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Cosmic-Ray Showers and Bursts

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I. INTRODUCTION

1. General introduction and definitions

WHEN many men in different countries are working independently on a comparatively new problem, the reports are numerous, often brief, sometimes incomplete and are published in many journals. Those who are doing research in other fields find that it requires much time to review adequately the literature on a subject such as "Cosmic-Ray Showers and Bursts." The purpose of this survey of the publications dealing with cosmic-ray showers and bursts is to make available a fairly comprehensive report of the experimental work and theoretical deductions on this subject.

A cosmic-ray shower may be defined as that radiation emerging from a nonradioactive block of matter exposed to cosmic rays, which will simultaneously discharge three Geiger-Müller (G-M) counters which are placed out of line. When such radiation passes through an expansion chamber the paths of two or more ionizing particles, apparently coming from one point in the block, are often seen. A shower may be induced by a photon or an ionizing particle and

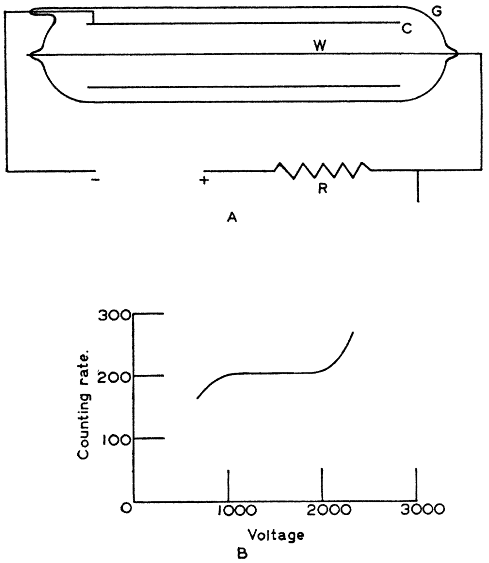

FIG. 1. (A) A Geiger-Müller counting tube. (B) Response *vs.* voltage curve for a hydrogen-filled G-M counter constructed by F. Shonka. (Shonka and Eckart.[38])

it may be made up of photons or ionizing particles or both.

A burst, or Hoffmann Stoss, may be defined as that radiation which will produce an abrupt and transient increase of the current through an ionization chamber, which is several times as great as the mean statistical fluctuation. While both bursts and showers are produced by the interaction between cosmic rays and matter we do not wish to assume, *a priori*, that they are produced by identical physical processes. However, we shall see that the great majority of bursts, probably all of them, are large showers generated in the shielding and walls of the ionization chamber.

As cosmic rays pass through matter they will be accompanied by the shower and secondary rays produced in it. Different materials are not equally efficient as shower producers and, when the radiation passes from one material to another, the relation between the incident rays and the secondaries will usually be changed, resulting in a variation of the total intensity. This variation of the intensity of the beam is called the transition effect or "übergangseffekte." The magnitude of this effect depends upon the absorption and shower-producing properties of both media.

Showers were first studied by expansion chambers and G-M counters, bursts and the transition effect by ionization chambers. At present all these instruments are used in studying various phases of the transition effect.

2. Cosmic-ray instruments

A G-M counting tube is an instrument which has been and is being used extensively in the study of cosmic-ray showers. As represented schematically in Fig. 1*A*, it is a coaxial condenser. The outer cylinder *C* is a thin-walled metal tube and the central electrode *W* is a wire of very small diameter. The whole is enclosed in a glass envelope *G* which contains a gas at a pressure in the neighborhood of 5 to 10 cm of mercury. The central wire is maintained at a positive potential with respect to the outer cylinder and some effective resistance *R* is interposed in the circuit. With proper adjustments of voltage and resistance an electric pulse between the electrodes is initiated when the gas in the G-M tube is ionized. The number of pulses per second, all produced by a standard ionizing source, is shown as a function of applied voltage in Fig. 1*B*.

It is seen that the *number* of pulses per second between 1000 and 2000 volts is practically independent of the applied voltage. The tube is operated on some voltage along this plateau. While exact voltage control is not required for tubes with a plateau of the magnitude of the one shown here, most tubes have a shorter and less nearly flat plateau and require a controlled voltage. Gingrich[36]* has given an excellent summary of types of circuits now employed for stabilizing voltages for this type of work.

The G-M counter is an efficient instrument for detecting the passage of ionizing particles. This efficiency decreases with the number of counts per second since the tube is insensitive for a small time interval after each pulse. As an example, Froman and Stearns,[38] using the method of Street and Woodward,[34] found the efficiencies of a single counter at altitudes 120 and 14,160 feet to be, respectively, 95 and 85

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* The reference numbers are the final digits of the year in which the paper was published. Letters are appended when it is desirable to refer to a particular paper of a number published in the same year by the same author. The numbers following the reference in the bibliography give the sections of this article in which the paper is mentioned.

percent. However, for detecting gamma-rays the efficiency is very low. Evans and Mugele[36] report that an especially designed G-M counter "gives the order of one count per hundred gamma-ray quanta traversing the cathode area." The γ-ray efficiency of standard cosmic-ray counter equipment is not more than one-fifth this amount.

From the considerations of efficiency it can be seen that several G-M counters in a straight line may be actuated by a single high energy ionizing particle passing through each, whereas the chance of a high energy photon producing simultaneous pulses is exceedingly small. In fact, combination cloud chamber and counter studies by Mott-Smith and Locher,[31] by Johnson, Fleischer and Street,[32] and by Blackett and Occhialini[32] have shown that multifold coincidences are almost always produced by ionizing particles.

After the discovery that a single particle could excite two counters placed in line, the obvious advantages of using three or more counters in the "telescope" became evident to Rossi,[30] Tuve[30] and Mott-Smith.[30] Thus the technique of recording multifold coincidences was well developed by the time Rossi[32a] discovered that showers could be detected with counters. The year before Rossi's discovery, Heidecke[31] had really detected shower rays with counters but he interpreted his data on the basis of ordinary scattering. Some of the early work on showers was done with two counters, but in most of the later work at least three counters were used.

Examples of modern recording circuits for multifold coincidences are those of Fussell and Johnson,[34] Neher and Pickering[38b] and Neher and Harper.[36]

Ionization chambers and Wilson[97, 99, 00, 01, 11, 23] cloud chambers are described in many textbooks of physics and used so extensively in other fields of investigation that only those modifications used in cosmic-ray work will be reported. For a given radiation, the current through an ionization chamber increases with the volume of the chamber, and the pressure and temperature of the gas. The current is also a function of the kind of gas. The Model C meter developed by Compton, Wollan and Bennett[34] is an example of the type of ionization chamber used by many workers in the field of cosmic rays. It has a large volume, 19 liters, is filled with argon at a pressure of 50 atmospheres, utilizes a null method which overcomes the temperature effect, and is self-recording.

Two modifications of the expansion chamber have been developed. The chamber itself is now placed between the poles of a strong electromagnet so that the energy of cosmic-ray electrons can be studied. In 1932 Blackett and Occhialini[32, 33] perfected their ingenious system of controlling the time of expansion of cloud chambers by a set of G-M counters. Counters are placed on either side of, or in, the Wilson chamber and an expansion occurs only when the counters are operated. This system, which secures many more photographs that show significant events than do those obtained by the random exposure method, is now in general use for cloud chamber work on cosmic rays.

The track of an ionizing ray in a photographic emulsion becomes visible on development. Jdanoff[35] and Wilkins and St. Helens[36] have pointed out that it is possible to distinguish between the tracks of fast protons and α-rays. Because of this, the photographic method may become very useful in the study of disintegration by cosmic rays since, in a cloud chamber, very fast particles are often very difficult to identify. The photographic method has the advantages, too, that the record is permanent; the emulsion is continuously sensitive; and the light weight of the equipment required is particularly adaptable for use with pilot balloons. Observing protons by this method, Wilkins[36a] found evidence of a disintegration without capture, a process previously unknown.

The stratosphere balloon, *Explorer II*, carried photographic plates for Rumbaugh and Locher[36] and for Wilkins.[36b] The balloon maintained an altitude of 22 kilometers, corresponding to a depth in the atmosphere of $\frac{1}{2}$ meter of water equivalent, for a period of two hours. Rumbaugh and Locher found that during this time as many tracks were made in the emulsion as would be obtained in a month at a depth of 6 meters of water equivalent, i.e., at an altitude of 4000 meters.

Methods of treating photographic plates for use in this type of work have been given by Blau[34] and by Blau and Wambacher.[34]

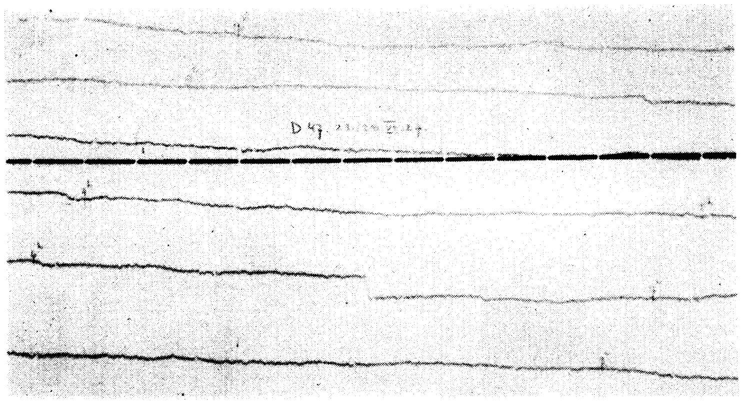

FIG. 2. Hoffmann's electrometer trace showing the first burst to be observed. The sharp deflection between 6h. and 7h. on the record of June 24, 1927, corresponds to a burst of 4×10^6 ions. Photograph by courtesy of Professor Hoffmann.

3. The discovery of showers and bursts

One of the earliest indications of any interactions between cosmic rays and matter, other than ordinary ionization and absorption, appeared in the work of Millikan and Otis[24] in 1924. These experimenters, using lead shields a few centimeters in total thickness around an electroscope, found a surprisingly high apparent absorption coefficient for the rays in lead. Although this result was misinterpreted at the time, it can be explained easily when account is taken of the air-to-lead transition effect. In 1927 Hoffmann[27] detected and investigated the transition effect. In the same year Hoffmann[34] also recorded the first cosmic-ray burst. The electrometer trace showing this burst is reproduced in Fig. 2.

