0
UNITED STATES ATOMIC ENERGY COMMISSION

UCRL-2412

PART A: A CLOUD-CHAMBER STUDY OF
COSMIC-RAY AIR SHOWERS AT SEA LEVEL
PART B: A DIFFUSION CLOUD CHAMBER
OF UNUSUALLY LARGE DIMENSIONS (thesis)

By
Kenneth E. Relf
Wilson M. Powell

November 1953

Radiation Laboratory
University of California, Berkeley

Technical Information Service, Oak Ridge, Tennessee

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Subject Category, PHYSICS.

Work performed under Contract No. W-7405-eng-48.

Issuance of this document does not constitute authority for declassification of classified material of the same or similar content and title by the same authors.

This report has been reproduced with minimum alteration directly from manuscript provided the Technical Information Service in an effort to expedite availability of the information contained herein.

Reproduction of this information is encouraged by the United States Atomic Energy Commission. Arrangements for your republication of this document in whole or in part should be made with the author and the organization he represents.

Printed in USA, Price 80 cents. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

UCRL-2412

**PART A: A CLOUD-CHAMBER STUDY OF COSMIC-RAY
AIR SHOWERS AT SEA LEVEL**
**PART B: A DIFFUSION CLOUD CHAMBER OF UNUSUALLY
LARGE DIMENSIONS (thesis)**

By Kenneth E. Relf and Wilson M. Powell

November 1953

TABLE OF CONTENTS

Abstract	4
Part A	
Introduction	5
Description of the Apparatus	16
The Experimental Results	
Criteria for Shower-Track Identification	18
Method of Data Reduction	21
Discussion of Individual Pictures	26
Conclusions	73
Part B	
Introduction	79
Historical Background	79
Factors Influencing the Operation of Diffusion Chambers	80
Vapors and Vapor Sources	80
Temperatures	82
Pressure	83
Cooling Systems	84
Clearing Fields	84
Photography	85
Notes on Operation	86
Fog Nuclei	86
Streamers or Waterfalls	86
Ion-Load Limit	86
Theory	86
Construction of the Chamber	87
The Bottom	87
The Side Walls	90
The End Walls	90
The Vapor Source	93

The Cooling System	99
The Camera and Shutter	104
The Mirror System	106
The Photographic Lights and the Viewing Light	106
Notes on Operating the Chamber	107
Acknowledgments	111
References	112

A CLOUD-CHAMBER STUDY OF COSMIC-RAY AIR
SHOWERS AT SEA LEVEL
and
A DIFFUSION CLOUD CHAMBER OF UNUSUALLY
LARGE DIMENSIONS

Kenneth E. Relf and Wilson M. Powell

Radiation Laboratory, Department of Physics,
University of California, Berkeley, California

November, 1953

ABSTRACT

[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.

In addition to the experimental results on air showers, a detailed description of the cloud chamber is given, since it is an unusually large chamber. Though the actual area is 32 square feet, the area photographed was 21 square feet or very nearly two square meters. The chamber was operated continuously for 30 days (720 hours) in which the chamber performed satisfactorily for 540 hours.

A CLOUD-CHAMBER STUDY OF COSMIC-RAY AIR
SHOWERS AT SEA LEVEL
and
A DIFFUSION CLOUD CHAMBER OF UNUSUALLY
LARGE DIMENSIONS

Kenneth E. Relf and Wilson M. Powell

Radiation Laboratory, Department of Physics,
University of California, Berkeley, California

November, 1953

I INTRODUCTION

The discovery of cosmic-ray air showers in 1938 by Auger and his collaborators¹ initiated intensive investigations of the structure of these large showers. Geiger-tube coincidence methods were used in the early experiments.^{1, 2} Since that time experiments have been performed with cloud chambers^{3, 4} and ionization chambers⁵⁻⁷ using all the refinements of modern electronic techniques. The results of some experiments are in general agreement with the cascade theory of electron-photon multiplication^{3, 8-12} but there are some that are not.^{5, 7, 13} The structure of the large air showers is of interest because of its dependence upon the nature of the initiating event. If the true structure of the large air showers were known, theories concerning their origin could be checked and a further insight into the nature of very high-energy nuclear events could be obtained. Some of the recent theories predict a multiplicity of cores.¹⁴ These theories differ in their predictions of the number of cores that may occur and of their spatial separation. Before proceeding to a review of the experiments on air-shower structure, a summary of some of the theories of their origin may be helpful.

Many mechanisms have been considered as possible explanations for the origin of the electron-photon component of air showers. One of the first and most obvious hypotheses was the existence of high-energy primary electrons which impinged upon the upper atmosphere.¹⁵

The shower developed longitudinally according to the well-known processes of bremsstrahlung and pair-production, while the lateral spread was attributed to Coulomb scattering of the shower electrons. In this case each shower would have a single narrow core with particles distributed around the core according to the law of Coulomb scattering. Molière calculated the distribution function for this case.¹⁶ This theory of the origin has lost favor, however, in the light of experiments which indicate that primary electrons either do not exist at all or that they constitute at most a very small fraction of the primary particles.

Another proposed initiating mechanism was the deceleration of primary protons as they pass near an air nucleus.¹⁷ Such a deceleration involved a bremsstrahlung process analagous to that of electrons. In a process of this type one expected an appreciable scattering of the original high-energy photons. The core may show a very weak concentration or it may exhibit multiple cores separated by distances of several centimeters.

Still another method of initiation is that proposed by Lewis, Oppenheimer, and Wouthuysen¹⁴ in which neutral mesons as well as charged mesons are produced in a high-energy nuclear collision. The existence of these neutral mesons was established by experiments at Berkeley in 1950.¹⁸ The upper limit of their mean life has been established as less than 10^{-13} second.¹⁹ That air showers originate from a high-energy nuclear collision is the most reasonable hypothesis at the present time, because such processes are known to occur²⁰ and because late experiments on the composition of air showers show that they contain not only electrons and photons but also penetrating particles and an N-component.^{21, 22} This hypothesis also overcomes the difficulty of explaining how primary electrons can acquire energies of the order of 10^{15} to 10^{16} electron volts in interstellar space.²³

The Lewis-Oppenheimer-Wouthuysen hypothesis has been criticized in some of its details. The multiplicity of production is said to be too high and the angular divergences too large.^{24, 25} Some numerical results of the Lewis-Oppenheimer-Wouthuysen theory have been tabulated by Williams.²⁴ They provide a picture of what one might expect to see if this hypothesis were correct. According to

these calculations, a primary particle of 10^{16} electron volts energy would produce, upon colliding with an air nucleus, 460 particles distributed approximately Gaussian in the laboratory system with the angle of standard deviation being 4.5×10^{-4} radian. The radius of the circle in which most of these showers would hit at 20 radiation lengths below the top of the atmosphere is 7.2 meters, with an average distance between cores of 0.6 meter and an average energy per core of 2×10^{13} electron volts. Similar calculations have been carried out for primary energies between 10^{13} and 10^{17} electron volts.

The theory of Fermi²⁶ seems to be more compatible with experimental results, though complete agreement has not yet been reached.²⁷ For an average collision* the Fermi analysis gives a lateral spread that is too great when the number of shower particles is correct; it gives too great a number of particles when the lateral spread is correct. For distant collisions* the analysis gives both a correct lateral spread and number of particles. The principal shortcoming of the Fermi model is that the primary energy necessary to give the desired relativistic contraction in the angle between the neutral mesons gives too much energy to them.

The conclusion to be drawn from these papers is that the actual production mechanism of the electronic component of the air showers is not known. Their origin is one of the outstanding problems of shower theory at the present time, and it has been the subject of several experimental investigations. These investigations have been directed at determining the shower structure from which attempts have been made to deduce their origin. Let us now review some of these experiments.

The first attempt to measure directly the lateral distribution of the particles in extensive air showers was made by Williams.²⁴ Three ionization chambers were placed at the vertices of an equilateral triangle and a fourth chamber at the center of the triangle. The chambers furnished four values of density at four points in the shower.

* The distinction between an average and a distant collision lies in the value of the impact parameter chosen.

Assuming the validity of the Molière function and using these four values of density, the position of the core of the shower could be located. The results of this experiment indicated that air showers have single cores of high density, the density falling off away from the core in accordance with the Molière distribution. Williams' results are most reliable at distances from 2 to 20 meters.

Blatt made a theoretical analysis of ionization-chamber data on large air showers, with particular reference to decoherence curves.* The results of Blatt's analysis showed that the detailed nature of the structure function of air showers could never be ascertained from decoherence experiments. The reason for this unfortunate fact was that the function $S[\rho/f(r)]$, the number of showers per unit time that would register in the two chambers a distance L apart, is essentially proportional to the second derivative of $W(\rho, L)$ with respect to L at the point $r = L$. The physical significance of this fact was that a decoherence counting experiment would have to run for lengths of time prohibitively long (years) before the statistical accuracy would be sufficient to give a significant value to the second derivative. Blatt further pointed out that this was the explanation for the agreement found between theory and experiment by investigators who assumed a structure function $f(r)$, a frequency function $S(N)$, and computed the counting rate $W(\rho, L)$. Any plausible structure function would fit, but very little could be deduced about the correctness of the choice.

