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ULTRA-HIGH-ENERGY EXTENSIVE AIR SHOWERS

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Extensive air showers having from 5×10^6 to 10^8 particles were investigated. Data are presented on the absolute shower intensity, the value spectrum exponent, and on the lateral distributions of the electron-photon component and of the μ mesons of these showers. Data on the electron-photon component indicate either that there is no equilibrium between the electron-photon and the nuclear components in ultra-high-energy showers in the lower layers of the atmosphere, or that the lateral distribution of the electrons on the periphery of the shower is determined not only by the Coulomb scattering, but also by the particle angular divergence in the elementary nuclear-cascade events.

INTRODUCTION

An investigation of ultra-high-energy showers is of particular interest in the determination of the origin of cosmic rays and in the study of the processes that lead to the development of such showers in the atmosphere. There are at present relatively few papers devoted to a study of ultra-high-energy showers. These pertain to the work done by Soviet scientists in 1952-1957 at sea level[1] and on mountains,[2] to the work of Cranshaw, Galbraith, et al.,[3-6] and the work of Clark et al.,[7] reported in 1957-1958 and performed at sea level.

The type of the muon lateral distribution function was determined, not very accurately, with a small hodoscopic array,[1] and the lateral distribution function of all the charged particles was obtained in that experiment from the "separation curve." Cranshaw's group[3-6] investigated in detail showers of the same energy as in reference 1, but the number of particles in each registered shower was not determined, and the data on both the shower particle spectrum and the lateral distribution function were averaged over showers that produced a definite charged-particle density within a circle of a specified radius. The use of luminescent counters has enabled Clark et al.[7] to investigate extensive atmospheric showers most accurately, but they merely verified whether the registered flux densities of all the charged particles satisfied certain lateral distribution functions (with a parameter value s = 1.4, see reference 8).

The present investigation was devoted to a study of showers with 10^6 to 10^8 particles. The work was performed with part of a large array built at the Moscow State University for an all-out investigation of extensive atmospheric showers at sea level. We note that the use of part of the array described in the present paper jointly with part of the array described earlier (see, for example, reference 9) yielded many new data on the energy characteristics of electron-photon and muon components.[10]

DESCRIPTION OF THE EXPERIMENT

The apparatus was mounted on ten laboratory carts. Seven of the carts were located at the center and at the corners of a hexagon inscribed in a circle 150 m in radius, while the remaining three were located on one straight line (Fig. 1) at distances up to 800 m. The carts had light covers made of canvas and glass wool, and the total amount of matter above the counters used to register the shower

FIG. 1. General plan of the installation. The numbers indicate the cart numbers, K – part of the apparatus described in reference 9.

particles did not exceed 1.5 g/cm^2. Charged-particle and penetrating-particle detectors were placed in each cart. The charged-particle detectors were self-quenching Geiger-Müller counters of 330 and 100 cm^2 area. In each cart there were 100 counters of the former type and 24 of the latter. The penetrating-particle detector comprised 24 counters (each of 330 cm^2 area) arranged in one row and surrounded by an absorber made of iron and lead. Figure 2 shows a section through the detector. Each counter of the apparatus was included in a GK-7 hodoscopic cell.

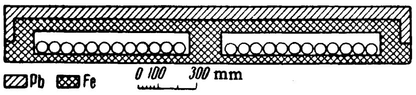

FIG. 2. Section through the penetrating-particle detector.

The apparatus was controlled upon simultaneous operation of four groups of counters, each of 3960 cm^2 area (12 counters of 330 cm^2 area connected in parallel). Each counter in the control groups was also connected to a corresponding hodoscopic cell. Two control counter groups were mounted on cart No. 9, and two on cart No. 10. The control pulses were transmitted to the hodoscopic cell through a high-frequency cable and delay lines, one in each cart. The delay time was chosen such that, during the registration of a shower with a vertical axis, the control pulse should arrive in the middle of the resolution-time interval of the hodoscopic cells. The minimum resolving times of the hodoscopic cells were 13 μsec in carts 1 — 3 and 9 μsec in carts 4 — 10; the resultant mean values were 20 and 15 μsec respectively

