Air-Shower Cores*

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A large cloud chamber has been used to study the density and energy distributions at the cores of air showers. The observed intensities of events with a local density $\geqslant 500$ particles/m^2 over an area less than one m^2 and of events attributed to shower axes that passed through the detector agree with ionization-chamber and G-M counter data. The observed density and energy distributions of the shower rays in events attributed to shower cores require a multiplicity of initiators with a low average energy. On the other hand, only a minor fraction of the cores shows direct evidence for multiplicity. A consistent explanation is difficult to construct.

I. INTRODUCTION

THE lateral structure of cascade showers has been investigated theoretically most recently by Eyges and Fernbach,[1] who have constructed lateral distribution functions for various depths. They have joined the distributions with Molière's[2] and have used the Molière results for small distances from the shower axis.

Experiments by the Cornell group[3] and by Williams[4] yielded results that are in agreement with the Molière distribution for distances from one meter to 250 meters from the shower axis. On the other hand, the results of Williams are probably inconsistent with the Molière distribution for distances less than one meter (as evidenced by his counting rates for detector separations less than one meter).[5] If we assume that the main development of air showers involves only the usual electromagnetic cascade phenomena, we apparently have disagreement with a model based on a single shower core. The reasonable interpretation seems to be that a multiplicity of cores occurs with separations of the order of one meter and less at an altitude of 3000 meters. Thus, a model for the origin of large air showers presumably should predict an initial multiplicity of γ-rays or electrons with angular separations of the order of 10^{-4} radian in the observation system. In the customary present model involving the production of π^0 mesons and their subsequent decay into γ-rays, angles of the order of 10^{-5} to 10^{-4} are generated in the decay process itself, and hence no additional mechanism is needed to explain the observed size of the non-singular region near a shower axis. However, the production of π^0 mesons is probably multiple at high energies, and, therefore, our model should also include production angles less than 10^{-4} for high energy (10^{12} to 10^{14} ev) events. Since the production angles are probably a function of energy and since the observed angles are certainly a function of energy, it is desirable to know the energy of each event that is observed.

A large cloud chamber, with observation area 25 by 80 cm, has been operated at a 3000-meter altitude in an effort to learn more about the structure of air showers within distances less than one meter from the axis. The cloud-chamber observations provide: (*a*) good resolving power for the study of lateral structure over small distances (the lateral structure is obtained from the spatial distribution of electrons in the top section); (*b*) a means of estimating the energies of the higher energy incident electrons and photons by observing the development of cascade showers in the lead plates; (*c*) a determination of the angle of incidence; and (*d*) qualitative information concerning the effect of the N-component. All the above information is available for each event.

The discussion will be divided primarily into sections on absolute intensities, predicted characteristics of cascade showers near the axis, a comparison with the observations, and conclusions.

II. EXPERIMENTAL ARRANGEMENT

The cloud chamber contained five one-inch lead plates. Since the plates occupied a region 40×90 cm in plan and only 28 cm high, the geometry was quite good in the sense that only a small fraction of the rays from inclined showers entered the array from the sides or ends; such rays could be identified from the stereoscopic photographs. The observation area was about 25×80 cm (0.2 m^2). The data chosen for analysis were taken with two or three inches of Celotex and wood above the cloud chamber which itself had a one-half inch Dural top.

The triggering, which was intended to be moderately selective for the high energy region of showers, was done by multiple coincidences among shielded counters below the cloud chamber and an unshielded counter tray (15×70 cm) about 2 meters to one side and level with the top of the chamber.

III. ABSOLUTE INTENSITIES

In this section we shall establish the validity of the criteria for identification of air-shower cores. It will be shown that the frequency of occurrence of events satis-

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[1] L. Eyges and S. Fernbach, Phys. Rev. 82, 23 (1951); Phys. Rev. 82, 287 (1951); S. Fernbach, Phys. Rev. 82, 288 (1951).
[2] See Eyges and Fernbach, Phys. Rev. 82, 23 (1951) for detailed references to other works.
[3] Cocconi, Tongiorgi, and Greisen, Phys. Rev. 76, 1020 (1949).
[4] R. W. Williams, Phys. Rev. 74, 1689 (1948).
[5] J. M. Blatt, Phys. Rev. 75, 1584 (1949).

fying the criteria agrees with ion-chamber and G-M counter data.

