impetus to a more extensive study of the decay modes of the various heavy particles already known.

V. ACKNOWLEDGMENTS

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A Cloud-Chamber Study of Cosmic-Ray Air Showers at Sea Level*

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A diffusion-type cloud chamber eight feet long, four feet wide, and five inches deep has been used to study the lateral structure of cosmic-ray air showers in a region near the core. Three showers were recorded in which the core lay within sixty to ninety centimeters from some point on the periphery of the chamber. The results show that the lateral distribution of the shower particles in all but one photograph follow exceedingly well the Molière distribution. The deviations from the Molière distribution are almost all within the expected Gaussian fluctuations. In those pictures exhibiting little or no gradient, the deviations from the average density were normal.

I. INTRODUCTION

MANY mechanisms have been considered as possible explanations for the origin of the electron-photon component of air showers. Among these are (1) the impinging of high-energy primary electrons upon the air molecules of the upper atmosphere,[1] (2) the deceleration of primary protons as they pass near an air nucleus and undergo a bremsstrahlung process analogous to that of electrons,[2] and (3) the emission of high-energy neutral mesons in a high-energy nuclear collision.[3,4] That air showers originate from high-energy nuclear collisions is the most reasonable hypothesis at the present time because such processes are known to occur[5] and because recent experiments on the composition of air showers show that they contain not only electrons and photons but also penetrating particles and an N component.[6,7] This hypothesis also overcomes the difficulty of explaining how primary electrons can acquire energies of the order of 10^{15} to 10^{16} electrons volts in interstellar space.[8]

Several attempts have been made to measure directly the lateral distribution of the particles in extensive air showers. Noteworthy among these are the experiments of Williams[9] analyzed by Blatt,[10] Singer,[11] the Cornell group[12] (Cocconi *et al.*), Fretter and Ise,[13] Barrett,[14] El-Mofty,[15] Hazen,[16,17] Heineman,[18] and Kasnitz.[19] A study of these experiments would seem to indicate that multiple cores probably do exist, but that they are separated either by very large distances so that only one core is observed, or that they are separated by very small distances which makes their detection difficult.

Theoretical predictions of the angular and lateral spread of the air-shower particles have been made by several workers.[20–31] The Molière distribution function[32]

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is, however, the only total (i.e., integrated over all energies) distribution function available to experimenters for evaluating their results.

Blatt[10] has made as detailed a study of the Molière function as the available literature permits. The obvious errors in the Molière calculation center around a few well-defined points: (1) the computations neglect ionization loss, being based on Approximation A defined by Rossi and Greisen,[33] (2) the over-all structure function is almost certainly wrong because of the use of Arley's approximation to find the total number of low-energy electrons, and because of using Approximation A, which gives an incorrect partial structure function for low-energy electrons, (3) an incorrect partial structure function for electrons near the critical energy was used, since it was only an extrapolation of the high-energy partial structure function. The combined effect of using the incorrect partial structure function for low energies and of underestimating the number of low-energy electrons is to make the Molière function less peaked than the true one. Blatt states that the magnitude of this effect is not known at this time. The form of the Molière function currently in use is the one offered by Bethe.[34] It is

$$\rho[N(t),r'] = \frac{0.454}{r'} N(t)(1+4r') \exp[-4(r')^{\frac{2}{3}}].$$

The terminology is as follows: $\rho[N(t),r']$ = the particle density at a depth t below the top of the atmosphere; $N(t)$ = the total number of electrons at depth t; r' = the distance from the shower axis measured in units of the characteristic scattering length, r_1, defined by $r_1 = (X_0/\epsilon)E_s = 74$ meters at sea level, where X_0 = a radiation length (330 meters at sea level), ϵ = the critical energy for air (83 Mev), and $E_s = 21$ Mev.

In this paper are presented the results of some work performed with a diffusion-type cloud chamber of unusually large size, operated for 730 consecutive hours. The purpose in building the large chamber was to attempt to obtain photographs of the cores of air showers where the structure is not well known. A brief description of the arrangement of the apparatus is given and the experimental results are discussed. A complete description of the cloud chamber has been submitted to another publication.

II. DESCRIPTION OF THE APPARATUS

The cloud chamber selected for this experiment was a downward diffusion-type chamber using methyl alcohol as the condensant vapor and air as the noncondensable gas. A diffusion-type chamber was an obvious solution to the demand for a large area, since the mechanical difficulties involved in the design of an expansion chamber of similar size would be prohibitive. The actual area of the chamber was 32 square feet, of which 21 square feet were photographed (avoiding use of the region near the walls). The sensitive depth was about three inches out of a total chamber depth of five inches. Non-stereoscopic photographs were obtained through the chamber top with the aid of six mirrors. The clearing field was usually about 30 volts (the top being negative), though for occasional short intervals it was turned off or increased to about 100 volts. The chamber was operated out-of-doors with only a canvas tent over it.