Singer²⁸ has performed a decoherence counting experiment in which the technique differed from that of previous workers. An extensive shower was first selected by one group of counters and then the coincidence rate between two additional counters in the vicinity of the selector was measured. The results showed that the counting rate was independent of counter separation for distances of the order of a few meters down to seven centimeters. This result was quite contrary to that of other experimenters, who found a rapid rise in the

*A decoherence curve is obtained by measuring the coincidence counting rate W of two ionization chambers placed a distance $2L$ apart as a function of the minimum density ρ to which they respond and the half-distance L between the two chambers. A plot of $W(\rho, L)$ versus L (keeping the minimum ρ the same by keeping the same bias on the chamber) is called decoherence curve.

counting rate as the counter separation was decreased. Several reasons for the discrepancy were offered, such as knock-on processes, narrow air showers, and possible other phenomena not directly associated with air showers. No definite conclusions were established. The conclusion reached by Singer, based on the flatness of the decoherence curve, was that sharp density gradients do not exist over distances of a few centimeters "and distributed throughout the extent of the shower." He does not exclude, however, the possibility of multiple cores within the main core separated by a few centimeters.

Cocconi, Tongiorgi, and Greisen,²⁹ in an effort to resolve some of the major difficulties in understanding air-shower structure, devised an experiment with the following aims: (1) to obtain evidence for a definite type of core structure, either multiple or single, (2) to measure the lateral distribution of the shower particles and to see if it is the same from shower to shower, (3) to compare the lateral distribution of the shower particles with that predicted by Molière on the basis of multiple Coulomb scattering, (4) to measure the penetrating power of the penetrating particles, and (5) to determine their lateral distribution.

Five core selectors were used with separations from 1 to 36 meters, which served to test the precision with which the core was determined and to identify multiple cores. In addition to the core selectors, two electron-density detectors were dispersed in such a way as to give the relative electron densities at two fixed distances from a core selector. A cloud chamber was operated in connection with the core selectors to give data on the penetrating particles. The experiment was performed at 3260 meters elevation.

The results of this experiment gave no evidence of multiple cores unless they were concentrated in a region of radius 2 meters or less. The correctness of the Molière function was established for distances between 5 and 200 meters within the accuracy of their density measurements, which was a factor of two. The lateral structure function was shown to be independent of shower size, i.e., the density ratio between any two fixed points at fixed distances from the shower core was a constant. The ratio of penetrating particles

to electrons increased slowly with distance from the core, but changed only by a factor of two between 5 to 200 meters while the density of the electrons decreased by a factor of 100.

Fretter and Ise,³⁰ recognizing the difficulty of analyzing counter and ionization-chamber data when high densities over small areas prevail, suggested that underwater studies be made. When an air shower passes into water, the lower-energy particles are absorbed; and after a density transition effect the entire shower is concentrated in a small area. The characteristic scattering length for air showers is 59.5 meters at 2765 meters elevation; in water it is 7.8 centimeters. Equilibrium in a medium is established after a penetration of about five radiation lengths. For water this length is about 2 meters. Hence multiple cores that overlap in air might be separate and distinguishable under water. A decoherence experiment recording two-and four-fold coincidences under nine feet of water at an elevation of 7500 feet revealed no striking effects. The counting rates were high, however, and the experiment seemed promising if greater depths of water were used.

The work of Fretter and Ise was extended by Barrett³¹ at 50 meters and 2765 meters elevation. Two-fold and four-fold coincidences were recorded for different separations as a function of depth from 0 to 10 meters of water and for counter separations of 0.38 meter to 4 meters. The conclusion in regard to multiple cores was that, if they exist, they are distributed over a region of less than 50 centimeters diameter.

El-Mofty,³² working with Fretter, performed another underwater experiment using two ionization chambers to obtain decoherence curves. Counter separations ranged from 87 centimeters to 645 centimeters; water depths ranged from 0 to 2.74 meters. The conclusion drawn from this experiment was that multiple cores do exist. This result was based on the fact that the computed decoherence curve using Molière's distribution function did not fit the experimental curve. The discrepancy was attributed to the use of counter separations very much larger than the dimensions of showers in water. The result was a counting rate that falls off very rapidly with distance.

The experimental data were explained satisfactorily by the following arguments. The probability of finding a core at a distance r in the horizontal plane from the axis of the shower is given by $\phi(r)$. The density of cores at a distance r is given by

$$\sigma = \nu\phi(r)$$

where ν is the total number of cores within the individual shower. If, now, a shower has its axis at a distance r from a chamber of area A , the probability that the chamber will not be hit by a core is

$$e^{-A\nu\phi(r)};$$

The probability that it will be hit is

$$1 - e^{-A\nu\phi(r)}.$$

These probabilities were used to compute a theoretical decoherence curve which fit the data reasonably well. The function $\phi(r)$ was assumed as a first approximation to be linear in r and have the form

$$\phi(r) = a - br.$$

The somewhat qualitative conclusions that resulted from the detailed analysis made may be summarized by stating that the density of cores in an average air shower "decreases linearly with the distance from the center of the shower to a value of zero at a distance r_0 ," r_0 being the maximum spread of the cores from the shower axis. A density of cores of about one per square meter and a limiting value of five meters of r_0 appeared to fit the data. The average shower probably contained about 20 cores.

The latest attempts to detect multiple cores in air showers have been made by Hazen³³ and by Heineman and Hazen.³⁴ In 1951 Hazen used a cloud chamber of area 0.2 square meter in connection with a core selector located beneath the chamber to study core structure at distances of the order of a few centimeters from the core.

The chamber contained lead plates which served to give an estimate of the energy of each event. Rays of energy equal to or greater than 10^{10} electron volts defined the core position within about 20 or 30 centimeters. This result was based on the lateral distribution functions computed by Eyges and Fernbach.³⁵ No marked density singularities were observed, hence no definite conclusions concerning the multiplicity of cores could be established on the basis of density observations. If multiple cores were present, they were probably contained in an area of 50 or 60 centimeters diameter.

The results, however, were not consistent with the assumption of a single initiating ray. The density distribution of all the electrons and the energy spectrum of the rays near the axis corresponded to much lower energies than that required for a single initiating ray. Energies satisfying cascade-theory predictions provided only about one-tenth enough electrons to agree with experimental observations. Yet, the density distribution showed no definite evidence for multiple cores. Hazen suggested that the contradictions might be lessened or eliminated if better approximations had been made in the arguments leading to the energy estimates and in the arguments leading to the core identifications. Another suggestion offered was that there might have been one or two cores of high energy and several of low energy. This would explain the large number of electrons observed, and yet would not add greatly to the high-energy spectrum near the axis or to the number of cores that could be distinguished.

A very recent experiment by Heineman and Hazen,³⁴ using a remarkable arrangement of 20 wires in a single enclosure to give the equivalent of 20 ionization chambers, gave evidence of the existence of multiple cores. The experiment was not reported in detail, but the tentative results seemed to be indicative of a multiple-core structure, the cores presumable being due to different neutral mesons.

In summarizing the experimental results obtained on the lateral structure of air showers, one seems to be led to the conclusion 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. The experiments of Williams and of Cocconi,

Tongiorgi, and Greisen seemed to show that widely separated cores are not likely, while the experiments of El-Mofty, Hazen, and Heineman gave great probability to the existence of closely-spaced cores. Let us now direct our attention to a brief resumé of the theoretical work that has been done on the lateral spread of the large air showers.

Theoretical predictions of the angular and lateral spread of the air-shower particles have been made by several workers. Euler and Wergeland³⁶ were the first to treat the problem of the sidewise development of showers. Their numerical results gave spreads too small, as was pointed out by Bethe³⁷ and by Roberg and Nordheim.³⁷ Landau's treatment³⁸ suffered because of numerical errors. Belenky³⁹ evaluated the mean square angular spread of electrons as a function of their energy, but the results seemed to give too flat a distribution. Roberg and Nordheim⁴⁰ have calculated quite accurately the mean square angles and distances of both electrons and photons in air down to energies of about 4 Mev. Fujimoto and Hayakawa⁴¹ calculated a total distribution function for use in analyzing the experimental results of Cocconi, Tongiorgi, and Greisen. Nishimura and Kamata,⁴² in an attempt to improve upon the Molière function, calculated a lateral structure function under Approximation B.* Their results are nearly identical to those of Janossy,⁴³ which were considered to be the most accurate. Many others⁴⁴ have investigated theoretically the lateral structure of the air showers, but as yet the Molière distribution function¹⁶ is the only total (i.e., integrated over all energies) distribution function available to experimenters for evaluating their results.

Blatt²⁵ 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,⁴⁵ (2) the over-all structure function

* Reference 51, page 223: "...the approximation in which the Compton effect is neglected, the collision loss is described as a constant energy dissipation, ϵ_0 , and the asymptotic formulae for radiation processes and pair production are used."

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.⁴⁶ It is

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

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

$$r_1 = \frac{X_0}{\epsilon} \quad E_s = 74 \text{ meters at sea-level,}$$

X_0 = a radiation length, 330 meters at sea-level,

ϵ = the critical energy, 86 Mev for air,

E_s = 21 Mev.

The latest theoretical work on the spread of the soft component of air showers has been performed by Green and Messel.⁴⁷ A very critical analysis of all the previous work has been made in which it is revealed that this work was seriously in error because of "errors of principle" or because of oversimplification of the mathematics.

The results of their studies indicated that present calculations do not provide either a qualitative or a quantitative picture of air showers. The very large errors attributed to other workers involved one or more of the following: (1) the neglect of certain moments, (2) the neglect of the density variation of the atmosphere, which can introduce errors up to 5000 percent, (3) the incorrect consideration of the depth dependence, (4) miscellaneous errors in evaluating already approximate integrals, (5) the use of the results of Molière for some of the moments and the distribution functions. Their analysis of Molière's work led them to conclude that his calculation bore no relation to the real physical problem. They cannot account for experiments, such as that of Cocconi and his collaborators, that seem to support the Molière calculation. The authors have improved considerably upon the present theories by formulating a set of diffusion equations which take into account ionization loss and density variation of the medium. Their results will enable them to compute in the near future a distribution function based upon "a realistic physical model."

