SOVIET PHYSICS JETP VOLUME 19, NUMBER 5 NOVEMBER, 1964

A STUDY OF "YOUNG" HIGH-ENERGY ELECTRON-PHOTON AIR SHOWERS

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Submitted to JETP editor July 15, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **46**, 1525-1539 (May, 1964)

Characteristics of the electron-photon component of "young" air showers with energies $E \geq 1.7 \times 10^{12}$ eV are investigated. The energy spectra of showers with various lateral electron-photon energy flux distributions are obtained. The absorption range of nuclear-active particles with energies $E \geq 2 \times 10^{12}$ eV in the lower part of the atmosphere is found to be $L_p = 109 \pm 8$ g/cm². Some possible mechanisms of production of "young" air showers are considered.

A study of the generation of mesons by nuclear-active particles with energy $\sim 10^{12}$ eV[1] has disclosed the occurrence of interactions in which the nuclear-active particles of high energy transfer a great part of their energy to the π^0 mesons. It is not excluded, however, that in these experiments some of the observed cases of large energy transfer to the π^0 mesons correspond to interactions between the particles and heavy nuclei (lead). In addition, the requirement that the registered interaction be produced in the apparatus by a nuclear-active particle which travels without an air accompaniment greatly limited the statistics in the high-energy region. In order to ascertain whether analogous cases of transfer of a large fraction of the energy to the π^0 mesons occur when particles interact with light nuclei, we have attempted to observe and study "young" air showers (YAS), i.e., cases where a high-energy electron-photon component is generated in the atmosphere not far above the array.

1. APPARATUS AND CRITERION FOR SELECTION OF THE INVESTIGATED SHOWERS

The present work was carried out at 3200 meters above sea level at the high-mountain scientific station on Mount Aragats, using the array shown schematically in Fig. 1, the parameters of which were described in detail in the earlier papers[1,2].

The array had a working area of 10 square meters and consisted of 6 rows of ionization chambers 330 cm long and 10 cm in diameter each.

During some of the time, a counter hodoscope was in operation in conjunction with the array. The counters were located from 1 to 10 meters away from the center of the array and made it possible to estimate the number of particles N_s in the air shower accompanying the given event registered by the array if N_s was contained in the range $10^4 < N_s \leq 5 \times 10^5$ particles.

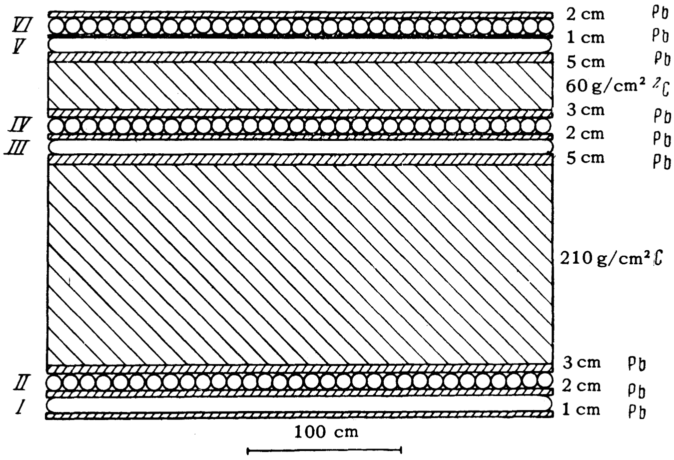

FIG. 1. Schematic arrangement of the array. I – VI are rows of ionization chambers.

The ionization was measured in the chambers only following a triggering signal that initiated the scanning of all the chambers and the registration of the ionization-pulse amplitudes.

To generate the triggering signal it was necessary to produce in the chambers of rows V and VII simultaneously an ionization exceeding (when summed over the row) that produced by 8500 relativistic particles[1)]. The events chosen from among

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[1)] The ionization in a row of chambers will henceforth be expressed in units of ionization produced by one relativistic particle.

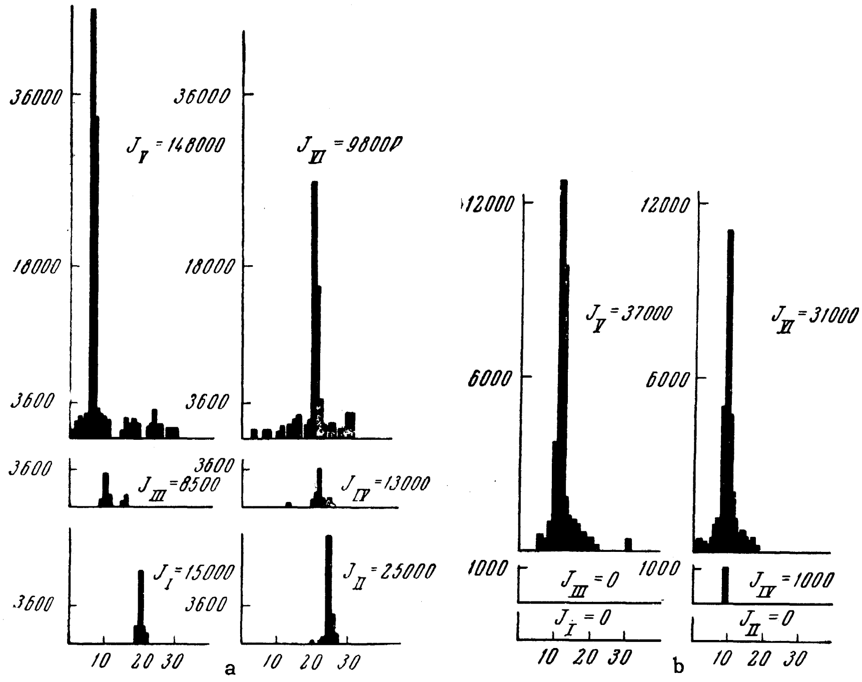

FIG. 2. Examples of the distribution of the ionization over the chambers in the registration of YAS. Abscissas – number of the chamber of the given row, ordinates – value of the ionization in the chamber of the corresponding row; a – m = 2, b – m = 3, $J_I - J_{VI}$ – total value of the ionization in the corresponding rows.

all the cases when the array operated, were those in which the total ionization in the upper row of the chamber, under a lead layer 3 cm thick, was $J_0 \geq 1.2 \times 10^4$, was not less than 60% of the ionization registered by the entire row, and was concentrated in m chambers, with m chosen arbitrarily in the range from 1 to 6. (The characteristics of the selected events as functions of m will be given later.) Examples of the selected cases are shown in Figs. 2a and b. As can be seen from the figure, the selected cases are characterized by a rather narrow lateral distribution of the electron-photon component energy flux.