When Hoffmann first observed the striking momentary increase in ionization current produced by a burst, he made a thorough study of the apparatus in order to make certain that it was not a spurious effect. Steinke,[30] Schindler,[31] and Steinke and Schindler[32] studied several bursts. Steinke suggested that a high speed proton might account for the effect, but Compton[32] showed that the ionization was, in some cases, ten times as great as would be expected from a proton's passage through the chamber. Montgomery and Montgomery[33] showed that the bursts were distributed at random in time. Early observations on bursts were made by Broxon,[32] Hoffmann and Pforte,[30] Messerschmidt,[32,33] Steinke and Schindler,[32] Steinke, Gastell and Nie,[33] Swann and Montgomery[33] and Tuwim,[33] and at present the phenomenon is observed daily by all of the scores of workers using ionization chambers.

Skobelzyn,[29,32] and Auger and Skobelzyn[29] first detected showers in Wilson expansion chambers but, since the showers were thought to be made up of Compton recoil electrons, cloud chambers were not much used in their study for several years. In 1931 Mott-Smith and Locher[31] used a cloud chamber to show that the simultaneous discharge of two counters always coincided with the passage of an ionizing ray through both of them. During the next year Johnson, Fleischer and Street[32] checked this result by causing the simultaneous discharge of two counters to flash a lamp which illuminated a continuously sensitive cloud chamber placed between the counters.

In 1932 Anderson,[32] Locher,[32] Kunze,[32] and Skobelzyn[32] found cases of two or three particles, ionizing like β-rays, arising at the same spot. Since it is extremely unlikely that two or more fast Compton recoil electrons will arise very close together, the shower process was recognized in cloud chambers at this time.

At about the same time that showers were first observed in an expansion chamber, Geiger and Müller[28,29] developed the tube counter; and Kolhörster,[28] and Bothe and Kolhörster[28,29] showed that a single cosmic-ray ionizing particle was capable of discharging two counters simultaneously. The technique of counter and counter circuit construction advanced rapidly in the hands of such workers as Rossi,[30b] Curtiss,[29, 30] Wynn-Williams,[31, 32] Street and Johnson,[32] Tuve,[30] and Mott-Smith.[30] In 1932 first Rossi,[32a] then Street and Johnson[32a] showed that showers could be detected with counters.

An excellent historical account of developments in cosmic-ray work is given by Corlin.[35]

II. Theoretical Deductions

1. Determination of the energy of ionizing particles

A proper interpretation of cloud chamber data often necessitates the identification of the particles involved and a measurement of their energies. For convenience some of the well-known relations required in energy measurements are listed.

The following relations apply to a particle of rest mass, m, charge, e, total energy, E, kinetic energy, T, moving with a velocity, v, in a magnetic field of strength, H, along a path of radius of curvature, ρ:

$$\begin{aligned}E&=mc^2(1-v^2/c^2)^{-\frac{1}{2}},\\ T&=E-mc^2,\\ He/c&=mv/\{\rho(1-v^2/c^2)^{\frac{1}{2}}\},\\ v/c&=H\rho[(mc^2/e)^2+(H\rho)^2]^{-\frac{1}{2}},\\ E&=H\rho ec/v=e[(mc^2/e)^2+(H\rho)^2]^{\frac{1}{2}}.\end{aligned}$$

For most of the cosmic-ray electrons $(mc^2/e)^2$ is negligible compared with $(H\rho)^2$, and we have for electrons, $E=eH\rho$ ergs $=300H\rho$ electron volts within 1 percent for $H\rho>1.3\times 10^4$ gauss* cm.

Unless it is certain that m is so small that $(mc^2/e)^2 \ll (H\rho)^2$, it is necessary to know both e and m in order to determine the energy from the curvature in a magnetic field.

The specific ionization produced by fast charged particles is a function of e and v, but depends so little on m that, for values of $H\rho>1.5\times 10^6$ gauss cm, it is impossible to distinguish between proton and electron tracks. However, in cases of relatively small $H\rho$, the relations among charge, mass, velocity, specific ionization, rate of energy loss, and range, are well established from observations of both natural and artificial radioactive products, where the nature of the ionizing rays is known. For purposes of particle identification it is sufficiently precise to consider the specific ionization, and the rate of energy loss, to be proportional to e^2/v^2 and the range proportional to v^3. An example of the appearance of electron and proton tracks in cloud chambers is shown in Fig. 30g. The Bethe-Heitler theory gives a minimum specific ionization for an electron of energy of 10^6 ev and Starr[37] has found such a minimum at about 1.5×10^6 ev. Whenever $H\rho$ is small for a cosmic-ray particle its energy can be calculated on any assumed values of its charge and mass. The specific ionization, energy losses and range, observed for the particle, can then be compared with the values known to prevail for particles of the assumed charge and mass having the calculated energy. Thus by assuming various combinations of e and m, the particle can be identified if $H\rho$ is sufficiently small. Much historical, analytical and experimental information on these relationships has been given by Rutherford, Chadwick and Ellis.[30]

In order to determine the sign of the charge it is necessary to know the direction of motion of the particle. It is not safe to assume the direction of a cosmic-ray particle. If, however, the particle is allowed to pass through an absorbing layer it will lose energy, and its direction of motion can be determined from the curvatures of the parts of its path on each side of the absorber.

In cloud chamber measurements of energy losses it has generally been assumed that the ionizing rays are electrons, and energies have been calculated on the basis of this assumption. In order to make good droplet counts for the estimation of *specific* ionization it is necessary to delay the expansion of the chamber for an appreciable time—the order of one second—after the passage of the ray, to allow sufficient diffusion of the ions. However, this diffusion reduces the precision in the measurement of ρ. It is not possible to determine the mass of the particle from the great majority of the energy loss photographs, since the particle is usually

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* In conformity with the usage in contemporary papers dealing with cosmic rays the *gauss*, instead of the *oersted*, has been retained as the unit of magnetic field strength.

not near enough to the end of its range for its specific ionization to be a marked function of its mass, and the expansions are taken too early for accurate determinations of the specific ionization. The *primary* ionization can be determined accurately by droplet count only if the photograph is made immediately after the passage of the particle. This cannot be accomplished in a counter-controlled chamber and usually the expansion is delayed to allow the ions to diffuse. It is extremely improbable that a particle will come to the end of its range in the illuminated field of the chamber. The usefulness of the mass-range relationship is almost always limited to the determination of a maximum range for a hypothetical mass. If the length of path observed significantly exceeds this maximum, the mass of the particle must be less than that which was assumed.

2. Production and absorption of showers

It is not the intention, in this section, to attempt a critical or complete discussion of the mathematical and theoretical background of theories of shower production. The objects are, rather, to state the assumptions upon which some of the theories are based and to present the main deductions.

In 1932 it was pointed out that showers were not produced directly by the penetrating cosmic rays for, if they were, the transition curve showing the relation between the frequency of shower production and the thickness of absorber, or scatterer, would decrease, with increasing thickness beyond the optimum, at the same rate as the intensity of the total radiation. In this range the rate of decrease in the frequency of shower production is very much greater than it is for the total intensity. Thus a part of the cosmic radiation, thought by many to be secondary in character, was selected to be the "shower-producing component."

As it was well known that the total radiation was absorbed nearly exponentially in the lower part of the atmosphere, it was a logical step to assume that the shower-producing component would be absorbed in the same way and that the actual shower rays would be absorbed exponentially or, if they were ionizing rays, they might be characterized by a definite range roughly equal to the optimum thickness for shower production. Rossi[31, 32b] gave a qualitative explanation of the shape of the shower production curve on the exponential absorption basis.

A quantitative treatment on this basis was given by Johnson[32a] who assumed that shower rays were produced at a rate proportional to the intensity of the shower-producing radiation and were absorbed exponentially. The production coefficient was taken to be a function of the material, and the absorption coefficient of the shower rays was assumed to be a function of both the absorbing material and of the material in which they were produced. On this basis Johnson,[32a] using Schindler's[31] data, calculated absorption and production coefficients for several substances. The curves constructed by means of these coefficients fitted well with the transition curves from air-to-lead, air-to-iron, iron-to-lead and lead-to-iron. The same process can be applied to the Rossi transition curves obtained with counters, and can be extended to as many materials as desired. It has been used extensively in this way by many workers. On the basis of this theory it is difficult to explain the differences in shape of the transition curves obtained with different arrangements of counters. The theory takes no account of the observed cumulative processes in shower formation and it gives a value of the shower absorption coefficient at variance with the value determined by direct experiment.

In early studies Barnóthy[33] developed an algebraic theory for burst production, which has been discussed by Steinke;[33] and Bhabha[33] considered the role played by showers in the absorption of the cosmic rays. More recently Bramley[35, 36] has applied electrodynamic theory to the problem of absorption of high energy rays and discussed, theoretically, the presence of photons in showers; Gross[36b] has developed an algebraic theory of energy losses in the formation of secondaries; Whittaker[37] has treated shower production as group events on the theory of probability; and Johnson[36] has discussed the relative importance of electrons and photons in causing the transition in the atmosphere.

In 1933 Swann[33] suggested that the rays produced in bursts in the atmosphere were the entities which actuated counters. Later[34] he suggested that particles of energy greater than 8×10^9 ev might produce showers, but no ionization in the usual sense. He also discussed the application of this theory to the rapid increase of burst frequency with altitude. A development of these ideas led Swann[35] to suggest that primary cosmic rays produce secondary rays at a rate per unit length of path proportional to the energy of the primary ray. It was possible, with this assumption, to explain a number of observations, including the approximate exponential absorption in the atmosphere, and the variations with altitude and latitude of both the total intensity and the east-west ratio.

In 1936 Swann[36a] developed his more generalized theory. The fundamental basis of the theory is the assumed equation:

$$-dE/dx=\alpha+\lambda E_x,$$

where E_x is the energy of a primary ray at a depth x below the top of a homogeneous atmosphere, α is the energy loss per unit of path by ionization and λ is a constant. Swann showed that the variation of the rate of shower production with altitude was consistent with the solution of this equation. In fact, on the basis of this theory, it is possible to derive an equation for the transition curve which will account for the difference in shape of the initial parts of the two-particle and the three-particle curves. The equation, however, contains parameters which must be fitted empirically, does not make allowance for the observed photon content of the shower, and gives no explanation for the large numbers of pairs observed in cloud chambers. Montgomery and Montgomery[37] have concluded, on the basis of Swann's theory, that the soft component of the cosmic rays is probably composed of protons.