The photographed events were generally attributable to (*a*) air showers of sufficient density and energy to register with the counters and (*b*) low density air showers in which a meson or an N-ray gave rise to a cascade shower in one of the lower lead plates by a bremsstrahlung process or by a specifically nuclear interaction. It was possible but improbable that the side tray be triggered by a secondary from an interaction in the cloud chamber. The triggering system was selective for high energy or high density portions of showers and also for showers inclined slightly from the vertical.

Only showers that displayed more than 100 electrons in the top section of the chamber or had a structure that seemed to be characteristic of a core were studied in detail. There were 105 events satisfying the above criteria.

A. Frequency for Local Densities >500 m^{-2}

There were 95 events in 272 hours in which more than 100 electrons appeared in the cloud chamber. Since the density distributions were essentially uniform in nearly all cases, these events would correspond to densities of about 500 m^{-2} over areas of the order of one square meter or less.

The transition effect for showers in general has been found experimentally to be negligible up to thickness of $\sim\frac{1}{10}$ radiation unit of brass by Palmatier.[6] On the other hand, Bethe[4] has derived a formula for small thickness which predicts an increase in number of electrons by a factor of $1+2(1-7.2/Z)t/X_0$, which becomes 1.15 for $\frac{1}{10}$ radiation unit of brass. Thus the magnitude of the transition effect predicted on the basis of theory is likely to be too high.

The above results apply roughly to the spectrum of all rays at the observation level regardless of distance from the longitudinal axis. This statement is not quite true for the experimental case because any counting rate is preponderantly due to minimum-size showers striking near the detector. In the present experiment, on the other hand, we are concerned only with effects near the shower axis where the electron and photon spectra are harder than for the average over the entire lateral extension of the shower. The effect of the harder spectrum of electrons is to decrease the fraction of electrons that will be absorbed by ionization in the transition layer (the number of electrons will will disappear by radiating all but a few Mev of their energy may be neglected). The effect of the harder spectrum of photons is to increase the fraction of photons that materializes in the transition layer. From the above, we should predict that the transition effect near the core is greater than for the shower as a whole. However, there is a compensating factor that we have not yet considered: the mean square lateral spread of photons is greater than that of electrons according to Roberg and Nordheim.[7] Thus the ratio of photons to electrons is less near the core of a shower than the average over the lateral extension of the shower. A numerical evaluation was made for the transition effect in $\frac{1}{8}$ shower unit of aluminum one meter from the axis of a shower for an initial energy E_0 of 5×10^{12} ev at a depth of 16 shower units. The track lengths of Richards and Nordheim[8] were used for the low energy distributions of electrons and photons, and the spectra obtained later in the paper were used for the high energies. The result is a prediction of a net increase in the number of electrons by 20 to 30 percent. In view of Palmatier's experimental results it is quite likely that the actual transition effect is less than calculated and therefore may be neglected in the present analysis.

The angular distribution of the observed events indicated a deficiency of showers from the vertical, as we should expect from the geometry of the detector. The undetected vertical showers presumably contained no very high energy particles in the region of the detector and were not of interest in the study of cores; but they should be included for a total intensity measurement. When we fill in the missing number of showers by using a $(\cos\theta)^8$ distribution,[9] the total number is increased by 40 percent. The correction is not very sensitive to the value of the exponent. After the above correction, the observed frequency becomes 0.5 hr^{-1}, which might be compared with Williams's[4] observation of one hr^{-1} for a density >500 m^{-2} over regions of the order of one m^2 or less.

Thus we conclude that about one-half of the events with a local density >500 m^{-2} contained electrons of sufficient energy to trigger the "core selector" system; and, in fact, we find that nearly all the events observed in the cloud chamber included rays of energy $>10^9$ ev.