Altogether 279 showers were registered. Their distribution over m is:

m:	1	2	3	4	5–6
Relative numbers of showers, per cent:	5	18	21	21	35

II. PRINCIPAL CHARACTERISTICS OF THE SHOWERS

1. Absolute Intensity of the Showers

The center or axis of the shower was defined as the place with maximum ionization under a lead layer 2–4 cm thick. The chambers of rows V and VI made it possible to determine the coordinates of the shower axis in two planes, since the axes of the chambers of the two rows were mutually perpendicular. Thus the position of the axis on the array level was located for each shower satisfying the selection conditions. To reduce the error in the determination of the shower energy (and consequently in the particle number discrimination) when the shower axis fell close to the edge of the array, the only showers selected, among those for which not less than 60% of the entire registered ionization was produced in m chambers, were those whose axes were more than (m/2) × 10 cm away from the edges of the array, i.e., the showers fell on an area $S(m) = (3.16-0.1\ m)^2$ square meters. Knowing the number $N(m; \geq J_0)$ of showers with given m falling during the known time of observation on the area S(m), we can determine the absolute frequency $\nu_1(m; \geq J_0)$ of the showers that produce a total ionization $J_0 \geq 1.2 \times 10^4$ under three centimeters of lead (J_0 is given without the correction for the absorption of the particles in the 2-mm brass walls of ionization chambers). The values of $\nu_1(m; \geq J_0)$ are listed in Table I.

We measured the showers at sea level with a similar installation[2]. From the results of the sea-level measurements, with allowance for the greater density of the atmosphere, we determined the absolute intensity of the showers with $J_0 \geq 1.2 \times 10^4$, for values of m which would be equivalent to $m \leq 3$ and $m \leq 6$ at 3200 meter altitude. These values of $\nu_2(m; \geq J_0)$ are also listed in Table I.

As can be seen from this table, on going over

Table I

$\nu\ (m; \geqslant J_0)$, 10^{-10} cm^{-2} sec^{-1}	$m \leqslant 2$	$m \leqslant 3$	$m \leqslant 4$	$m \leqslant 6$
ν_1; $H = 3200$ m	2,6±0.3	4.5±0,4	6.7±0.5	12.3±0.74
ν_2; $H = 0$	—	0,31±0,07	—	0,74±0,12

from sea level to an altitude of 3200 meters the intensity of the selected showers increases by 14—16 times, i.e., it increases with altitude the same way as the intensity of the nuclear component of cosmic rays.

2. Absorption of Electron-photon Component of Showers in Lead

We assume that the selected showers are electron-photon air showers with narrow lateral distribution of particles, bearing the bulk of the shower energy (for arguments in favor of such a treatment see the discussion below).

On striking the lead, these particles should produce characteristic avalanches that develop in accordance with the cascade theory. In order to reconstruct from the experimental data the dependence of the number of particles in the cascade on the thickness of the lead absorber, N(t), we obtained for each shower the ratio of the ionization registered by 7 chambers under the layer of lead of thickness t, where the ionization was the largest, to the total ionization measured by all the chambers of the row under 3 centimeters of lead. The dependence N(t) obtained in this fashion for showers with different m is shown in Fig. 3. As can be seen from this figure, N(t) has the following characteristic features:

a) N(t) increases with increasing t, reaching a maximum at lead-absorber thickness 3—4 cm, after which it decreases rather rapidly.

b) The coefficient of absorption of radiation under large thicknesses of lead (on going from 6 to 8 cm of lead), averaged over all three curves, is $\mu = 0.16 \pm 0.04$ (cascade unit)$^{-1}$.

c) The ratio of the number of particles at the maximum of the cascade to the total area under the curve is ≈ 0.13 for all three groups of showers (for the electron-photon cascade curves this ratio ranges from 0.145 to 0.08 as the primary electron and photon energies vary from 2×10^7 to 10^{12} eV, respectively). Thus, the qualitative and quantitative characteristics of N(t) confirm the assumption that events satisfying the chosen selection criteria are electron-photon showers in which the bulk of the energy of the electron-photon component (not less than 60%) is registered by m chambers ($m \leq 6$).

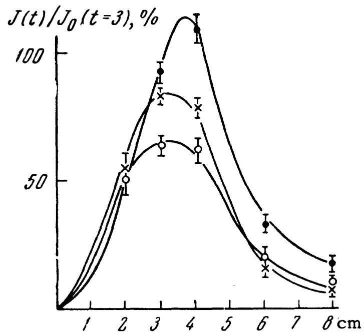

FIG. 3. Translation effect of the electron-photon component of "young" showers in a lead absorber (● – m = 1 – 2; × – m = 3 – 4; o – m = 5 – 6.

Since the maximum development is reached in the selected showers at lead-filter thicknesses 3—4 cm, the total ionization J_0 (t = 3) measured under a layer of lead 3 cm thick is proportional to the total energy $E_{e.p}$ of the electron-photon shower component

$$E_{e.p} = kJ_0(t=3), \text{ where } k = 10^8\,\text{eV}.$$

(For showers with m = 1—2, we introduce for the determination of $E_{e.p}$ a coefficient 1.15 which takes account of the fact that $J_{0\,\max}/J_0\,(t=3) = 1.15$.) Since we restricted the shower selection to $J_0\,(t=3) \geq 1.2 \times 10^4$, it was required, taking account of the corrections for the absorption of the particles in the ionization-chamber wall (a factor 1.4), that the total number of particles under the 3 centimeters of lead be not less than 1.7×10^4, corresponding to $E_{e.p} \geq 1.7 \times 10^{12}$ eV.

