FORMATION OF HIGH ENERGY GAMMA QUANTA IN EXTENSIVE AIR SHOWERS WITH ENERGIES $10^{14}-10^{15}$ eV *IN THE UPPER THIRD OF THE ATMOSPHERE*

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Experimental data on the energy spectra of γ quanta in extensive air showers containing 10^5-10^6 particles are obtained for $10^{12}-10^{13}$ eV quanta at depths of 311 and 197 g/cm^2 in the atmosphere. The multiplicity of pion production in interactions involving particles with energies $\sim 10^{15}$ eV calculated from these data appreciably exceeds that predicted by the Landau theory. The degree of energy dissipation approaches the limiting value of energy division consistent with Heisenberg's theory.

INVESTIGATION of the production of the electron-photon high-energy component in extensive air showers (EAS) that are in their initial stage of development is of particular interest, since experiment can then yield directly data on the generation of pions in ultra high energy interactions. It is known [1] that in the lower third of the atmosphere the average number of nuclear-active particles with energy $> 10^{12}$ eV per shower with $N \sim 10^5$ particles is less than unity, while the energy of the gamma quanta contained in the EAS does not exceed $\sim 10^{10}$ eV [2]. The presence of fluctuations in the development of the showers does not enable us to trace in the lower third of the atmosphere the energy degradation of the particles which carry the bulk of the shower energy. We consequently have at present only very indirect data on the spectra of pion production in interactions at energy $> 10^{14}$ eV.

We chose an experimental procedure based on registering those electron-photon cascades in EAS which are caused by gamma quanta produced in the layer of atmosphere over the apparatus. The experiments were made at pressures 197 and 311 g/cm^2. Electron-photon cascades with energy above 7×10^{11} eV were registered. At the same time, the size of the EAS was determined by registering the particle density in the shower at several points.

Calculations made by Baradzeĭ et al.[3] show that at gamma quantum energies exceeding 10^{12} eV the dissipation of the energy in a shower passing through a layer of 200—300 g/cm^2 is small, and an instrument with area ~ 1 m^2 will register a larger fraction of the gamma quantum energy, even if the gamma quantum was generated at the top of the atmosphere. At pion perpendicular momenta $\sim 5 \times 10^8$ eV/c we can expect cascades from different gamma quanta to be registered by the array separately. Experiments made under low atmospheric density conditions greatly facilitate separate registration of the cascades.

Thus, registration of electron-photon cascades in EAS enables us to determine the integral number of high-energy gamma quanta generated in the layer of the atmosphere over the instrument in interactions that initiate the shower. Assuming that the main fraction of the gamma quanta is produced as a result of π^0 meson decay, we can obtain data on the pion generation.

We have registered the particle density in the EAS with the hodoscopic array previously described.[4]

Gas discharge counters of 30 mm diameter and 300 mm long were placed in three hodoscopic points lying on one straight line. In the central point there were 80 counters, and at two peripheral points 7 and 12 m away from the center there were 20 counters each. In order to be able to estimate the zenith angles of shower incidence, half of the counters of the central point was installed vertically [4]

We used an array of ionization chambers [3] to register electron photon cascades in the EAS. Fifteen cylindrical ionization chambers 90 cm long and 10 cm in diameter were arranged in one row in contact with each other. A 3.5 cm layer of lead placed over the chambers ensured registration of the number of particles with energy $10^{11}-10^{13}$ eV in the cascade near the maximum of cascade development. It was assumed that the energy of the electron-photon components striking the

Table I.
Distribution by number of cascades striking the ionization chambers

Depth, g/cm²	Electron-photon cascade energy, eV	Number of electron-photon cascades in one event						Average number of electron photon cascades
		1	2	3	4	5	>5	
For events connected with EAS								
311	$\geqslant 7.5\cdot10^{11}$	178	38	9	1	1	—	1.28 ± 0.13
	$\geqslant 1.7\cdot10^{12}$	85	13	2	—	—	—	1.17
	$\geqslant 5.2\cdot10^{12}$	31	2	—	—	—	—	1.06
	$\geqslant 9.4\cdot10^{12}$	14	1	—	—	—	—	1.06
197	$\geqslant 7.5\cdot10^{11}$	184	33	17	1	—	—	1.30 ± 0.13
	$\geqslant 1.7\cdot10^{12}$	63	15	7	—	—	—	1.34
	$\geqslant 5.2\cdot10^{12}$	12	—	1	—	—	—	1.15
	$\geqslant 9.4\cdot10^{12}$	3	—	1	—	—	—	1.50
For events not connected with EAS (density of particle flux in both peripheral points $\lesssim$ 1 m⁻²)								
311	$\geqslant 7.5\cdot10^{11}$	28	1	—	—	—	—	
197	$\geqslant 7.5\cdot10^{11}$	103	1	1	—	—	—	