The Geiger tubes were 30 inches long with an outside diameter of $1\frac{1}{2}$ inches. Four such tubes were used in a fourfold-coincidence circuit with the tubes arranged in a manner similar to that used by Cocconi.[12] Three tubes parallel to each other and to the horizontal plane were placed at the vertices of an equilateral triangle eight inches on a side, and were enclosed in a lead housing with two-inch side walls and a one-inch roof. These three tubes were placed beneath the chamber with the geometric centers of the cloud chamber and of the lead house lying on a common vertical line. One additional counter tube was situated one meter from the lead house to prevent the recording of coincidences caused by showers produced in the lead shield surrounding the counter tubes. This arrangement of counters does not meet the requirement proposed by Cocconi[35] for recording extensive showers, but it was believed that the photographs themselves would provide the distinction between narrow showers, other irrelevant events, and large air showers. The results confirmed this expectation.

A sample cloud chamber picture is shown in Fig. 1.

III. THE EXPERIMENTAL RESULTS

1. Criteria for Shower-Track Identification

The three criteria established for identifying the shower tracks were direction, length, and age, the age being estimated by the density and sharpness of the track.

Most of the shower tracks in a photograph appeared to be nearly parallel. This is to be expected if a shower has a single core (or one dominant core) around which the shower particles are radially symmetric.

The projected length of a track helped to decide whether or not it was to be attributed to a shower

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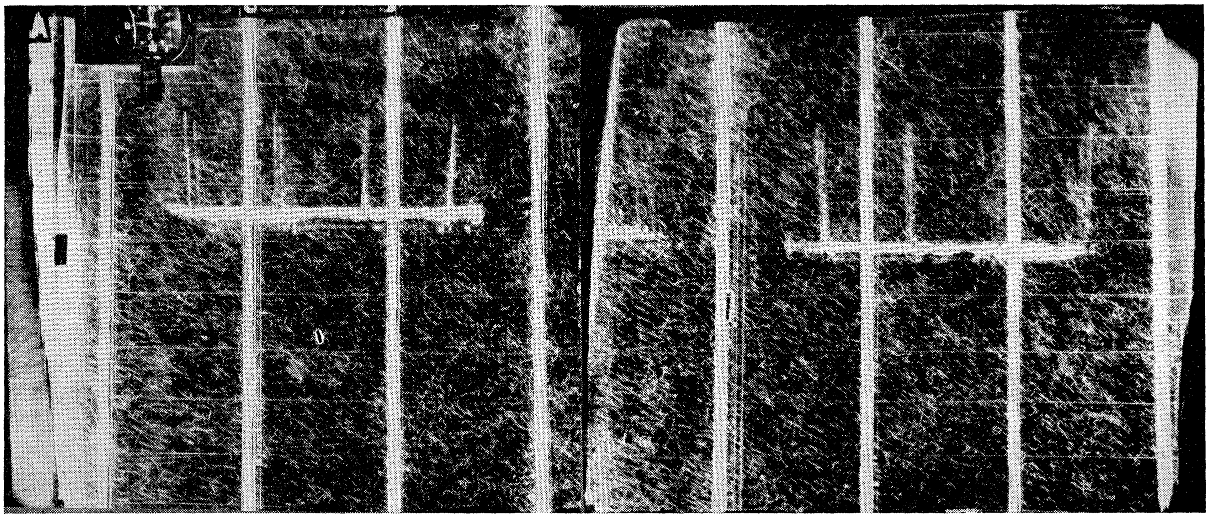

FIG. 1. Sample cloud-chamber picture. Total number of shower tracks, 2906; average number of tracks per 300-cm² sections, 46.3. (The standard deviation from 46.3 is 14.1.)

particle. Most showers arrive at angles not greater than 30° from the vertical.[9] The projected length of a track arriving at 30° from the vertical and viewed directly from above, computed on the basis of a sensitive chamber depth of three inches, was 1.75 inches. This meant that all shower tracks could be expected to be no longer than half the distance between the heating wires which, together with the alcohol trays, formed a natural grid structure in the photograph.

The age of the track was suggested by its blackness and its sharpness. A track satisfying the criteria of direction and length was often eliminated because it was considered too faint or too dark or too diffuse. In the final analysis, the age of the track was usually the deciding factor. The direction and length of a track served as a rapid means of sorting out those tracks believed to be true shower tracks, while careful study of the age served as the final discriminating test.

Each of these criteria had its limitations because of the influence of other phenomena. The directions of the individual tracks, for example, were influenced by scattering and by distortion from viewing the tracks as a point projection. Because of the very high energies of the electrons, the individual scattering of the particles was not large enough to alter appreciably the dominant direction of the tracks. The distortion introduced by viewing the tracks as a point projection was far more significant in altering the apparent direction of a track. Completely parallel vertical tracks appeared as dots directly under the lens and elsewhere as lines directed toward the point under the lens. Similar tracks parallel to a line from the lens to one corner of the chamber all appear to be directed toward that corner. The angle the shower axis made with the vertical could be determined by finding that point on the photograph (or off the edge of the photograph) where the extensions of the tracks intersected, and using that point and the geometry of the chamber and lens to calculate their direction. The direction of the tracks was useful in determining whether or not they belonged to the shower, because they followed this definite pattern if they were parallel to one another.