B. Frequency for Shower Axes

Events that showed concentrations of high energy rays or marked singularities in the density distribution of incident electrons associated with high energy rays numbered 24. Only 14 of the 24 had more than 100 electrons appearing in the top section of the chamber. Thus, there was 0.05 event per hour that we might attribute to shower axes passing through the chamber and with 100 or more electrons incident on the chamber from the air. Since the area was 0.2 m^2 and since, as we shall see later, the fraction of electrons included within the chamber area is about 1/200 of the total number, we obtain a rate of 0.25 hr^{-1} m^{-2} for showers in which the total number of electrons is greater than 2×10^4. We have used the Molière distribution just as have others. Blatt's analysis[5] of Williams's data gives a rate of 0.3

[6] See reference 3, p. 1025.

[7] J. Roberg and L. W. Nordheim, Phys. Rev. **75**, 444 (1949).

[8] J. A. Richards and L. W. Nordheim, Phys. Rev. **74**, 1106 (1948).

[9] M. Deutschmann, Z. Naturforsch. **2**, 61 (1947).

to 0.63 $\text{hr}^{-1}\ \text{m}^{-2}$ depending on which ion-chamber geometry is used. The counter measurements by Ise and Fretter[10] gave a rate of 0.31 $\text{hr}^{-1}\ \text{m}^{-2}$. Thus, the flux of cores observed in the cloud chamber agrees with the flux of shower axes calculated from ion-chamber or counter measurements.

C. Probability of Shower Axis within the Chamber

The absolute shower rate can also be verified by the application of the lateral distribution function in the analysis of the cloud-chamber results alone. We can calculate the fraction of events with n or more particles incident on the chamber area that should be due to the presence of a shower axis within the chamber.

If we let a be the detector area and R the radius of the circle within which a shower axis must strike in order to display n electrons within the detector area, we have

$$P=\int_{N_m}^{\infty} af(N)dN \Big/ \int_{N_m}^{\infty} \pi R^2 f(N)dN$$

for the probability that an event with n or more electrons within a is due to a shower axis within a. The quantity $f(N)dN$ is the experimentally determined frequency of occurrence of shower events with a total number of electrons N at the point of observation.[4, 5, 10] It has been found that

$$f(N)dN=KN-\gamma dN,$$

where $\gamma=2.5$ for $N<10^6$ and 2.9 for $N>10^6$. In setting up the denominator in the expression for P, it was assumed that the detector area is small (or circular). Actually, the region within which a given-size shower must strike is not circular for a rectangular detector; but a more exact treatment shows that the area of the region is not very different from the area of the circle.

Strictly speaking, N and R are related through an integral of the lateral-distribution function over the area of the detector. However, a sufficiently good approximation is obtained by assuming that the average particle density within the detector is the same as the particle density at the center of the chamber; whereupon

$$n/a=(0.454N/R)(1+4R)\exp(-4R^{2/3}),$$

if we use the analytical expression of Bethe.[4]

For the case of a shower axis within the detector area, which must be considered in establishing the value for N_m, the above approximations are less valid. Hence a graphical solution that gives an average value of $n/N=1/200$ for the case of axes passing through a rectangular area 25 by 80 cm was used. The function n/a was approximated by power laws in R with an appropriate power for each of three intervals. The integration of the denominator in the expression for P could then be performed analytically. The result for $n=100$ and $a=0.2\ \text{m}^{-2}$ is $P=0.1$.

[10] J. Ise and W. B. Fretter, Phys. Rev. **76**, 933 (1949).

The observed probability that an event is attributable to a shower core for cases where the local density $\geqslant 500\ \text{m}^{-2}$ was 14/95 before corrections. The correction for variation of detector sensitivity with angle presumably applies chiefly to lower energy events and, therefore, to a first approximation, should be applied to the 81 events with axes outside the chamber but not to the 14 with axes inside the chamber. Since the correction was about 40 percent, we obtain $14/(14+1.4\times 81)$ or 0.11 for the observed probability.