array was equal to $E_{ep} = 1.9 \times 10^8$ N (eV), (N—the ionization registered in the chambers and expressed in terms of the number of relativistic electrons). The counters of the central hodoscopic point were placed approximately 0.7 m above the ionization array.

As a rule, one electron photon cascade struck the ionization chamber. The number of triggered chambers was small, and the distribution of the ionization over the chambers had a sharp maximum. If several cascades struck the chambers, each was triggered independently. Assuming that several cascades struck the array, it was possible to segregate groups of chambers which were separated from one another by other chambers in which the ionization was at least 30 per cent lower than the maximum ionization in each group. Table I lists the distribution of the registered cases by number of cascades. We see that in the overwhelming majority of cases one or two cascades were registered.

The experimental distribution of the ionization among the individual chambers in the cascade is somewhat broader than what follows from calculations made under the assumption that the points of cascade generation have an exponential depth distribution with an absorption range of 120 g/cm², but can be attributed to the energy dissipation in the cascade processes, if the gamma quanta are generated in the upper layer of the atmosphere.

To determine the average number of electron-photon cascades in a shower of given size, and consequently also the number of gamma quanta generated in the atmosphere above the observation point, the following calculation can be used[1)]

[1)]The authors are grateful to G. B. Khristiansen who pointed out the possibility of such an approach.

We select showers registered by the hodoscopic system in such a way that the shower density at the peripheral point I is smaller than the shower density at the peripheral point II, i.e., $\rho_I \leq \rho_{II}$. The shower axis will then strike the half-plane in which point II is located, and $r_1 \geq r_2$ (r_1 and r_2 are respectively the distances from the point of passage of the axis to points I and II). If the function of the lateral distribution of the electrons in the shower is f(R), i.e.,

$$\rho(R) = Nf(R), \qquad \int_0^\infty f(R)\cdot 2\pi R dR = 1,$$

and the differential particle-number spectrum of the showers is given by $dn/dN = AN^{-(\kappa+1)}$, then the number of showers selected in accordance with the foregoing criterion, with density in the interval from ρ_1 to $\rho_1 + d\rho_1$, is

$$\frac{dp}{d\rho_1}(\rho_1)\, d\rho_1 = 2A\rho_1^{-(\kappa+1)}\, d\rho_1 \int_0^{\pi/2} d\alpha \int_0^\infty f^\kappa(r_1)\, RdR;$$

$$r_1^2 = R^2 + a^2 + 2aR\cos\alpha.$$

We select further those showers in which a gamma quantum with energy larger than E is incident on the chambers. Let $\Phi(>E, N)$ be the number of γ quanta with energy larger than E in a shower with N particles, and let the lateral distribution of these γ quanta be given by a function $\varphi(R)$, i.e., let the density of the γ quanta be

$$\sigma(R) = \Phi(>E, N)\,\varphi(R), \qquad \int_0^\infty \varphi(R)\cdot 2\pi R dR = 1.$$

If $\sigma S < 1$ (S—area of ionization array), then the number of showers selected in accord with both criteria will be

$$\frac{dk(>E,\rho_1)}{d\rho_1}d\rho_1 = 2\int_0^{\pi/2} d\alpha \int_0^{\infty} \frac{dp}{d\rho_1}(r_1)\, d\rho_1 \sigma(>E,R)\, SRdR$$
$$= 2S\, d\rho_1 \int_0^{\pi/2} d\alpha \int_0^{\infty} \frac{dp}{d\rho_1}(r_1)\, \Phi(>E,N)\, \varphi(R)\, RdR.$$

