INVESTIGATION OF A SHOWER CONSISTING OF 200,000 PARTICLES AND RECORDED IN A NUCLEAR PHOTOGRAPHIC PLATE

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Electron-sensitive photographic plates were used to investigate the lateral and angular distributions of particles of a large shower that developed in lead. It is shown that at a shower energy on the order of 4×10^{13} ev the lateral distribution of all particles and the angular characteristics of the particles in the central portion of the shower are in agreement with the cascade theory.

1. LATERAL DISTRIBUTION OF PARTICLES; NUMBER OF PARTICLES, AND SHOWER ENERGY

A very large electron-photon shower, with an axis inclined 15° to the normal to the plane of the plate, was found on a NIKFI type R plate ($200\,\mu$), exposed in 1956 on Mt. Aragats in apparatus with ionization-chambers.[1] Figure 1 shows a microphotograph of the central portion of this shower.

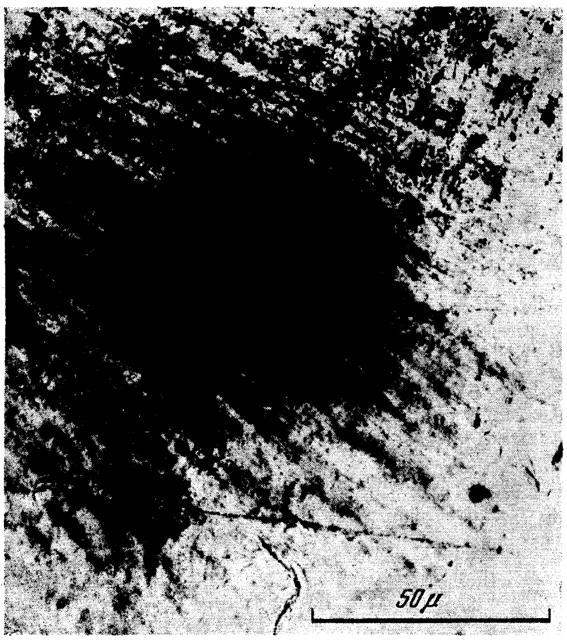

FIG. 1. Microphotograph of the central portion of the shower.

Using the RA-1 drawing apparatus, mounted on one of the eyepieces of the MBI-2 microscope set at magnification 1350, all the particles of the shower and of the background were transferred to paper. These particles were located in four-mutually perpendicular sections at distances $500\,\mu \le r \le 10{,}000\,\mu$ from the axis of the shower (Sections I and III are perpendicular to the direction of the shower-axis projection, while II and IV are parallel to the projection, see Fig. 2). To determine the background on a given plate, all the tracks of relativistic particles were traced on several sections 2 — 5 cm outward from the center of the shower. The background was found to be $(1.02 \pm 0.03) \times 10^{-3}$ particle/μ^2. After subtracting the background, we obtained the lateral distribution of the shower particles in the distance interval $500 \le r \le 10{,}000\,\mu$.

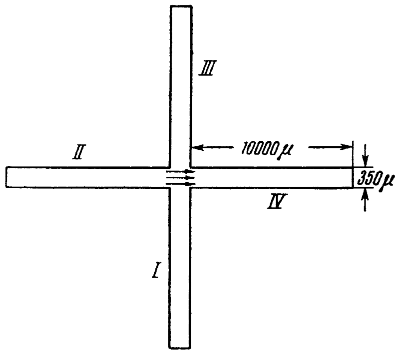

FIG. 2. Relative positions of the traced sections of the shower. The arrows indicate the direction of the projection of the shower axis.

At distances $r < 500\,\mu$ from the axis, the particle density is too great to be determined directly. Therefore the data on the lateral distribution at small distances from the shower axis were obtained by photometry with a MF-4 microphotometer. For this purpose, a negative of the shower, magnified 30 times, was obtained on a photographic film and the photometric evaluation was made at a magnification 30, with a slit 1.1×5.0 mm. If these slit dimensions are referred to the true size of the shower, we find that the photometry covered a shower section measuring $1.2\,\mu \times 5.6\,\mu$, i.e., an area of $6.8\,\mu^2$. The photometric results were compared with the calibration of the nuclear emulsion, made with electrons of energy $E \gtrsim 1$ Mev. The density $\rho(r)$ thus obtained, together with the density at $r > 500\mu$, is shown in Fig. 3.