The apparatus made it possible to locate the axis and the number of particles of the registered shower, provided the axis was within the limits of the apparatus and the shower had a sufficient number of particles. The density distributions recorded by our apparatus were such that in most cases when the shower axis fell within the hexagon its position could be located accurate to half the distance between measurement points without using any particular type of lateral distribution function. To place the axis position more accurately it was assumed that the lateral distribution function for the investigated showers was the same at distances r up to 250 or 300 m from the axis as for showers with $N \leq 5 \times 10^5$ particles:[11]*

$$\rho(r) = \frac{2\cdot 10^{-3}N}{r} e^{-r/60}, \qquad r \leqslant 96 \text{ m},$$

$$\rho(r) = \frac{0{,}60N}{r^{2.6}}, \qquad r > 96 \text{ m}, \qquad (1)$$

*The results given in this reference confirm that the lateral distribution function for the charged particles of the investigated showers is $\sim r^{-2.6}$ at $r > 100$ m.

where $\rho(r)$ is the particle density at a distance r from the axis.

To find the axis and the number of particles in the shower we used the readings of the carts arranged in a hexagon. From the known formulas

$$\rho = \frac{1}{\sigma}\ln\frac{n}{n-m}, \quad \Delta\rho = \frac{1}{\sigma}\frac{1}{\sqrt{(n/m)}\,(n-m)}$$

we determined the most probable density ρ at the cart location, when m out of the n counters of area σ in the cart operated. The ratio of the particle density at two measurement points and the distance between these points were used to plot the geometric locus of the axis for a specified lateral distribution function. Since the determined density was subject to an error, two curves were plotted for each specified density ratio k, corresponding to $k + \Delta k$ and $k - \Delta k$; the region between these two curves was taken to be the region of most probable axis location. We could choose for our apparatus at least three independent pairs of density registration points and find the intersection of the three regions corresponding to these three. independent pairs. The center of the new region thus obtained was taken to be the shower axis.

The average number of shower particles $\overline{N}$ was determined, after finding the shower axis, from the formula

$$\overline{N} = \frac{1}{n}\sum_{i=1}^{n} N_i, \qquad N_i = \rho(r_i)\,\varphi(r_i),$$

where

$$\varphi(r_i) = r_i e^{r_i/60}/2\cdot 10^{-3}, \quad r_i \leqslant 96 \text{ m},$$

$$\varphi(r_i) = r_i^{2.6}/0.60, \qquad r_i > 96 \text{ m},$$

and $\rho(r_i)$ is the density reading of the i-th point, located at a distance r from the axis.

The error in the determination of the axis was 25 m when the axis fell within a circle of 150 m radius centered at cart 8; the error in the determination of the number of particles was not more than 20% for each individual shower.

A total of 1000 showers was recorded by the apparatus after 1420 hrs of observation. To determine the absolute intensity in the lateral distribution functions, we selected for further data reduction those showers in which not less than 30 counters of 330 cm^2 area were operated in each of three carts. This criterion led to a separation, with 100% probability, of showers with more than 0.7×10^7 particles and with an axis within the hexagon. Approximately 300 such showers were selected. It must be noted that in 15% of the 300 showers we could not find the axis position, although the showers had a clearly pronounced charged-particle flux-density gradient within the limits of our apparatus. In approximately one-third of these showers we could assume, with equal probability, that the shower axis passed either inside or outside the location of our apparatus, and in two-thirds of these showers the distribution of the densities was in sharp contradiction to the lateral distribution function selected by us. We estimated the number of shower particles for the first shower group under the assumption that the axis was located within a circle of 150 m radius. It was found that these showers always had less than 1×10^7 particles. All these showers were excluded from further consideration.*

The probability of registering showers in our apparatus was nearly 100% for $N \geq 1 \times 10^7$. Direct numerical integration has shown that the probability of registering showers with our apparatus within a circle of 150 m radius (with allowance for the dependence of the registration on the angle of inclination of the showers) coincides within 2 — 3% with the registration probability calculated under the assumption that the shower axes are vertical.