In summarizing these introductory remarks, one sees that the current state of knowledge of air showers is indeed inadequate. Experiments of greater resolving power need to be designed and executed; more powerful mathematical tools are needed to aid the theoreticians in solving the complex equations necessary to describe adequately the physical processes taking place in shower development. The answer to the latter need may lie in part in the rapid growth of the number and variety of electronic computers available to research workers. The answer to the former lies in the continued efforts of physicists to utilize new ideas and techniques to design apparatus of greater sensitivity and resolving power. A study of the details of recent experiments shows that progress is being made in this direction. In this paper we should like to submit the results of our work performed with a new version of an old instrument, a diffusion-type cloud chamber of unusually large size. Our purpose in building the chamber was to attempt to attain the higher resolving power that seemed so desirable for further work on the structure of air showers. We first give a brief description of the arrangement of the apparatus and then discuss the experimental results. The complete details of the cloud chamber are discussed in Part B of this paper.

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 numerous and extremely complicated. The actual area of the chamber was 32 square feet, out 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. The chamber was photographed through the 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 either 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 1-1/2 inches. Four such tubes were used in a fourfold coincidence circuit and were located as illustrated in Fig. 1. Three tubes were placed horizontally 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 Cocconi⁴⁸ 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.

Fig. 1 — Arrangement of the Geiger tubes with respect to the cloud chamber.

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 particle. Most showers arrive at angles not greater than 30° from the vertical.²⁴ 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. (See Figs. 45 and 46).

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 section III.2), each track received a final discriminating evaluation before 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 typical background photograph is shown in Fig. 44.

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:

$$\frac{\text{time interval in which a shower must arrive to be photographed}}{\text{total time interval between counts}} = \frac{0.4 - 0.1}{30 \text{ min.} \times 60 \text{ sec.}} = \frac{0.3}{1800} = \frac{1}{6000}$$

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 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* 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. Nonetheless, the results are believed to be as reliable as most other data on air showers obtained up to this time.

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

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 8-1/2 x 8-1/2 inches on Kodalith Film from the original 1-1/4 x 1-1/4 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* was large (e.g., 25 or greater) over a sufficiently large area of the picture, the procedure was as follows: Two sections whose counts could be reasonably called identical (perhaps 5 to 10 percent difference) were selected. 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,

* 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 — Illustrating the procedure for locating the shower axis.

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 meters) 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 drawn through the points in such a way as to best represent the data. These graphs are presented with each picture.

A second method of locating the shower axis involved the use of the Molière distribution function as approximated by Bethe. The final choice of position was always determined by the actual data, however, and not by the Molière function. 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 had 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 (see Fig. 3), 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 (section 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 centers 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, therefore, with the aid of only the actual 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. Since the position of the core was determined by means entirely independent of any theory of particle distribution, the experimental results provide data against which to compare various distribution functions. Our methods of locating the shower axis may be summarized by stating that they depend only on the assumption that the electron-photon showers are racially 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., $\sqrt{n}$. The exception to this deviation is discussed in connection with the picture in which it is found.

Fig. 3—The Molière chart.

When the shower axis was found at distances greater than about 1 meter from any point on the periphery of the chamber, the gradient was found to be quite small or to be masked by such small variations in track counts that the differences could not be considered significant. The method of analysis in these cases consisted of finding the average number of tracks per section for the whole photograph, computing the mean-square deviation, and making a plot of the data on statistics paper. Comparison of the two plots showed that it was reasonable to say that at three or four meters from the core the distribution follows very closely the Poisson distribution law. The fluctuations, however, may be much larger than expected from approximating the Poisson distribution by a Gaussian distribution. More detailed discussions are given with the individual pictures.

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 Individual Pictures

Figure 4. June 13, 1953--2:12 A.M. This shower exhibits the largest gradient of all the showers photographed. The shower axis is located 1.85 meters from the center of the cloud chamber and 0.8 meter from the corner of the chamber. The position of the axis is determined principally from the four sections marked with asterisks. The gradient is steep enough so that the use of Molière's distribution function is not necessary. In this picture, moving the core seven inches from its final position presents difficulties in matching the overall distribution.

In Fig. 5 the density of tracks per section is plotted versus the distance of the center of the section from the core. The smooth curves drawn through the experimental points are curves of the Molière function. The errors associated with the experimental points are the Gaussian standard errors ($\sqrt{n}$) only. The points themselves are averages obtained as described in section III. 2. The distance intervals are nine centimeters each.

Fig. 4—Number of tracks in the chamber, 1708; distance of axis from chamber, 1.85 meters. June 13, 1953, 2:12 A. M.

Fig. 5—The density distribution for Fig. 4.

Fig. 6—Showing the shower tracks only of Fig. 4. See section III. 2.

Fig. 7—Showing the position of the shower axis for Fig. 4.

The density distribution is well described by the Molière function for distances between 1.3 meters and 2.9 meters, but the departure from the Molière function between 0.9 meter and 1.3 meters is pronounced. This deviation from the Molière distribution may be explained in several ways, three of which are: (1) the Molière function itself may be in error, (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 distribution function, as pointed out in section I, is known to be in error in the form of the structure function itself, and in the estimation of the number of low-energy electrons. The Molière function, furthermore, is calculated only for the maximum of the shower. The combined effect of under-estimating 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.

The existence of multiple cores is a possibility, but in our opinion the photograph does not suggest this. The chamber area enclosed by an arc of 1.3 meters radius is about 0.16 square meters. 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.^{29, 49, 50}

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.

A lower limit for the energy of the initiating particle may be estimated with the aid of the theory of cascade shower development. The following estimates are made:⁵¹

$\text{Log}_{10} N$	$\text{Log}_{10} E_o/\xi_o$	$t_{\text{max.}}$
5	6.05	13 rad. lengths
5.3	6.35 (est.)	14 " "
5.5	6.55	14.5 " "

N = total number of positive and negative electrons in the shower estimated from the Molière function,

E_o = energy of the initiator in Mev,

ξ_o = the critical energy for air, 86 Mev,

$t_{\text{max.}}$ = height of shower origin above the cloud chamber located at sea level.

The minimum energy of the primary electron required to initiate this shower is 2.15×10^{14} electron volts. The shower originates 14 radiation lengths above the cloud chamber. Since a radiation length in air is 37.7 g/cm.^2 , 14 radiation lengths corresponds to 528 g/cm.^2 or a height above sea level of just slightly less than six kilometers.

Figure 8. June 9, 1953--8:19 A. M. The shower axis is located 1.65 meters from the center of the cloud chamber and 0.65 meters from the corner of the chamber. The position of the axis is determined with the aid of the Molière distribution function and of the gradient as described in section III. 2.

The density distribution is plotted Fig. 9; the smooth curve is the Molière distribution function for $N = 1.91 \times 10^5$. The errors associated with the experimental points are the Gaussian errors ($\sqrt{n}$) only. The points themselves are averages obtained as described earlier in section III. 2. The distance intervals are nine centimeters each.

Fig. 8—Number of tracks in the chamber 1042; distance of axis from chamber center, 1.65 meters; June 9, 1953, 8:19 A. M.

Fig. 9—The density distribution for Fig. 8.

Fig. 10—Showing the shower tracks only of Fig. 8. See section III. 2.

Fig. 11 — Showing the position of the shower axis for Fig. 8.

The density distribution is well described by the Molière distribution function over the entire range of distances covered by the photograph. The fluctuations from the Molière distribution are nearly all within the statistical error, n . The fluctuations might be expected to exceed the statistical deviations based on a Gaussian distribution, since the electrons are not independent but are related to each other through their ancestors.

The minimum energy of the primary electron required to initiate this shower is approximately the same as for the previous picture, viz., 2.0×10^{14} electron volts. The shower originates at about 14 radiation lengths above the chamber or six kilometers above sea level.

The experimental data for this picture lead to the conclusion that it originated from a single electron (or photon) and is described by the assumption of a single core. The density distribution with respect to this core is adequately described by the Molière distribution function.

Figure 12. June 20, 1953--7:03 P.M. The shower axis is 1.5 meters from the center of the chamber and 0.54 meters from the edge of the chamber. The position of the axis is determined with the aid of the Molière distribution function (see section III. 2). The determination of the axis position for this picture is rendered difficult by the small gradient and by the direction of incidence of the shower. The estimated angle of incidence is 23° from the vertical. The result is that circular arcs do not quite represent equal distances from the axis.

The density distribution is plotted in Fig. 13. The smooth curve is the curve of the Molière distribution function for $N = 10^5$. The errors associated with the experimental points are the Gaussian errors only. The points are average values obtained as described in section III. 2. The distance intervals are again each nine centimeters.

The Molière function fits the experimental data very well the fluctuation being for the most part within the Gaussian statistical errors, i. e., $\sqrt{n}$.

Fig. 12—Number of tracks in chamber. 643; distance of axis from chamber center, 1.5 meters. June 20, 1953, 7:03 P. M.

Fig. 13—The density distribution for Fig. 12.

JUNE 20 7:03 PM

Fig. 14—Showing the shower tracks only of Fig. 12. See section III. 2.

Fig. 15—Showing the position of the shower axis for Fig. 12.

The minimum energy of the primary ray required to initiate this shower is estimated to be 9.7×10^{13} electron volts. The shower originates 13 radiation lengths above the cloud chamber or approximately six kilometers above sea level.