Figure 3 shows also the function of the lateral distribution for $E_0 = 4 \times 10^{13}$ ev for a shower at the maximum of its development ($S = 1.0$), obtained by interpolation from the data of Kamata and Nishimura.[2] The lateral distribution of Kamata and Nishimura agrees well with the experimental lateral distribution. The discrepancy in the region $r < 100\mu$ may indicate that this shower is an electron-nuclear shower, generated in lead.

The number of the particles in the shower was counted separately in the following regions. 1) $0 \le r \le 250\mu$, where $\rho(r)$ was determined by photometry, $N_1 = 10{,}000$ particles. 2) Summation by rings (for $250\mu \le r \le 10{,}000\mu$) yields $N_2 = 150{,}000$ particles, i.e., $N_1 + N_2 = 160{,}000$ particles. 3) At $r > 10^4\mu$, a power law $\rho(r) = B/r^3$ or $\rho(r) = B/r^4$ is assumed; if $\rho(r) \sim r^{-3}$, then $N_3 = 88{,}000$ particles, and if $\rho(r) \sim r^{-4}$, then $N_3 = 42{,}000$ particles.

Since scattering is stronger in lead than in air, $\rho(r)$ is expected to drop off at large distances no faster than in air. Then, assuming $\rho(r) \sim r^{-3}$ at $r > 10{,}000\mu$, we obtain $N_0 = 160{,}000 + 88{,}000 = 248{,}000$ particles. The error in the total number of particles, due to errors in the determination of $\rho(r)$, is approximately 20%. Thus, $N_0 = (248 \pm 50) \times 10^3$ particles.

If it is assumed that the shower is observed at the maximum of its development, i.e., $N_0 = N_{max}$, we can determine the energy of the soft component of this shower from the following formula

$$N_{max} = 0.17\,(E/\beta)/\sqrt{\ln(E/\beta)} = N_0. \quad (1)$$

From (1) we obtain $E_0 \ge E = (3.6 \pm 0.7) \times 10^{13}$ ev.

Were this shower to be created by a primary electron (photon), ordinary cascade theory would give $t_{max} = \ln(E_0/\beta) = 15.5$ t-units. But we observe the shower at a depth $t = 21.7$ t-units, i.e., six t-units deeper than the maximum of the number of particles. This difference is either due to the Pomeranchuk-Migdal effect, or else we deal with an electron-nuclear shower of high energy.