The variation with distance from the axis of the transition effect in the Duralumin chamber top would give a small correction, again in the direction of reducing the observed probability. The effect of multiplicity of cores is more difficult to evaluate. The *a priori* probability is, on the one hand, increased by the presence of a multiplicity of cores with separations comparable to the detector dimensions, but, on the other hand, diminished by the decrease in rapidity of the density variation as we leave the region of the cores. The probability of core identification may also be diminished in the case of multiplicity. The errors in the Molière distribution have been discussed qualitatively by Blatt.[5] The actual distribution for a shower at its maximum is probably more peaked than the Molière distribution, but the smaller showers may be beyond the maximum in their longitudinal development and may therefore have a distribution that is flatter than at the maximum.

Since the corrections are not predominantly in one direction, it seems unlikely that the above predictions of shower intensities based on the Molière distribution are wrong by as much as a factor of two. Thus we have again demonstrated that many of the core identifications must be valid if we agree on the essential correctness of the lateral distribution of Molière.

IV. SHOWER THEORY PREDICTIONS FOR PROPERTIES OF AIR-SHOWER CORES

In this section, the existing calculations of the electron cascade shower theory will be used to describe the expected characteristics of the showers. Since we are interested only in effects near the axis of a shower, the expressions for the density distribution are simple, and only in the normalization need we be concerned with the entire distribution. For particles of all energies we use Bethe's[4] expression for the density distribution

$$\rho(N,r')=N(0.454/r')(1+4r')\exp[-4(r')^{\frac{2}{3}}],$$

where N is the total number of electrons and r' is in units of $\sim 10^4$ cm at an elevation of 3000 m. The simpler expression $N(0.454/r')$ is accurate to within 15 percent to distances of one meter and a factor of two at 10 meters and hence will usually suffice.

A. Observed Fraction of Particles

If we calculate the maximum fraction of particles observed within the cloud-chamber area of 2000 cm^2 for an axis centered in the cloud chamber and assuming

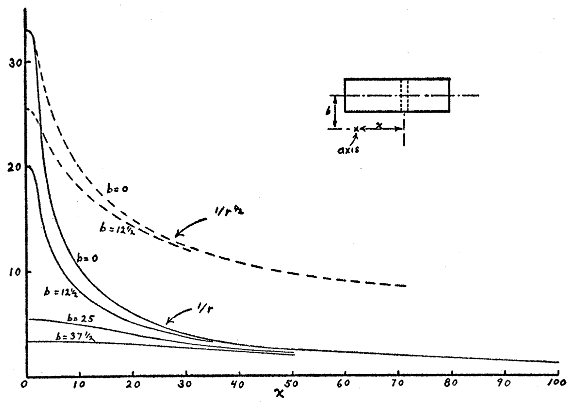

FIG. 1. Predicted density distributions of electrons incident on the cloud chamber. The densities are given as the number of electrons in finite areas 5×25 cm. The diagram in the upper right hand corner shows the meaning of the symbols (x and b are in cm); the heavy lines outline the cloud chamber and the dotted lines a 5×25 cm area. For the $1/r$ distribution the absolute number of electrons is obtained by multiplying an ordinate by 0.454 $N/10^4$, where N is the total number of electrons. The curves for the $1/r^{\frac{1}{2}}$ distribution have the correct heights relative to each other but the absolute scale is unknown.

a circular area, we have ($k=0.454$)

$$(n/N)_{\max}=\int_0^{(a/\pi)^{\frac{1}{2}}}(k/r')2\pi r'dr'$$

which is 1/140 for $a=2000$ cm^2.

A more accurate calculation in which the rectangular shape is treated exactly but the density distribution is still approximated by kN/r' gives only a slight change: $(n/N)_{\max}$ varies from 1/150 to 1/300 and has an average value of 1/200. The last figure is the reason for the earlier statement that only events of $N>2\times10^4$ contribute to the observations where $n>100$.

B. Density Distribution within the Detector Area

When the axis of a shower is within or near the detector area, the distances are so small that $\rho(N,r')=kN/r'$ is an excellent approximation to the Molière distribution. We observe the projected density in the cloud chamber, which is given by

$$\rho(N,x)=kN\int\frac{dy}{(x^2+y^2)^{\frac{1}{2}}}=kN\left[\sinh^{-1}\frac{y}{x}\right]_{y_1}^{y_2},$$

and in cases where $y/x\gg1$, the approximation $kN\ln(2y/x)$ was used. For the sake of comparison with the observations, an interval $\Delta x=5$ cm was chosen, since statistical variations of the number of tracks in a cell 5×25 cm were expected to be reasonable for the size shower usually studied.