We have calculated the vertical shower intensity I_0 ($\geq N$) with more than N particles per unit time, unit area, and unit solid angle, using the following formula

$$I_0(\geqslant N) = \frac{\nu + 2}{2\pi} \frac{1}{T} \int_S \frac{C(N)\,dN}{\int W(N, x, y)\,dx\,dy},$$

where T is the time of registration, S is the area of registration, equal to the area of a circle of 150 m radius, $C(N)\,dN$ is the number of showers registered with particles ranging from N to N+dN, $W(N, x, y)$ is the probability of registering a shower with a vertical axis passing through the point (x, y), and ν is the exponent of angular distribution of the showers, taken from reference 12.

After 1484 hours of operation we registered, in an area 7×10^4 m^2, 75 showers with $N \geq 10^7$ and 8 showers with $N \geq 3 \times 10^7$, which yields the following absolute intensities:

$$I(\geqslant 10^7) = (1.36 \pm 0.2) \cdot 10^{-6} \text{ m}^{-2}\text{hr}^{-1}\text{sr}^{-1}$$

$$I(\geqslant 3 \cdot 10^7) = (1.24 \pm 0.43) \cdot 10^{-7} \text{ m}^{-2}\text{hr}^{-1}\text{sr}^{-1}.$$

On the basis of these data we recalculated the value spectrum exponent γ, using the formula

$$\gamma = \ln[I(N_1)/I(N_2)]/\ln(N_1/N_2)$$

and obtained $\gamma = 2.0 \pm 0.35$.

The results obtained in our apparatus are also used to determine the value spectrum exponent by the method of area variation. Since the control groups of counters represented 12 counters in parallel, each connected in a hodoscopic cell, we could calculate the number of four-fold coincidences of the counter groups with areas 3960 and 1320 cm^2. From this we could calculate the value spectrum exponent on the basis of γ' using the formula

$$\gamma' = \ln[C(\sigma_1)/C(\sigma_2)]/\ln(\sigma_1/\sigma_2),$$

where $C(\sigma)$ is the number of four-fold coincidences of counter groups with area σ. For 1000 four-fold coincidences of groups of 3960 cm^2 counters, 112 four-fold coincidences of 1320 cm^2 counters were registered and we obtained $\gamma' = 2.0 \pm 0.10$. The value spectrum calculated by us indicates that this exponent belongs to the shower interval $(0.3 - 1.2) \times 10^7$ particles.

To construct the lateral distribution functions we used the 200 densest showers with $N \geq 5 \times 10^7$, the axes of which were not farther than 200 m from the center of the hexagon. These showers were used to plot the averaged lateral distribution functions of electrons and muons. The averaging was for four shower groups over the number of particles and over the distance intervals.

The intervals of averaging over N were $0.5 \times 10^7 - 1 \times 10^7$, $1 \times 10^7 - 3 \times 10^7$, $3 \times 10^7 - 7 \times 10^7$, and $7 \times 10^7 - 10^8$. The intervals of averaging over r were: 100 — 130, 130 — 160, 160 — 200, 200 — 250, 250 — 320, 320 — 400, 400 — 500, 500 — 640, 640 — 800, and 800 — 1000 meters. The averaging over N was under the assumption that the flux particle densities were proportional to the number of particles in the shower.

The determined average densities were referred to the center of the interval r and to a shower with $\bar{N} = \Sigma' N_i/n$ particles, where n is the number of showers entering within the interval over which the averaging over r is carried out; N_i is the number of particles in the i-th shower from this interval.

The average value of N for different distances had a spread not greater than 20%. This spread was taken into account by suitable normalization in the construction of the lateral distribution function of the electron component and of the penetrating particles.*

*For the remaining 2/3 of the showers we have also estimated the number of particles in the shower, under the assumption that the axis falls within the hexagon and the function is close to that selected by us. If the indicated estimates are true and the axes actually lie within the hexagon, then the absolute intensity given in the article may be undervalued by 15%.

*In the construction of the lateral distribution function for the muons it was assumed that the number of muons is proportional in first approximation to the number of shower particles N; if the actual dependence, $\sim N^{0.75}$ (reference 6), is taken into account, an insignificant error results.