3. Energy Spectrum and Shower Air Accompaniment

The ionization measured by the row of chambers under 3 centimeters of lead determines the energy of the electron-photon component, and therefore we can assign to each shower a definite energy $E_{e.p}$ and construct the energy spectrum for showers with different degrees of lateral energy concentration (different m). Table II lists the number of registered showers with energy $E_{e.p}$ larger than the specified value, for different values of m.

If we plot the integral energy spectrum of the showers, we find that it can be expressed in the form $N(\geq E) = AE^{-\gamma}$. The values of γ are listed in the last row of Table II. A characteristic feature of the spectrum of YAS is that in the case of high lateral energy concentration the power expo-

Table II

E, eV	$m \leqslant 3$	$m \leqslant 4$	$m \leqslant 6$
$\geqslant 1.7 \cdot 10^{12}$	122	180	279
$\geqslant 3.4 \cdot 10^{12}$	31	43	87
$\geqslant 5.1 \cdot 10^{12}$	16	22	46
$\geqslant 8.4 \cdot 10^{12}$	6	8	21
$\geqslant 1{,}7 \cdot 10^{13}$	1	2	10
$\geqslant 3{,}4 \cdot 10^{13}$	0	1	4
γ	1.87 ± 0.17	2.00 ± 0.13	$1{,}69 \pm 0{,}08$

nent is close to the exponent of the high-energy nuclear-active particle energy spectrum, 1.92 ± 0.05[4]. With increasing m, i.e., with decreasing degree of lateral concentration of the shower energy, the exponent of the energy spectrum has a tendency to decrease, and at sufficiently large values of m it approaches the value of the exponent of the energy spectrum of extensive air showers (EAS). This shows that there is some arbitrariness in drawing the borderline between EAS and the events selected by us.

The fact that small values of m correspond to events which differ noticeably from EAS is demonstrated by data on the intensity of the shower accompaniment of the selected showers with different parameters m.

In estimating the number N_S of air shower particles we have assumed that the axis of the air shower coincides with the registered shower, and that the particle lateral distribution function has at distances smaller than 10 meters from the shower axis a form which is standard for all showers, $\rho(r) = 1.5 \times 10^{-3} N_S/r$. Under these assumptions, it was found from the data of the hodoscopic counters that $N_S < 10^4$ in 50% of the registered cases of YAS with m = 1, in 37% of the cases with m = 2, in 30% for m = 3—4 and in 15% for m = 5—6.

Thus, the larger m (the broader the lateral distribution of the electron-photon component energy fluxes), the larger, in the mean, is the air shower accompanying the given shower (for a fixed value of E), i.e., the larger apparently the average "age" of the registered showers.

4. Lateral Distribution of Electron-photon Component Energy Flux; Shower "Age"

In order to obtain information concerning the lateral distribution of the energy flux of the electron-photon component of the selected showers, we have proceeded in the following fashion. Selecting showers with given m, we took as 100% the total ionization registered by all the chambers of the row under 3 centimeters of lead. We next determined the fraction of the ionization registered only by the central ("axial") chamber. We then added to the central chamber two neighboring chambers (left and right), four neighboring chambers, etc., and averaged the results over all the showers with given m. We thus obtained the fraction of the energy of the air shower contained in a band of width 10, 30, 50, 70, and 90 cm, relative to the total ionization registered over an area of 10 square meters.

The result of this experimental-data reduction is shown in Fig. 4 for different showers (m = 1—2, m = 3—4, and m = 5—6).

In order to go over from this "one-dimensional" distribution of the ionization to a lateral distribution of the energy flux, we have assumed that the density of the energy flux $\rho_E(r)$ can be approximated by a function of the type $\rho_E = A/r^n$ with $r_0 < r < 2$ meters and $\rho_E = \text{const}$ for $r < r_0$. We assumed $r_0 = 5$ cm because the chamber diameter was 10 cm. We further calculated for different values of n the distribution of the ionization over the chambers 330 cm long and 10 cm in diameter, under the assumption that the shower axis falls at the center of the array.

The curves of Fig. 4 represent the result of such a calculation.

As follows from Fig. 4, all the showers can be well described by a function of the type $\rho_E(r) = A/r^n$ with n = 3.0 for m = 1—2, n = 2.3 for m = 3—4 and n = 1.8 for m = 5—6.

In this connection we note that for EAS at the same distances from the shower axis, the exponent n has a value ~ 1.2[3]. Thus, the experimental data on the lateral distribution of the energy fluxes of the electron-photon component in the showers selected by us indicate that they are sufficiently young air showers. Since we require in accordance with the shower selection method that not less than 60% of the ionization be contained in m chambers, we can readily determine from the known value of $\rho_E(r)$ the radius of the circle R within which 60% of the energy striking a square array of 10 square meter area is contained. We have R = 10 cm for m = 1, R ≅ 30 cm for m = 3, and R ≅ 7 cm for m = 5—6; i.e., R ≅ 10m cm.

III. DISCUSSION

1. Imitation of Air Showers by Generation of an Electron-photon Component in the Array

Particle interaction in a layer of lead over chamber row IV, accompanied by an energy transfer $E \geq 1.7 \times 10^{12}$ eV to the electron-photon component, can imitate an event classified as a YAS in accordance with the selection criteria. Such interactions can be caused, in principle, by: a) high-energy muons and b) nuclear-active particles.

The very fact that the frequency of the YAS increases by a factor 14—16 from sea level to mountain altitude indicates that muons do not play a major role.