2. ANGULAR DISTRIBUTION OF PARTICLES

A. Distribution of particles about the shower axis. Figure 4 gives an idea of the character of

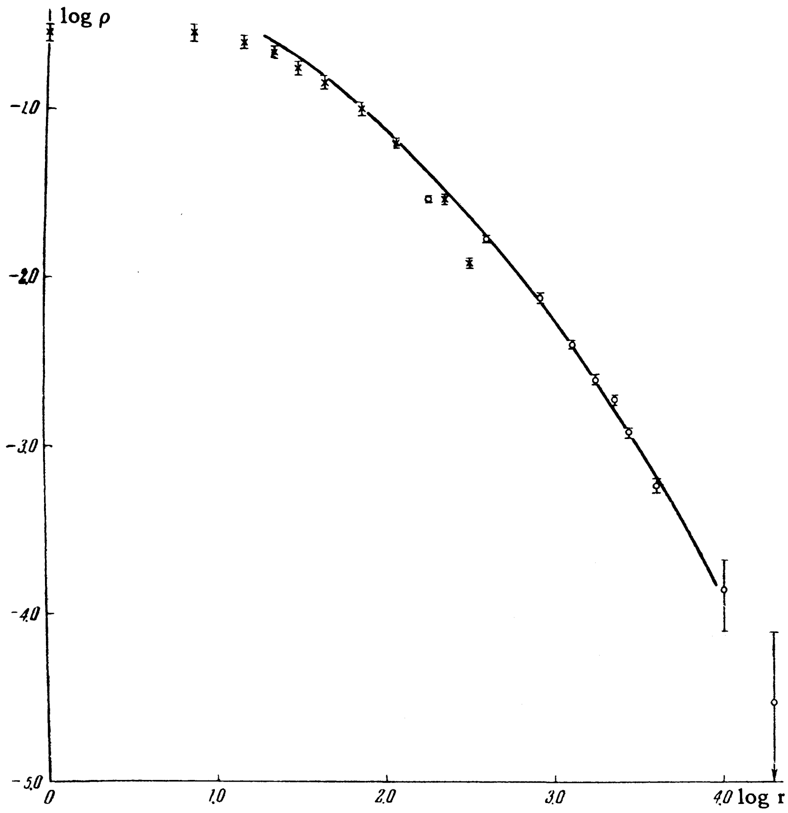

FIG. 3. Lateral distribution of shower particles. Abscissa – logarithm (to the base 10) of the distance from the center of the shower in microns; ordinate – logarithm (to the base 10) of the density of the shower particles ρ (particles/μ^2), × – photometry data, mean-squared error; o – data obtained by counting the number of particles directly, statistical error; solid line – theoretical curve obtained from the Kamata and Nishimura data.[2]

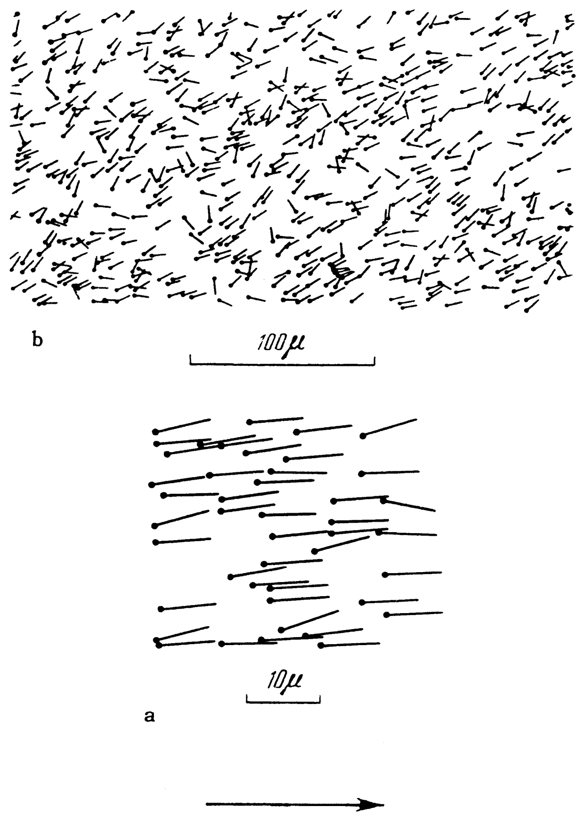

FIG. 4. Angular distribution of particles at a distance 100μ (a) and 600μ (b) from the center of the shower. The dashes represent the projections of the particle tracks on the emulsion plane, the dots represent the points where the particles enter the emulsion, and the arrow represents the direction of the projection of the core of the shower.

the angular distribution of particles in the shower. The figure shows the projections of the particle tracks in two sections, 100 μ and 600 μ away from the center of the shower.

It is seen from Fig. 4, that at a given distance r from the shower axis the projections of the particle tracks follow on the average a certain common direction, determined by an angle $\bar{\lambda}$. A detailed measurement of the angles λ_i between the projections of the track and of the shower core on the plane of the emulsion shows that as the distance r from the center of the shower increases, the average angle $\bar{\lambda}$ of a particle group increases first in proportion to r, and then at a slower rate.

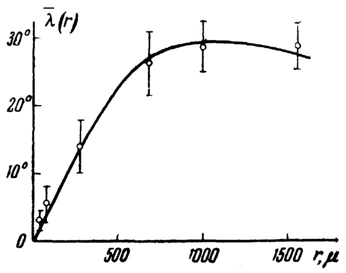

FIG. 5. Dependence of $\bar{\lambda}$ on the distance r from the center of the shower. Mean-squared errors.

