ANGULAR DISTRITUTION OF AXES OF EXTENSIVE AIR SHOWERS AT SEA LEVEL

A. T. ABROSIMOV, V. I. GOMAN'KOV, I. A. IVANOVSKAIA, and L. I. SARYCHEVA

Moscow State University and the P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

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A cloud-chamber study was made of the angular distribution of the axes of extensive air showers at sea level. The angular distribution was approximated by a $\cos^n\theta$ law of exponent $n = 8.3 \pm 1.4$.

FOR the purpose of studying the characteristics of extensive air showers in 1954 we constructed apparatus which consisted of a large cloud chamber and 288 hodoscope counters. This apparatus was used in Moscow to obtain the angular distribution of the axes of extensive air showers, the energy spectra of the electron-photon and nuclear-interacting components, the lateral distribution of the nuclear-interacting particles and a number of other characteristics of the showers. In the present paper we present only the results for the angular distribution of the axes. The other data will be published later.

The arrangement of the cloud chamber and four hodoscopic points is shown in Figs. 1a and 1b. The cloud chamber,[1] which measured $60 \times 60 \times 30$ cm (with an effective area of 0.15 m^2), contained 7 lead plates. The thickness of the uppermost plate was 0.5 cm; that of the others was 1.5, 2, 2, 2.5, 2 and 2.5 cm. The cloud chamber served for the determination of the directions of the particles, for detection of the interactions between nuclear-interacting particles and lead nuclei, and for determination of the energies of electrons and photons from their cascade multiplication in the lead plates.

The hodoscopic sets, each of which consisted of 72 counters (24 counters with each of the areas 330, 100 and 24 cm^2) enabled us to determine the flux of particles at four points of the shower cross section, thus making it possible to find the position of the axis and the total number of particles in individual showers.

In the first series of measurements the hodoscope and cloud chamber were controlled by a pulse M_1 which resulted from coincident discharges in four groups of counters, each of 660 cm^2 area, located at the center of the apparatus and denoted by numbers 1, 2, 3, and 4 in Fig. 1b. In the second series the hodoscope and cloud chamber were actuated by either of two master pulses. One of these pulses, M_2, resulted from the coincidence of discharges in counters 1, 2, 3, and 4 and the absence of discharges in counters of the same area in groups I and V (Fig. 1a); the other pulse, M_3, resulted from the coincidence of pulses in any four counters of the 10 (each of 180 cm^2 area) placed under 10 cm of lead alongside of the cloud chamber (Fig. 1b), with pulses in two unshielded counters (5 and 6 in Fig. 1b) of 330 cm^2 area placed at about 2 meters from the lead block. In the second series hodoscopic point I was shifted to position Ia.

The position of the axis r and the number of particles N in an extensive shower were determined in the usual manner[2] from the particle flux ρm^{-2} registered by three groups (II, III, and IV in Fig. 1a) of hodoscope counters. It was assumed that the lateral distribution of the flux was known,[3] and that in the range of r from 2 to 10 meters it was represented by* $\rho(r) = 2.7 \times 10^{-3}\, Nr^{-1}$. The flux in group I and in the cloud chamber had to correspond to the observed distance from the shower axis.

The number of hodoscope counters which we used enabled us to determine the particle flux in each of the groups I, II, III, and IV with an error which fluctuated between 20 and 35%. The resulting errors in the determination of distances from the axis were of the order of 40% for $r \leq 3$ m, 50 — 60% in the range 3 — 6 m and approximately 80% in the range 6 — 10 m. Because of this relatively low accuracy in determining the axis position we grouped all detected showers according to the three given ranges of distances

*The numerical value of the coefficient, 2.7×10^{-3}, was taken from the preliminary results in Ref. 3, whose authors have now corrected the value. However, since we were interested only in relative data concerning showers with different numbers of particles, we did not readjust the values of N in the detected showers.

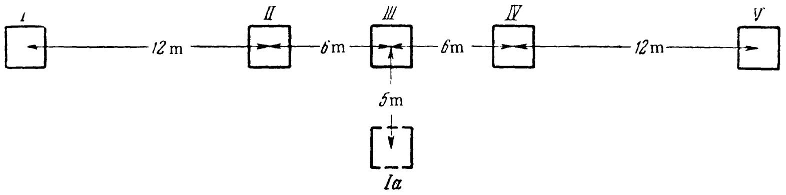

FIG. 1a. Arrangement of the groups of hodoscope counters.