Until 1934 the stopping power of matter for fast charged particles was considered to be due to three main causes: (i) ionization, (ii) nuclear scattering, and (iii) radiation under the influence of the field of a nucleus. Quantum theory estimates of the energy losses by processes (i) and (ii) have been made by Bethe,[30, 32] Möller[32] and Bloch.[33] Heitler[33] made an early estimate of losses by process (iii) by deriving a value of the cross section, Φ, for energy loss by radiation. He found

$$\Phi\sim\frac{Z^2}{137}\left(\frac{e^2}{mc^2}\right)^2, \quad \text{for} \quad E\gg mc^2,$$

where these letters have their usual significance. In 1934 Heitler and Sauter[34] gave further theory on this process, and Bethe and Heitler[34] took into account the effect of screening with its dependence on primary energy. Weizsaeker[34] and Williams[34] studied the validity of the Bethe-Heitler formulae theoretically, and concluded that they were valid for, approximately, $10^6<E<10^9$ ev. The theoretical energy loss for electrons was so high that the great penetration of the cosmic rays could be explained only on the assumption that the rays were not electrons, or that the theory broke down at high energies. To account for the observed penetration, Born and Infeld[34] suggested that the range of the interaction forces on photons decreases, for decreasing wave-length, to the order of the electron's radius. Bhabha and Hulme[34] pointed out that if the Bethe-Heitler formulae broke down at high energies it would be the first case in which quantum mechanics theory was not applicable to extra-nuclear phenomena. Bhabha and Hulme calculated the cross section for annihilation of positrons by bound K electrons. This process gives the emission of a single quantum, whereas two quanta are obtained on the annihilation of a free electron by a positron. However, they found that the contribution by K electrons of heavy elements to the annihilation of positrons amounted to only a few percent.

In 1934 Heitler and Nordheim[34] concluded that there were practically no indications of the mode of shower formation in quantum mechanics as developed to that date. Oppenheimer[35a] has given a summary and an analysis of quantum mechanics formulae in use at the end of 1934, and some additional points have been made by Williams.[35]

Beck[33] and Oppenheimer and Plesset[33] independently began the treatment of electron pair production by photons. They found this theoretical cross section to be about equal to Φ, the cross section for energy loss by radiation.

Furry and Carlson[33] estimated the cross section for pair formation by high energy electrons to be about the same, but Nordheim[35] found this cross section to be only about 1/100 of the cross section for γ-ray production by an electron. He found the probability of γ-ray production by an electron to be about equal to that for positron-electron creation by a γ-ray. Oppenheimer[35b] made similar calculations for the pairs of electrons created by radiation from high energy electrons in nuclear fields. A comprehensive account of the theory of electron radiation and of pair creation in nuclear fields can be found in *The Quantum Theory of Radiation* by Heitler.[36]

In 1936 Solomon[36] calculated probabilities for the production of heavy particles by γ-rays, and Nordheim[36] extended the theory of radiation and pair production. On the basis of the theory Oppenheimer[36] calculated the optimum thickness for shower production by incident rays of definite energies. For $E=3\times10^9$ ev the optimum thicknesses were 2.2 cm and 45 cm, and the maximum number of electrons in the showers from the optimum thicknesses 12 and 2.3, for lead and aluminum, respectively. These values agree well with experiment. It was predicted that the optimum thickness would increase slowly and the maximum number of particles would increase rapidly with increasing values of E.

In 1934 Montgomery[34] suggested the "cascade" theory of burst formation. According to this theory at least some of the rays in a burst were capable of producing, by an undefined process, new groups of rays. In this way Montgomery was able to account, approximately, for the frequency-size distribution observed for bursts. In 1935 Auger[35b] described the process of shower formation as a succession of radiative collisions and pair creations. Shortly afterward Bhabha and Heitler[37] and Carlson and Oppenheimer[37] independently derived results for the number of shower electrons, and photons, expected per unit time as a function of the thickness and kind of the shower-producing material and the energy of the incident radiation. Probably these calculations which are discussed briefly below, would have been made sooner if the validity of the quantum mechanics formulae for energy loss by fast electrons had not been in question.

In deriving a theory for shower production two types of showers must be considered. The most common type of shower consists of photons, electrons, and positrons, and the high energy shower particles are well collimated, and have transverse momenta corresponding to an energy of only a few Mev. These showers increase in passing through matter and, when large, exhibit no well-defined focus. In the rarer type of shower, transverse momenta corresponding to energies of the order of 100 Mev are common; the particles are not collimated at all; heavy recoil particles are seen; and the number of particles is small.

The deductions of the following cumulative pair-production theory apply to only the first type of shower and the problem has been considered a unidimensional one. Moreover, the results are applicable only to rays of energy $\gtrsim 25$ Mev. Only three elementary processes, pair production by photons, radiation by electrons, and ionization losses by electrons, are considered. The Compton effect and rare multiplicative processes, such as the production of high energy secondary ionizing particles by electrons, and direct production of pairs by electrons, are neglected. Analytical forms for the probabilities of pair creation and γ-radiation closely approximating those deduced by quantum theory considerations are used and a theoretical spectrum of constant γ-ray intensity is assumed.

In the multiplicative shower process a close nuclear encounter causes an energetic electron to radiate roughly half its energy as γ-radiation, and a similar nuclear encounter by an energetic photon results in the creation of a negatron-positron pair. The photon disappears completely in the second event, and the electrons of the pair carry its total energy, each electron absorbing about half. Both pair creation and electron radiation give two rays for one. The newly-born electrons and photons reenact these processes until the energies of the individual rays become so low that the probability of radiation-pair-creation processes disappears and the rays are absorbed by ordinary ionization. The process may begin with an electron, a photon or a group of these rays. The results of Bhabha and Heitler are in excellent accord with those of Carlson and Oppenheimer; the main differences in their results are due to the inclusion of ionization losses by the latter writers.

The theory has been developed for shower production in a material of atomic number, Z, atomic weight, A, and density, ρ, containing N atoms per unit volume. The thickness, t, of the shower producer is measured in units approximately proportional to $Z^2\rho/A$. $t=1$ corresponds to a thickness of $1/a\Phi N$ cm where $\Phi=(Z^2/137)\times(e^2/mc^2)^2$, and a is a parameter which varies slightly with Z. $a=20$ for lead and 23 for air or water. $t=1$ corresponds roughly to $\frac{1}{2}$ cm of lead or to 40 cm of water. In traveling a unit distance ($t=1$) it is found that the probability of pair production by a photon is somewhat less than $\frac{1}{2}$ and the probability of radiation by an electron slightly exceeds $\frac{1}{2}$. For an electron the rate of energy loss by ionization, $\beta=-\partial E/\partial t$, is given by $\beta\sim 5\times 10^8 Z^{-1}$ ev $=6.5\times 10^6$ ev for lead. Some of the results of the theory, as summarized by Carlson and Oppenheimer, are given below. E_0 is the energy of the incident ray, E that of a shower ray and $\lambda=\log_e(E_0/E)$.

(1) For $\beta<E\ll E_0>3\times 10^9$ ev and $t>\lambda/2$, the number of electrons per unit energy is about inversely proportional to E^2.

(2) For a given energy and $t>1$, there are more photons than electrons and the ratio becomes 1.5 to 2 when the shower is near its maximum.

(3) For $E\gg\beta$ the energy-frequency distribution of the shower particles with respect to t is independent of Z. For example, the number of shower particles and their energy distribution should be identical for showers produced in $\frac{1}{2}$ cm of lead or in 40 cm of water by high energy rays.

(4) The number of particles of energy $>E_1$, where $E_1>\beta$, passes through a maximum for a value of t which is quite close to $\log_2 E_0/E$.

(5) The maximum number of particles with energies less than some small multiple of β is attained for values of t slightly less than $\log_e E_0/\beta$, and t for this maximum number increases slowly with increasing Z. The total number of particles in this energy range is approximately proportional to Z.

(6) The maximum size of the shower is limited only by E_0 with which it increases not quite linearly: an increase in E_0 by a factor of 100 gives an increase in shower size of about 70.

(7) The passage of a shower from material (1) to material (2) increases the size of the shower if $Z_2>Z_1$ and decreases the size if $Z_2<Z_1$. The transition takes place for $t_2\sim 1.5$.

(8) If the incident energy, E_0, is divided among a few electrons and γ-rays the course of the shower is essentially unaltered.

Some of the deductions of this theory are illustrated in Figs. 3, 4, 5, and 6. The numbers of shower electrons, and their energy distributions, are illustrated in these figures for various values of the incident energy, E_0, and of the thickness of the scatterer, t. Landau and Rumer[38] have given a more exact mathematical treatment of the multiplicative theory.

This theory can be applied to the transition effect in the atmosphere, and a reasonable energy spectrum for the incident radiation can be found for which the theory gives results in fair agreement with experiment for high altitudes, except that the observed maximum of ionization occurs at a slightly higher altitude than is expected. Snyder[38] has given an improved treatment of the problem which, applied to the atmosphere, gives the maximum at an altitude in better agreement with experiment. The position of the theoretical maximum is calculated on the assumption that the primary radiation is composed of electrons and photons only. Bhabha[38]

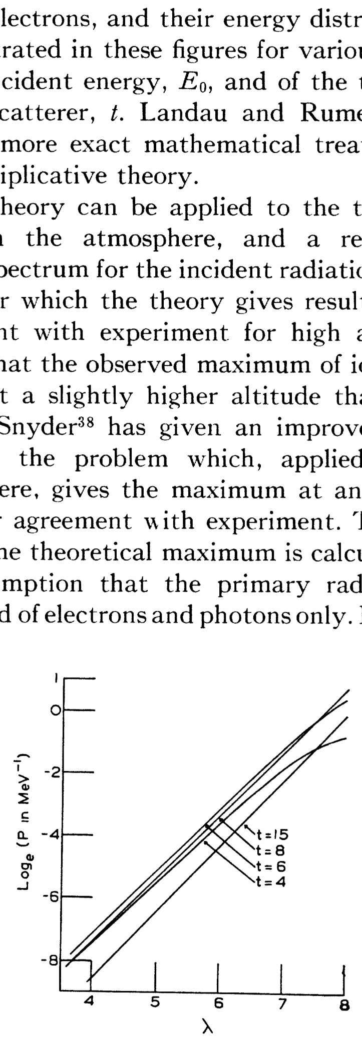


FIG. 3. A logarithmic plot of energy distributions for shower electrons, made for Pb, $E_0=1.5\times 10^5$ Mev and $t=15$, 8, 6 and 4, respectively. Abscissa are $\lambda=\ln E_0/E$ where E_0 is the energy of an incident ray and E is the energy of the shower ray. If the slope of the line is 2, the distribution law would be of the form K/E^2. Except for $t=4$, all energies obey this distribution within five percent. (Carlson and Oppenheimer.[37])

has suggested that the difference in the positions of the theoretical and observed maxima may be due to the high ionization of the upper atmosphere.