Graphs of the projected densities for positions of a shower axis in the midplane of the chamber, along the front or back edges, and $12\frac{1}{2}$ or 25 cm before or behind the chamber are shown in Fig. 1. We see that a very marked singularity is expected when the axis is within the chamber and an easily detected variation in density if the axis is within $12\frac{1}{2}$ cm of the boundaries in any direction.

TABLE I. Cascade theory predictions with the shower axis within the cloud chamber area. W_0 is the energy of the initiating photon, $n(0)$ is the number of electrons of all energies and $n(E)$ is the number of electrons *and photons* of energy $\geq E$ within the chamber area, and t is the depth in shower units.

W_0		10^{12}	5×10^{12}	10^{13}	2×10^{13}	5×10^{13}	10^{14}
$n(0);t$	16	1.5	12	28	75	200	400
	18		7	17	45	120	300
	20		4	10	27	85	170
$\frac{n(10^9)}{n(0)};t$	16	0.38	0.50	0.55	0.65	0.80	0.95
	18		0.40	0.46	0.52	0.60	0.72
	20		0.32	0.34	0.38	0.48	0.66
$n(10^{10});t$	16	0.12	0.75	3	10	40	110
	18			1	4	18	54
	20			0.4	1.7	8	23
$n(10^{11});t$	16			0.3	1	4	11
	18					2	5
	20					0.8	2

C. Energy Distribution

Only a small sample of a given shower is observed with the cloud chamber, and the small samples of particular interest are those at or near the cores. Since the high energy rays are concentrated near the core, the energy spectrum near the core is much flatter than for the shower as a whole. For the sake of comparison with experiment, the relative number of rays with energy greater than E, where $E=10^9$ to 10^{10}, is the most useful information. Since the high energy rays are identified only by the showers that they make in lead, it is usually impossible to distinguish photons from electrons.

We shall calculate the density of electrons and photons with energy greater than E relative to the density of electrons of all energies near a shower axis. The density of electrons of all energies is kN/r' near the axis, which gives $2\pi kNr'$ for the number within a circle of radius r'. The lateral distributions for electrons and photons of high energy have been calculated by Eyges and Fernbach,[1] who have fitted their distribution, which is accurate at values of $Er>0.4$ (their E and r are in scattering units, 21 Mev, and shower units, respectively) to the Molière distribution, which is presumed to be accurate for smaller values of Er. They give probabilities from which we find that the integrated probability of finding a ray within a circle, r, is approximately 1.5 Er at the shower maximum and 1.0 Er at a depth twice the maximum, when $Er\leq0.3$. Since the energy spectrum is about dE/E^2 for $\epsilon\ll E\ll E_0$, which is valid in our case, the probability of an electron of energy $>E$ lying within a circle of radius, r, is

$$\int_E^{E_{\max}}1.5E'r\frac{dE'}{(E')^2}\bigg/\int_E^{E_{\max}}\frac{dE'}{(E')^2},$$

which becomes 1.5 $Er\ln E_{\max}/E$; similarly we have

$Er \ln E_{max}/E$ at twice the depth of the maximum. For comparison with observation a convenient value for E is 50 (i.e., 10^9 ev), since showers caused by rays of this energy are recognizable. For E_{max} we select 10 E, for there are few rays of greater energy and the assumptions we have made limit the validity of the results to regions within 50 cm of the axis for rays of 10^{10} ev energy. Since the region of validity is 5 meters for 10^9 ev, since the spectrum is very steep, and since the approximations do not rapidly become bad for larger distances, the results are useful for distances of 1 or 2 meters, which is exactly the region we wish to study.

The ratio of the probability for a ray of energy $>E$ to the probability for an electron of any energy to fall within r is 1.5 $Er \ln(E_{max}/E)/2\pi kr'$, which becomes 15 for the shower maximum or 10 at twice the depth of the maximum (we must note that $r/r'=\frac{1}{4}$).