The lengths of the tracks in any one photograph were not always the same, because the direction of arrival of the shower may have been along the line of sight of the lens. In this case some of the tracks were observed end-on and appeared as round dots or as very, very short tracks. The tracks were then not only of varying lengths but also of varying apparent age. The criterion of direction was useful for those cases in which the criteria of length and age were doubtful. The procedure in each picture was to ascertain the approximate azimuthal direction of arrival, and then to evaluate each track with the different effects constantly in mind. Each picture was counted at least twice with the aid of a viewer, and finally, in the making of the Ozalid tracings (see Sec. III.2), each track received a final discriminating evaluation before being traced as a true shower track.

The effect of the normal random cosmic-ray background was determined by making a series of random exposures and counting the straight background tracks. There was an average of three sharp straight tracks per section, but they were not usually parallel. These three sharp tracks could be mistaken for counter controlled shower tracks if they happened to be parallel to the shower tracks. It is safe to say, however, that on the average less than two background tracks were counted per section as belonging to a shower. Since the numbers per section ranged from 6 to 104, it can be seen that background introduced a negligible error.

There was an average of seventeen tracks per section in a random photograph, but there was no difficulty in sorting out the straight tracks. The remainder were crooked, indicating that they were low energy electrons, or they were broad and slightly curved, indicating that they had been formed more than 0.4 second before the flashing of the lights.

A last consideration was the probability of a random shower's occurring between the time the desired shower particles traversed the chamber and the time the photograph was taken. An estimate of this probability was made in the following manner. The delay-time was measured to be 0.4 second. The average counting rate was two counts per hour. Assuming that a random shower would have to arrive at least 0.1 second before the picture was taken, the following result for the probability that a random shower would arrive during the delay-time was formulated:

$$\frac{\text{(Time interval in which a shower must arrive to be photographed)}}{\text{(Total time interval between counts)}}=\frac{0.4-0.1}{30\text{ min}\times 60\text{ sec}}=\frac{1}{6000}.$$

This probability was considered sufficiently small to be neglected.

The criteria of direction, length, and age, therefore, were believed to be necessary and sufficient to judge whether or not a given track was produced by a shower particle, when the other relevant factors just discussed were considered. When there was a great uncertainty as to the number of shower tracks in a section, the range was recorded, i.e., the minimum and the maximum counts. Uncertainties occurred when it became necessary to "read" a track through curtains[36] in the chamber, or when a track seemed to be on the borderline of belonging. After a few minutes of observation, eye fatigue set in and the ability to make fine discriminations became lessened. Frequent rests were necessary. Each picture studied contained about 1000 shower tracks or more, and each track had to be individually evaluated.

2. Method of Data Reduction

The process of obtaining the final data from the original negatives involved three steps. The first step was to make enlarged positive transparencies $8\frac{1}{2}\times 8\frac{1}{2}$ inches on Kodalith Film from the original $1\frac{1}{4}$- $\times 1\frac{1}{4}$-inch negatives. Second, Ozalid tracings of the shower tracks in each picture were made by placing the transparency together with a sheet of Ozalid tracing paper over a specially-made light box and drawing in each individual track. During this procedure, the original film was at hand in a viewer so that each track could be studied before drawing it in as a true shower track. When the tracing had been completed, it was run through the Ozalid machine to produce a print.

The third operation was the actual locating of the shower axis. When the gradient was steep and the track-count per section[37] was large (e.g., 25 or greater) over a sufficiently large area of the picture, the procedure was as follows: Two sections were selected whose counts could be called reasonably identical (perhaps 5 to 10 percent difference). The geometric center of each of these two sections was located. These two midpoints were connected, the joining line bisected, and a perpendicular to it drawn in the direction of the shower axis. Visual inspection of the picture allowed one to select the quadrant in which the axis lay. Two other sections at the far end of the chamber were selected in which the track count was quite certain. (Most pictures had areas in which the contrast was very good, the background low, and the shower tracks clearly visible.) The midpoints of these sections were located, the connecting line drawn, this line bisected, and the perpendicular drawn out to intersect the first perpendicular that was drawn. The intersection determined the position of the shower axis. The procedure is illustrated in Fig. 2. This was not always the final choice of the position, because the final choice had to be a point which satisfied best the over-all density distribution. Other combinations of two best sections were selected, and a number of perpendiculars were drawn to see if there was an area in which most of them intersected. A suitable compromise point was then chosen. When the position of the shower axis had been tentatively selected, the accuracy of the choice was judged by drawing arcs of different radii with the tentative axis position as center through the chamber area and noting if these arcs passed through or near points of similar density. Large errors in the choice of position were readily detected.

When the shower axis had been located in this manner, the distances of the geometric centers of each of the sections from the core position were measured and recorded. Convenient intervals of distance were assumed (e.g., 0.5–0.59 meter) and a chart prepared in which the number of tracks in a section was entered in the appropriate column designating the distance of the geometric center of this section from the axis position. Upon completion of the chart, the number of tracks in each distance interval was averaged and this value taken as the average number to be expected at a distance from the core corresponding to the midpoint of that interval. A graph was made with the number of tracks per section as the ordinate and the distance from the shower axis as the abscissa. A smooth curve was

[36] A curtain refers to an area of fog looking like a waterfall, which at times appeared in the chamber.