Apart from the authors of the theory, many writers including Heitler,[37] Nordheim,[38] Euler,[37] Bowen, Millikan and Neher[38] and Bhabha[38] have discussed the application of the theory to the intensity-depth curve.

In connection with showers produced in thick layers of material, March[37] has applied the problem of the shortest possible wave-length to the question of radiation losses, and Sokolow[37] has given the theory for the radiation of pairs on interaction with a charged particle. Kobayasi and Ozaki[38] have calculated the energy loss of heavy electrons in the direct formation of pairs. They find that for $m \gtrsim 10m_e$, this type of energy loss is very much greater than is the radiation loss.

Bhabha[38] has given a comprehensive treatment of the heavy electron, including the application of quantum theory to some of the possible processes by which it might initiate a shower. He considers that showers could be produced by heavy particles by (i) production of a fast electron by a direct collision, (ii) emission of a quantum, (a) with and (b) without change of proper mass, and (iii) directly by some process akin to Heisenberg's shower process. Present quantum mechanics cannot be applied to process (iia). Landau and Rumer[37] have calculated the probability for process (i) and Bhabha has shown that the probability for process (i) is much greater than that for (iib) if $m \sim 100m_e$. He has found that the frequency of small showers induced by particles of this mass is nearly independent of Z, but that the frequency of large showers increases with Z. Bhabha suggested that the second maximum in the air-to-lead transition curve, at about 17 cm thickness, is evidence indicating the production of heavy electrons in the lead. Some results of his calculations on shower production by heavy particles are given in Table I.

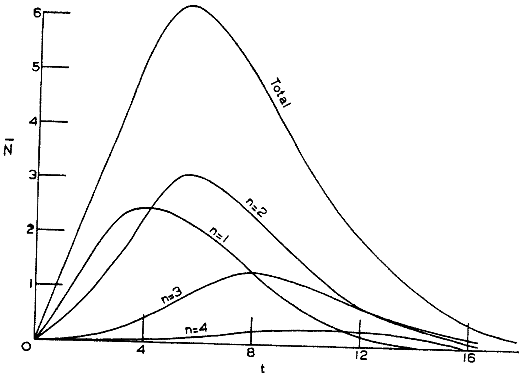


FIG. 5. The plot shows the average number, $\bar{N}$, of electrons or positrons of energy larger than E produced by 1 primary electron with energy E_0. t is the thickness in units characteristic of the material and in this case $\ln E_0/E = 5$. $n = 1, 2, 3 \cdots$ for the curves represents secondary, tertiary, $\cdots$ electrons expected at the depth t. The sum of these curves (total) shows that about 6 negatrons and 6 positrons are produced at the maximum, ($t \sim 5.6$). The total number of shower particles is about twice this number. (Bhabha and Heitler.[37])

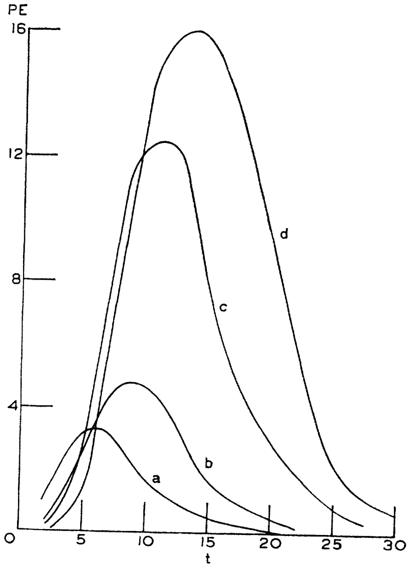


FIG. 4. Plots of PE against t for $E = 50$ Mev in Pb. PE is the number of electrons of energy ≥ 50 Mev expected at depth, t, when an incident ray of energy E_0 falls upon the scatterer. Scale for PE: $a \times 1$, $b \times 4$, $c \times 10$ and $d \times 50$. E_0 for $a = 2.7 \times 10^9$; for b, $= 2 \times 10^{10}$; for c, $= 1.5 \times 10^{11}$; for d, $= 1.1 \times 10^{12}$ ev. (Carlson and Oppenheimer.[37])

Bhabha and Heitler[37] and Bhabha[38] have pointed out that if, as experiments seem to indicate, showers of more than 100 particles are produced frequently in lead sheets of thickness

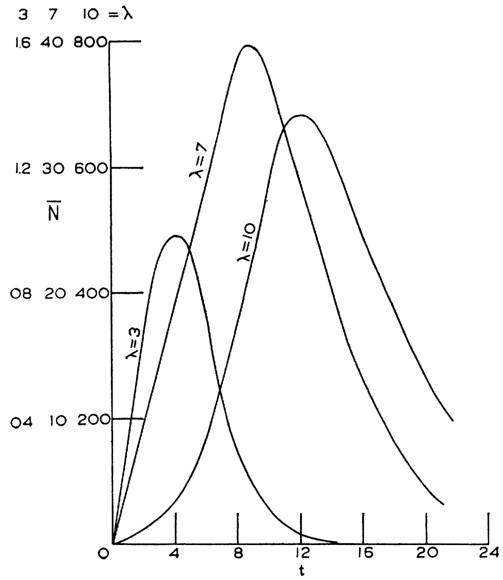


FIG. 6. Plots showing how the total average number, $\bar{N}$, of electrons varies with t for different values of $\lambda = \log E_0/E$. (Bhabha and Heitler.[37])

less than 1 cm, it would indicate that the multiplicative theory is inadequate to explain them. Heisenberg[36] has shown on Fermi's β-ray theory that such processes are to be expected.

III. EXPERIMENTAL RESULTS

1. Transition curves

a. The air-to-metal transition curves.—The multiplicative theory of shower production enables us to estimate the number of shower rays expected per incident photon or electon of given energy, for any given thickness of the shower producing block. The graph obtained by plotting the number of shower particles expected against the thickness of the shower-producing material, or its equivalent, constitutes the theoretical transition curve from air to the material of the scatterer. In order to make a precise quantitative test of the predictions of the theory it is necessary to know the energy and the frequency distribution of the photons and the electrons incident upon the scatterer, and to measure the number of particles emerging from it. Since such detailed data are not easily obtained experimentally it is not usually possible to make exact comparisons of the observations with the predictions of the theory. However, the theory does give us the general shape of the curve and the position of the maximum, with which we can compare the results of experiment.

The Rossi transition curve, or shower-production curve, is the graph obtained when the rate of counting produced by showers is plotted against the thickness, or its equivalent, of the shower-producing material. This rate of counting is not a direct measure of the rate of production of shower rays for the counting system is more sensitive to large than to small showers and also the counting rate is a function of the angular divergence of the showers.

The term "transition curve" has been applied to two somewhat different cases in ionization chamber work. In the first case the curve is obtained by plotting the mean ionization current obtained, with a given thickness of absorber above the chamber, against the thickness of the absorber. In this case two effects are produced: some of the rays incident on the absorber are absorbed and showers are produced in the absorber. By correcting for the absorption the number of shower particles traversing the ionization chamber can be determined approximately. In the second case the frequency of occurrence of bursts is plotted against the thick-

TABLE I. *Shower production by heavy particles.**

$E_0 - Mc^2$	Mc^2	N	1	2	4	5	10	50
10^8 ev	5×10^6 ev	Lead	2.4	0.4	0.014	—	—	—
		Water	—	—	—	—	—	—
10^{10} ev	5×10^6 ev	Lead	4.7	1.5	0.58	0.40	0.12	0.37×10^{-2}
		Water	2.5	0.72	0.25	0.16	0.034	—
	5×10^7 ev	Lead	4.6	1.4	0.57	0.38	0.12	0.34×10^{-2}
		Water	2.5	0.69	0.22	0.11	0.026	—
	Protons	Lead	2.9	0.6	0.08	0.025	—	—
		Water	—	—	—	—	—	—
10^{12} ev	5×10^6 ev	Lead	4.7	1.5	0.60	0.42	0.13	0.54×10^{-2}
		Water	2.8	0.88	0.36	0.24	0.077	0.29×10^{-2}
	5×10^7 ev	Lead	4.7	1.52	0.60	0.42	0.13	0.54×10^{-2}
		Water	2.8	0.88	0.36	0.24	0.077	0.29×10^{-2}
	Protons	Lead	4.7	1.5	0.60	0.42	0.13	0.52×10^{-2}
		Water	2.8	0.86	0.35	0.24	0.074	0.26×10^{-2}

* "The figures give the probabilities percent of the heavy particle being accompanied by a shower containing N particles above the critical energy. The total number of particles in the shower is roughly twice this. The upper figures in each row refer to lead, the lower figures to air or water. *If showers started by emitted quanta be also taken into account, then the figures for particles of $M = 10m$ would be somewhat more than doubled, and the others would be unaffected.*" (Bhabha.[38])

ness of the absorber. The second case is analogous to the transition curve for showers. However, with the ionization chamber the number of rays in the burst can be estimated.

Transition data directly comparable with theory may be obtained by a long series of random exposures of an expansion chamber containing a shower-producing block, but the time required for collecting sufficient data by this method to plot a complete transition curve is almost prohibitive.