TABLE I. Values for the exponent n for the electron component

Distances from the axis, m	N				
	0.7·10⁷	1.7·10⁷	4.6·10⁷	1.1·10⁸	$\bar{N}$ = 2·10⁷
80—350	2.66 ± 0.14	2.6 ± 0.1	2.69 ± 0.24	—	$\bar{n}$ = 2.66 ± 0.14
350—1000	3.35 ± 0.8	2.6 ± 0.6	—	2.6 ± 0.6	$\bar{n}$ = 2.7 ± 0.5

TABLE II. Values of the exponent n for mesons

Distances from the axis, m	N				
	0.7·10⁷	1.7·10⁷	4.6·10⁷	1.1·10⁸	$\bar{N}$ = 2·10⁷
350—1000	2.0 ± 0.4	2.4 ± 1.2	2.0 ± 1.2	2.5 ± 1.4	$\bar{n}$ = 2.3 ± 0.2

Random coincidences were accounted for at large distances from the shower axis. The maximal correction, corresponding to a distance of 900 m and showers with $N = 0.7 \times 10^7$ particles amounted to 25% of the registered particle density. In plotting the muon lateral distribution functions it was assumed that the contribution of the nuclear-active particles was negligible at these distances.[5] Each firing of the counter in the detector under the lead was assumed to be due to a muon. Corrections were introduced for δ-electrons. The number of firings of two neighboring counters at distances more than 300 m from the axis was determined experimentally. The number of such events was 10% of the total operating counters under lead at these distances. It was assumed then that 10% of firings under lead were due to δ-electrons. This percentage agrees with estimates of the number of δ-electrons obtained for analogous detectors in other investigations.[11]

We plotted the radial distribution functions for the electron and meson components of the shower. The electron density was determined as a difference between all the charged particles and the mesons with equilibrium electrons, and it was assumed that the equilibrium electrons amount to 30% of the number of muons. The lateral distributions obtained for the electronic and mesonic components were approximated with an r^{-n} law.

Tables I and II give the values of n for showers with different numbers of particles for different distances from the axis. It is seen from the tables that the lateral distribution functions are independent of the number of shower particles within the limits of statistical error. We have therefore averaged further and obtained the lateral distribution functions for showers with $\bar{N} = 2 \times 10^7$, as shown in Figs. 3, 4, and 5. The exponent $\bar{n}$ for the average functions is listed in Tables I and II.

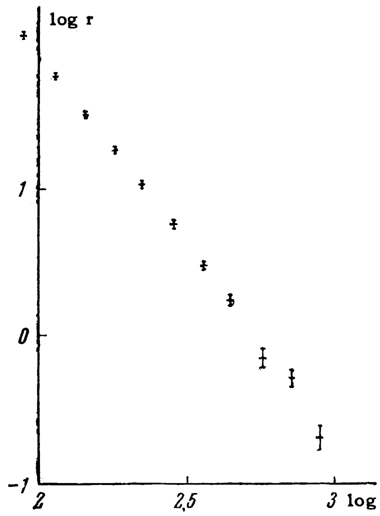

FIG. 3. Lateral distribution of charged particles for $\bar{N} = 2 \times 10^7$.

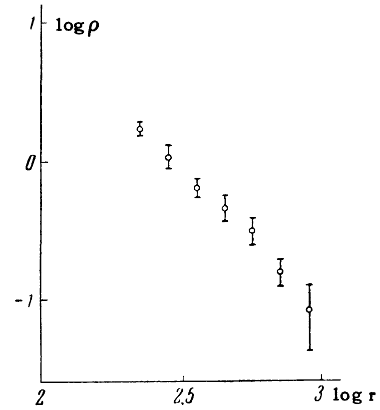

FIG. 4. Lateral distribution of nuons for showers with $\bar{N} = 2 \times 10^7$.