[37] The sections referred to throughout the paper are the areas formed by the apparent intersections of the heating wires running lengthwise of the chamber and the alcohol trays running crosswise. Each area is about 300 square centimeters.

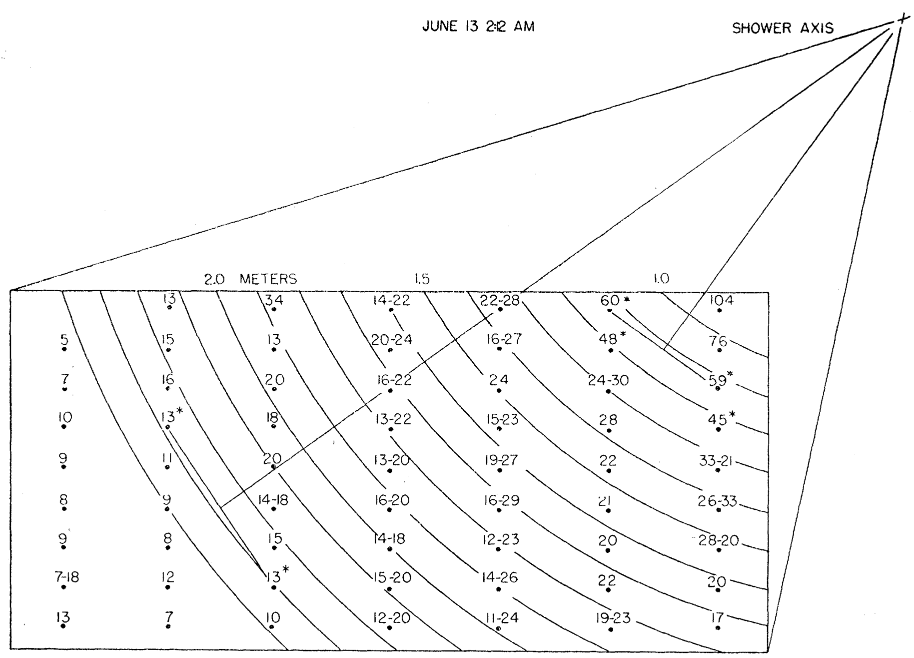

FIG. 2. Illustration of the procedure for locating the shower axis when a gradient across the chamber could be determined.

drawn through the points in such a way as to represent best the data.

A second method of locating the shower axis involved the use of the Molière distribution function as approximated by Bethe. This method was used when the gradient was not considered sufficiently large to use the first method. An order-of-magnitude value for the gradient between 0.5 and 1.5 meters from the core for the three showers in which the core was located was fifteen tracks per half-meter. Sections of the picture were chosen in which the track counts were considered to be quite certain. (As mentioned earlier, almost every picture has a few of these sections in which the shower tracks were very well defined.) These sections were chosen from widely separated areas of the picture rather than from one local area. The values of these densities were used to enter a "Molière chart," previously prepared, and from this chart distances were read off corresponding to the densities obtained from the photograph. For a given density, different distances were read off corresponding to varying values of N (Sec. I) in the Molière equation. A table was prepared in which the distances corresponding to the chosen densities were set forth for fixed values of N. Circles were described about the center of the selected sections, their radii being the distances from the core read from the Molière chart for the particular density assigned to the section. The intersections of the circles defined an area in which the axis of the shower must have hit. A choice could be made for a best fit. When the position had been determined, the data were plotted in the manner described in the preceding paragraph.

The location of the shower axis was carried out in this case by fitting the Molière function to the experimental data. Other experiments of this type had not yielded data of adequate detail to allow this to be done as accurately as has been done here. In the pictures to be discussed later, the shower axis was always between 0.6 meter and 1 meter from some point on the periphery of the cloud chamber. This gave a very detailed picture of the shower structure up to 60 centimeters from the core. The methods of locating the shower axis may be summarized by stating that they depend only on the assumption that the electron-photon showers are radially symmetric about their axes.

The secondary purpose of the experiment was to study the statistical distribution of the electrons near the core. For these small distances no special analysis was made. The charts made earlier for purposes of locating the core showed that nearly all the section track counts for a given radius lay within the average number plus or minus the standard deviation, i.e., $\sqrt{n}$.

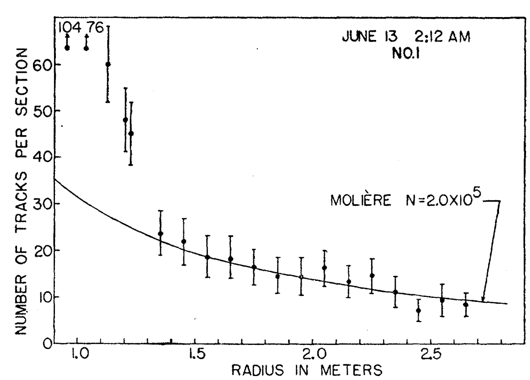

FIG. 3. The density distribution for shower No. 1, Table I.