Figure 7 shows some of the more common arrangements of counters and shower-producing blocks. The major differences introduced by the different geometrical arrangements lie in the number of rays necessary to produce coincidence, in the angular spread of the shower particles, and in limitations on the type of the incident shower-producing ray. Rossi has commonly used system *e* with a wide scattering block. In this case a minimum of two shower rays arising from near the edges, or three rays from near the center of the scatterer, are needed for coincidence. Johnson and Street[32] used two counters arranged as *b*, with a scatterer at *A*, to show the transition effect with a vertical counter telescope. Stearns and Hedberg,[34] with the same system, took the difference in counting rates with the scatterer at *A* and at *B* to be the rate of shower and secondary production, since the absorption of the block should be the same in both cases. For this arrangement single secondaries may cause coincidence. System *f* has been used to measure the absorption of the shower rays in materials placed above the lowest counter; system *g* to detect showers produced by ionizing rays only; system *i*, with three or more counters in the bottom row, to differentiate between showers having a minimum of two, three, etc., rays. System *d* is probably the most common. For any of these arrangements the probability of detection of a shower increases with the number of ionizing rays in the shower. In the following discussion it should be kept in mind that for *n* counters arranged to detect showers it requires $(n-1)$ ionizing rays to produce a multiple coincidence.

Figure 8 gives examples of shower production curves for thin lead scatterers. The data were chosen at random from the work of several experimenters and were divided into three classes, depending on whether a minimum of one, two or three secondary rays are required for coincidence in the particular arrangement used. The only data specifically omitted were from experiments in which it was difficult to fix the class. All values have been normalized to unity at the maximum. Values in the first class have been obtained from apparatus arranged as *b*, Fig. 7, and the excess count with the scatterer at *A* may not be due entirely to true shower radiation. Data obtained by arrangement *d* have been put in the second class because it is unlikely that an incident ray with a single secondary would cause coincidence in this case. Some data obtained with arrangement *c* fit poorly in the second class. Extremely wide scattering blocks were used in this instance and the effective thickness is difficult to determine.

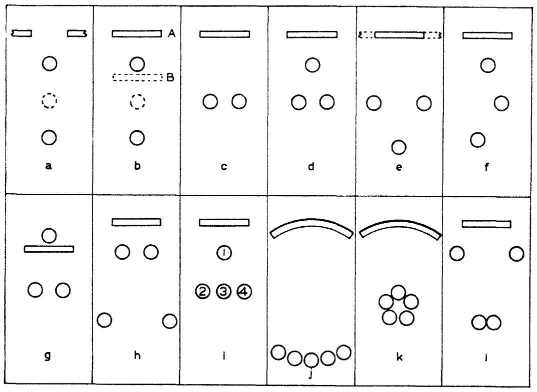


FIG. 7. Various arrangements of counters which have been used in the study of showers.

This classification of the data results in essential agreement among all observers on the position of the maximum and the general shape of the curves. In qualitative agreement with the theory the optimum thickness of the shower-producing block increases with the size of the shower.

Comparisons of the shapes of the initial parts of the lower two curves have been made by Morgan and Nielsen,[35, 36] by Watase,[37] by Watase and Kikuchi,[36] and by Froman and Stearns.[37b] The results of these comparisons definitely show, as indicated by Fig. 8, that for showers of two particles the curve starts approximately linearly, and for showers of more than two particles the frequency of coincidence increases faster than the first power of the thickness. The fact that doubling the thickness of a very thin scatterer more than doubles the number of three-particle showers, whereas it only doubles the number of two-particle showers, definitely indicates that an accumulative or multiplicative process, beginning with a pair, is, at least, the most common process in shower production.

Data from various sources do not give good agreement on the slope of the three-particle curve at zero thickness. It is apparent that this type of shower production is not a linear function of thickness near the origin, yet the slope of the curve is finite and probably greater than zero.

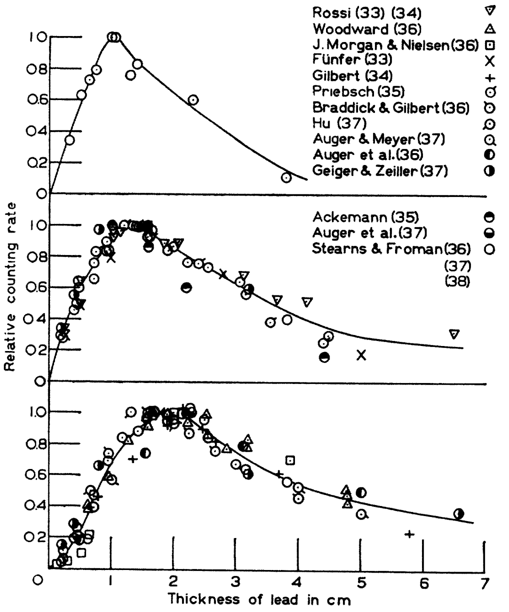


FIG. 8. Shower production curves for various counter arrangements. For the lower curve at least three ionizing rays are required to actuate the recording system. For the middle curve at least two, and for the upper curve, a single secondary ray may be sufficient.

If all showers of three or more particles were produced by a multiplicative pair-production process from rays incident singly on the scatterer, we would find zero slope at zero thickness. If, however, some showers are produced by other processes, or, if an appreciable number of two-particle showers originating in the atmosphere are incident on the scatterer, the slope would be positive at zero thickness. Even if it were certain that the slope exceeds zero there would be no proof here of any process other than pair production since showers are known to occur in the atmosphere. Moreover, for very thin scatterers the metal in the counters is comparable to that in the scatterer, and, as Montgomery^{38} pointed out, this may produce an unreliable counting rate.

In this discussion it has been assumed that if counters are arranged in a way to detect two or more particles the majority of coincidences will be caused by showers of only two particles. A qualitative check of this assumption can be made by comparing the counting rates of counters, 1, 2, 3, and 1, 2, 3, 4, arranged as at *i*, Fig. 7. The ratio of these rates from data obtained by Froman and Stearns$^{37b,\,38}$ at two altitudes is plotted in Fig. 9. The high value of the ratio shows that, when the scatterer is very thin, although the triple coincidence arrangement is more efficient than the quadruple one for the detection of showers of any size, most of the showers detected by the former must contain only two particles.

Beyond the maximum the rate of shower production decreases more rapidly with increasing thickness of the absorbing block than does the total intensity of the cosmic rays. On the basis of the cumulative pair production theory this would not be true if all the cosmic radiation consisted of electrons and photons; hence, either the theory is in error or there is a penetrating component of the cosmic rays other than photons or electrons which is less effective in producing showers.

Additional counter studies of the simple air-to-metal transition effect have been made by Ackemann,^{34} Auger *et al.*,^{35} Bernardini,^{34} Böggild,^{36} Follett and Crawshaw,^{36} Geiger and Fünfer,^{35} Geiger and Zeiller,^{35} Heidel,^{35} Hummel,^{34} Itoh,^{37} Maass,^{36} Morgan,^{36} Nielsen and Morgan,^{37} Pickering,$^{35,\,37b}$ Pollermann,^{35} Sawyer,$^{33,\,35}$ Schwegler,^{35} Swann^{37b} and Zeiller.^{35}

Brode and Starr^{37} have used a counter-controlled chamber to obtain transition effects from air to lead. The material above the chamber had a thickness equivalent to about 1 cm of lead and they placed lead scatterers of various thicknesses

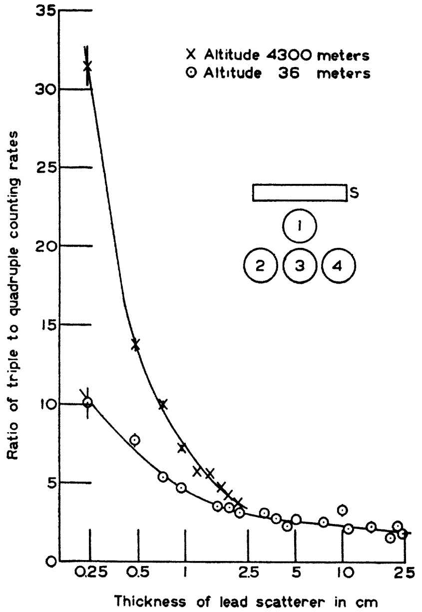


FIG. 9. Ratio of the rate of counting by counters 1, 2 and 3 to the rate by counters 1, 2, 3 and 4, as a function of the thickness of the lead scatterer. Two or more ionizing rays are required for triple coincidence and three or more for quadruple coincidence.

in the chamber. They found the optimum thickness of the lead scatterer for pair production to be 5 mm, for three-particle showers, 6 mm, and for showers of five or more particles the optimum thickness was beyond 1.65 cm, the greatest thickness used. These results agree with the theoretical expectation that the optimum thickness shifts to larger values for larger showers. Starr[38] has found a similar result, which also agrees with counter observations.

In 1934 Maass[34] and Kulenkampff[34] extended the air-to-iron transition curve to greater thicknesses than had been used previously. In the same year Ackemann,[34] Hummel[34] and Drigo[34] showed that there was a second maximum in the transition curve at a thickness of about 20 cm of lead. Maass and Kulenkampff had not used iron quite thick enough to show the second maximum, but in 1935 Kulenkampff[35] found it with iron. Further work at great thicknesses has been done by several observers: Ackemann,[35] Clay *et al.*,[36] Kulenkampff,[35] Maass,[36] Nielsen and Morgan,[37] Nye,[37] Schwegler,[36] and Schmeiser and Bothe.[37] Morgan and Nielsen[37] have carried the shower production curve to very much greater thicknesses. Only two of these observers do not find the second maximum and the precision of their work is hardly great enough to detect a maximum of the size reported by others. Schmeizer and Bothe[38] find the second maximum is much more pronounced for small angle showers. This may account for the fact that certain observers have not found this second maximum.

The air-to-metal transition curves are given for large thicknesses for aluminum, iron and lead in Fig. 10. The counting rate with no metal scatterer has been subtracted from all the values and they are all normalized to unity at the lead maximum. It seems fairly clear that the second maximum exists for iron and lead but there is not general agreement on the relative heights of the two maxima. This may be due to differences in counter arrangements and to differences in altitude.