In our array, in a lead layer 3 cm thick, the

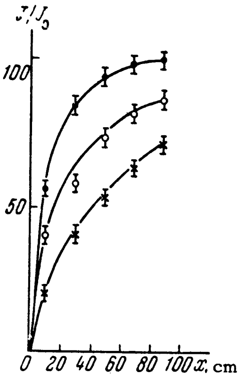

FIG. 4. Lateral distribution of energy fluxes in "young" showers: ■ – m = 1 – 2; ○ – m = 3 – 4; × – m = 5 – 6.

muons generate ionization bursts with $J_0 \geq 1.2 \times 10^4$ at a frequency 3.6×10^{-4} m^{-2} hr^{-1} = 1.0×10^{-11} cm^{-2} sec^{-1}[1]. The intensity of YAS with $J_0 \geq 1.2$ and 10^4 and $m \leq 6$ is 1.2×10^{-9} cm^{-2} sec^{-1}. Consequently, at mountain altitudes the contribution of the muons to the registered YAS does not exceed ≈ 0.01. Since the intensity of the high-energy muons does not vary from mountain altitudes to sea level, the muons will imitate at sea level YAS with a frequency 1.0×10^{-11} cm^{-2} sec^{-1}. However, the intensity of a YAS at sea level is 0.74×10^{-10} cm^{-2} sec^{-1}, i.e., at sea level the contribution of the muons to the generation of events which imitate YAS amounts to $(1.0 \pm 0.4) \times 10^{-11}/(7.4 \pm 1.2) \times 10^{-11} = 0.14 \pm 0.06$.

In order to estimate the imitation of YAS by nuclear-active particles, we have calculated the expected frequency of bursts of magnitude $J_0 \geq 1.2 \times 10^4$, generated by these particles under a lead filter 3 cm thick. In the calculation it was assumed that the average fraction of the energy transferred to the π^0 mesons in the interaction with the lead nucleus is $\bar{K}_{\pi^0} = 1/3$ and can vary from case to case (in this case $\overline{K^{1.9}} = 0.3$), and the effective energy of the γ quanta is $\bar{\epsilon}_\gamma = 8 \times 10^{10}$ eV. The energy spectrum of the nuclear-active particles was taken from our earlier work[1].

The calculation presented has shown that under the assumptions made the number of bursts with $J \geq 1.2 \times 10^4$ due to the interaction of the nuclear active particles in the lead filter of thickness 3 cm, will be

$$N(\geqslant 1{,}7\cdot 10^4) = 2{,}1\cdot 10^{-11}\ \text{cm}^{-2}\text{sec}^{-1}.$$

Since the intensity of the registered YAS (with $m \leq 6$) is $(123 \pm 7.4) \times 10^{-11}$ cm^{-2} sec^{-1}, the nuclear interactions in the lead filter of thickness 3 cm will imitate not more than 2% of the observed YAS with $m \leq 6$ and not more than 8% of YAS with $m \leq 2$.

Consequently, the events selected in accordance with the criterion indicated above are air showers with a large lateral concentration of the electron-photon component.

It is well known that the degree of lateral concentration of the energy flux in a cascade shower is determined by its "age"—the parameter S. Since we know the function of the lateral distribution of the energy flux in the YAS, we can, by using the calculations of [5], obtain the limiting thickness of the layer of the atmosphere t (in cascade units), within which a shower generated by γ quanta with energy ϵ will diverge to such a degree, that 60% of the energy incident on an area of 10 m^2 will be contained in a circle of radius R. Knowing t, we can easily determine the age parameter S. The results of these calculations are listed in Table III.

In the last column of the table is given the thickness of the layers of the atmosphere t_{max} (in cascade units), in which a shower initiated by γ quanta with energy ϵ reaches the maximum of its development.

Table III shows that the satisfaction of the requirement $m \leq 6$ actually leads to a selection of showers which are initiated in a layer $t \ll t_{max}$ with small value of the age parameter S.

The values of t and S indicated in Table III have been obtained under the assumption that the π^0-meson scattering angle in the elementary act is zero. An allowance for the finite scattering angle $\theta = cp_\perp/E_\pi$ will lead to a decrease in t, and consequently also in S (for a given energy ϵ).

Table III

ε, eV	$m = 1$		$m = 3$		$m = 5\div6$		t_{max}
	t	S	t	S	t	S	
$3\cdot10^{10}$	—	—	—	—	∼0,8	<0,4	—
10^{11}	<0.5	<0.27	1.1	—	1.8	0.45	7.1
$3\cdot10^{11}$	1.0	0.27	2.0	0.41	2.8	0.50	8.2
10^{12}	2,1	0,39	3.0	0,49	3.8	0.57	9.4
$3\cdot10^{12}$	3.0	0.45	4.0	0.51	4.6	0.6	10.5

2. Mechanism of YAS Generation

The altitude dependence of the intensity of YAS indicates that they are generated in the atmosphere by nuclear-active particles of high energy. The most natural assumption is that the formation of the YAS is based on typical interactions characterized by an average inelasticity coefficient $\bar{K}$, with the share of energy transferred to the π^0 mesons being $\bar{K}_{\pi 0} = \bar{K}/3$.

Since we are including among the YAS also showers in which more than 60% of the energy lies in a circle of radius $R \leq 70$ cm, this requirement imposes definite and rather stringent limitations on the dimensions of the layer of the atmosphere within which the interaction can ensure the observed energy concentration.

