis of the results of the measurements of the nuclear-active component of YAS leads to the same conclusions concerning the characteristics of the interactions responsible for the formation of YAS, which we drew on the basis of the analysis of the electron-photon component of the YAS, namely:

1. Young air showers are generated as a rule in one active interaction between the nuclear-active particle and the air nuclei.

2. Interactions which lead to the formation of YAS differ substantially in their characteristics from the average interactions: the average value of the total inelasticity coefficient for them is

$\bar{K} \geq 0.8$, and the average fraction of the energy transferred to the π^0 mesons is $\geq 0.67 \pm 0.06$.

3. Interactions with almost complete inelasticity ($\bar{K} \approx 1$) and with transfer of $\sim 70\%$ of the primary-particle energy to the π^0 mesons in a single act are realized with a probability $0.10 \leq W < 0.25$. These interactions make an appreciable contribution, approximately 50%, to the total energy lost to the production of π^0 mesons.

4. The bulk of the YAS is not generated as a result of decay of hyperons or known isobars into a π^0 meson and nucleon.

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