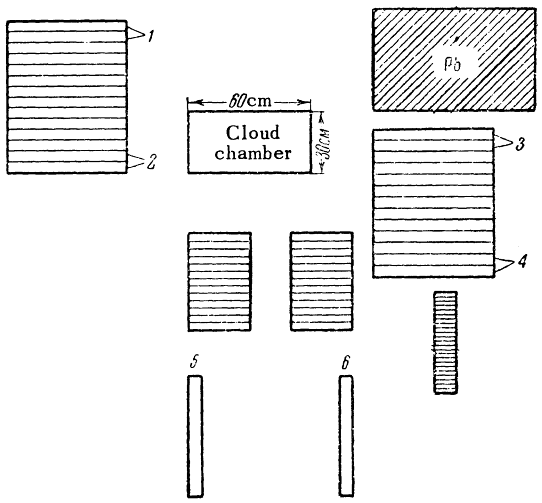

FIG. 1b. Arrangement of the hodoscope counters and cloud chamber in group III.

and put into a separate group those showers whose axes were more than 10 m distant from the cloud chamber. In addition to distributing showers according to intervals of distance we combined into different groups the showers which contained different numbers of particles. Table I contains the distribution of all of the detected showers according to intervals of r and N.

TABLE I

N	$r \leqslant 3$	$3 < r \leqslant 6$	$6 < r \leqslant 10$	$r > 10$	Σ_r
10^3—$5 \cdot 10^3$	33	4	—	—	37
$5 \cdot 10^3$—10^4	96	8	—	—	104
10^4—$5 \cdot 10^4$	407	349	54	26	836
$5 \cdot 10^4$—10^5	97	221	139	81	538
10^5—$5 \cdot 10^5$	50	192	131	190	563
$5 \cdot 10^5$—10^6	8	14	15	26	63
10^6—$5 \cdot 10^6$	—	6	5	23	34
$\sum_N$	691	794	344	346	2175

Figs. 2a and 2b show the distribution with respect to r and N of showers registered by the different systems of control. As can be seen from Fig. 2a, the M_2 and M_3 systems effectively selected showers whose axes were less than 10 m distant from the cloud chamber, while the M_1 system registered the large number of showers whose axes were more than 10 m distant from the cloud chamber.

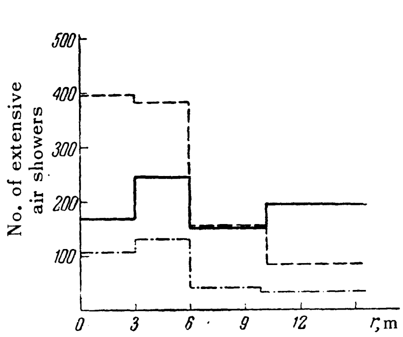

FIG. 2a. Distribution of showers over intervals of distance for different systems of control. Solid line — M_1; dashed line — M_2; dots and dashes — M_3.

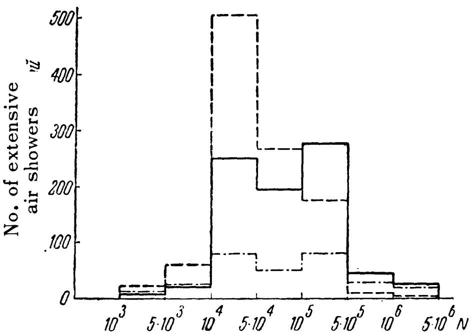

FIG. 2b. Histogram of shower distribution over intervals of N for different systems of control. Solid line — M_1; dashed line — M_2; dots and dashes — M_3.

From the error in determining distances to the shower axis we estimated the probability that a group of showers at a given distance from the cloud chamber would include showers from other distance intervals. These estimates are given in Table II, from which we see that each group of showers within a definite interval of distances between the axis and the cloud chamber contains some admixture of showers from other distance intervals. This fact was taken into account in studying the dependence of various shower characteristics on the distance of the axis.

For determination of the angular distribution of the axes we selected showers which satisfied the following requirements:

1. The shower axis passes the cloud chamber at a distance $r \leq 3$m in the horizontal plane. This requirement is associated with the fact that the direction of the shower axis is determined by the directions of the electrons, and that at large distances from the axis the electrons have low energies, are

strongly scattered, and move in directions which do not correspond to the direction of the shower axis.

2. The number of shower particles is $N \geq 3 \times 10^4$, and all showers are recorded, whose axes are ≤ 3 m from the cloud chamber, regardless of their directions.

3. The cloud chamber contains either three parallel tracks or an electron cascade developed in the lead plates with a clearly defined core and a parallel track. Tracks were regarded as parallel if their directions did not differ by more than 10°.

These conditions were satisfied by 154 showers. As a rule, each photograph included some tracks which were parallel within 10°. A stereocomparator was used to measure the space angles between these tracks, with an accuracy between 1° and 3°. The results were averaged taking into account the statistical weight, which was assumed to be proportional to the square of the energy of the electron producing a given track.* Thus the direction of the shower axis was determined mainly by high-energy electrons which pass close to the shower axis and maintain its direction.