If the function $\varphi(R)$ decreases rapidly with the distance, then r_1 depends weakly on R in the integration region. From the mean value theorem we have

$$\frac{dk}{d\rho_1}(>E,\rho_1)\, d\rho_1 = A\rho_1^{-(\varkappa+1)}\, d\rho_1 S\Phi(>E,\bar{N})\, f^{\varkappa}(\bar{r}_1)$$
$$\times 2\int_0^{\pi/2} d\alpha \int_0^{\infty} \varphi(R)\, RdR = \frac{1}{2}A\rho_1^{-(\varkappa+1)}\, d\rho_1 f(\bar{r}_1)\, \Phi(>E,\bar{N})\, S.$$

where $\bar{r}_1$ is some mean value of r_1 and $\bar{N}$ is the size of the shower corresponding to a density ρ_1 with the axis passing at a distance $\bar{r}_1$.

Thus, the number of γ quanta with energy > E, produced in the layer of atmosphere over the apparatus in a shower with $\bar{N}$ particles is

$$\Phi(>E,\bar{N}) = \frac{dk(>E,\rho_1)/d\rho_1}{dp(\rho_1)/d\rho_1}K;$$
$$K = 4\int_0^{\pi/2}\int_0^{\infty} f^{\varkappa}(r_1)\, RdRd\alpha / Sf^{\varkappa}(\bar{r}_1).$$

The factor K can be calculated by assuming that the lateral distribution of the electrons in the shower is described by a Nishimura-Kamata function. Then K is determined by the quantities $\bar{R}$, κ, and the cascade parameter s.

Calculation shows that K does not depend strongly on $\bar{R}$, κ, or s. Thus, for an atmosphere depth p = 311 g/cm^2 K changes by 25 per cent when κ is varied from 1.5 to 1.7 (s = 0.8, $\bar{R}$ = 5 m), by 25 per cent when s is varied from 1.0 to 0.8 (κ = 1.7, R = 5 m), and by 30 per cent when $\bar{R}$ is varied from 5 to 2 m (κ = 1.7, s = 0.8). The values of $\bar{R}$, κ, and s should be estimated from experiment.

In Table II are listed experimental data on the number of registered events.

The quantities s and $\bar{R}$ can be estimated by analyzing the ratio of the particle flux densities in the shower at different hodoscopic points. Figure 1 shows the integral density spectra for each of the three hodoscopic points, in showers accompanied by the incidence of an electron photon cascade with energy $E \geq 7 \times 10^{11}$ eV and $E \geq 3.5 \times 10^{12}$ eV on the ionization-chamber area.

The average density ratio is determined by the lateral particle distribution in the shower, or, if the lateral distribution of the particles is described by a Nishimura-Kamata function, by the value of the cascade parameter s. According to the data of Fig. 1, the density ratio at two peripheral points ρ_7/ρ_{12}, does not depend on the particle flux density in the shower and amounts to ~1.6 at 311 g/cm^2 and ~ 1.8 at 197 g/cm^2. The error in the determination of this ratio is approximately 0.2. Such a ratio corresponds to Nishimura-Kamata functions with 0.9 < s < 1.1 for a pressure 311 g/cm^2 and 0.7 < s < 0.9 for a pressure of 197 g/cm^2. In the calculations of the coefficients K we have assumed s = 1.0 and s = 0.8 for 311 and 197 g/cm^2, respectively.

The value of $\bar{R}$ can be estimated from the ratio of the densities in the central (ρ_0) and peripheral (ρ_7) points. In Table III are given values of $\bar{R}$ for different γ-quantum energies and shower sizes.

It must be noted that these data are also of interest in themselves, since $\bar{R}$ characterizes the transverse momentum of the generated γ quanta. An estimate starting from ~10^4 m for the height of a shower generation leads to values

$$p_{\perp} \approx (1-5)\cdot 10^8\ \text{eV}/c.$$

The value of κ (the particle-number spectrum exponent) can be obtained from the data on the density spectrum of vertical EAS at the altitudes under consideration. In accordance with [4] we have assumed κ = 1.7. The error in this quantity does not exceed 0.2. The experimentally obtained