Figure 5 shows the results of the measurements of $\bar{\lambda}$ at various distances r from the center of the shower in sections I and III. Since sections I and III in the emulsion plane are perpendicular to the projection of the shower core, the quantity $x = r/\tan\bar{\lambda}$ gives the coordinate of the point to which the continuations of the projections of the shower-particle tracks converge. This point is located from 0.84 mm (for tracks with r = 43 μ) to 1.84 mm (for tracks with r = 1000 μ) from the center of the shower (in the emulsion plane). Thus, over a wide range of distances from the center of the shower, the particles have at each point of the shower a common direction, inclined to the shower axis at an angle $\bar{\theta}$ given by $\tan\bar{\theta} = r/y$, where y is the height of the cone, measured along the axis of the shower from the plane of observation, and r is the distance from the center of the shower in a plane perpendicular to the shower axis. We can readily obtain the value of y from the known values of x and of the angle β_0 between the shower axis and the normal to the emulsion plane.

$$x = y\sin\beta_0.$$

From these relations we obtain the connection between the angles $\bar{\lambda}$ and $\bar{\theta}$

$$\bar{\theta} = \tan^{-1}(\sin\beta_0\tan\bar{\lambda}). \qquad (2)$$

The shower considered has $\beta_0 = 15°$, and thus y = 3.9 x and $\bar{y} = 3.9\,\bar{x}$. The average over the range $43\,\mu \le r \le 1000\,\mu$ is (1.2 ± 0.23) mm. Thus, $\bar{y}$ = (4.7 ± 0.9) mm. The shower unit in lead is 5.2 g/cm² or 4.6 mm. Consequently, $\bar{y}$ = (1.0 ± 0.2) t-units and $\bar{\theta}(r) = \tan^{-1} \times [r/(1.0 \pm 0.2)]$ for $r \le 0.2$ t-units.

B. Distribution of the particles about the mean direction. If one takes an area, with dimensions considerably smaller than the distance r from the area to the center of the shower, then the particles that strike this area, which have a common mean direction determined by the angle $\bar{\lambda}$, are distributed in some manner relative to this mean direction (see Fig. 4). The average spread, $\overline{\Delta\lambda} = \sum^{n}\Delta\lambda_i/n$ (where $\Delta\lambda_i = |\lambda_i - \bar{\lambda}|$), was determined for all sections (I, II, III, and IV) and at various distances r from the center of the shower. The dependence $\overline{\Delta\lambda}(r)$ is shown in Fig. 6.

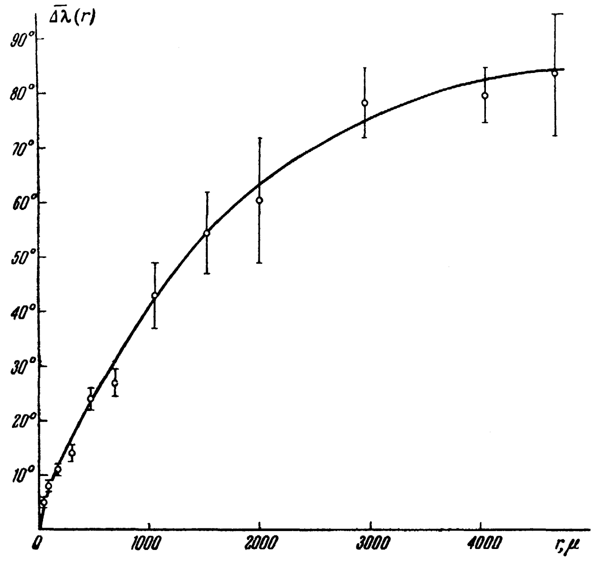

FIG. 6. Dependence of $\overline{\Delta\lambda}$ on the distance r from the center of the shower. Mean-squared errors.

