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ON THE ZENITH ANGLE DISTRIBUTION OF HIGH-ENERGY EXTENSIVE AIR SHOWERS

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A cloud chamber ~ 600 cm^2 in area and a hodoscope consisting of a large number of counters were used to study the zenith-angle distribution of extensive air showers initiated by ultra-high-energy primaries of $\sim 10^{17}$ ev. The data obtained indicate that, contrary to accepted ideas, such showers are past the stage of maximum development at mountain altitudes.

A direct study of the longitudinal development of extensive air showers (EAS) is extremely difficult. At the same time, the position of the maximum in EAS, which depends on the character of nuclear interactions of ultra-high-energy particles, is of considerable interest. The present experiment set out to provide an estimate of the absorption, at mountain altitudes, of extremely energetic EAS initiated by particles of $\geq 10^{17}$ ev, from their zenith-angle distribution.

The measurements were carried out at 3860 m, using a small cylindrical cloud chamber 30 cm in diameter with an illuminated region 6 cm deep, in conjunction with a hodoscope array described in reference 1 (cf. Fig. 1). The hodoscope made it possible to locate the axes of the EAS with respect to the chamber, and to determine the total number of particles in individual showers.

Since the direction of the particle flux in EAS is nearly vertical, the cloud chamber was placed horizontally.* The effective area of the chamber for vertical flux was 615 cm^2. The pictures were taken from above, the lens axes of the stereoscopic camera forming an angle of 30° with the vertical.

An electric field was used to split the particle tracks to enable us to distinguish shower particles from those arriving at random.* For that purpose the field was switched off after a relatively long delay of $\sim 10^{-2}$ sec with respect to the trigger pulse.

The measure of splitting corresponding to shower particles was found in a separate experiment, in which we determined the splitting of the track of single charged particles, which triggered the chamber. Measurements on the tracks of particles which did not trigger the chamber and which were recorded in random expansions has shown that, on the average, not more than 0.3 random tracks per picture exhibited the splitting accepted as the identification of shower particles.

Altogether 75 EAS were recorded by the array. All tracks of shower particles in the chamber were relativistic.

The distribution of EAS with respect to the number of tracks observed in the cloud chamber is given in Table I. The density spectrum of shower particles measured by the hodoscope[1] and the data of Table I, yield the following features of EAS: the mean shower-particle density averaged over the density spectrum,† the number of cases in which no shower particle fell upon the chamber, and the number of cases when one, two, etc. particles fell upon the chamber. These results are given below

*The chamber was placed in a light plywood hut with a lid 3.5 g/cm^2 thick. The thickness of the top glass of the chamber amounted to 1.5 g/cm^2.

*Following a suggestion of N. G. Birger.

†The densities are based on a chamber area of 615 cm^2.

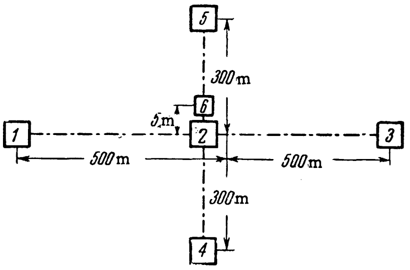

FIG. 1. Plan of the array. 1, 2, 3, 4, 5 – groups of hodoscope counters (for details cf. reference 1); 6 – cloud chamber.

for the hodoscope and the cloud chamber:

	$\bar{\rho}$	$\overline{e^{-\rho}}$	$\overline{\rho e^{-\rho}}$
Cloud chamber measurements	4 ± 1.3	0.5 ± 0.1	0.24 ± 0.05
Hodoscope measurements	3.4	0.34	0.20

It can be seen from the above that there is good agreement between the statistical data obtained by means of the cloud chamber and hodoscope respectively.

The axis position and the total number of particles for nine showers with the largest number of tracks in the cloud chamber are given in Table II.