TABLE I. Summary of numerical results obtained from the experiment.[a]

Shower number	No. of shower tracks in chamber	Average No. per section	Standard deviation	Estimated No. of shower particles	Estimated energy of initiating ray (ev)	Distance of axis from chamber center (meters)	Gradient observable	Height of origin (radiation lengths)	Angle with respect to vertical
1	1708			2.0×10^5	2.15×10^{14}	1.85	yes	14	8
2	1042			1.91×10^5	2.0×10^{14}	1.65	yes	14	13
3	643			1.0×10^5	9.7×10^{13}	1.5	yes	13	18
4	1641	28.8	10.1	*10^6*	*3×10^{15}*	*4*	no	15	24
5	651	11.2	5.6	*3×10^5*	*10^{15}*	*3.6*	no	14.5	7
6	625	9.6	4.8	*3×10^5*	*10^{15}*	*4*	no	14.5	26
7	418	6.8	3.8	*3×10^5*	*10^{15}*	*4.6*	no	14.5	7
8	2906	46.3	14.1	*$>10^6$*	*3×10^{15}*	*4*	no	15	11
9	1078	17.2	6.1	*3×10^5*	*10^{15}*	*3*	no	14.5	9
10	693	11.2	5.5	*3×10^5*	*10^{15}*	*3.6*	no	14.5	9
11	345	5.6	3.5	*10^5*	*9.7×10^{13}*	*2.6*	no	13	12
12	632	10.0	3.7	*3×10^5*	*10^{15}*	*4*	no	14.5	21

[a] The numbers in italics are order-of-magnitude estimates only.

The exception to this deviation is discussed in connection with the picture in which it is found.

The data obtained in this experiment have been analyzed, then, in one of two ways. For those pictures exhibiting a definite gradient, the shower axis was located and the radial density distribution determined and plotted. For those pictures exhibiting a nearly flat distribution, the actual distribution was compared with the Poisson distribution.

3. Discussion of the Photographs Obtained

The numerical data obtained from the photographs are presented in Table I and the density distributions for the three showers exhibiting gradients are illustrated in Figs. 3, 4, and 5. Figure 6 is illustrative of the density distributions in the photographs which did not show a gradient.

The density distribution shown in Fig. 3 departs from the Molière distribution between 0.9 meter and 1.3 meters from the core. This deviation from the Molière distribution function may be explained in several ways, the most likely being: (1) the Molière function itself may be in error,[31] (2) multiple cores may exist, or (3) the tracks observed may not be those of electrons but those of other particles associated with the shower. Each of these possibilities can be examined in detail as far as existing knowledge, both experimental and theoretical, permits. Consider the Molière function. The Molière function, as pointed out in Sec. I, is known to be in error in the form of the structure function itself, and in the estimation of low-energy electrons. Furthermore the Molière function is calculated only for the maximum of the shower. The combined effect of underestimating the number of low-energy electrons and using the incorrect partial structure function for low energies tends to make the Molière function less peaked than the true one. No estimate of the magnitude of this effect is available at the time of writing. The added possibility that the shower may not be fully developed (i.e., has not yet reached its maximum) would seem to be sufficient explanation for the observed sudden increase of density at distances close to the core.

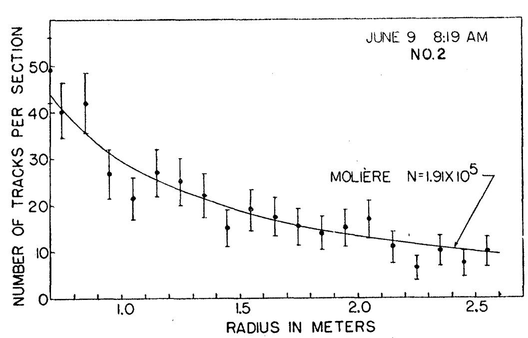

FIG. 4. The density distribution for shower No. 2, Table I.

The existence of multiple cores is a possibility, but the photograph does not suggest this. The chamber area enclosed by an arc of 1.3 meters radius measured from the shower axis is about 0.16 square meter. Careful scrutiny of this area on the photograph reveals no obvious clusters of tracks.

It is possible that the sharp increase in density as one approaches the core is caused by the presence of tracks other than those of shower electrons. Experimental data on the composition of shower cores indicate that the ratio of penetrating particles to electrons is usually about two or three percent near the core, but this ratio is observed to be much greater in some instances.[12,38,39]

The conclusion is that this shower is best described by attributing it to the development of a single core. The disagreement with the Molière function near the core is explained by assuming that the shower has not yet reached its maximum and (or) that it is a shower in which the ratio of penetrating particles to electrons is larger than usual.

For those pictures not exhibiting a gradient, the

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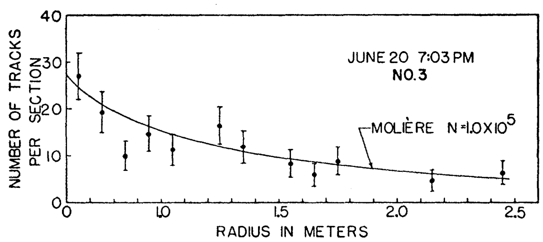

FIG. 5. The density distribution for shower No. 3, Table I.

average densities and the standard deviations were computed and tabulated in Table I. In addition, the integral density distribution was plotted on probability paper. Those plots indicated that the distributions were practically Poissonian. Figure 6 is an example of the density distribution as it appears when plotted on probability paper.