TABLE II

Interval of distances m	Total number of showers in the distance intervals.*	Probable fraction of the showers assigned to adjacent distance intervals**	Probable addition from adjacent distance intervals**	
			Interval, m	Addition, %
$r \leq 3$	554	10.5%	3—6 m 6—10 m	23 2.5
				Total 25,5
3—6	762	28%	$r \leq 3$ 6—10	8 9
				Total 17
6—10 $r > 10$	324 297	57%	3—6	—27

*Table II includes only showers in which the number of particles is between 10^4 and 5×10^5.

**Relative to the total number of showers in the given distance interval.

Table III contains the distribution of extensive showers over the intervals of angles which their axes formed with the vertical. If this angular distribution is approximated by a $\cos^n\theta$ law, we see from Fig. 3 that the exponent is $n = 8.3 \pm 1.4$.

TABLE III

Angular interval	0°—10°	10—20°	20—30°	30—40°	40—50°
$\bar{\theta}$ *	6°	15°50′	25°	35°40′	43°40′
Number of extensive air showers	22	49	51	22	10
Number of extensive air showers per unit solid angle** $J(\bar{\theta})$	232±54	178±25	121±17	42.7±9	18.4±6

*$(\bar{\theta})$ is defined as the arithmetic mean of the angles which were registered in the respective intervals.

**The variation of the effective area in the registering of extensive showers forming the angle $\bar{\theta}$ with the vertical was taken into account by introducing the factor $1/\cos\bar{\theta}$.

The literature contains numerous investigations of the angular distribution of extensive air showers both at sea level[4-7] and at mountain altitudes,[6-12] in which various methods were used. As a rule, in all work with counters and a cloud chamber, in which the direction was determined by statistical averaging of the directions of the registered particles in extensive showers,[6,7,12] the exponent n in the $\cos^n\theta$ approximation of the angular distribution was found to be smaller than in those investigations where the directions of the showers were measured according to the flux of high-energy particles[4,8,9-11] or by means of scintillation counters.[5] It must be noted that when the directions of individual particles are averaged statistically a distortion is introduced by the scattering of these particles, whereas the high-energy particles in the cores of extensive air showers are scattered less and preserve the direction of the shower axis. The most reliable measurements of the angular distribution are those in which the directions of high-energy particles are determined. Our results are in agreement with these measurements.[4]

*We know that the statistical weight w is by definition inversely proportional to the square of the error: $w \sim 1/(\Delta\theta)^2$. Since the error in the angle, due to scattering, is inversely proportional to the particle energy, $\Delta\theta \sim 1/E$, and we have $w \sim E^2$.

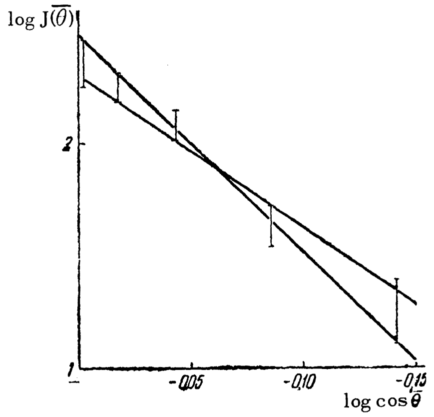

FIG. 3. Angular distribution of the axes of extensive air showers.

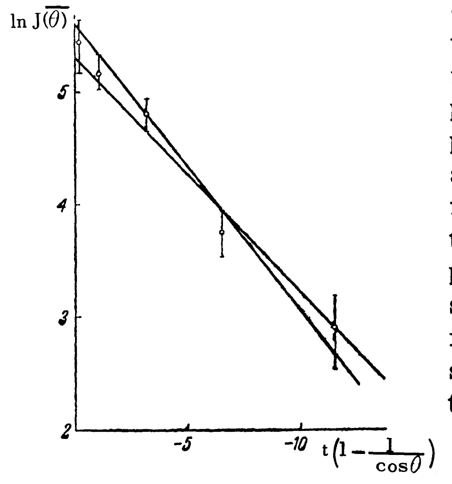

FIG. 4

From the angular distribution of the axes we can determine μ, the shower absorption coefficient in air. If it is assumed that the primary particles enter the atmosphere isotropically and that showers are absorbed exponentially, depending only on the amount of matter traversed and not on the length of path (thus neglecting decay processes), we easily obtain the following relation between the shower intensity $J(\theta)$ at angle θ and the vertical shower intensity $J_\perp$:[13]

$$J(\theta) = J_\perp \exp\left\{\mu t\left(1 - \frac{1}{\cos\theta}\right)\right\}.$$

Figure 4 shows the experimentally determined relation between $\ln J(\overline{\theta})$ and $t(1 - 1/\cos\theta)$ for t = 30 radiation units. The slope of the line is determined by the value of the shower absorption coefficient, which is 0.237 ± 0.025 or 145 ± 15 g/cm^2, in agreement with the value obtained from a study of the barometric effect.[14]

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