Table II

	Shower satisfying the requirement $\rho_1 \geqslant 16$ particles/m^2		Events with an incident electron-photon cascade of energy $E \geqslant 7\times10^{11}$ eV and $\rho_1 \gtrsim 1$ particle/m^2		Events with an incident electron-photon cascade of energy $E \geqslant 7\times10^{11}$ eV	
	H = 9 km	H = 12 km	H = 9 km	H = 12 km	H = 9 km	H = 12 km
Net operating time of the apparatus, hours	10.6	8.7	39.0	34.0	39.0	34.0
Number of registered events	750	339	229	237	521	1008

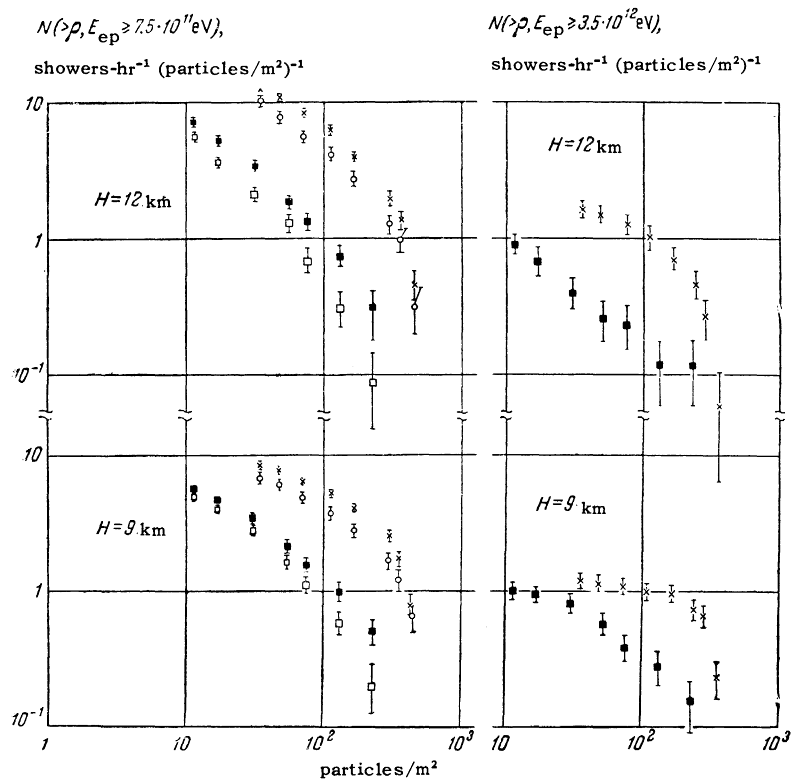

FIG. 1. Integral density spectra for showers accompanied by an electron-photon cascade with energy $E \geqslant \times 10^{11}$ eV and $E \geqslant 3.5 \times 10^{12}$ eV incident on the ionization-chamber area for two altitudes H = 12 km (197 g/cm²) and H = 9 km (311 g/cm²). ×—central hodoscopic point, horizontal counters; o—central hodoscopic point, vertical counters; ■—hodoscopic point located 7 m from the center of the array; □—hodoscopic point located 12 m from the center of the array.

spectra $dk(E > 7 \times 10^{11})/d\rho_1$ and $dp/d\rho_1$ are shown in Fig. 2. In order to obtain the spectrum $dp/d\rho_1$, several flights were made, during which time the triggering counters were not at the center of the array but at two peripheral points directly below the hodoscopic counters. All the showers accompanied by electron-photon cascades were broken up into three groups with respect to ρ_1 in such a way, that the average number of particles in the shower was $\sim 7 \times 10^4$, $\sim 3 \times 10^5$, and $\sim 1.5 \times 10^6$, respectively.

In Table IV are given the values of the coefficient K, calculated for each group of showers. The uncertainty in the coefficient K, due to errors in the values of s, κ, and $\bar{R}$, is 20—30 per cent. For each group we plotted the energy spectrum of the electron-photon cascades, registered by the ionization apparatus.

From these data we calculated the quantities $\Phi(>E, \bar{N})$ given in Fig. 3—the average numbers of γ quanta in a shower with $\bar{N}$ particles, generated in the layer of atmosphere over the apparatus. It must be borne in mind that γ-quantum energy is somewhat higher than the experimentally registered energy of the electron-photon cascade, since some of the energy is dissipated. Estimates based on the data of Baradzeĭ et al.[3] show that for the main fraction of the γ quanta the dissipated energy does not exceed $1/3$ of its initial value.