For these showers, an estimate of the distances from the center of the chamber at which the shower axes struck was made in the following way. Figure 7 can be used as a specific example to illustrate the method. The average value of 28.8 tracks per section was used to enter the Molière chart. The particular value of N selected was chosen by assuming the effective length of the chamber to be two meters. Sliding this length along the horizontal line corresponding to 28.8 tracks per section, one finds a Molière curve that fits inside the limits of 28.8 ± 10 (the standard deviation) over a length of two meters. The core was assumed to have struck at the midpoint of this interval, i.e., three meters away. The results obtained are listed in Table I. The estimated energies of the initiators that are listed were obtained from cascade shower theory on the basis of a single

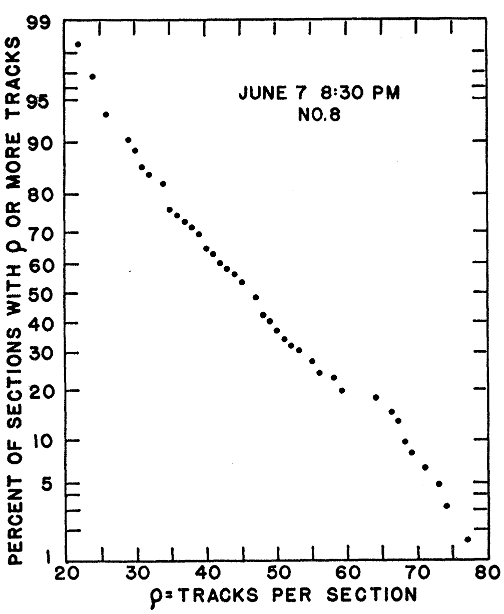

FIG. 6. The density distribution for shower No. 8, Table I.

core.[40] The angles listed are the angles that the shower axes make with the vertical. These were estimated in the manner described in Sec. III.1.

IV. CONCLUSIONS

That only three showers exhibited an appreciable gradient was an expected result. Singer,[11] working at sea level, obtained the following differential number spectrum for air showers:

$$f(N)dN = 2.5\times10^4 N^{-2.4} dN \text{ hr}^{-1} \text{ min}^{-2}.$$

The total number of particles N in the individual showers exhibiting a gradient varied from 1.0×10^5 to 1.9×10^5. The average distance of the shower axis from the center of the chamber was computed to be 1.7

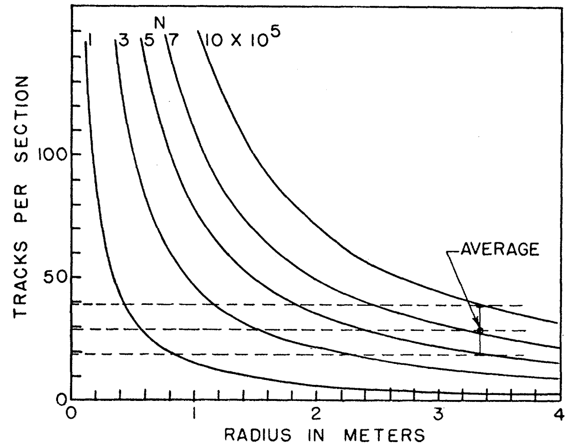

FIG. 7. Illustration of the procedure for locating the shower axis when little or no gradient is present.

meters. The number of showers whose size lay between 1.0×10^5 and 1.9×10^5 particles and whose axis struck within a radius of 1.7 meters from the chamber center during a time interval of 540 hours was calculated to be approximately five. Agreement within a factor two was considered to be good in view of the approximations.[9,13]

That air showers might originate at these low altitudes was also not unreasonable in the light of the hypothesis advanced by Cocconi,[7] *viz.*, that an extensive air shower is not a special event, but rather a "unique process in which the cosmic radiation present in the lower atmosphere is created." This hypothesis is supported by several experimental observations:

1. All the types of particles found in extensive air showers are also found in the cosmic radiation in the lower atmosphere.

2. An extensive air shower is recorded every time three or more coherent penetrating particles coming from the air are recorded.

3. The probability of recording an extensive air

[40] Bruno Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), first edition, 259.

shower accompanying the N component increases with increasing energy of the N component.[41]

Clay[42] and his collaborators have also considered the question of whether or not the continuous cosmic radiation and the extensive air showers are produced by the same processes. They pointed out that if two conditions prevailed—namely, that (1) the primary proton producing the mesons had a high energy, and (2) the initial collision occurred in the lower atmosphere—then the mesons and their secondaries would be observed as a shower. Experimental evidence confirming the theory that the large air showers were produced at low levels was provided by experiments on the barometric coefficient.[43] The variation of intensity of the soft and penetrating components with air pressure was found to be the same as the decrease in the number of protons in the atmosphere,[44] being 14 percent and 15 percent per centimeter Hg respectively.