The transition curve decreases beyond 20 cm of lead at about the same rate as the total radiation which, for this thickness, is made up mainly of the penetrating component. It would seem from the shower production curve at great thicknesses and from the number of showers observed at depths below sea level, that the

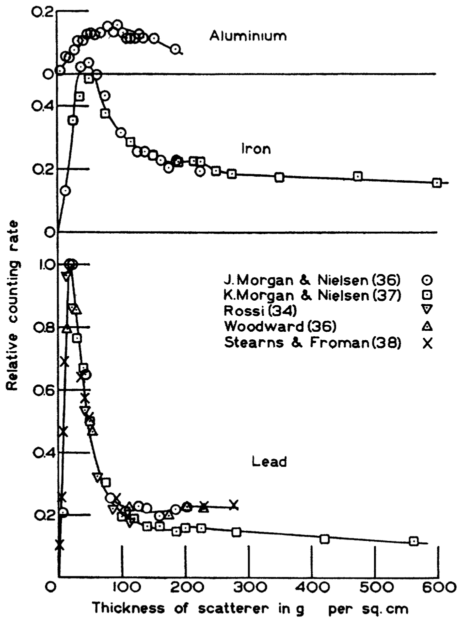


FIG. 10. Shower production curves extended to great thicknesses for aluminum, iron and lead.

penetrating component gives rise to showers at a rate approximately proportional to its intensity.

If the frequency of occurrence of bursts in a given size range is plotted against the thickness of the absorber above the chamber, a transition curve for bursts is obtained. This curve is very similar to the transition curve for showers obtained with counters, the main difference being that the frequency of burst occurrence in an unshielded chamber is relatively much greater than the shower frequency in the absence of a scatterer.

In Fig. 11 two sets of burst transition curves are given for bursts of several different sizes. It is obvious that the optimum thickness for burst production increases with the mean size of burst. If the total number of bursts of all sizes be considered in constructing the transition curve, a great variability is to be expected among observers. Some values found for the optimum thickness of lead on the basis of total bursts are: Young,[37] and Street and Young,[35] 1.3 cm, Carmichael,[36] 2.5 cm, Nie,[36b] 4.5 cm, Messerschmidt,[35] 3.5 cm, and Messerschmidt,[36] 5 cm. A value of 3 cm has recently been found by Jesse and Doan[38] for very large bursts estimated to contain between 200 and 4000 rays. The mean size was about 450 particles. According to the quantum theory of shower production the optimum thickness of lead for showers of this size is about 4 cm. In addition to the 3 cm of lead, the iron wall of the ionization chamber was 1.25 cm thick, so that the optimum thickness observed is in quite good agreement with the theoretical expectation.

Some additional data on the burst transition effect are given by Doan,[35] Young,[36] and Street and Young.[34]

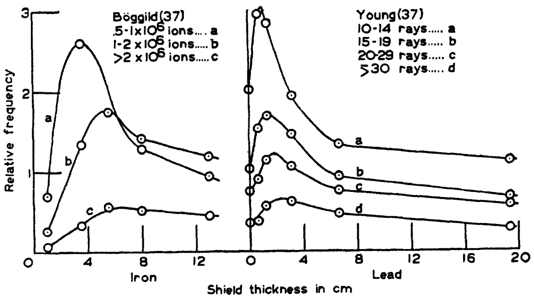


FIG. 11. Air-to-metal transition curves for bursts.

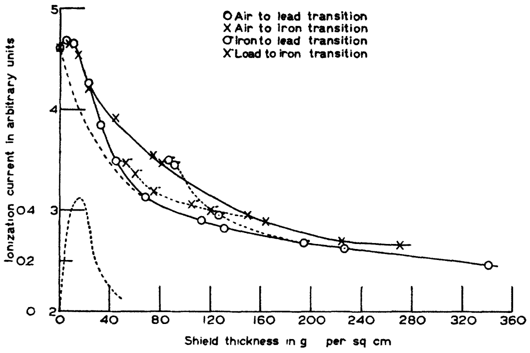


FIG. 12. Graphs showing transition effects observed with an ionization chamber. (Schindler.[31])

The absolute value of the optimum thickness, and its variation with burst size are in striking agreement with the corresponding values obtained in the counter studies of shower production.

In 1927 Hoffmann[27] found the total ionization as recorded by an ionization chamber increased when it was surrounded by thin absorbers. Further work was done in the next few years by Steinke[28, 30] and by Myssowski and Tuwim.[28] In 1931 Schindler[31] made a careful and exhaustive study of both air-to-metal transitions and transitions involving more than two substances. Similar measurements have been made recently by Vinzelberg.[38]

Some of Schindler's data on the air-to-metal transition are plotted in Fig. 12. The ionization produced by incident rays which penetrate the absorber must decrease with increase of absorber thickness. If this part of the ionization be subtracted from the total it can be seen that, at least qualitatively, the difference curve will resemble the transition curve obtained for showers with counters. Without data from other sources, such as counter telescope absorption results, it is difficult to estimate accurately how the ionization produced directly by those rays incident on the absorber will decrease with absorber thickness. However, we know from counter experiments that the number of showers produced at great thicknesses is relatively small and, with this in mind, a very rough approximation of the true absorption curve for lead is shown by a dashed line in Fig. 12. The difference between the ordinates of this curve and the observed ionizations make up the typical air-to-lead transition curve for showers, and is shown by a dotted line in Fig. 12. The position of the maximum is not determined accurately by this process, but for any reasonable estimate for the true absorption curve, the optimum thickness is usually slightly less than that found with counters. In fact, this difference curve resembles the upper curve of Fig. 8 more closely than the lower two curves.

Total intensity-depth curves obtained from ionization chamber measurements in the atmosphere are essentially transition curves of the type shown in Fig. 12. In this case the transition occurs between interstellar material and air. We will not consider these intensity-depth curves in detail.

Transition curves, similar to the one shown in Fig. 8, for the air-to-lead effect can be obtained for transitions from air to any other substance. The maximum frequency of shower production is a function of the atomic number of the scatterer. It is obvious, therefore, that no unit for the measurement of the thickness of the scatterer can be devised which will enable us to use precisely the same curve for different substances. It has been shown by Carlson and Oppenheimer[37] and by Bhabha and Heitler,[37] on theoretical bases, that the total number of shower particles and therefore, roughly, the frequency of shower production, is a function of nZ^2 or $Z^2\rho/A$, where n is the number of atoms per unit volume of scatterer, ρ the density, A the atomic weight and Z the atomic number. On this basis the transition curves of all elements are roughly the same if the thickness is measured in units proportional to $Z^2\rho/A$. This is not quite true, for the theory predicts that the maximum number of shower particles increases very slowly with Z. By measuring the thickness of any scatterer in these units we can calculate the equivalent thickness of lead. The ratio, R, of the frequency of shower production by various substances, to that produced by an equivalent thickness of lead, is plotted against the atomic number of the scatterer in Fig. 13. The values for the number of showers produced by the lead are taken from the appropriate curve of Fig. 8. Estimates of the probable errors of the ratios plotted in Fig. 13 have not been shown, but most of them, especially for the very light elements, are rather high; furthermore, only data for thin scattering blocks equivalent to less than 6 mm of lead were used. A careful consideration of the data indicates that most of these ratios do not differ significantly from unity. In general the most precise values of the ratio lie close to one. Thus present experimental data on very thin scatterers are in agreement with the theoretical prediction that, for the same thickness measured in units characteristic of the element, all materials are equally good shower producers.

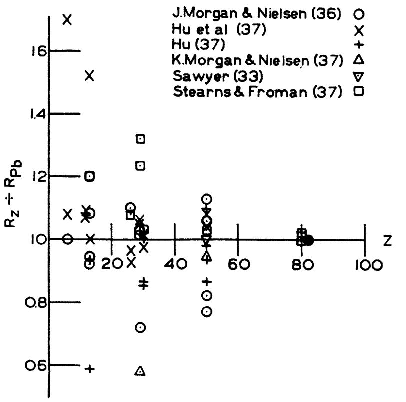


FIG. 13. Ratio of the rate of shower production in thin scatterers to the rate produced in lead of an equivalent thickness, measured in units proportional to $Z^2\rho/A$, as a function of atomic number, Z, of the scatterer.

For a proper test of the theory the numbers of showers produced by the same thicknesses of different materials, measured in units proportional to $Z^2\rho/A$, or their transition curves in which the abscissae are measured in these units, should be compared. The latter method has been used by Hu,[37] Hu *et al.*[37] and by Stearns and Froman.[37] The former method of comparison is used in Fig. 13.

For showers of two or more particles the initial part of the transition curve is nearly linear and for showers of two particles the number of showers per atom from scatterers of equal masses per unit area is theoretically quite closely proportional to Z^2. However, for showers of three or more particles the frequency of production is not a linear function of thickness. In this case the theory does not indicate, as was assumed by several experimenters, that the frequency of showers from scatterers of equal mass per unit area, or from scatterers of equal number of atoms per unit area, should vary as Z^2. On the basis of the theory, due to the particular range of thickness which has been chosen for the scatterers, an approximately linear relation with Z^2 has been found.

The variation of R for aluminum and iron, with thickness, is shown in Fig. 14. It appears that agreement with the predictions of theory is found for only very thin thicknesses. In the case of iron there is good confirmation of Bhabha's[38] prediction that the frequency of shower production should be nearly independent of Z for deep scattering blocks.

The production of showers by various chemical compounds has been measured by Nye,[35, 37] but the precision of the measurements is hardly high enough to make comparisons with theoretical predictions profitable.

It has been shown by Morgan[36] and by Morgan and Nielsen[36] that, for thin scatterers, the departure from linearity of the three- or more-particle transition curve increases rapidly with the atomic number of the scatterer.

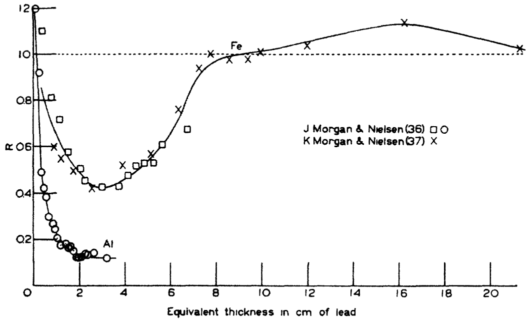


FIG. 14. Ratios of the rate of shower production in iron and in aluminum to the rate produced in lead of an equivalent thickness, measured in units proportional to $Z^2\rho/A$, as a function of this equivalent thickness.