Roberg and Nordheim[7] find a value for the second moment of the photon distribution that is larger than for electrons. On the other hand, Eyges and Fernbach[1] find a narrower distribution for photons. Therefore, we shall assume the same distribution for photons and electrons.

The other factor that enters into the determination of the relative number of high energy rays near the axis is the total number of rays of energy $>E$ or W, i.e., $\Pi(W_0, E, t)+\Pi(W_0, W, t)$, in the notation of Rossi and Greisen, compared with the total number (N) of electrons of all energies. Thus, the relative density near the axis becomes $R=15$ or $10\,[\Pi(W_0,E,t)+\Pi(W_0, W, t)]/N$ at the maximum or twice the depth of the maximum, respectively. The second factor in R is a slowly varying function of initial energy (W_0) with values ranging from 0.03 to 0.06 as W_0 goes from 10^{12} to 10^{14} ev. Finally, $R=0.45$ to 0.9 for $W_0=10^{12}$ to 10^{14} at the shower maximum, and $R=0.3$ to 0.6 at depth twice that of the maximum. A more exact numerical evaluation of R as a function of W_0, E, and r has also been made, but the present observations are not sufficiently detailed to justify the more meticulous treatment.

In Table I figures for the relative density of rays with energy $\geqslant 10^9$ ev are given, since we expect enough rays to make density a satisfactory concept in this case. For energies $\geqslant 10^{10}$ ev, the probability equation has been used to find the expected number of rays within the chamber area.

D. Radial Distribution of High Energy Rays

The cores of showers should be regions with concentrations that become more and more marked as we consider only rays of higher and higher energies. The final limitation of this method for identifying core positions within narrower and narrower limits is the decrease in number of rays with increasing energy.

In Part C it has been pointed out that the lateral distributions of Eyges and Fernbach[1] give a probability of 1.5 Er for finding a ray of energy E within a circle of radius r. If we choose a probability of 0.5 as a reasonable

TABLE II. Properties of events attributed to shower axes striking the cloud chamber. Notation is similar to Table I. θ is the projected angle. The positions of concentrations of high energy rays are indicated by asterisks.

Observations

Event No.	124 19	128 5	128 24	130 7	132 1	132 14	137 19	144 19	149 18	150 1	154 7	165 20	172 6	172 7	177 4
θ	8	18	37	15	4	12	7	6	27	2	13	42	22	0	24
$n(0)$	145	100	150	115	200	>500	170	>500	>100	115	200	125	250	500	150
$n(10^9)/n^{10}$	0.13	0.25	0.20	0.25	0.12		0.12			0.12	>0.10	0.14	0.08		0.13
$n(10^{10})$	3	5	10	10	7	12	4	2	10	2	5	3	3	6	3
$n(10^{11})$	1	1	1	1	1	0	0	0	1	0	0		0	0	0
No. of incident electrons per 5-cm band	7	4	16*	12	13	Uniform	8	Uniform	No data	4	12	10	13	Saturated	8
	7	10	10	13*	11*		9			6	13	10	18		9
	6	18*	12	10	17		8			7	7	9	16*		16
	6	13	10	12	14		12			7	8	14	19		11
	10	3	13	10	17		9			11	7	9*	18		7
	6	6	14	10	19		10			9	15	7	17		12
	11	7	14	8	16		9			9	7	6	19		9
	12	6	12	9	17		11			13	14	7	20		12*
	10	10	12	5	15		12			8	12	8	18		10
	9	6	10	6	12		12			5	16	8	Uniform		11
	12*	1	6	3	11		12			12	25*	12*			11
	11	5	7	4	15		16			14	20*	9			15*
	11	5	7	8	13*		20*			6	25*	8			8
	14	5	7	4	11					3	20	10			14

Cascade theory

	Single photon				4 photons		10 photons	
	$t=16$		$t=20$		$t=16$	$t=20$	$t=16$	$t=20$
$n(0)$	100	200	100	200	110	110	120	100
$n(10^9)/n^{10}$	0.7	0.5	0.8	0.7	0.55	0.4	0.5	0.34
$n(10^{10})$	15	11	40	28	12	7	7.5	4
$n(10^{11})$	1.5	1	4	1.5	1	0.5	1	