If the air showers are initiated by neutral mesons produced by the high-energy primaries, their height of origin depends on the cross sections for collisions between the primaries and the air nuclei. According to Rossi,[45] the best-established experimental result yielding this information is the curve giving the rate of occurrence of high-energy nuclear interactions as a function of depth in the atmosphere as obtained by Tinlot.[46] These nuclear interactions can be produced by protons, neutrons, and pi mesons, defined as the N component or "N rays." (The high-energy alpha particles and heavier nuclei in the upper atmosphere are not included in this terminology.) From the data obtained by Tinlot, the N rays are absorbed exponentially with a collision mean free path of about 120 g/cm^2 in air.[44] At an elevation of 3260 meters the intensity of the N-component capable of producing nuclear interactions is about one percent of the total number of ionizing particles in the shower.[47] At altitudes of 6000 meters and higher, therefore, there should be an abundance of high-energy particles capable of initiating electron-photon showers.

Greisen[41] pointed out that if a large fraction of the energy in a nuclear interaction is given to mesons, and the charged mesons interact further with air nuclei to produce more mesons while the neutral mesons decay into two photons to initiate air showers, a consistent picture can be formulated. The result of such a sequence is that most of the energy, after five to ten collision mean free paths, would be transferred to the electronic component leaving ten to twenty percent about equally divided between nucleons and mu mesons. Five mean free paths represent 600 g/cm^2 or 4500 meters, slightly lower than the computed height of the maximum for those showers observed in this experiment. Tinlot records ten high-energy nuclear events per hour at 600 g/cm^2 and twenty high-energy events at 500 g/cm^2. Further evidence of the occurrence of high-energy nuclear events at low altitudes is found in data from photographic emulsions. Gerosa and Setti[48] observed an emulsion star at 4550 meters with a singly charged primary and two well-defined forward cones of particles with angles 0.004 and 0.1 radian respectively. The energy of the event was estimated as 10^{13} electron volts.

A quantitative picture of the nature of the high-energy event causing the shower has been formulated by Hazen and his collaborators.[49] They have applied the Fermi theory of high-energy nucleon-nucleon collisions to the problem of determining the energy distribution, the energy dependence of the angular distribution, and the number of emitted pi mesons as a function of primary energy and impact parameter. The total number of emitted neutral mesons for several values of primary nucleon energy and two values of impact parameter is presented in Table II. Two cases are considered; one in which only pi mesons are produced and one in which nucleon-antinucleon pairs are produced. The latter is considered important when W/Mc^2 is equal to or greater than 100, i.e., when the primary nucleon energy in the laboratory system exceeds 5×10^{12} electron volts. Some calculations were made for this experiment utilizing the work of Hazen. The procedure was as follows:

TABLE II. A reproduction of part of Table I from the paper by Hazen, Heineman, and Lennox with the number of neutral mesons emitted for various primary energies and impact parameters.

Primary nucleon energy W' (ev)	Impact parameter (nucleons and mesons) $\rho=0.959$	0.990	Impact parameter (mesons only) $\rho=0.959$	0.990
	Total number of neutral mesons emitted			
1.2×10^{12}	1.3	0.72	3.3	1.7
1.9×10^{13}	2.6	1.4	6.5	3.5
1.2×10^{14}	4.2	2.3	10.3	5.5
4.7×10^{14}	5.9	3.2	14.6	7.8
1.9×10^{15}	8.3	4.5	21	11.0
1.2×10^{16}	13	7.2	33	17.3
1.9×10^{17}	26	14.3	65	35

1. The energy of the initiating ray was estimated by calculating the total number of particles in the shower from the Molière function, and using cascade shower theory[40] to compute the energy required to produce that number of particles at the maximum of the shower.

2. The initiating ray was assumed to be a photon produced by the decay of a neutral meson. Most photons are emitted at a minimum angle defined by[49]

$$\sin\theta_{\min}/2=Mc^2/U,$$

[41] Greisen, Walker, and Walker, Phys. Rev. **80**, 535 (1950).
[42] J. Clay, Phys. Rev. **81**, 645 (1951).
[43] J. Clay, Physica **16**, 278 (1949).
[44] D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1941), first edition, 324.
[45] Bruno Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), first edition, 486.
[46] J. H. Tinlot, Phys. Rev. **73**, 1476 (1948); **74**, 1197 (1948).
[47] G. Cocconi and V. Cocconi Tongiorgi, Phys. Rev. **79**, 730 (1950).
[48] A. Gerosa and R. L. Setti, Nuovo cimento **8**, 601 (1951).
[49] Bruno Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1942), first edition, 199.