In the calculation of $\Phi(>E, \bar{N})$, two corrections were made.

1. It was assumed in the calculation that $\sigma S < 1$. In order to take into account the effect connected with the presence of structural bursts, the resultant value of $\Phi(>E, \bar{N})$ must be multiplied by the average number of cascades incident on the chamber area. The value of this quantity was taken equal to 1.30, in accord with the experimental data (see Table I).

2. The angular distribution of the showers accompanied by bursts differs from that of showers without such accompaniment. Since we are interested in the number of γ quanta in showers which arrive in a nearly vertical direction, the correction connected with this affect reduces from first approximation to a multiplication of $\Phi(>E, \bar{N})$ by the ratio of the corresponding average solid angles $\Omega/\Omega(>E)$.

Figure 1 shows the shower density spectrum with the densities determined by vertical counters. A comparison of this spectrum with the density spectrum obtained from data of the horizontal counters of the central point has enabled us to estimate the angle of incidence of the showers accompanied by incidence of an electron photon cascade with energy $E > 7 \times 10^{11}$ eV on the area of the ionization chambers. This angle amounts to $30° \pm 5°$. Comparing the angular distribution of all the registered showers[4] with the angular distribution of the showers accompanied by electron-photon cascades, we obtain $\Omega/\Omega(>E) = 1.5$ for H = 9 km and $\Omega/\Omega(>E) = 2$ for H = 12 km. The

Table III

Electron-photon cascade energy, eV	ρ_7, particles/m²	Number of particles in shower, N	ρ_0/ρ_7	$\bar{R}$, m
Altitude H = 9 km				
$> 7\cdot 10^{11}$	10	$5\cdot 10^4$	8—12	0.8—1.2
	50	$3\cdot 10^5$	5—8	1.1—1.9
	250	$2\cdot 10^6$	1.5—2.5	4—6
$> 3.5\cdot 10^{12}$	10	$5\cdot 10^4$	8—12	0.8—1.2
	50	$3\cdot 10^5$	5—8	1.1—1.9
	250	$2\cdot 10^6$	1.5—2.5	4—6
Altitude H = 12 km				
$> 7\cdot 10^{11}$	10	$5\cdot 10^4$	8—12	1.1—1.8
	50	$3\cdot 10^5$	5—6	1.6—2.1
	250	$2\cdot 10^6$	1.5—2.5	4—6
$> 3.5\cdot 10^{12}$	10	$5\cdot 10^4$	12—18	0.7—1.1
	50	$3\cdot 10^5$	5—7	1.4—2.1
	250	$2\cdot 10^6$	1—2	4—9

Table IV

ρ_1, particles/m²	$\bar{R}$, m	Number of particles in shower, N	$\bar{N}$	K, H = 9 km	K, H = 12 km
5—15	1	$5\cdot 10^4$—$1.5\cdot 10^5$	$7\cdot 10^4$	$7\cdot 10^2$	$6,7\cdot 10^2$
15—70	2	$1.5\cdot 10^5$—$7\cdot 10^5$	$3\cdot 10^5$	$8\cdot 10^2$	$7,7\cdot 10^2$
70—300	5	$7\cdot 10^5$—$3\cdot 10^6$	$1.5\cdot 10^6$	$1.2\cdot 10^3$	$1.1\cdot 10^3$