A single core in which the density distribution is given by the Molière distribution function describes the density variation in this picture within the experimental errors.

Figure's 17 to 44, inclusive. The photographs are representative of showers that did not exhibit a gradient sufficiently large to allow the core position to be determined accurately. For these pictures the average densities and the standard deviations were computed and are tabulated in Table I. In addition, the integral density distribution was plotted on statistics paper, and is presented with each photograph. These plots indicate that the distributions are practically Poissonian. The single points on some of the photographs lying off the straight line are probably caused by knock-on processes, narrow air showers, or other phenomena unrelated to extensive air showers.

A crude estimate of the distances from the center of the chamber at which the shower axis struck was made in the following way. Figure 17 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 as shown in Fig. 16. 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 plus or minus 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 utilizing this method are also recorded in Table I. The estimated energies of the initiators that are listed were obtained from cascade shower theory on the basis of a single core. The angles listed are the angles that the shower axes make with the vertical. These were estimated in the manner described in section III.1. Table I is a summary of the results obtained for all twelve photographs.

Figure	No. of tracks in chamber	Average no. per section	Standard deviation	TABLE I		Distance of axis from chamber center	Gradient observable	Height of origin	Angle with respect to vertical
				Estimated no. of shower particles	Estimated energy of initiating ray				
4	1708			2.0×10^5	2.15×10^{14} ev	1.85 meters	Yes	14 r.l.	8°
8	1042			1.91×10^5	2.0×10^{14}	1.65	Yes	14	13
12	643			1.0×10^5	9.7×10^{13}	1.5	Yes	13	18
17	1641	28.8	10.1	10^6	$3. \times 10^{15}$	4	No	15	24
20	651	11.2	5.6	$3. \times 10^5$	10^{15}	3.6	No	14.5	7
23	625	9.6	4.8	$3. \times 10^5$	10^{15}	4	No	14.5	26
26	418	6.8	3.8	$3. \times 10^5$	10^{15}	4.6	No	14.5	7
29	2906	46.3	14.1	$> 10^6$	$3. \times 10^{15}$	4	No	15	11
32	1078	17.2	6.1	$3. \times 10^5$	10^{15}	3	No	14.5	9
35	693	11.2	5.5	$3. \times 10^5$	10^{15}	3.6	No	14.5	9
38	345	5.6	3.5	10^5	9.7×10^{13}	2.6	No	13	12
41	632	10.	3.7	$3. \times 10^5$	10^{15}	4.	No	14.5	21

The numbers in the box are order-of-magnitude estimates only.

Fig. 16—Illustrating the procedure for locating the shower axis when little or no gradient is present.

Fig. 17 — Number of tracks in chamber, 1641; average no. per section 28.8; std. deviation, 10.1. May 31, 1953.

Fig. 18—The density distribution for Fig. 17.

MAY 31 (2)

Fig. 19 — Showing the shower tracks only of Fig. 17. See section III. 2.

Fig. 20—Number of tracks in chamber, 651; average no. per section 11.2; std. dev., 5.6. June 3, 1953, 1:39 P. M.

Fig. 21 — The density distribution for Fig. 20.

Fig. 22 — Showing the shower tracks only of Fig. 20. See section III. 2.

Fig. 23—Number of tracks in the chamber 625; average no. per section, 9.6; std. dev., 4.8. June 4, 1953, 1:10 P. M.

Fig. 24—The density distribution for Fig. 23.

Fig. 25—Showing the shower tracks only of Fig. 23. See section III. 2.

Fig. 26 — Number of tracks in the chamber, 418; average number per section, 6.8; std. dev., 3.8; June 4, 1953, 7:49 P. M.

Fig. 27—The density distribution for Fig. 26.

Fig. 28—Showing the shower tracks only for Fig. 26. See section III. 2.

Fig. 29—Number of tracks in the chamber, 2906; average no. per section, 46.3; std. dev., 14.1. June 7, 1953, 8:30 P. M.

Fig. 30—The density distribution for Fig. 29.

Fig. 31—Showing the shower tracks only of Fig. 29.

Fig. 32 — Number of tracks in the chamber, 1078; average no. per section, 17.2; std. dev., 6.1; June 10, 1953, 7:53 A. M.

Fig. 33 — The density distribution for Fig. 32.

Fig. 34—Showing the shower tracks only for Fig. 32.

Fig. 35 — Number of tracks in the chamber, 693; average no. per section, 11.2: std. dev., 5.5; June 13, 1953, 1:07 A. M.

Fig. 36—The density distribution for Fig. 35.

Fig. 37 — Showing the shower tracks only of Fig. 35.

Fig. 38—Number of tracks in the chamber, 345; average no. per section, 5.6; std. dev., 3.5; June 15, 1953, 9:51 P. M.

Fig. 39—The density distribution for Fig. 38.

Fig. 40—Showing the shower tracks only of Fig. 38. See section III. 2.

Fig. 41 — Number of tracks in the chamber, 632; average no. per section, 10; std. deviation, 3.7; June 19, 1953; 6:59 P. M.

Fig. 42 — The density distribution for Fig. 41.

JUNE 19 6:59 PM

Fig. 43—Showing the shower tracks only of Fig. 41. See section III. 2.

Fig. 44—A photograph of the normal random cosmic-ray background. The total number of tracks in such a picture is about 1000. The number of straight tracks in a background picture is of the order of 200.

IV CONCLUSIONS

That only three showers exhibited an appreciable gradient was an expected result. Singer,²⁸ working at sea level, obtained the following differential number spectrum for air showers:

$$f(N)dN = 2.5 \times 10^4 N^{-2.4} dN \text{ hr.}^{-1} \text{ m}^{-2}$$

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 meters. The number of showers whose size lay between 1.0×10^5 and 1.9×10^5 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.^{24, 30}

That air showers might originate at these low altitudes was also not unreasonable in the light of the hypothesis advanced by Cocconi,²² 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 shower accompanying the N-component increases with increasing energy of the N-component.⁵²

Clay⁵³ 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.⁵⁴ 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,⁵⁵ 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,⁵⁶ 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.⁵⁷ 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 Tinlot, the N-rays are absorbed exponentially with a collision mean free path of about 120 g/cm^2 in air.⁵⁵ 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.⁵⁸ At altitudes of 6000 meters and higher, therefore, there should be an abundance of high-energy particles capable of initiating electron-photon showers.

Greisen⁵² 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 Setti⁵⁹ 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.²⁷ 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.

TABLE II

Primary Nucleon Energy(W')	Impact parameter (nucleons and mesons)		Impact parameter (mesons only)	
	$\rho = 0.959 \quad 0.990$		$\rho = 0.959 \quad 0.990$	
	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

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 our experiment utilizing the work of Hazen. The procedure was as follows:

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 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 by⁶⁰

$$\frac{\sin \theta_{\min}}{2} = \frac{Mc^2}{U}, \text{ when}$$

$\frac{U}{2} = E_1 = E_2$, the energies of the emitted photons,

$\theta_{\min}$ = the minimum angle between the decay photons in the laboratory system,

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.²⁷ The minimum value for W' is computed to be about 1.2×10^{16} electron volts. 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} electron volts. 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 600 kilometers below the point of origin would be about 30 centimeters. Each neutral meson, however, decays into two photons with individual energies of 10^{14} electron volts. 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 six kilometers is then calculated to be 0.6 centimeter. 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:

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 collision, which predicts multiple cores, because they would be so closely spaced as to be unresolved in this experiment. This does not imply that air showers are necessarily originated by the decay of neutral mesons, however. 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^{24, 33} with the exception of one.³⁴ The second result can be considered to extend the results of Williams²⁴ and of Cocconi, Tongiorgi, and Greisen²⁹ 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.²⁵

The experimental results do not contradict the experimental work of El-Mofty or the theoretical predictions of Fermi. The results, together with those of Cocconi and his collaborators, do provoke a question, however, in regard to the Molière distribution function. Unless the large errors pointed out by Green and Messel are of such a nature as to cancel one another, it is difficult to understand the excellent agreement of experiment with theory.

PART B

THE CLOUD CHAMBER

I INTRODUCTION

1. Historical Background

The continuously sensitive cloud chamber was first described by Hoxton⁶¹ in 1933. This chamber consisted of a system for passing air over water heated to 70°C and then allowing the warmed air to flow through an observation channel whose periphery was cooled by a water jacket. Electric discharges were used to produce condensation ions along the channel instead of radioactive radiations.

Another continuously sensitive cloud chamber was described by Vollrath in 1936.⁶² This chamber utilized two interdiffusing vapors such as hydrochloric acid vapor and water vapor, both of which became supersaturated.

Langsdorf⁶³ described the first continuously operating cloud chamber to be of practical use, and put forth a detailed theory for its operation. This chamber utilized methanol vapor diffusing through carbon dioxide gas. The bottom of the chamber consisted of two glass plates slightly separated to allow circulation of a coolant liquid and the chamber was photographed through this transparent bottom.

Interest in diffusion chambers seems to have lapsed after 1939, and not until 1950 did this interest become revived when Cowan⁶⁴ and Needels and Nielsen^{65, 66} published articles illustrating diffusion chambers of simpler design than that of Langsdorf. These chambers were all quite small, varying from a small two-liter glass beaker to more elaborately designed chambers of the order of 10 inches on a side (or 10 inches diameter) and 5 to 10 inches deep. The small size of these chambers allowed the parameters influencing their operation to be varied easily, so that detailed studies of the chamber characteristics could be made. Some of the results of these studies are summarized.