where $\frac{1}{2}U=E_1=E_2$, the energies of the emitted photons; θ_{min} = the minimum angle between the decay photons in the laboratory system, and Mc^2 = the rest energy of the neutral meson. The energy of the neutral meson is then taken to be twice the value of the photon energy computed in step one above. On this basis the estimated energies of the mesons in this experiment lie between 2×10^{14} and 2×10^{15} electron volts. The primary nucleon energies to be associated with these neutral-meson energies are not uniquely determined, because the neutral mesons are emitted with a distribution of energies. Any reasonable primary energy yields a number of neutral mesons as shown in Table II, but the percentage of that number whose energy exceeds a given energy decreases with increasing meson energy. By requiring that at least two neutral mesons be produced, one can compute a minimum energy for the primary nucleon. The reason for requiring at least two is that it is known from the angular distribution of the emitted mesons that one-half of them will be emitted in the backward direction and one-half in the forward direction.[50] The minimum value for W' is computed to be about 1.2×10^{16} ev. From Table II, it is seen that a total of 13 neutral mesons are emitted, and from the work of Hazen about 25 percent of these (or 3) have energies greater than 2×10^{14} ev. Half of these are to be found in the forward cone and half in the backward cone. The angular width of these cones is about 14° in the center-of-mass system estimated from Table II of the Hazen paper. This corresponds to about 5×10^{-5} radian in the laboratory system. If the two neutral mesons were emitted at the extreme angle of 5×10^{-5} radian, the separation of the two main shower axes 6 km below the point of origin would be about 30 cm. Each neutral meson, however, decays into two photons with individual energies of 10^{14} ev. The minimum angle between these photons is given by the equation above and is computed to be about 10^{-6} radian. The separation between cores due to the two photons of a single neutral meson produced at a height of about 6 km is then calculated to be 0.6 cm. The two cores produced either by the individual neutral mesons or by the decay photons would not have been observed in this experiment because of overlapping.

The results of this experiment, then, may be summarized as follows:

[50] Hazen, Heineman, and Lennox, Phys. Rev. 86, 198 (1952).

1. Multiple cores were not observed. Each shower, within statistical errors, consists of a single core. This observation is not inconsistent with the Fermi theory of nucleon-nucleon collisions, which predicts multiple cores, because they would be so closely spaced as to be unresolved in this experiment. However, this does not imply that air showers are necessarily originated by the decay of neutral mesons. The data obtained from this experiment do not allow one to make any definite statements about the detailed mechanism of air-shower origin or to discriminate between different modes of origin.

2. The Molière distribution function describes the lateral structure of these showers up to distances of sixty centimeters from the shower axis within Gaussian fluctuations.

3. The statistical distribution of the shower particles three to four meters from the shower axis is Poissonian.

Our first result, the absence of multiple cores, is typical of the results of other workers who have sought to identify multiple cores on the basis of density observations alone. Those who have reason to believe in the existence of multiple cores base their belief on data obtained from energy distributions[9,16] with the exception of one.[18] The second result can be considered to extend the results of Williams[9] and of Cocconi, Tongiorgi, and Greisen[12] from two or three meters down to distances of one meter and less. The third result is not a surprising one; it is to be expected as was pointed out by Blatt.[10]

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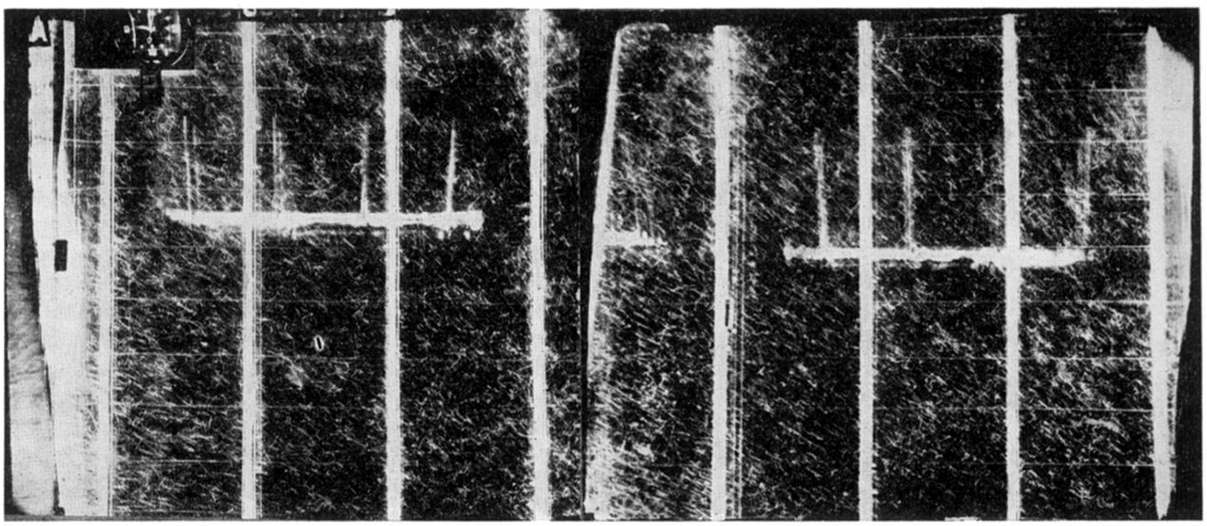

FIG. 1. Sample cloud-chamber picture. Total number of shower tracks, 2906; average number of tracks per 300-cm² sections, 46.3. (The standard deviation from 46.3 is 14.1.)