Some additional reports of the dependence of shower production on atomic number have been made by Ackemann,[34] Alocco and Drigo,[34] Clay, van Gemert and Wiersma,[36] Heidel,[35] Hummel,[34] Kulenkampff,[34] Maass,[34] Morgan and Nielsen,[37a, b] Priebsch,[36] and Valkó.[38]

Many observers have compared the frequencies at which bursts are produced in different materials. Heyworth and Bennett[36] have compared paraffin and lead for the production of large bursts of three or four hundred million ion pairs. They find that lead is much more effective in the production of bursts, but that, since the number of large bursts detected depends upon the proximity of the scattering matter to the chamber, it is difficult to compare these two substances. A thickness of paraffin equivalent in weight to even a few centimeters of lead is so great that much of the paraffin is at a considerable distance from the chamber. Swann and Ramsey[34] have compared aluminum, paraffin and copper as burst producers. Montgomery, Montgomery and Swann[35] found an enhancement of the frequency with which bursts occur in an unshielded iron chamber by a layer of water above the chamber. The number of bursts increased for additional water up to a thickness of 79 cm and then decreased until, at 136 cm of water, the frequency was the same as without any water. This effect with the water is not found with a magnesium chamber, and is probably connected with the ordinary transition effect. Montgomery and Montgomery[35c, 36b, c] found from their own and others' results on burst production in equal masses of magnesium, iron, tin and lead, that the rate of production of bursts of sizes between N and $N+dN$ is proportional to $(Z^2/N^s)dN$, where s is not a function of Z. The results of Nie[36a] on very large bursts agree with this. It will be remembered that shower production for equal masses is roughly proportional to Z^2.

b. The Schindler effect.—Morgan and Nielsen[37c] have made counter studies of transition effects between lead and iron. The results are shown in Fig. 15. With iron above the counters, thin lead blocks are placed between the iron and the counters. The number of showers emerging from the lead increases to a maximum and then falls off until the frequency curve coincides with the air-to-lead transition curve. The curve obtained with the iron below the lead shows a minimum. The multiplicative theory indicates an increase of the size of shower in the first case and a decrease in the second. This would result in more showers being detected in the first case and fewer in the second.

Counter studies of this kind of transition effect made by Auger and Rosenberg,[35a] Auger *et al.*,[36b] Rossi and Alocco,[35] Rossi and Crino[32] and Sawyer,[35] have given similar results.

Steinke[28] observed some cases of transitions from one metal to another by means of an ionization chamber but the first very comprehensive data were taken by Schindler.[31] Two cases of transition between metals are shown in Fig. 12. These cases are typical examples of the Schindler effect. For the case of transition from a material of low to one of high atomic number, the ionization produced under various thicknesses of lead below a constant thickness of iron is plotted against the mass per unit area of the total scatterer. As the thickness of lead increases from zero there is a rise to a maximum in the curve which then decreases to approach the air-to-lead transition curve. In the transition from lead to iron the sharp decrease in ionization for very thin layers of iron under the lead, found with counters (Fig. 15) does not appear, but the curve does not show a maximum, and the interpretation is complicated by the ionization of rays which penetrate the absorber. As the thickness of iron is increased the curve approaches the air-to-iron curve.

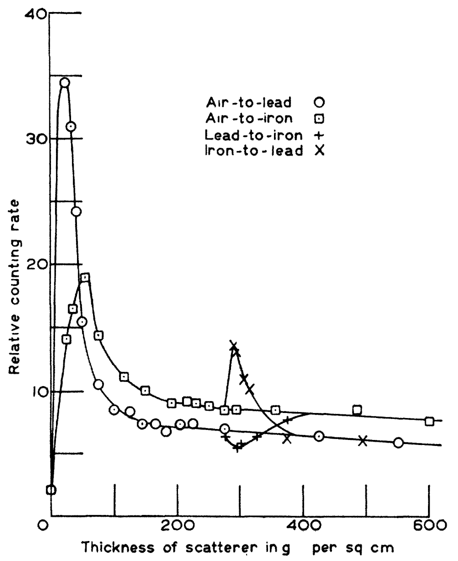


FIG. 15. Transition curves obtained with counters. (Morgan and Nielsen.[37c])

There is some evidence that the total ionization depends slightly upon the relative humidity. This led Messerschmidt[36a] to measure the ionization in a chamber shielded with 5 cm of lead and placed under a layer of water of variable thickness. He found a maximum ionization under 2 cm of water. This is an ordinary case of transition and it seems doubtful that it can be applied to the humidity problem since the geometrical arrangement of the water is different in the two cases. The concentration of a shower-producing substance around the chamber tends to increase the ionization, since, if it is concentrated, there is a high probability that most of the shower particles will pass through the chamber. In fact Scholz[35] has found an increase in ionization due to an increase in the density of the lower atmosphere for constant values of the barometric pressure. Clay[35a] has found a reversal of the barometric effect in an ionization chamber at a shield thickness of about 9 cm of lead.

The thickness and atomic number of the material of the walls of an ionization chamber are important in connection with the transition effect. This factor is of special importance in the reduction of ionization chamber data to absolute ionization values in free air. Clay and his co-workers[34, 35, 37] have paid particular attention to this problem. Clay[34] has also observed a low maximum in the intensity-depth curve at about 250 meters water equivalent below sea level.

2. Size-frequency distributions

The size of a burst can be measured directly by the number of ion pairs it produces in the chamber. If the range of any of the ionizing rays exceeds the linear dimensions of the chamber, the size of burst, measured in this way, will be a function of the size and shape of the chamber and of the gas pressure within it; therefore data from different types of ionization chambers filled to different pressures are not comparable. Measurements of the total ionization in a single chamber are reliable for determining effects of changes in external conditions such as shield thickness, altitude, latitude, etc. It is often desirable to give a burst size in terms of the number of ionizing rays making up the burst. In order to do this it is necessary to know the mean specific ionization of the rays in the gas of the chamber, and to calculate the number of rays from the geometry of the experimental arrangement. This calculation should involve an estimate of the fraction of the rays in a burst which traverse the chamber, but this estimate is seldom made. Experimental values of the specific ionization vary by at least a factor of three. A number of these values are quoted by Froman and Stearns.[38] It is thought that the absolute number of rays in a burst recorded by an ionization chamber cannot be determined, at present, much closer than to order of magnitude, but the relative sizes of bursts observed with the same apparatus can be determined with much higher precision. Bursts containing fewer than ten rays are too small to differentiate from statistical fluctuations at present, and many experimental arrangements cannot be used to detect bursts smaller than many times this value. With the largest chambers statistical fluctuations may limit the measurement of burst sizes to values greater than 100 rays.

In order to compare the size-frequency distribution of bursts obtained by different observers the relative frequencies have been plotted, in Fig. 16, against the ratio of the size of burst to the size appearing with maximum frequency. The data were chosen at random from several sources. Although the relative frequency is a function of the thickness of shield, it does not change rapidly with this thickness, and the fact that the different sets of observations shown in Fig. 16 were taken with different shielding does not make them incomparable. Each plotted point represents the relative frequency of occurrence of bursts in a size interval whose mean is given by the abscissa. The size intervals chosen by the different observers vary by a factor of about 50, and the size of the most frequently occurring burst varies by at least a factor of 20. The agreement among various observers is almost as good as is the consistency in the data from a single source. There appears to be a definite tendency for the points to fall into two groups at the larger burst sizes. The reason for this may be that most of the values in the upper group are mean values for several different altitudes, whereas most of the values in the lower group were obtained at sea level. We shall see later that the increase of burst frequency with altitude is more marked for large bursts.

It is seen from Fig. 16 that some of the observers find that the maximum frequency occurs at the smallest detectable burst size, whereas others find that the smallest bursts are not quite as numerous as those of slightly greater size. There is the same disagreement among other observations not shown in Fig. 16. Böggild[35] and Montgomery[34] have found an ever-increasing frequency down to bursts of the smallest size, whereas Nie[36b] has not. In many cases of both kinds the observations are so numerous and self-consistent, that it is extremely difficult to reconcile these two results. Often two nearly identical sets of apparatus give conflicting results in the same burst size range. The problem of measuring the frequency of occurrence of the smallest bursts is complicated by statistical fluctuations in the total ionization. The ionization produced by detectable bursts is usually less than 0.1 percent of the total, so that these fluctuations become very important.

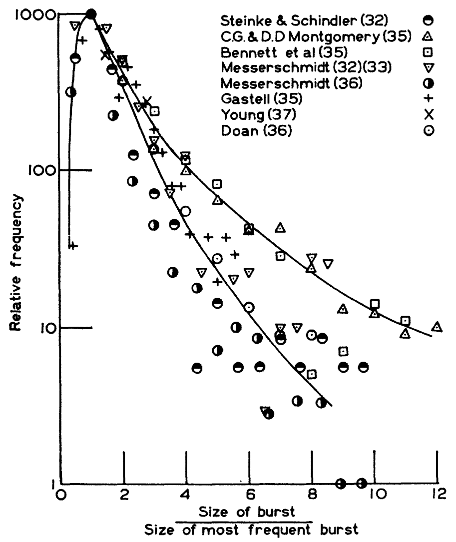


FIG. 16. The relative frequency of occurrence of bursts as a function of burst size. Each point is plotted at the middle of the size range in which the corresponding frequency was observed. Unit size was chosen at the middle of the range in which bursts were most frequently observed and this unit varies greatly for the results of the different observers.

Messerschmidt,[33a] Carmichael,[36] Gastell[35b] and others have shown that the variation in size of large bursts with gas pressure in the chamber follows the same law as does the ionization produced by fast β-rays. The size of large bursts is proportional to the density of extra-nuclear electrons. Cox[34] has shown that γ-ray ionization and, therefore, β-ray ionization, differs from proportionality with extra-nuclear electron density by as much as 15 percent in some cases, but the corresponding experiments with bursts are hardly precise to within 15 percent. Hopfield[33] has shown that the ratio of ionization in air to ionization in argon is slightly greater for cosmic rays than it is for γ-rays, but again the size of large bursts has not been determined in different gases with sufficient precision to detect any difference from γ-ray ionization. Lea[34] has suggested that the ionization of recoil atoms might account for Messerschmidt's result, but Carmichael, using different gases, has found the burst ionization to be proportional to extra-nuclear electron density for all of them.