2. Factors Influencing the Operation of Diffusion Chambers

Vapors and Vapor Sources. The vapor and gas used in a diffusion cloud chamber must satisfy the requirement that the gas density be greater than the vapor density, in order that the system be stable against convection. Several combinations have been tried, among which are those listed in Table III. In all cases, successful performance depends upon the top temperature and the pressure, and the top temperature is dependent upon the chamber dimensions. The original articles should be consulted for optimum operating conditions.

Langsdorf recommended that vapor sources should avoid the following sources of aggregates:

- "1. Bubbling of boiling liquid.
- "2. Contact of boiling liquid and a metal surface.
- "3. Contact of vapor with a chilled (wet) surface or with an overheated surface."

These aggregates were believed to be the source of the continuous rain observed in his chamber. Nielsen and his collaborators, however, have not observed fog nuclei from the latter two sources Langsdorf mentioned.

Cowan found that an excellent vapor source was formed by using a pad of black velvet soaked with alcohol and warmed by a heated metal plate which formed the top of the chamber. Mixtures of ethyl alcohol, methyl alcohol, and water provided the deepest sensitive layer, but since the composition of the mixture varied with evaporation, methyl alcohol alone was finally used.

TABLE III

<u>VAPOR</u>	<u>GAS</u>	<u>WORKER</u>	<u>COMMENT</u>
Methanol	Nitrogen	Langsdorf	Not completely stable against convection.
Water Vapor	Nitrogen	Langsdorf	Freezes before optimum floor temperature is reached.
Methanol	CO ₂	Langsdorf	Best combination tried.
Ethanol with 5% H ₂ O	CO ₂	Langsdorf	
Butyl alcohol	Dichloro-difluoro methane	Langsdorf	Not satisfactory due to slow rate of inter-diffusion of dense materials. This cuts down supply of vapor available to form tracks.
Methyl alcohol	H ₂	Miller, Fowler, Shutt	Successful operation depends upon pressure and top temperature.
"	He	"	"
"	Air	Miller, Fowler, Shutt; Cowan	"
Ethanol	Air	Needels and Nielsen; Cowan	Satisfactory.
Propanol	Air	"	"
Methanol	Argon	Cowan	"

Most of the vapor sources in the diffusion chambers that have been constructed so far consist of a pad of cloth, usually felt, soaked with methanol or ethanol and attached to a metal plate which forms the top of the chamber. This metal plate is then heated by an electric heater such as a flatiron element, coffee-percolator heating element, or heaters from soldering irons. An input power of 40 to 60 watts in most cases provides adequate heating. A common top temperature seems to be about 30°C , but it varies from 10° to 65°C , depending upon the gas-vapor combination and the pressure.

Temperatures. The top and bottom temperatures at which a given chamber operates at its best depend upon the dimensions of the chamber and the vapor used. The temperature of the floor, however, does not seem to be critical. Cowan found that tracks could be observed as soon as the floor reached a temperature of -30°C . At -70°C , however, droplets begin to form on non-ion nuclei near the bottom of the chamber, producing a layer of fog about $1/8$ inch deep above the chamber floor.

The roof temperature is apparently more critical. One of the chambers described by Cowan was $9 \times 9 \times 5$ inches and operated best with a roof temperature of 34°C . Another circular chamber 12 inches in diameter and 7 inches deep filled with argon and methyl alcohol produced a sensitive layer 3 inches in depth with an optimum roof temperature of 39°C . When the same chamber is filled with air and methyl alcohol, an optimum roof temperature of 44°C produces a sensitive layer 3 inches deep. Filling the chamber with argon and a mixture of methyl alcohol, ethyl alcohol, and water produced a sensitive depth of 5 or 6 inches with a roof temperature of 55°C to 65°C .

The phenomenon that takes place as the roof temperature is increased is well described by Cowan.⁶⁴ At first the depth of the sensitive layer increases until an optimum temperature is attained, but above the optimum temperature the sensitive volume splits into two layers. Droplets that form on ions in the upper layer grow very rapidly because of their proximity to the vapor source. As they fall to the bottom, they remove vapor from the lower layer that otherwise would have increased the supersaturation of this layer. The net result

is that drops are not formed below the upper layer except very near the bottom plate, where the temperature gradient is large. When the temperature reaches the point at which the vapor pressure of the liquid approaches the total pressure in the chamber, the top layer rises to the top of the chamber and produces a general rainfall. Track formation is no longer discernible in this layer because the exceedingly rapid growth of droplets produces a competition for vapor. Only a few ions near the very top of the layer then find themselves in a region of sufficient supersaturation to allow drop formation.

The vertical and radial distribution of temperatures in a diffusion cloud chamber has been measured by inserting copper-constantan thermocouples at strategic points in the chamber.⁶⁷ The chamber used for the investigation was 23 cm in diameter and 10.5 cm high and was operated with 95% ethyl alcohol and air at atmospheric pressure. The results of this investigation indicated that a temperature gradient in the sensitive region (3.0 to 3.5 cm) of at least 10°C per centimeter was necessary for track formation. At temperature equilibrium, the gradient was nearly linear within the sensitive depth and had a magnitude of 12.5°C per cm, whether or not heat was applied to the top of the chamber. When no heat was applied to the chamber top, the gradient over the full vertical depth was 3.9°C per cm; when heat was applied, the gradient rose to 5.3°C per cm. The theoretical over-all average gradient necessary for track formation was 3.6°C per cm.⁶⁸

This experiment also provided an insight into the temperature gradients existing between the top of the bottom plate and the alcohol layer, and between the alcohol layer and the vapor immediately above. These measured temperature differences were 20°C and 12°C , respectively, compared to computed values of 25°C and 8.1°C . The total measured temperature difference between the plate and the vapor was 32°C compared to a calculated temperature difference of 33.1°C .

Pressure. The difference in performance obtained by operating at pressures different from one atmosphere was not considered by Cowan to be sufficiently advantageous to justify the added trouble. Cowan performed experiments at pressures varying from 0.1 to 2 atmospheres with no outstanding difference in performance.

A high-pressure chamber is desirable for some types of experiments, however, and some work has been done to perfect such an instrument.⁶⁹ The chamber is said to work well when filled with H_2 at a pressure of 12 atmospheres. The bottom temperature is near $-78^{\circ}C$ (dry ice-alcohol mixture) and the top temperature is $10^{\circ}C$. A controlled temperature gradient of $36^{\circ}C$ per cm is established with the aid of heating wires soldered to its stainless-steel walls. Two to three times sea level cosmic-ray intensity was recorded continuously by the chamber, giving good definition over the whole diameter through a sensitive depth of 2 or 3 inches.

Cooling Systems. The simplest construction for a small diffusion chamber utilizes a piece of black Bakelite or black-anodized aluminum placed in contact with a block of dry ice.^{64, 65, 66} The most complicated construction utilizes a gear or centrifugal pump to circulate a cooling liquid, usually alcohol, which at some point in the system has made contact with dry ice.^{63, 66} Very little is said about the details of the various cooling systems except in the paper by Langsdorf, in which a sketch of a specially designed centrifugal pump appears. Actually, none of the refrigerating systems is complicated. The system employed depends a great deal upon the whim of the experimenter and his ingenuity, the only final criterion being the attainment of a bottom plate uniformly cooled to the desired temperature.

Clearing Fields. Electric clearing fields are employed in most of the diffusion chambers so far described to remove ions from the nonsensitive part of the chamber volume. Sometimes the electric field is established merely by impressing a potential difference between the top and bottom of the chamber, of magnitude 10 to 100 volts per centimeter. In some instances particular attention has been given to the clearing field design. Langsdorf experimented with two arrangements. One arrangement allowed a simple vertical electric field of magnitude up to 130 volts per centimeter. The other arrangement utilized a horizontal grid of wires (30 B and S gauge wire) two inches apart, the alternate wires being positive and negative. The grid wire system suffered from the condensation of vapor on the wires, which no doubt resulted in drops' falling into the alcohol pool on the bottom. Langsdorf did not reach a definite conclusion as to which system was better, but he did recommend the use of some type of clearing field.

For the wall of one chamber, Cowan used two 12 inch-diameter glass rings, one 3 inches high and one 4 inches high, separated by a conducting rubber gasket which formed one sweep-field electrode. The top and bottom, connected electrically, formed the other sweep-field electrode. This arrangement removed the ions from the upper part of the chamber without forcing them down into the sensitive layer. It was planned to pulse the chamber with a sweep-voltage pulse of 600 volts amplitude after each burst of particles from the synchrotron; a recovery time of three or four seconds was anticipated. When the chamber was counter-controlled, a 600 volt pulse of 1.5 seconds' duration was applied every 45 seconds.

Needels and Nielsen, in their simple beaker-chamber, found that a vertical clearing field was more desirable than a horizontal field, and observed no difference in operation when using fields of 50 to 100 volts per centimeter. They point out that the use of a clearing field imposes an additional ion load which prevents the supersaturation from reaching the fog limit, which in turn allows sharper tracks to be observed. This would seem to be a questionable procedure because the desired tracks would be deprived of alcohol vapor.

Photography: [Every chamber has been photographed in accordance with the requirements of the particular experiment being performed from the top, the side, or the bottom. Carbon arcs and flash tubes have provided the illumination. A popular source of illumination now in use is the General Electric Type FT-422 flash tube. Cowan utilized this lamp and discharged through it 250 microfarads capacity charged to a potential difference of 2000 volts.