In fact, it is well known that the average value of the perpendicular component of the momentum of a particle generated in an elementary interaction act does not depend on its angle of emission or on the energy of the primary particle E_0. For simplicity in calculation we shall assume that $p_\perp = \text{const} = 3 \times 10^8$ eV/c. Then the particles generated with energy E, $E + dE$ at an altitude h above the array will strike the array within a radius r, $r + dr$, where $r = \theta h = cp_\perp h/E$, and $dr = cp_\perp vE/E^2$. If the spectrum of the generated particle is $n(E, E_0)dE$, then the energy in a circle of radius R will be

$$\int_{E(r)}^{E_0} En(E; E_0)\, dE = \int_{cp_\perp h/R}^{E_0} En(E; E_0)\, dE.$$

In order to be able to identify this interaction as a YAS, it is necessary that this circle contain not less than 60% of the entire energy. This imposes a definite requirement on the maximum height h_{max}

$$\int_{cp_\perp h_{max}/R}^{E_0} En(E; E_0)\, dE = 0{,}6 \int_0^{E_0} En(E; E_0)\, dE$$
$$= 0.6\, \bar{K}_{\pi^0} E_0. \tag{1}$$

The value of R is specified by the selection criterion. It is approximately equal to $R = 10m$ cm. Therefore for each E_0 we obtain from (1) the value of $x_{max} = \rho h_{max}$ — the thickness of the layer of atmosphere over the array, within which the particles with energy E_0 can generate a young shower satisfying the requirement that not less than 60% of its energy fall on m ionization chambers.

If at the observation level the intensity of the nuclear-active particles is $N(E_0)dE_0 = BdE_0 E_0^{-\gamma}$, then the flux of nuclear active particles on the layer x_{max} will be $E_0^{-\gamma} BdE_0 \exp(x_{max}/L_{abs})$, where L_{abs} is the absorption range of the nuclear-active particles. In a layer x_{max} there will interact a fraction of these particles, equal to $1 - \exp(-x_{max}/L_{int})$. We shall thus observe a number of "young" showers with an electron-photon component energy $E_{e.p}$, $E_{e.p} + dE_{e.p}$ equal to

$$N_{\mathrm{YAS}}(E_{\mathrm{e.p}})\, dE_{\mathrm{e.p}}$$
$$= \frac{BdE_{\mathrm{e.p}}}{E^{\gamma}_{\mathrm{e.p}}} \overline{K^{\gamma-1}_{\pi^0}}\, e^{x_{max}/L_{\mathrm{abs}}} (1 - e^{-x_{max}/L_{\mathrm{int}}}). \tag{2}$$

Let the effective energy of the γ quanta be E_γ and let their multiplicity be $\bar{n}$, i.e., $E_\gamma = E_{e.p}/\bar{n}$. The layer thickness x_{max} is determined, generally speaking, by two processes: the scattering of the neutral pions in the elementary interaction act, and multiple scattering of the cascade-shower particles. The first process yields for the γ quanta with energy E_γ:

$$x'_{max} = \frac{\rho R E_\gamma}{cp_\perp} = \frac{6{,}3 \cdot 10^{-2} E_\gamma}{cp_\perp} \text{ g/cm}^2$$

For γ quanta $cp_\perp \cong 2 \times 10^8$ eV, i.e.,

$$x'_{max} = 0.31 \cdot E_\gamma = 0{,}31\, E_{\mathrm{e.p}} / \bar{n} \text{ g/cm}^2, \tag{3}$$

(we shall henceforth express $E_{e.p}$ in GeV).

The second process yields[5]

$$x''_{max} = 37 \ln\left(\frac{E_\gamma}{11}\right) \text{g/cm}^2 = 37 \ln\left(\frac{E_{\mathrm{e.p}}}{11\bar{n}}\right). \tag{4}$$

The effective layer of the atmosphere within which the interactions that produce the "young" showers take place is determined by the smallest of the two values, x'_{max} or x''_{max}. During the "pionization" process we have

$$\bar{E}_\gamma = \frac{E_{\mathrm{e.p}}}{2\bar{n}_0} = \frac{E_{\mathrm{e.p}}}{\bar{n}_{\pi\pm}}, \quad \bar{n}_{\pi\pm} = 3E_0^{1/4}, \quad E_{\mathrm{e.p.}} = K_{\pi^0} E_0,$$

i.e.,

$$E_0 = E_{\mathrm{e.p}}/K_{\pi^0} \text{ and } \bar{E}_\gamma = E^{3/4}_{\mathrm{e.p}} K_{\pi_0}/3.$$

When $\bar{K}_{\pi 0} = 0.1$ we have $(\bar{K}_{\pi 0})^{1/4} = 0.56$, and when $\bar{K}_{\pi 0} = 0.17$ we have $(\bar{K}_{\pi 0})^{1/4} = 0.65$; therefore

$$\bar{E}_\gamma \cong \frac{0.6}{3} E^{3/4}_{\mathrm{e.p}} = 0.2\, E^{3/4}_{\mathrm{e.p}}.$$

Substituting this value into the expressions for x'_{max} and x''_{max}, we find that $x'_{max} = x''_{max}$ when $E \cong 2.8 \times 10^{13}$ eV. Thus, when $E_{e.p} \ll 3 \times 10^{13}$ eV, the effective layer is determined by the quantity $x_{max} = 6.4 \times 10^{-2} E^{3/4}_{e.p}$ g/cm². When $E_{e.p} \gg 3 \times 10^{13}$ eV, the effective layer will be determined by the multiple scattering, i.e.,

$$x_{max} = 37 \ln (E_{\text{e.p}}^{3/4}/55).$$

If we confine ourselves to young-shower energies $E_{\text{e.p}} \leq 1 \times 10^{13}$ eV, then when such showers are generated by interactions with average characteristics, the thickness of the effective layer for the YAS with $m \leq 6$ will be $6.4 \times 10^{-2}\ E_{\text{e.p}}$ g/cm², while for $m \leq 3$ it will be half as large. Using (2), we can readily verify that in both cases the differential spectrum of the YAS will have the form

$$N_{\text{YAS}} (E)\, dE = \frac{B\overline{K_{\pi^0}^{\gamma-1}}\, a(m)\, dE}{10^3} \left(\frac{10^3}{E}\right)^{2.1}, \qquad (5)$$

where $a(m \leq 6) = 9.1 \times 10^{-2}$ and $a(m \leq 3) = 4.6 \times 10^{-2}$. Figure 5 shows the differential spectrum of YAS for $m \leq 6$. The experimental value of the spectral exponent is $\gamma = 2.8^{+0.4}_{-0.2}$. The absolute value of the number of YAS in the energy region $1.7 \times 10^3 \leq E \leq 1.5 \times 10^4$ GeV is obtained by integrating (5):

$$N_{\text{YAS}} (1.7 \cdot 10^3 - 1 \cdot 10^4 \text{ GeV}, m)$$
$$= 0{,}9 \cdot 10^{-9}\, a(m)\, \overline{K_{\pi^0}^{1.9}} \text{ cm}^{-2} \text{ sec}^{-1}.$$