The fact that the projections of the particle tracks are distributed about the angle $\bar{\lambda}(r)$ in the emulsion plane denotes that the particles have a certain distribution in space about the angle $\bar{\theta}(r)$ between the particle group and the shower axis. To evaluate the distribution of the particles about a mean direction, specified by an angle $\bar{\theta}(r)$, we measured the angles λ_i and $\Delta\theta_i$, where $\Delta\theta_i = |\theta_i - \bar{\theta}|$ is the angle between the track of the i-th particle and the mean direction corresponding to $\bar{\theta}(r)$. The measurements were made 850 μ from the center of the shower, in sections I and III. The distribution of the particles about the angles $\Delta\theta_i$ is shown in Fig. 7, which also shows the Gaussian distribution. As can be seen from the diagram, the distribution of the particles about $\bar{\theta}(r)$ is Gaussian, i.e., $n(\theta) = C\exp\{-\theta^2/2\Delta\theta^2\}$. From

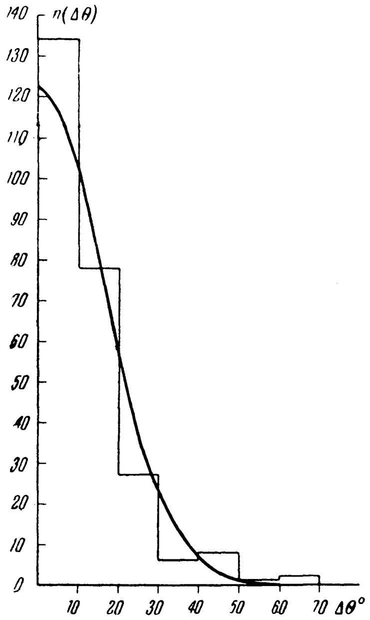

FIG. 7. Distribution about the angles $\Delta\theta_i$, obtained for particles at a distance 850μ from the center of the shower. Curve – Gaussian distribution.

these measurements, performed for $r = 850\,\mu$, we obtained $\overline{\Delta\lambda} = 33°$ and $\overline{\Delta\theta} = 13°$.

It is impossible to measure $\overline{\Delta\theta}$ at smaller distances directly, since the particle density is too high. We therefore proceeded as follows. Calculation has shown that $\overline{\Delta\lambda}$ and $\overline{\Delta\theta}$ are linearly related up to $\Delta\theta \sim 10°$. Using the coefficient of proportionality between $\overline{\Delta\lambda}$ and $\overline{\Delta\theta}$, determined experimentally for $r = 850\,\mu$ $(\overline{\Delta\theta}/\overline{\Delta\lambda} = 0.4)$, we were able to evaluate $\overline{\Delta\theta}$ from the known $\overline{\Delta\lambda}$. Thus, we obtained $\overline{\Delta\theta}$ for various r and from the known $\overline{\Delta\theta}$, assuming the $\overline{\Delta\theta}$ to be due essentially to Coulomb scattering of the particles, we determined the effective energies of the shower particles at various distances from the center of the shower, namely $E = E_S/\overline{\Delta\theta}$, where $E_S = 21$ Mev.

The data obtained in this manner were compared with the data of Guzhavin and Ivanenko,[3] who calculated $\theta_x E/E_S$ for electrons (θ_x is the mean of the projections of the angles between the particles and the shower axis on the plane in which the shower axis is located) as a function of $\tilde{x}_0 = x_0 E/E_S$ (x_0 is the distance from the shower axis, in t-units). The values for θ_{exp} were determined from (2). (see table).

x_0	$\overline{\Delta\theta}=0.4\overline{\Delta\lambda}$, deg	E, ev	$\tilde{x}_0$	θ_x	θ_{exp}
0.01	1.6	$7.5\cdot10^8$	0.357	0.6	0.7
0.04	4.8	$2.5\cdot10^8$	0.476	2.1	2.7
0.10	9.2	$1.3\cdot10^8$	0.620	4.6	6.1
0.20	15.2	$0.8\cdot10^8$	0.760	8.1	8.5

The agreement obtained cannot be deemed absolute, since θ_x and θ_{exp} differ somewhat, but it can be stated that our data (within the limits of the assumptions made) do not contradict the cascade theory.

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[1] Brikker, Grigorov, Kondrateva, Podgurskaja, Savel'eva, Sobinjakov, and Sestoperov, Nuovo cimento **8**, Suppl. No. 2, 733 (1958).

[2] K. Kamata and J. Nishimura, Progr. Theoret. Phys. Suppl. No. 6, 93 (1958).

[3] V. V. Guzhavin and I. P. Ivanenko, JETP **36**, 1509 (1959), Soviet Phys. JETP **9**, 1070 (1959).

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