Predicted lateral distributions

	$1/r$ singularity		$1/r^{0.5}$ singularity	
No. of incident electrons per 5-cm band	On center line	At edge	On center line	At edge
	16	16	16	16
	8	9.6	12	13.5
	5	6.4	10	11
	4	4.8	8	10
	3	4	7	9
	2.5	3.2	6.5	8
	2	3	6	8
	1.5			
		2		
	1	1	4	5

way of defining the position of a shower core in terms of concentrations of high energy rays, we find $0.5=1.5\ Er_m$ from which $r_m=3\times10^{11}/E$, where r_m (the radius corresponding to probability one-half) is in centimeters and E in electron volts. At a depth twice the depth of the maximum $r_m=4\times10^{11}/E$. Therefore rays of energy $\geqslant 10^{10}$ should define the position of the shower axis within about 20–30 cm.

V. COMPARISON WITH OBSERVATIONS AND DISCUSSION

In Section III it was established that the observed intensity of core-like structures agreed with counter and ionization-chamber determinations of absolute intensities. In consequence, it is believed that the identification criteria for cores are adequate and that, by and large, we are really studying core structure.

A. Density Distribution

During the qualitative examination of the pictures, cases were noted in which there seemed to be a variation in density of the tracks in the top section of the chamber. Later, an actual count was made and in most cases there was no significant variation in density of tracks. The chamber was "saturated," as far as track counting was concerned, when the density became greater than about $20/5\times25=0.16\ \text{cm}^{-2}$, i.e., $1600\ \text{m}^{-2}$. The events that showed really marked singularities usually had only a small total number of particles. The density distributions are given in Table II for the events believed to be due to shower cores within the chamber area. The positions of concentrations of high energy rays are indicated by asterisks. The largest variations are seen to be only factors of two (perhaps three for 182–5) when statistical fluctuations are taken into account. The calculated density variations to be expected for the Molière distribution ($1/r$ singularity) and for a very old shower, $s=1.5$, with a $1/r^{\frac{1}{2}}$ singularity are listed for comparison. It is seen that the less peaked singularity describes the results better. However, the extreme case of $s=1.5$ corresponds to an initiating energy $\sim10^{12}$ ev and would require too many cores (>50) in order to make the required total number of electrons observed in the cloud chamber. On the other hand, if we require fewer cores, perhaps eight, the initiating energy becomes 5×10^{12} ev and s is only about 1.3 at $t=16$.

B. Energy Distribution

The energies of the incident rays can be estimated for energies greater than 10^9 ev, if we note the development of cascade showers in the lead plates. Clearly, photons as well as electrons are included in such an identification procedure since the large density of incident electrons precludes the possibility of distinguishing between photons and electrons. The usual figures of cascade theory for "total" number of electrons *versus* depth were halved in order to obtain a reasonable approximation for what might actually be observed in lead. This correction is based on observations of showers by primaries of known energy.[11]

The estimates of the number of high energy rays are presented in Table II and are intended to be upper limits. No rays from the air showers generated showers in lead corresponding to an energy appreciably greater than 10^{11} ev.

For comparison, the predicted characteristics of shower cores are given in Table II. We see that it is again necessary to go down to initiating energies less than 5×10^{12} in order to approach agreement with the observations.

C. Multiplicity of Cores

Since the density singularities are not very marked it is impossible to say very much about evidence for multiple cores from observations of density structure. We can say this much, however: The density seems to vary about like $1/r^{\frac{1}{2}}$ for a single core, and, since density variations do not appear in many cases, we might conclude that there are unresolved singularities. The separations would then be <50–60 cm according to the figures of Table II.

Only three or four pictures showed more than one concentration of high energy rays ($E>10^{10}$ ev) and none of these gave clear evidence for more than one core, each having at least one ray with an energy $\simeq10^{11}$ ev.

D. High Energy Rays from Nuclear Interactions

Cascade showers of energy $\sim10^{11}$ ev in the chamber were produced nearly as frequently (8 events) by mu-mesons or by N-rays as by air showers with 100 or more electrons incident on the cloud chamber. Most of the nuclear events were presumably associated with air showers, since the side tray subtended a solid angle at the cloud chamber that was rather small and in the upper hemisphere.