If we assume that in interactions described by average characteristics $K_{\pi^0} = K/3$, where K is the total inelasticity coefficient, then, taking from [6,7] the distribution function over the inelasticity coefficients K, we get $\overline{K_{\pi^0}^{1.9}} = 2.7 \times 10^{-2}$ and

$$N_{\text{YAS}} (1.7 \cdot 10^3 - 10^4 \text{ GeV}; m \leqslant 6) = 2.2 \cdot 10^{-11} \text{ cm}^{-2} \text{ sec}^{-1},$$
$$N_{\text{YAS}} (1.7 \cdot 10^3 - 10^4 \text{ GeV}; m \leqslant 3)$$
$$= 1.1 \cdot 10^{-11} \text{ cm}^{-2} \text{ sec}^{-1}. \qquad (6)$$

Experiment yields for the same energy interval with $m \leq 6$ a value $N_{\text{YAS}} = (1.2 \pm 0.07) \times 10^{-9}$ cm^{-2} sec^{-1}, and for $m \leq 3$ we get $N_{\text{YAS}} = (4.5 \pm 0.4) \times 10^{-10}$ cm^{-2} sec^{-1}. Thus, interactions with average characteristics and with average inelasticity coefficient $\overline{K} = 0.33$ ($\overline{K}_{\pi^0} = 0.11$) can yield only ~ 2% of the observed YAS. On the other hand, if we assume that $\overline{K}_{\pi^0} = 0.17$ ($\overline{K} = 0.5$), then the number of YAS generated in interactions with average characteristics increases ~ 5% of the number of observed YAS. From the foregoing estimates we see that the interactions with average characteristics [inelasticity coefficient $\overline{K} = 1/3 - 1/2$, the π^0 mesons receive 1/3 of the total energy lost by the nucleon during the interaction, the pions are generated with average energy $(0.02 - 0.03)\, E_0$] are in sharp disagreement with the experimental data—both the absolute intensity of the observed YAS and their energy-spectrum exponent.

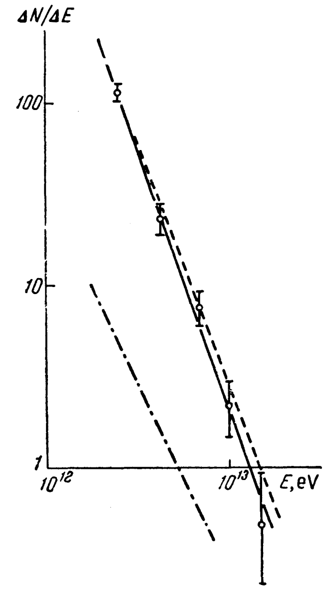

FIG. 5. Differential spectrum of "young" showers with $m \lesssim 6$. Continuous line – experiment, dashed – calculation assuming low effective multiplicity of π^0 mesons, dash-dot – calculation with average characteristics. Frequency of the showers is given in relative units.

If we take further account of the fact that part of the nuclear-active particles with $E \geq 2 \times 10^{12}$ eV is contained in the EAS and can therefore not be a source for the production of YAS, then the total flux of nuclear-active particles capable of generating YAS should be decreased, and the estimates made serve as an upper limit for the number of the YAS generated as a result of interactions with average characteristics.

Consequently, the YAS are produced in interactions which differ greatly from average, typical interactions.

What features should such interactions possess?

First, the average energy of the γ quanta generated in these interactions should be appreciably larger than in typical interactions, so that the thickness of the effective layer be determined not by the angle of scattering of the π^0 mesons during their generation, but by the Coulomb scattering of the particles in the developing electromagnetic cascade, i.e., the effective energy E_γ of the γ quanta should be such that $x''_{\text{max}} < x'_{\text{max}}$. From this condition (for YAS with $m \leq 6$) we find that $37 \ln (E_\gamma/11) < 0.32\, E_\gamma$. Hence $E_\gamma > 4 \times 10^{11}$ eV. Since this condition should be satisfied also for YAS with $E_{\text{e.p}} = 1.7 \times 10^{12}$ eV, the effective multiplicity of the generated π^0 mesons should be of the order of $\bar{n}_{\pi^0} = 2 \times 10^{12}/2E_\gamma = 2.5$.

It is natural to assume that with increasing energy of the YAS the effective multiplicity of the γ quanta producing the shower also increases. Let us assume that $\bar{n}_\gamma = b\,(E_{e.p}/10^{12})^{1/4}$. When $E_{e.p} = 2 \times 10^{12}$ we have $\bar{n}_\gamma = 5$, i.e., $b = 4$. Then $x_{max} = 37 \ln (E_\gamma/1.1 \times 10^{10}) = 37 \ln (22.5\, E^{3/4}_{e.p})$, if we express the energy henceforth in units of 10^{12} eV. Since the small effective multiplicity (i.e., the high energy of the individual π^0 mesons) is not realized in each interaction act, we should assume that the interactions responsible for the generation of the YAS occur with a certain probability W, and in them the average fraction of the energy transferred to the π^0 mesons is equal to $K_{\pi 0}$. Assuming that $L_{abs} = 120$ g/cm^2, $L_{int} = 80$ g/cm^2, and $\gamma = 2.9$ we get from (2)

$$N_{\text{YAS}}\,(E_{e.p}\,;\, m \leqslant 6)\, dE_{e.p} = \frac{2{,}6 \cdot BW\overline{K^{1{,}9}_{\pi^0}}\, dE_{e.p}}{E^{2.9-0{,}23}_{e.p}} \left[1 - \frac{0{,}24}{E^{0{,}35}}\right]. \tag{7}$$

We see from (7) that the proposed process gives a YAS spectrum with an exponent $2.9 - 0.23 = 2.67$, which agrees well with the experimental data (see Fig. 5).