A lens aperture of $f/8$ admitted adequate light to produce an image on Kodak Linagraph ortho or Kodak Linagraph Pan film. When the chamber was counter-controlled, a delay time of 20 milliseconds allowed sharp tracks to be photographed. Delay times up to 180 milliseconds were successfully used. Short delay times are not a necessity with a diffusion-type chamber, however, because the ions do not diffuse before droplet growth begins.]

3. Notes on Operation

Fog Nuclei. When a diffusion chamber is first put into operation, a fine fog appears just above the floor, which is the result of condensation on dust particles found in the ordinary room air. This disappears in a few minutes.

Irradiation nuclei are also usually present unless a suitable filter is used with the viewing light. When this light is a tungsten projection bulb or a carbon arc, a yellow filter is required.

Streamers or Waterfalls. Streamers (which look like waterfalls if closely observed) sometimes form in diffusion chambers and use up vapor that would otherwise be used for track formation. These occur usually when the chamber is cooling, and are caused by contaminated air entering through leaks. They also occur whenever the barometric pressure changes, up or down, after the chamber has reached equilibrium. These streamers are stable over periods of several hours, and they are difficult to eliminate once they are formed.

Ion-Load Limit. The permissible ion load of a diffusion chamber depends upon the degree of supersaturation that can be maintained in the chamber, and this is dependent upon the vapor-gas combination, the pressure, and the temperature gradient. As mentioned earlier, light vapors and gases are most desirable because of the greater speed of inter-diffusion. Langsdorf found that his chamber would stand a continuous uniform amount of ionization equal in intensity to the ordinary cosmic-ray background, but it would respond to larger amounts for short periods of time. A simple calculation based on Stokes's law to determine the mass of the droplets and using the obvious fact that the mass flux of drops cannot exceed the amount of vapor diffusing in at the top confirms this fact. Cowan found that his chamber would operate satisfactorily with a background level several times the cosmic-ray intensity at sea level, though such operation reduced the height of the sensitive region.

4. Theory

The two papers so far published on the theory of diffusion chambers are those of Langsdorf and of Shutt,^{63, 68} the latter paper being somewhat more rigorous in its treatment. These theories are not discussed here, since they are rather long and detailed, but it

can be said that theory and experiment are in fair agreement and that a mastery of the theory is desirable and helpful in building a diffusion chamber.

II CONSTRUCTION OF THE CHAMBER

1. The Bottom

A sheet of dural 8 ft. long, 4 ft. wide and $1/4$ inch thick was selected to be the floor of the chamber. This was black-anodized to provide a background against which to photograph the tracks. Other attempts to obtain a black background had failed. Special alcohol-resistant paints peeled off; black velvet reflected too much light. The anodized dural sheet proved very satisfactory and showed no sign of deterioration. It should be mentioned that the anodizing process did not give a jet-black surface, but if a pool of alcohol mixed with black Putnam dress dye was allowed to form $1/16$ inch deep over the surface, an extremely black background was obtained. One tablespoonful of dye mixed with one gallon of methyl alcohol provided an excellent jet-black background.

A rubber dam, $1/4$ inch high and set in about 1 inch from the edges, was put around the periphery of the dural bottom (B, Fig. 45.) This wall consisted of ordinary weather-stripping material (Rubbershim) which, after being put in place, was coated with a mixture of Vulcalock and black Apiezon wax dissolved in toluene.* Ordinary $1/4$ inch rubber gasket material was tried, but the glue gave way when the chamber was cooled because of the contraction of the dural sheet. Rubbershim is not rigid and can expand or contract with equal ease. It is supplied with one adhesive surface so that it can be easily applied or removed.

To allow the bottom to drain the excess alcohol provided by condensation of the downward diffusing alcohol vapor, a $1/4$ inch pipe 2 inches long was threaded into one corner of the sheet so that it protruded $1/16$ inch above the floor. The other end was connected through a hose to a pump (Fig. 46.)

* Twelve sticks of black Apiezon wax was dissolved in 300 ml of toluene to make a syrup. This syrup was then mixed with an equal amount of Vulcalock, a Goodrich Rubber cement.

Fig. 45—A cut-away illustration showing the details of the cloud-chamber construction.

89

Fig. 46 — The cloud chamber complete with photographic equipment.

2. The Side Walls

The side walls of the chamber are 4 inches high and are double, with a 1 inch air space between them. The inner side walls are 1/4 inch plate glass 92 inches long; the outer side walls are 1/2 inch plywood 94 inches long. Between the inner and outer walls a length of mirror was inserted to reflect the light back into the chamber for better illumination of the tracks. Each wall was hermetically sealed at top, bottom, and ends with strips of Homolite cut to proper size and glued in place with Pliobond No. 30 cement. The hermetic seal served to prevent condensation of water vapor inside the double walls.

3. The End Walls

The end walls of the chamber were 4 inches high and were double with a 1 inch air space between them (H, J - Fig. 45). The inner end walls were 1/4 inch plate glass 45-1/2 inches long; the outer end walls were 1/4 inch plate glass 47-1/2 inches long. Each wall was hermetically sealed as the side walls were (G, K - Fig. 45).

The chamber was illuminated through the end walls. Two mirrors were used to lengthen the optical path of the light beam so that it could widen out to the width of the chamber. One of these mirrors was mounted on the end wall as is illustrated in Fig. 47 and shown partially in Fig. 48. The mirror, 49 inches by 5 inches, was glued to the end wall so that its plane made an angle of 49° with the plane of the wall. Both ends of the enclosed air space were sealed with triangular plywood blocks glued into place and painted with the mixture described in section II. 1. A length of plate glass glued over the top of the enclosed air space completed the hermetic seal. All the seams of this unit were covered with black photographic masking tape and the masking tape was covered with a heavy coat of the Vulcalock-wax mixture. This seal was rugged and impervious to moisture and alcohol.

The four walls were made a part of the chamber by resting them on the rubber dam around the dural bottom plate and sealing the inside and outside corner intersections with photographic Scotch tape painted with the Vulcalock-wax mixture.

Fig. 47 — Illustrating the details of the construction of the end-walls.

Fig. 48 — End of chamber showing end-wall, light box, pressure gauge for coolant pump, and blower for preventing moisture condensation on the top-glass of the end-wall.

4. The Vapor Source

The vapor source for this chamber was necessarily more complicated than the simple felt pad attached to a heated metal plate that was used in the smaller-sized chambers. Since the chamber was to be photographed through the top, it was necessary that the chamber lid be transparent. The system that was finally adopted consisted of a set of eight very narrow trays spaced twelve inches apart and suspended by a metal frame resting on the top of the glass walls (Fig. 49). Each tray was $1/2$ inch wide, $3/8$ inch deep, and 44 inches long (N, Fig. 45). A piece of $1/8$ inch copper tubing was soldered to the inside bottom surface of the tray (O, Fig. 45) and cut off so as to allow a $1/2$ inch protrusion at each end of the tray. These ends were thrust into holes drilled in the metal frame and soldered in place. The purpose of the tubing was to carry warm water to supply the heat of vaporization to the alcohol in the tray.

The frame into which the ends of the tubing were soldered was constructed from 1 inch-square brass tubing (F, Fig. 45). An inlet and an outlet pipe were soldered into the frame, and two square plugs were also soldered in in such positions that the circulating water was forced to flow through the eight parallel paths provided by the 8 inch copper tubes. (Fig. 50).

A reservoir of 5 gallon capacity and mounted on a 6 foot platform (Fig. 51) fed methyl alcohol into the trays through the distributing system shown in Fig. 45. It consisted of another length of square brass tubing, sealed at one end, into which arched feed pipes were soldered (E, P, Fig. 45). A solenoid valve controlled by a timing motor allowed any desired amount of alcohol to flow into the trays at intervals of eighty minutes. One quart usually filled all the trays. Not all of this went into the trays, however; the trays nearest the feed pipe overflowed somewhat before the farthest tray was full.

94

Fig. 49—Showing the assembled bottom, glass walls, and alcohol trays.

Fig. 50—Illustrating the circulating-water paths.
The water furnished the heat of vaporization for
the alcohol.

Fig. 51 — The methyl-alcohol reservoir mounted on a six-foot step-ladder. The glass-funnel arrangement was for filling the reservoir.

The temperature of the incoming alcohol was not the same as the equilibrium temperature of the trays. Streamers formed near the alcohol trays immediately after the admittance of alcohol. We believed that this effect could be minimized by having the temperature of the incoming alcohol approximately the same as that of the circulating water. This was accomplished by immersing in the circulating-water reservoir (Fig. 52) a flask and arranging the plumbing so that the alcohol entering the chamber came from the bottom of the flask. New alcohol flowed in at the top and had eighty minutes in which to acquire the temperature of the circulating water. The optimum temperature was about 18°C . A lower temperature appeared to provide an insufficient vapor supply; a higher temperature produced a deeper sensitive layer, but it also increased the general rain.

The temperature of the circulating water was not controlled at first. Records soon showed, however, that the temperature was falling to 5°C at night and rising to 22°C at midday. A Fenwal switch was installed to control a 250-watt immersion heater so that any desired temperature could be maintained within a $1/4^{\circ}\text{C}$. (Such accuracy was not necessary, but it was inherent in the switch). Controlling the temperature of the vapor source provided more stable operation and a more uniform depth of sensitive layer.