VI. CONCLUSIONS

The cloud-chamber observations show that the structure at the axis of air showers is inconsistent with a single initiating ray; both the density distribution of all electrons and the energy spectrum near the axis correspond to much lower energies than required for a single initiating ray. Initiating energies less than 5×10^{12} ev are required in order to approach agreement with cascade-theory predictions of local structure. A multiplicity of 10 is then required in order to produce the number of electrons observed in the chamber area; here we have used the Moliere distribution even for "old" showers, and, consequently, 10 is probably a lower limit. On the other hand, the distributions of

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[11] A. M. Shapiro, Phys. Rev. **82**, 307 (1951).

high energy rays observed with the cloud chamber appear to be inconsistent with a high multiplicity of cores.

The apparent contradiction stated above might possibly be eliminated if better approximations were made, (*a*) not only in the arguments that led to the energy estimates, but (*b*) also in the arguments that led to the core identifications.

(*a*) The transition effect in $\frac{1}{2}$ inch of Dural was estimated to be small, but if it were actually a factor of two near the core, the multiplicity would be reduced to about five. The fact that the absolute intensity agrees with ion-chamber and counter measurements is, however, an argument that the transition effect is indeed small. The normalization involved in finding the total number (N) of electrons depends on the Molière distribution, which has been verified for distances greater than a few meters. The present work indicates a less steep distribution near the axis, but this means that we have underestimated N by assuming the steeper distribution. The shower theory for longitudinal development should be at its best in this case of high energy air showers, but any change of cross sections that resulted in a more rapid degradation of energy or added processes that diverted energy to mesons would aid in the explanation of the contradiction.

(*b*) The observed result could be explained by the addition of one or two cores of high energy and many cores of low energy; the latter would add greatly to the total number of electrons but would add little either to the high energy end of the local spectrum or to the number of distinguishable cores.

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Soft Radiation at Balloon Altitudes*

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Results are given on cloud-chamber observations of electron showers and "spray" events at high altitude (18 millibars). The fluxes derived for initiating radiation are consistent with a common origin for showers and "sprays," and thus support the conclusion by Rau and Wightman that "sprays" are showers produced in a single lead plate. However, less than one-fourth as many such events occur as would be expected from observations on mu-mesons if mesons are produced with a spectrum that does not vary with altitude. If all soft radiation at 18 millibars were of primary origin, it would constitute less than 0.6 percent of the total cosmic-ray flux.

INTRODUCTION

Daytime operation of cloud chambers which are carried to high altitudes by balloons is a well-established procedure. The chambers, together with controlling and recording mechanisms, are enclosed in a pressurized gondola. Solar radiation maintains a temperature in the gondola that is approximately 70° Fahrenheit. By means of lead plates, placed in the useful part of the chamber. the various components of the cosmic radiation at high altitude can be identified on the basis of their ionizing and penetrating properties in the usual way.

Among the cosmic-ray events, electron showers are readily identified through their characteristic multiplication in passing through the lead plates (which are 1.2-radiation units thick in the experiments reported here). These events have been analyzed previously[1] to establish an upper limit on the flux of soft component in the primary cosmic radiation. The present paper includes greater detail of such an analysis. A typical electron shower is shown in Fig. 1.

The second type of event considered in this study is the "spray" phenomenon reported by Oppenheimer and Ney,[2] which is the multiple production in lead of ionizing tracks that are near minimum ionization but that, for the most part, do not penetrate neighboring lead plates (see Fig. 2).

The cloud-chamber pictures obtained in seven flights at altitude, at 55°N magnetic latitude, were examined for both electron showers and sprays. In six of these flights the plates in the cloud chambers were horizontal. In the remaining flight the plates were vertical so as to change the response of the system relative to the vertical and horizontal components of the initiating rays. The

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[1] Critchfield, Ney, and Oleksa, Phys. Rev. **79**, 402 (1950).
[2] F. Oppenheimer and E. P. Ney, Phys. Rev. **76**, 1418 (1949).