The total number of YAS with $E_{e.p} \geq 1.7 \times 10^{12}$ eV is obtained by integrating (7):

$$N_{\text{YAS}}\,(E_{e.p.} \geqslant 1.7 \cdot 10^{12};\ m \leqslant 6) = 0{,}55 BW\overline{K^{1{,}9}_{\pi^0}} = 1{.}1 \cdot 10^{-8}\, W\overline{K^{1{,}9}_{\pi^0}}.$$

The experimental value of $N_{YAS}(E_{e.p} \geq 1.7 \times 10^{12}$ eV; $m \leq 6) = (1.23 \pm 0.07) \times 10^{-9}$, and therefore $W\overline{K^{1.9}_{\pi 0}} = 0.11$. On the other hand, if the generation of the π^0 mesons were to proceed only by this hypothetical process, then $W\overline{K}_{\pi 0} \leq 0.17$ (since the average inelasticity coefficient for the nucleons is $\bar{K} \approx 0.5$). Therefore $(W)^{0.9} = 0.39$, i.e., $W \leq 0.28$. Hence $K_{\pi 0} \geq 0.60$.

These estimates show that the dominating interactions in the generation of YAS are apparently those in which the π^0 mesons receive in one act a fraction of energy which is several times larger than the fraction they receive in the mean. Such interactions should be realized with relatively low probability and be characterized by a large concentration of the energy over a relatively small number of π^0 mesons.

Akashi et al.[8] investigated with the aid of a large emulsion chamber placed at 2,720 meters above sea level air showers containing γ quanta and electrons with energy $\geq 10^{11}$ eV. The authors could separate the air showers generated near the array and determine their generation height. They found that at a total shower energy from $\approx 2 \times 10^{12}$ to 10^{13} eV, only 30% of the showers were generated at a distance from 1,000 to 2,000 meters. The remaining 70% of the showers were generated at distances $h < 1{,}000$ meters, i.e., $t < 2$ cascade units. These young showers were observed with frequency 1.8×10^{-10} cm^{-2} sec^{-1} at a total shower energy $\geq 1.7 \times 10^{12}$ eV. If we recognize that in a layer of atmosphere ~ 2 cascade units a considerable fraction of the total energy of the shower has time to go over into particles with $E < 10^{11}$ eV, which cannot be detected by the array, it becomes clear that the YAS frequency observed by the authors at 2,720 meters is compatible with our experimental data obtained at 3200 meters (for a complete agreement between the frequencies of the observed YAS it is necessary to assume that approximately 50% of the energy of the YAS which we registered is concentrated in particles with $E < 10^{11}$ eV). It follows from [8] that in YAS there is actually a rather high concentration of energy over a small number of γ quanta (electrons) — 47% of the entire energy of the YAS is carried by one particle.

3. Absorption Range of Nuclear-active Particles with Energy $\geq 2 \times 10^{12}$ eV

Regardless of the specific mechanism of YAS generation, we can state that they are generated in a limited layer of the atmosphere above the array. Furthermore, the thickness of the effective layer, in which they are generated, is determined by the energy of the registered YAS and by the condition for their registration (the number of chambers m on which the specified fraction of the YAS energy falls). For fixed values of $E_{e.p}$ and m, the variation of the frequency of the registered YAS with the depth of the atmosphere will be determined only by the absorption range L_{abs} of the nuclear-active component. Our calculations[9] have shown that within the atmosphere the absorption range of the nuclear-active component is determined only by the absorption of the nucleon component, in spite of the fact that the fraction of the $\pi^\pm$ mesons in the depth of the atmosphere, among particles with energy $\geq 10^{12}$ eV, can reach 40% and more of the nucleon flux. It therefore seems to us that a determination of the range L_{abs} of the nucleon component from the altitude variation of the YAS is more reliable than a determination of this quantity from the altitude variation of large ionization bursts between sea level and mountain altitudes (for in this case it is necessary to account for the fact that part of the burst is produced by muons) or else from the altitude dependence of the ionization burst between mountain levels and the stratosphere (for in the latter case the admixture of pions in the flux of the nuclear-active particles of high energy can increase appreciably, by not less than 15%, the true value of the nucleon absorption range[9]).

If the density of the atmosphere on going from sea level to mountain altitudes were to remain constant, then to determine the absorption range of the nucleon component L_{abs} it would be necessary to introduce a correction only for the different angular distributions of the showers at different observation levels, which can be written in the form

$$N_{YAS}(\geqslant E;\, x;\, \theta)\, d\omega = N_{YAS}(\geqslant E;\, x;\, 0) \cos^n \theta\, d\omega,$$

$$n = x/L_{abs}.$$

Taking account of the geometry of the array, the total number of YAS registered at a given depth x will be

$$N_{YAS}(E;\, x;\, m) = \frac{2\pi}{n+2} N^0_{YAS}(E;\, x;\, m) = \frac{A(E)}{n+2} e^{-x/L_{abs}}, \tag{8}$$

where $N^0_{YAS}(E;\, x, m)$ is the number of YAS with energy $\geq E$ at a depth x, incident on the array in a vertical direction per unit solid angle. Replacing m by x/L_{abs}, we get

$$\frac{N_{YAS}(E;\, x_1;\, m)}{N_{YAS}(E;\, x_2;\, m)} = \frac{x_2/L_{abs}+2}{x_1/L_{abs}+2} e^{-(x_1-x_2)/L_{abs}}. \tag{9}$$

Actually, however, at sea level (x_1 = 1,000 g/cm^2) and at mountain altitudes (x_2 = 700 g/cm^2) the air densities differ by a factor 1.43. Therefore as indicated already above, in order to make the measurements at both altitudes identical, it is necessary to stipulate that at equal YAS energy an identical fraction of ionization in the upper rows of the chambers be contained in m chambers at sea level and in 1.43m chambers at an altitude 3200 meters, under the condition that the linear dimensions of the arrays at these altitudes also differ by a factor 1.43. Therefore, in order to determine the altitude variation of the YAS we have selected showers in which more than 60% of the ionization in the chambers under 3 cm of lead is contained in 4 chambers at sea level and in 6 chambers at an altitude of 3200 meters above sea level. However, even under these conditions total identity of the arrays will still not be attained or identity in the selection system at different altitudes.