Temperature control of the plate-glass sheet forming the lid of the chamber should be included in discussion of the vapor source (O, Fig. 45). This sheet of glass, 4 feet by 8 feet by $3/8$ inch, rested on a layer of Rubbershim which served as a gasket between the rectangular brass frame and the glass (B, Fig. 45). Whenever Rubbershim was used as a gasket, the spacings produced had to be sealed with extra-wide Scotch tape because of the porous character of the Rubbershim. To thermally isolate this glass lid of the chamber from the surrounding air, another sheet of $1/4$ inch plate glass (A, Fig. 45) was mounted two inches above the first with an enclosed air space between the two. This air had to be heated, for otherwise alcohol condensed on the bottom surface of the $3/8$ inch glass top and prevented the photographing of the chamber. The temperature of

98

Fig. 52—The water reservoir showing the circulating pump, Fenwald switch, thermometers, and immersed flask for preheating the methyl alcohol.

the enclosed air was determined by a heating element consisting of 100 feet of Constantan No. 14 wire strung lengthwise of the chamber with a spacing of four inches between strands (M, Fig. 45). A relay, operated by a Fenwal switch located between the two glass plates, provided on-off control of a heating current of fifteen amperes. A temperature of 30°C was maintained day and night in spite of a noonday high of 42°C and a night-time low of 28°C of the air in the tent housing the chamber.

Two trays of silica gel were placed between the two glass plates to absorb the water vapor which might condense on the inner glass surfaces if the heating current failed.

The importance of preventing horizontal temperature gradients along the $3/8$ inch plate glass was demonstrated at one time when a crack occurred in the $1/4$ inch plate glass. Curtains (or streamers) appeared in the chamber within a few minutes, but they disappeared shortly after the crack was sealed with Scotch tape.

The addition of the second glass top served not only to keep the chamber lid at a constant temperature and to prevent the formation of horizontal temperature gradients, but it also provided a surface for dust collection that was elevated out of range of the light beam. The dust particles therefore were not photographed, as they were not illuminated. The top glass was kept moderately clean, however, by vacuuming it with an Electrolux cleaner mounted in the tent. In addition, it was wiped once every 24 hours with Kimwipes moistened with Turco window cleaner.

5. The Cooling System

The construction of the cloud chamber proper has been described thus far. An inspection of Fig. 46 shows that the chamber was mounted on a large black chest. This chest and its contents constituted the refrigerating system used to cool the dural bottom plate of the cloud chamber down to -67°C .

The details of the chest are illustrated in Fig. 53. It actually was a box within a box with a spacing between them of twelve inches, this space being filled with 700 pounds of Vermiculite insulation contained in flour sacks. The boxes were built of $3/4$ inch moistureproof plywood with all seams glued. The inner box was lined around the

Fig. 53—Illustrating the details of the chest upon which the cloud chamber rests.

sides with a 1/32 inch stainless-steel apron sloped so as to allow drainage of the coolant into the galvanized-iron return chute. An additional rubber apron was draped over the stainless steel to prevent leaking through the nail holes and joints necessary to hold the stainless steel apron in place.

The refrigerating system was comprised of a gear pump, a seventeen-gallon reservoir, and a set of three spray pipes which sprayed the dural bottom plate with alcohol cooled to -67°C . The reservoir was made "bread-pan" fashion, i.e., a single sheet of copper was bent into shape, so that expansion and contraction would not produce leaks at the seams. The outlet of the reservoir was shielded by a large housing of copper screen to keep out stray foreign particles that might clog the jets. In addition, a filter was employed between the reservoir and the pump. This filter was removed and cleaned about three times a week.

The gear pump required a small pressure head to operate effectively. For this reason it was located on the floor below the chest; the reservoir itself was inside the chest. The gear pump operated very satisfactorily without lubrication for 720 hours of continuous operation. A 1/4 horsepower synchronous motor was adequate to operate the pump.

The spraying system consisted of three lengths of 1 inch pipe each 7-1/2 feet long in which 3/32 inch holes had been drilled every 4 inches as shown in Fig. 54. The arrangement is illustrated in Fig. 55. At the ends of each pipe a few additional holes were drilled at such an angle as to produce a stream reaching to the ends of the dural bottom plate. Before this was done, no tracks appeared within 15 inches of each end of the chamber. After the holes were drilled the sensitive region extended out to within 2 inches from the end walls.

The cooling cycle began with the pumping of warm alcohol through the spray pipes. This alcohol struck the bottom plate of the chamber and then fell upon the dry ice, where it was cooled as it flowed down the return chute to the reservoir. After five minutes the bottom of the cloud chamber became cool enough to produce a very thin layer of droplets near the bottom. After twenty-five minutes thin tracks were observed near the floor. After two to three hours, the chamber was ready to be photographed.

Fig. 54—Showing the details of the jet holes in the spray pipes.

Fig. 55—A cross section drawing showing the placement of the coolant reservoir, dry ice, spray pipes, and cloud chamber bottom.

Twelve hundred pounds of dry ice was consumed every twenty-four hours. Since the capacity of the chest was only 400 pounds, three loadings each day were required.

The temperature of the bottom plate was not controlled automatically, but the range over which it was allowed to vary was restricted by visual monitoring of the coolant temperature. A copper-constantin thermocouple was anchored in the coolant reservoir 1 inch above the floor. The output of this thermocouple was indicated on a galvanometer located on a panel at the control desk. The reference junction was maintained at -78°C by keeping it immersed in an alcohol-dry ice bath contained in a Dewar flask. A 10° rise in the coolant temperature was tolerated.

Other methods of cooling the bottom were tried but none were so effective as the spraying.

6. The Camera and Shutter

The photographs were taken with one of the cloud-chamber cameras available in the laboratory. Though the camera was designed for stereo photography, it was not used in this manner. Instead, each lens was used to photograph one-half of the chamber volume. This system produced an image twice as large as would have been obtained if stereo pictures had been taken. Stereo pictures were not a requirement for this experiment, since the number of tracks per unit area was the only information required.

Leica Elmar f/4.0 lenses of 90-mm focal length were used with the camera. These lenses were sent out to be coated to improve their efficiency. An improvement in light transmission of at least 5 percent per surface was obtained, which yielded a total gain of 30 percent.

A shutter, operated by a solenoid upon receiving a signal from the coincidence circuit, was placed in front of the lenses to prevent fogging of the film when the tent was opened for entry or exit (Fig. 56).

Most of the pictures were taken on Kodak Linagraph Panchromatic film cut to a width of 1.8 inches. The film was developed 14 minutes at 68°F in D-19, or 5 minutes at 68°F in Atkins A-72 stock solution diluted four to one with water. Film was developed early in the morning and again in the evening to be certain that all equipment was working properly.

105

Fig. 56—The camera and shutter mounting with four of the six mirrors used to guide the image of the chamber into the lens of the camera.

7. The Mirror System

The optical path length between the chamber floor and the camera lens was 117 inches or about 10 feet. To avoid building a housing of such a large vertical dimension and to allow the camera to be at a level easily accessible, a system of mirrors was used to direct the image of the chamber to the camera lens. The arrangement of these mirrors is shown in Fig. 44. One mirror, 34 inches square, was mounted 44 inches above the chamber and centered with respect to one of the halves of the chamber. The plane of this mirror could be tilted slightly antiparallel to the plane of the bottom of the chamber and locked in position. A second and third mirror, 14 x 16 inches and 4 x 6 inches, respectively, were mounted on the same board as the camera (Fig. 56). These mirrors were experimentally aligned so that the image reflected from the 34 x 34 inch mirror was reflected into the lens of the camera. An identical arrangement was made for the lens photographing the other half of the cloud chamber.

Proper alignment of the mirrors was attained by utilizing the viewing light to illuminate the chamber and by examining the image formed on a piece of ground glass inserted in the back of the camera. None of the mirrors was front-surfaced. The four small mirrors were cleaned twice a day; the two large mirrors were cleaned twice a week.

8. The Photographic Lights and the Viewing Light

The photographic lights were two General Electric FT-422 flash tubes mounted behind focusing lenses of 5 inch focal length (Fig. 46). A bank of capacitors totaling 1000 microfarads was charged to 1.5 kilovolts and connected across each flash tube. Firing of the tubes was accomplished by wrapping a few turns of wire around the tube and connecting it to the secondary of an automobile ignition coil. The primary of the coil was connected to a relay in such a way that a condenser was discharged through the coil primary when the relay received a pulse from the coincidence circuit.

Two such lights were utilized to illuminate the interior of the chamber. A light path of 4 feet was required in order to allow the light beam to reach a width of about 4 feet before it entered the chamber.

This was necessary in order that the entire chamber would be uniformly illuminated. This optical path was realized by employing two mirrors to guide the light into the chamber (Fig. 46). One of the mirrors was mounted on the end wall in the manner described in section II. 3. The other mirror was mounted on the light stand as shown in Fig. 46. The light beam emerging from the light box was aimed skyward to the first mirror where it was reflected down into the mirror glued to the end wall. This mirror directed the light into the chamber along a path parallel to the chamber floor. The mountings of the light box and the mirror were designed to allow rotational and translational adjustments; the light stand itself could move only toward or away from the chamber. Each light stand was completely covered with a hood of black cloth to prevent unwanted reflections. Light was admitted to the chamber only through the channels provided by the mirrors. In Fig. 46 one light stand is uncovered to show the details; the other is covered with the hood just mentioned.

The viewing light used was a General Electric AH6, 1000 watt, water-cooled mercury arc using a commercial power supply. This light was mounted at one end of the chamber and another set of three mirrors guided this light into the chamber (see Fig. 57).

The delay time between the arrival of a shower and the taking of the picture by firing the lights was determined by a one-shot multivibrator circuit. The delay time during this experiment was set at 0.4 second.