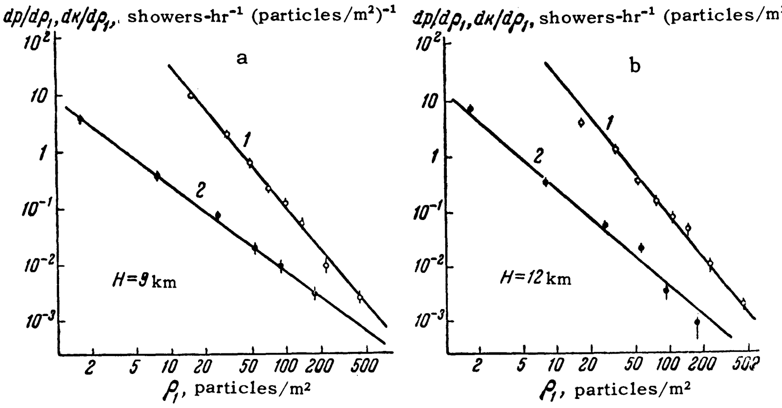

FIG. 2. Density spectra of registered showers $dp/d\rho$ (curve 1) and $dk/d\rho_1$ (> 7×10^{11} eV) (curve 2) for two altitudes, H = 9 km (311 g/cm²) and H = 12 km (197 g/cm²).

accuracy of these ratios is 20—30 per cent.

The counting rate of the showers from each of the three groups agrees with the data concerning the primary spectrum of the cosmic radiation [1], if we assume a conversion coefficient from the number of particles in the shower to a primary particle energy $\sim 2\times 10^9$ eV, which is a reasonable assumption for the observed showers.

Thus, our data give average energy spectra for the γ quanta generated in air layers 197 and 311 g/cm² thick in EAS with average energy $\sim 1.5\times 10^{14}$—3×10^{15} eV.

It must be noted that the energy carried by the γ quanta registered in the experiment in the spectral region from 10^{12} to 10^{13} eV constitutes an appreciable fraction of the total energy of the EAS. Thus, for EAS with $\bar{N} = 1.5\times 10^6$ this energy amounts to $\sim 6\times 10^{14}$ eV.

If we assume that, in accordance with isotopic invariance, $\pi^{\pm}$ mesons, are also produced along with the π^0 mesons, then the energy transferred to the pions with energy in the interval 10^{12}—10^{13} eV, amounts to about half the shower energy.

Comparison of the spectrum of the γ quanta generated in a layer of thickness 311 g/cm² with the analogous spectrum for the 197 g/cm² layer shows that the overwhelming majority of γ quanta are generated in the upper layers of the atmosphere. It follows therefore that the cascade multiplication of the pions makes a small contribution to the spectra under consideration and that thus, in first approximation, the spectra reflect the

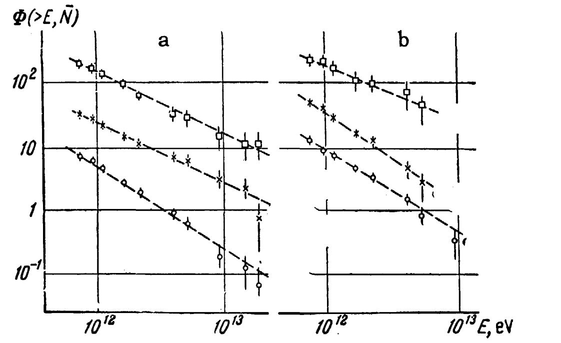

FIG. 3. Average number of γ quanta with energy > E generated in the layer of atmosphere over the apparatus: a—H = 9 km (311 g/cm²) and b—H = 12 km (197 g/cm²) in a shower with the following number of particles: o—$\bar{N} = 7 \times 10^4$; x—$\bar{N} = 3 \times 10^5$; □—N = 1.5×10^6. The energy dependence of Φ (> E,$\bar{N}$) can be approximated by a power law. The corresponding values of the energy exponents (ϵ) were calculated by the method of least squares. For the curves a: o—ϵ = 1.3 ±0.2; x—ϵ = 0.96±0.17; □—ϵ = 1.0±0.2. For curves b: o—ϵ = 1.3±0.2; x—ϵ = 1.4±0.3; □—ϵ = 0.9±0.45.

generation of pions in the first interactions of the high-energy nucleons initiating the shower.

The spectra obtained indicate the high degree of energy dissipation during the production of pions in nuclear reactions, leading to the formation of showers with energy $\sim 10^{15}$ eV. The degree of division of the energy is much higher than predicted by the Landau hydrodynamic theory[5], and approaches the extreme degree of energy dissipation, arrived at by the Heisenberg fire ball representation. Upon decay of such a fire ball[6], the energy of the produced pions does not depend on the initial energy. For a more accurate solution of the question it is necessary to know the nuclear composition of particles, which produce the extensive air showers under consideration.

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