For an equal lateral distribution function of the energy flux for a shower of given energy and of given age, identical YAS energies will be incident on an array area S at sea level and an area $(1.43)^2$S at mountain altitudes. Our measurements were carried out with an array having the same area S = 10 sq. m. at both altitudes. Therefore at mountain altitudes for some YAS (with not too steeply decreasing lateral distribution function of the energy flux density) part of the energy of the electron-photon component of the shower was not measured, and consequently, the number of YAS with given energy E was underestimated. Consequently, it is necessary to introduce a correction for the measured number of showers, the magnitude of the correction depending on the lateral distribution function of the energy flux density, i.e., on m.

For showers with m = 5–6, the density of the energy flux as a function of the distance can be represented in the form $\rho_E(r) = C_1/r^{1.8}$ (see Fig. 4). For $\rho_E(r)$ in this form, an increase in the array dimensions by a factor 1.43 would lead to an increase of 9% in the energy incident on the array, i.e., taking into account the spectrum of showers with m = 5–6, this would lead to an increase in the number of the registered YAS by 11%. For showers with m = 3–4, $\rho_E(r) = C_2/r^{2.3}$ the correction is $\Delta E = 0.04\,E$, which yields $\Delta N_{YAS}/N_{YAS} = 7.5\%$. For showers with m = 1–2, $\rho_E = C_3/r^{3.0}$, $\Delta E < 0.01\,E$, and $\Delta N_{YAS}/N_{YAS} < 1.9\%$.

Showers with m = 5–6 constitute about 40% of all the registered YAS; showers with m = 3–4 —approximately 40%, and showers with m = 1–2 —approximately 20% of all the YAS. Therefore the correction for the total number of YAS with m ≤ 6, which would be registered at mountain altitudes if the dimensions of array were to be 1.43 times larger, amounts to 7.4%. The experimentally determined frequency of YAS with m ≤ 6 at an altitude of 3200 meters above sea level is $(12.3 \pm 0.74) \times 10^{-10}\,\text{cm}^{-2}\,\text{sec}^{-1}$; with a correction of 7.4% it will be equal to $(13.2 \pm 0.8) \times 10^{-10}\,\text{cm}^{-2}\,\text{sec}^{-1}$. The frequency of YAS measured under equivalent conditions at sea level is $(0.74 \pm 0.12) \times 10^{-10}\,\text{cm}^{-2}\,\text{sec}^{-1}$.

The muons produced under a layer of lead of 3 cm at sea level $(1.0 \pm 0.4) \times 10^{-11}\,\text{cm}^{-2}\,\text{sec}^{-1}$ bursts with $E \geq 1.7 \times 10^{12}$ eV, which imitate YAS. With this correction, the true number of YAS at sea level is

$$N_{YAS}(E \geqslant 1.7 \cdot 10^{12}\ \text{eV};\ m \leqslant 6)$$

$$= (6.4 \pm 1.2) \cdot 10^{-11}\ \text{cm}^{-2}\,\text{sec}^{-1}.$$

Taking into account the foregoing corrections we get, using expression (9),

$$L_{abs} = 109 \pm 8\ \text{g/cm}^2.$$

Thus, the absorption range in the atmosphere, for nucleons with energy $E > 2 \times 10^{12}$ eV, is 109 ± 8 g/cm^2

If the interaction range L_{int} for the nucleons in the atmosphere is 80 g/cm^2, then the value of L_{abs} = 109 g/cm^2 corresponds to an average inelasticity coefficient $\bar{K} = 0.5$. If L_{int} = 90 g/cm^2, then $\bar{K} = 0.6$.

CONCLUSIONS

1. Young air showers at altitudes of 3200 meters above sea level have an energy distribution of the form

$$N(\geqslant E) = A(10^{12}/E)^{\gamma},$$

where

$$A = (3.0 \pm 0.2)\cdot 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}; \quad \gamma = 1.69 \pm 0.08$$

for showers in which more than 60% of the energy is concentrated in a circle of radius 70 cm, and

$$A = (1.20 \pm 0.11)\cdot 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}; \quad \gamma = 1.87 \pm 0.17$$

for showers in which more than 60% of the energy is concentrated in a circle of 30 cm radius.

2. The form of the spectrum and the absolute intensity do not agree with the assumption that YAS are formed in interactions of nuclear-active particles of high energy with nuclei of air atoms, which are typical of ''pionization'' processes (large multiplicity of the produced pions, 0.1—0.2 of the energy transferred to the π^0 mesons).

3. The energy spectrum and the absolute intensity of YAS can be explained by assuming that they are generated in interactions in which the electron-photon component receives in one act 60—70% of the energy of the generating particle, and the effective multiplicity of the γ quanta carrying away this energy (if π^0 mesons are generated) is small, on the order of 4—8 for showers with energy 2×10^{12}—2×10^{13} eV. The probability of such interactions is less than 0.25.

4. The absorption range of the nucleon component with energy $E > 1.7 \times 10^{12}$ eV has been found to be $L_{abs} = 109 \pm 8$ g/cm^2. Such a value of L_{abs} corresponds to an average inelasticity coefficient $\bar{K} = 0.5$, if the range for the interaction is L_{int} = 80 g/cm^2 and $\bar{K} = 0.6$ if L_{int} = 90 g/cm^2.

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Translated by J. G. Adashko
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