DISCUSSION OF THE RESULTS

The results on the absolute intensities of showers agree, within the limits of errors, with analogous data given in references 5 and 7. According to reference 7, $I(\geq 1 \times 10^7) = (1.95 \pm 0.6)$

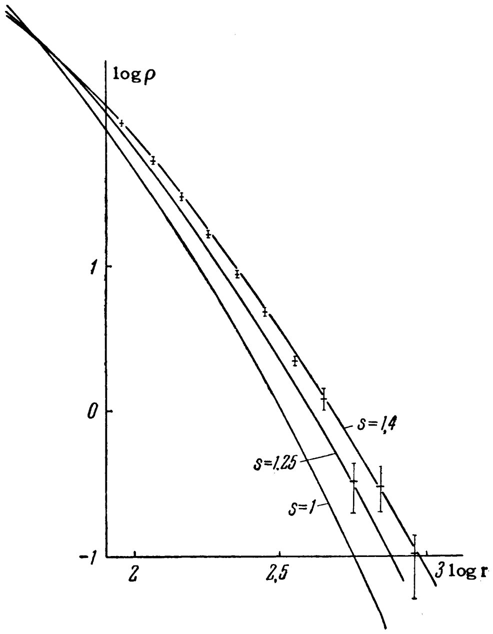

FIG. 5. Lateral distribution of the electron component for showers with N = 2 × 10⁷. Curves – theoretical lateral-distribution functions for different values of s. The experimental and theoretical curves were normalized to the total number of particles in a shower at a distance from 10 to 1000 m, and the experimental points for distances less than 100 m were extrapolated in accordance with formula (1).

$\times 10^{-6} m^{-2} hr^{-1} sr^{-1}$. According to reference 5, $I (\geq 1 \times 10^7) = (1.25 \pm 0.3) \times 10^{-6} m^{-2} hr^{-1} sr^{-1}$. It was found in reference 3 that the integral value spectrum exponent experiences a sharp change in the region $N \sim 10^6$. Our data obtained for showers with more than 3×10^6 particles confirm these results.

We have compared our experimental lateral distribution functions for electrons with the results calculated by the electromagnetic cascade theory[8] (Fig. 5). The form of the lateral distribution function is determined by the values of the constants used in the cascade theory formulas, viz: the radiation unit length t_0 and the critical energy β. In many foreign investigations, including those of Nishimura and Kamata,[8] from which we took our theoretical curve for comparison, these constants were $t_0 = 37.7$ g/cm², and $\beta = 84.2$ Mev. But there is more justification for assuming $\beta^* = 72$ Mev and $t_0^* = 32.4$ g/cm².[14] Then, considering that the shapes of the theoretical curves are determined only by the parameter s, we should assign to the curves with parameter s, given by Nishimura and Kamata[8] a parameter $s^* = s \times (0.9 + 0.033 s)^{-1}$. This follows from the definition[8]

$$s = 3t / [t + 2 \ln (E_0 / \varepsilon_0)].$$

We have plotted the electron lateral distribution functions, taking for r_0 the following value:[15]

$$r_0 = E_s X_0^* T / \beta^* (p - 0.07) 273 = 80 \text{ m},$$

where $\beta^* = 72$ Mev, X_0^* is the length of one t-unit in meters at the level of observation, p is the pressure in the atmosphere, T is the average absolute temperature during the time of measurements (T = 290°K), and E_s is the scattering constant, assumed by us to be 19 Mev in accordance with reference 16. As can be seen from the comparison of the theoretical and experimental curves (Fig. 5), the electron lateral distribution function fits a theoretical curve with a single s.

Nishimura and Kamata have proved[17] that if π^0 mesons are formed only in the axis of the nuclear-cascade shower, and the photons have the same direction as the shower axis, then the structural electron function can be represented by the structural function of a single electron-photon cascade of age s, which is determined by the value of the free absorption path λ of the particles in the shower. In this case, on the basis of the values of λ measured by Cranshaw et al.,[6] one would expect the experimental data for our showers to coincide with the theoretical curves at a parameter $s \geq 1.17$. The equality occurs when the electron component and the nuclear avalanche are balanced. We can therefore conclude from our experimental results that in ultra-high-energy showers there is either no equilibrium between the electron-photon and nuclear components in the lower layers of the atmosphere, or else the electron lateral distribution is determined not by Coulomb scattering alone, but also by the angular divergence of the particles during the acts of the nuclear-cascade process.

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