TABLE II

No. of event	Number of shower-particle tracks in the chamber	Total number of particles in the EAS	Position of the axis (Distance from the cloud chamber, m)
1	6	10^8	200
2	6	$5\cdot10^7$	160
3	12	10^8	170
4	11	10^8	190
5	7	$5\cdot10^6$	700
6	26	10^8	100
7	26	$8\cdot10^8$	250
8	20	$5\cdot10^7$	90
9	80	$2\cdot10^8$	100

It can be seen that in all nine cases the cloud chamber was at the periphery of the high-energy EAS.

The photographs of shower particles enable us to study the angular distribution of shower particles at the periphery of EAS.

The direction of the tracks was determined by projecting the pictures through the same camera which was used for photography.[2]

The direction of each trajectory was found by measuring the zenith and azimuth angles ϑ_i and φ_i (cf. Fig. 2). These were used in turn to determine the mean direction of the shower particle flux and the deviation of single trajectories from the mean in each measured shower. The mean

TABLE I

Number of particles observed in the chamber	Number of showers	Number of particles observed in the chamber	Number of showers
0	28	9	0
1	22	10	0
2	13	11	1
3	2	12	1
4	1	—	—
5	1	>20	1
6	2	26	1
7	1	26	1
8	0	~80	1

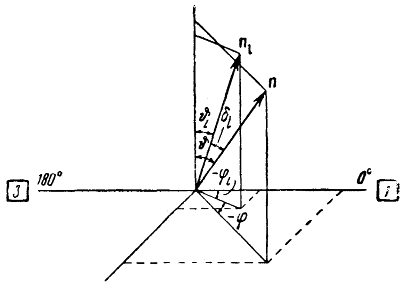

FIG. 2. Angles used in the determination of the mean direction of shower tracks (n) and the deviation of individual tracks (n_i) from it. $\bar{\vartheta}$, $\bar{\varphi}$ – angles determining the mean direction; ϑ_i, φ_i – angles determining the direction of individual particles; δ_i – angles characterizing the deviation of individual tracks from the mean direction. 1 and 3 – hodoscope counter groups (cf. Fig. 1).

direction was defined as a vector, the Cartesian components of which are

$$\overline{l_i \cos\vartheta_i}\ ;\quad \overline{l_i \sin\vartheta_i \cos\varphi_i}\ ;\quad \overline{l_i \sin\vartheta_i \sin\varphi_i}$$

where the index i refers to individual tracks.*

The deviation of individual tracks from the mean direction is characterized by the angle δ_i (Fig. 2) between the mean direction and the track.

The angular distribution of shower particles is characterized by the angle $(\overline{\delta^2})^{1/2}$.

Results of the corresponding calculations are given in Table III.

It should be noted that the mean direction of the shower particle flux at the periphery of EAS is very nearly vertical. Clearly, the axes of these showers should be even closer to the vertical. In spite of poor statistics, it is possible to draw conclusions about the zenith-angle distribution of the recorded showers. Let us assume that the zenith-angle distribution Y(v) is of the form $A\cos^x\theta$, where $A = (x+1)/2\pi$, so that

*The factor $l_i = s_0/(S_0 \cos\vartheta_i + s_0 \sin\vartheta_i)$, where S_0 is the area of the horizontal cross section of the chamber, and s_0 the area of the vertical cross-section along the diameter, takes into account the detection probability of particles going at an angle ϑ_i to the vertical.

$$\iint A \cos^x \theta \sin \theta \, d\theta \, d\varphi = 1.$$

We shall apply now Bayes' Theorem to find the distribution function of the variable x and its most probable value. According to this theorem, the distribution of x is given by the expression

$$P(x, \theta_1, \theta_2, \theta_3 \ldots) = C(x+1) \prod_{i=1} \cos^x \theta_i \sin \theta_i,$$

where it is assumed all values of x have the same a priori probability, and that the probability of occurrence of an angle between $\overline{\theta}_i$ and $\overline{\theta}_i + d\overline{\theta}_i$ under the assumption of a $\cos^x \theta$ distribution is given by the expression

$$[(x+1)/2\pi] \cos^x \theta_i \sin \theta_i \, d\theta_i.$$

TABLE III

No. of event	No. of particles, n	θ,(deg)	φ,(deg)	$(\overline{\delta^2})^{1/2}$, deg
1	6	25	−150	31
2	6	15	+ 53	28
3	12	16	− 65	32
4	11	14	−156	18
5	7	25	− 51	10
6	26	5	+110	26
7	26	18	+ 20	30
8	>20	≈30	+135	—
9	~80	≈40	+150	—