9. Notes on Operating the Chamber

To complete the description of the cloud chamber, a few remarks concerning its daily operation over a period of thirty days may be interesting. The amount of work entailed in maintaining a successful schedule is indicated by a glance at one of the daily log sheets kept during that time (Fig. 58). Operational information was divided into five major categories and six other lesser categories which required a log sheet 22 inches in width divided into 35 columns. An attempt was made to make routine entries every two hours during the daytime and to make special entries as required. The chamber demanded so much detailed attention, however, that this was not always possible.

108

Fig. 57 — Showing the light box and the viewing light with its three mirrors to guide the light into the chamber.

[illegible]

Fig. 58—A small section of the daily log kept of the operations.

The reasons for keeping such a detailed record of operations were threefold: (1) to be able to refer back to chamber conditions when studying the pictures, (2) to learn more about the factors influencing diffusion-chamber operation, and (3) to overcome the tendency of the human mind to forget when it is burdened with a great number of details. Many of the columns did not require the recording of information, but only a check mark to indicate that all was well or that some task had been performed. At the end of the thirty days, it was clear that the keeping of such a record had actually been a necessity in carrying out the run successfully.

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to Professor Wilson M. Powell for suggesting this project and for his sustained effort and interest in bringing it to a successful conclusion. To Mr. Richard Lander I would like to express my gratitude for his excellent assistance in the building and operation of the chamber, the analysis of the film, and the making of the drawings. For the excellent work done in the early stages of developing the chamber, I am deeply indebted to Mr. Baxter Armstrong. I wish to acknowledge the kindness of Professors R. W. Brode and W. B. Fretter in allowing me to operate the chamber on the Cosmic-Ray Deck and to utilize other of their facilities. My thanks are also extended to all members of the cloud-chamber group who helped during the construction and operation of the chamber.

REFERENCES

1. P. Auger, R. Maze, and T. Grivet-Meyer, *Comptes rendus* 206, 1721 (1938).
2. K. Schmeiser and W. Bothe, *Ann. Physik* 32, 161 (1938).
3. P. Auger, R. Maze, P. Ehrenfest, and A. Freon, *J. de Phys. et rad.* 1, 39 (1939).
4. J. Daudin, *J. de Phys. et rad.* 7, 302 (1945).
5. L. Lewis, *Phys. Rev.* 67, 228 (1945).
6. R. Lapp, *Phys. Rev.* 69, 321 (1946).
7. K. L. Kingshill and L. Lewis, *Phys. Rev.* 69, 159 (1946).
8. N. Hilberry, *Phys. Rev.* 60, 1 (1941).
9. G. Cocconi, A. Loverdo, and V. Tongiori, *Phys. Rev.* 70, 846 (1946).
10. H. Kraybill and P. Ovrebo, *Phys. Rev.* 72, 351 (1947).
11. G. Molière, *Cosmic Radiation*, ed. by W. Heisenberg, New York, Dover Publications, 1946, Ch. 3.
12. H. W. Lewis, *Phys.-Rev.* 73, 1341 (1948).
13. L. Wolfenstein, *Phys. Rev.* 67, 238 (1945).
14. J. W. Lewis, J. R. Oppenheimer, and S. A. Wouthuysen, *Phys. Rev.* 73, 127-140 (1948).
15. J. G. Wilson, ed., *Progress in Cosmic Ray Physics*, New York, Interscience Publishers, Inc., 1952 (also Amsterdam, North-Holland Publishing Co., 1952) pp. 324-327; M. F. Kaplon and D. M. Ritson, *Phys. Rev.* 88, 386-397 (1952).
16. G. Molière, *Cosmic Radiation*, ed. by W. Heisenberg, New York, Dover Publications, 1946, pp. 26-40.
17. J. L. Powell, *Phys. Rev.* 75, 32 (1949).
18. R. Bjorklund, W. E. Crandall, B. J. Moyer, and H. F. York, *Phys. Rev.* 77, 213-218 (1950).
19. Reported by H. F. York at the April, 1950, meeting of the American Physical Society in Washington.

20. J. J. Lord, J. Fainberg, and M. Schein, Phys. Rev. 80, 970-973 (1950).
21. J. G. Wilson, ed., Progress in Cosmic Ray Physics, New York, Interscience Publishers, Inc., 1952; (also Amsterdam, North-Holland Publishing Co., 1952) p. 326.
22. G. Cocconi, Letter in Phys. Rev. 79, 1006-1007 (1950).
23. E. Fermi, Phys. Rev. 75, 1169 (1949).
24. R. W. Williams, Phys. Rev. 74, 1689-1706 (1948).
25. J. M. Blatt, Phys. Rev. 75, 1584-1598 (1949).
26. E. Fermi, Phys. Rev. 81, 683 (1951); E. Fermi, Prog. Theor. Physics 5, 570 (1950).
27. W. E. Hazen, R. E. Heineman, and E. S. Lennox, Phys. Rev. 86, 198-204 (1952).
28. S. F. Singer, Phys. Rev. 81, 579-592 (1951).
29. G. Cocconi, V. Cocconi Tongiori, and K. Greisen, Phys. Rev. 76, 1020-1033 (1949).
30. W. B. Fretter and John Ise, Jr., American Physical Society Bulletin F11, Phys. Rev. 78, 92 (1950).
31. P. H. Barrett, Phys. Rev. 84, 339-344 (1951).
32. Osman El-Mofty, Cosmic Ray Showers Under Water, unpublished thesis, University of California, Berkeley, California, 1953.
33. W. E. Hazen, Phys. Rev. 85, 455-461 (1952).
34. R. E. Heineman and W. E. Hazen, Phys. Rev. 90, 496 (1953).
35. L. Eyges and S. Fernbach, Phys. Rev. 82, 23-29 (1951); S. Fernbach, Letter in Phys. Rev. 82, 288 (1951).
36. H. Euler and H. Wergeland, Astrophys. Nor. 3, 1651 (1940); Naturwiss. 28, 41 (1940).
37. H. A. Bethe, Phys. Rev. 59, 684 (A) (1941); L. W. Nordheim, Phys. Rev. 59, 929 (A) (1941); Jane Roberg, Phys. Rev. 62, 304 (A) (1942).
38. Landau, Journ. Phys. USSR 3, 237 (1940).
39. S. Z. Belenky, J. Phys. USSR 8, 9 (1944).

40. Jane Roberg and L. W. Nordheim, Phys. Rev. 75, 444-457 (1949).
41. Y. Fujimoto and S. Hayakawa, Letter in Progr. Theor. Phys. 4, 579-581 (1949).
42. J. Nishimura and K. Kamata, Letter in Progr. Theor. Phys. 5, 899-901 (1950).
43. L. Janossy, Cosmic Rays, 2nd ed., London, Oxford Univ. Press, 1950 pp. 324-327.
44. A. Borsellino, Nuovo cimento 7, 700-702 (1950); A Borsellino, Nuovo cimento 7 (No. 3 bis) 1950.
45. B. Rossi and K. Greisen, Rev. Modern Phys. 13, 240 (1941).
46. H. Bethe, Phys. Rev. 72, 172 (1947).
47. H. S. Green and H. Messel, Phys. Rev. 88, 331-338 (1952).
48. G. Cocconi, Rev. Mod. Phys. 21, 26-30 (1949).
49. C. B. A. McCusker and D. D. Millar, Proc. Phys. Soc. (London) A, 64, 915-920 (1951).
50. Y. Watase, M. Oda, S. Higashi, and T. Kubozoe, J. Phys. Soc. Japan 6, 403-404 (1951).
51. Bruno Rossi, High-Energy Particles, 1st ed., New York, Prentice-Hall, Inc., 1952, p. 259.
52. K. Greisen, W. D. Walker, and S. P. Walker, Phys. Rev. 80, 535-545 (1950).
53. J. Clay, Letter in Phys. Rev. 81, 645 (1951).
54. J. Clay, Physica 16, 278 (1949).
55. D. J. X. Montgomery, Cosmic Ray Physics, 1st ed., Princeton, Princeton University Press, 1949, p. 324.
56. Bruno Rossi, High-Energy Particles, 1st ed., New York, Prentice-Hall, Inc., 1952, p. 486.
57. J. H. Tinlot, Phys. Rev. 73, 1476 (1948); 74, 1197 (1948).
58. G. Cocconi and V. Cocconi Tongiori, Letter in Phys. Rev. 79, 730-732, (1950).
59. A. Gerosa and R. L. Setti, Letter in Nuovo cimento 8, 601 (1951).

60. Bruno Rossi, High-Energy Particles, 1st ed., New York, Prentice-Hall, Inc., 1952, p. 199.
61. L. G. Hoxton, Proc. Virginia Acad. Sci., Abstr. 9, 23 (1933-34).
62. R. E. Vollrath, Rev. Sci. Instr. 7, 409 (1936).
63. A. Langsdorf, Rev. Sci. Instr. 10, 91-103 (1939).
64. E. W. Cowan, Rev. Sci. Instr. 21, 991-996 (1950).
65. T. S. Needels and C. E. Nielsen, Rev. Sci. Instr. 21, 976-977 (1950).
66. C. E. Nielsen, T. S. Needels, O. H. Weddle, Rev. Sci. Instr. 22, 673-677 (1951).
67. H. L. Morrison and G. J. Plain, Rev. Sci. Instr. 23, 607-609 (1952).
68. R. P. Shutt, Rev. Sci. Instr. 22, 730 (1951).
69. D. H. Miller, E. C. Fowler, and R. P. Shutt, Rev. Sci. Instr. 22, 280 (1951).

THIS PAGE
WAS THIS PAGE ALLY
WAS INTENTIONALLY
LEFT BLANK