The function $P(x, \theta_1, \theta_2 \ldots \theta_9) \equiv P(x)$ is shown in Fig. 3. It enables us to find the most probable value of x and its error: $x = 11^{+4.5}_{-3.5}$. The zenith angle distribution is therefore very steep. This is confirmed also by the distribution of the angle φ (Table III). According to Table III, the distribution is uniform; it is almost independent of the bias of the experimental setup,[7] which detects with a higher probability showers with axes lying in the vertical plane passing through the line 1 — 2 — 3 (Fig. 1), i.e., with φ close to 0 and 180°.

It is interesting to compare the measured zenith angle distribution of EAS with that calculated according to the electromagnetic cascade theory for showers of similar energies. The zenith-angle distribution of the axes of showers with the number of particles $N > 10^8$* calculated according to the cascade theory is shown in Fig. 4. The experimental distributions $\cos^x \theta$ for x = 7.5 and x = 15.5 are included. A large discrepancy is seen between the experimental and theoretical distributions.

*This corresponds, according to the cascade theory, to $\sim 10^{17}$ ev primary energy at 3860 m altitude.

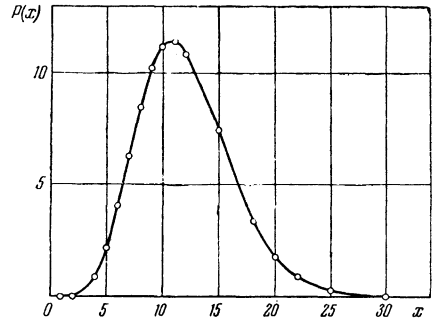

FIG. 3. Distribution function P(x) of the exponent x in the expression for the zenith angle distribution of recorded showers ($\cos^x\theta$). The y axis represents the probability of a given x in arbitrary units.

It is known[6] that the absorption mean free path for shower particles is given by the expression $\lambda = \kappa t/x$, where κ is the exponent of the size spectrum, and t is the depth of the observation level. According to reference 1, $\kappa = 2.1$ for large showers with $N \sim 10^8$; for the Pamir station t = 650 g/cm^2. For the found values of x we have, therefore, $\lambda = 124^{+58}_{-36}$ which does not contradict the analogous results obtained recently at sea level[6] for showers of the same energy.

The experimental data indicate therefore that EAS initiated by high-energy primaries are, even at mountain altitudes, far beyond the maximum of their development, contrary to accepted ideas. More detailed experiments on the longitudinal development of high-energy showers would be therefore of considerable interest.

In conclusion we wish to give an estimate of the energy of electrons at the periphery of EAS from the values of $(\overline{\delta^2})^{1/2}$ given in Table III.

From the multiple-scattering theory we have for $E \ll \beta$ (where β is the critical energy, equal to 72 Mev for air), $(\overline{\vartheta^2})^{1/2} = 19 \text{ Mev}/(E_\beta)^{1/2}$.

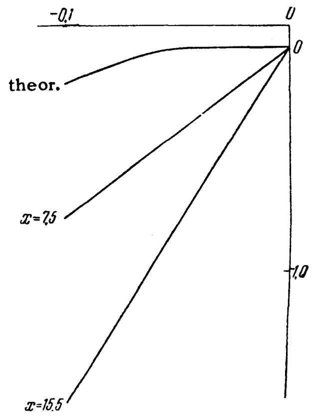

FIG. 4. Comparison between the theoretical and experimental zenith angle distribution of the axes of EAS with the number of particles $N \geq 10^8$ at the depth of 19 radiation units. The x axis represents log cos v, the y axis – log Y(v).

From Table III we obtain for E values on the order of 10 to 20 Mev.

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