Korff[38] has observed the frequency of occurrence of bursts in a Millikan-Neher electroscope surrounded by 11 cm of lead under several different conditions. He found that the frequency of occurrence of bursts is given by $AE^{-2.7}$ where E is the burst size in ions and A is a constant independent of altitude and latitude. Carmichael[36] and Messerschmidt[36] found that the frequency of occurrence of large bursts in relatively thin scatterers is greater than is anticipated for electron-photon-produced showers.

Additional work on the sizes and frequency of occurrence of bursts has been done by Hoffmann and Pforte,[30] Montgomery,[34] Schindler,[31] Steinke,[30] Steinke, Gastell and Nie,[33b, c] Steinke and Schindler,[32] and Street and Young.[35]

The arrangement of the control counters around an expansion chamber determines, to a considerable extent, the size and type of shower likely to be photographed. For example, if one of the counters is placed above the chamber there is certain to be a bias in favor of showers produced by ionizing rays. Locher[37a] has shown experimentally that the type of shower detected is a function of both the disposition of the counters and the kind of shower-producing material present. Before counters were used to control expansions, a considerable amount of data was obtained on the size-frequency distribution of showers by random expansions. Anderson,[33] Kunze,[33] Skobelzyn,[32] Locher[32], and Reider and Hess[34] have given data on the relative frequency of occurrence of 0, 1, 2 $\cdots$ etc. particles in randomly expanded chambers. The results from the different observers are not easily compared because the amount and disposition of shower-producing material were not the same in the different experiments. However, all these measurements agree among themselves, and with later measurements, in order of magnitude.

Schneider[36, 38] has observed the size distribution of showers produced in a lead plate 6 mm thick by taking random expansions. His results, summarized below, agree in general with the other data available. Very approximately, Schneider finds that for each 100 ionizing rays which pass through the 6 mm of lead, 50 are stopped in it, 50 are produced in it by non-ionizing radiation, 10 pairs of electrons are produced, and 1 shower containing three or more ionizing rays is produced. Street and Stevenson[36a] used a cloud chamber controlled by one counter above and two below it. They found $2\frac{1}{2}$ times as many three- or more-particle showers as pairs from 1.3 cm of lead, whereas Schneider found 10 times as many pairs as larger showers. Although a certain amount of this difference may be due to the difference in thickness of the lead, no doubt it is caused, in part, by the fact that the large showers have a higher probability of discharging the counters than have the small ones. Also, since one counter was placed above the cloud chamber, the counters tended to select the showers produced by ionizing rays, and the smallest shower expected from an ionizing ray on the multiplicative theory contains three electrons. However, Brode and Starr[37] have observed roughly equal numbers of pairs, emerging from a lead plate, due to incident electrons and photons.

Haenny[38] observed showers in a counter-controlled cloud chamber 8.5 meters underground with, and without, a scattering block. He found no essential difference between these showers and those found at sea level.

Many observers have reported on the mean number of ionizing particles in showers observed by means of counter-controlled cloud chambers. The usual result is from 5 to 10 rays depending on the scatterer and the arrangement and number of counters.

Statistical studies of the fluctuations of ionization current give some indication of the frequency of the appearance of showers in the chamber. Evans[34] and Evans and Neher[34] find that the frequency of shower production, determined in this way, agrees well with cloud chamber and counter results. These fluctuation studies show that both the mean size, and the frequency ratio to total intensity, increase with altitude. It seems that the fluctuation measurements bridge the gap between ordinary small showers and the relatively infrequent very large bursts.

3. Variations with geographical and meteorological factors

The variation of cosmic-ray intensity with altitude can be measured by ionization chambers, by single Geiger-Müller counters and by counter telescope arrangements. All these methods give an increase in intensity with altitude. The intensity, as measured by the first two methods, reaches a maximum at a very great altitude and decreases beyond this point. The third method has not been used at such great heights. It is found, however, that the increase of intensity measured with the ionization chamber is greater than that measured with the counter telescope. The reason for this difference probably lies in the fact that if a shower be produced above, or in the walls of the ionization chamber the ionization produced by all of the shower particles will be recorded, whereas if such a shower is incident upon a train of counters only a single coincidence will be registered. Hence, either the frequency of production of showers, or their average size, or both, increases with altitude faster than does the intensity of the incident cosmic radiation.

The frequency of multiple coincidence of counters placed out of line is a measure of the frequency of production of the showers, modified by the fact that the probability of detection increases somewhat with shower size. We would expect then, that the frequency of multiple coincidence for showers would increase with altitude considerably faster than the total intensity as measured by the telescope or by the ionization chamber.

During the past five years this point has been studied by Auger *et al.*,[36b] Gilbert,[34] Johnson,[35a, b] Rossi and de Benedetti,[34] Stearns and Froman,[36] Stearns and Hedberg,[34] Stevenson and Johnson,[34] and Woodward and Street.[36] All of the reports on these studies, excepting the early one of Gilbert,[34] agree that the frequency of shower production by a given scatterer increases with altitude much faster than the intensity of the total radiation. A later report by Braddick and Gilbert[36] gives results in agreement with those of others.

The results of Woodward[36] and Johnson[35a, b] show that the ratio of shower intensity to the vertical intensity, measured with a telescope arrangement, is very roughly a linear function of pressure, between pressures of 44 and 76 cm Hg. From the latter to the former pressure the vertical intensity increases by a factor of 3.5, while the shower intensity increases by a factor of 8.5. Woodward's results indicate that the increase with altitude is slightly less than this for thick scatterers. In general it has been found that the shower intensity is approximately proportional to the intensity of the so-called soft component of the cosmic rays. This soft component is the part which is practically all absorbed at sea level by 10 cm of lead, and consists of photons and positive and negative electrons.

It is interesting to compare the two curves of Fig. 9 in connection with the variation of shower intensity with altitude. It is evident from these curves that, especially for very thin scatterers, the ratio of the frequency of two-particle showers to that of all larger showers is markedly greater at the high altitude. In contrast, as we shall see later, ionization chamber data show definitely, for bursts exceeding 10 particles, that the relative frequency increases faster with altitude for large bursts than for small ones. The data of Fig. 9 indicate the reverse of this result for two- and more than two-particle showers. These data were taken with the same apparatus and the values of the plotted ratio are unquestionably greater for the higher altitude. Near sea level the penetrating component is relatively more important in shower production, and it may be that the initial stages of the growth of a shower produced by penetrating rays is quite different from the initial stages of the more usual type of shower. There is another possible explanation for the great difference of this ratio at the two altitudes. On the multiplicative pair-production theory, showers are built up by two processes, each of which gives two rays for one. If the generating ray is a photon, an electron pair is produced on absorption of the photon, and if the generating ray is an electron, it radiates part of its energy as a photon. In order to obtain a shower of two ionizing rays, two close encounters with a nucleus are required for an electron-induced shower, and only one close encounter for a photon-induced shower. In order to obtain more than two ionizing rays, three close encounters are required for a photon-induced shower. In a thin scatterer the probability of multiple close encounters decreases very rapidly with increase in the number of encounters. On this basis, we would expect most of the two-particle showers recorded from thin scatterers to be pairs produced by photons, and most of the larger ones to be three-particle showers produced by electrons. If the proportion of electrons to photons varies with altitude, the ratio of triple to quadruple coincidence will vary too. If this explanation for the marked difference in the ratio at the two altitudes is correct, it means that photons are relatively more abundant than electrons at the high elevation.

Stearns and Froman[38] have found that the ratios of the frequency of shower production by 1.5 cm of lead to that by 19.4 cm are 3.84 and 6.79 at altitudes of 1600 and 4300 meters, respectively. Probably most of the showers from the thin scatterer were produced by the soft component and those from the thick scatterer were produced by the penetrating rays. These measurements were suggested by Professor J. C. Street.

Lenz[37] has measured the frequency of shower production by rays incident at various zenith angles. He finds that the intensity of the showers decreases faster with zenith angle than does the intensity of the total radiation measured by means of a telescope arrangement. This is in agreement with the altitude observations.

In 1935 Swann and Cowie[35] arranged two counters diametrically on opposite sides of an ionization chamber. They observed the number of large bursts in the chamber which were coincident with discharge of the counters. The counters were placed in two positions: in the vertical plane and in a plane making an angle of 45° with the vertical. The ratio of total counting rates of the counter telescopes in the two positions was 1.5/1, whereas the ratio of frequencies of bursts coincident with discharge of the counters was 10/1. Thus bursts can be produced by ionizing rays, or some burst rays are projected upward to excite the upper counter. The former explanation must be true for, with the counters inclined with the vertical, there would be a much greater likelihood of excitation of the upper counter by means of back rays. For the second arrangement of counters the equivalent thickness of the atmosphere above the chamber is much greater than for the first arrangement, and the results agree with altitude measurements in that increased depth in the atmosphere causes a greater decrease in burst frequency than in total intensity.

Stevenson and Johnson[34, 35] and Froman and Stearns[37a] have measured the barometer effect at sea level on both the vertical and shower intensities. Stevenson and Johnson find these intensities are decreased by (3.62 ± 2.3) percent and (5.42 ± 0.27) percent per cm Hg increase in pressure, respectively. The corresponding values found by Froman and Stearns are (3.9 ± 2.3) percent and (5.45 ± 0.44) percent. The latter found for showers an increase of (0.83 ± 0.10) percent per centigrade degree increase in local atmospheric temperature, an insignificant increase of (0.02 ± 0.01) percent per gamma-increase in the horizontal component of the earth's magnetic field, and no measurable variation with solar or sidereal time, or with atmospheric humidity.

It has been found by Priebsch,[35] Stearns and Froman,[36a] Woodward,[36] and Woodward and Street[36] that the general shape and the position of the maximum of the air-to-lead transition curve is independent of altitude from sea level to an altitude of 4300 meters. Veksler and Isajev,[37b] however, find some evidence that the maximum occurs at a greater thickness at 4250 meters than it does at sea level. Priebsch[35] reports that for the optimum thicknesses of iron and lead the greater shower-producing property of the lead is accentuated at high altitudes.

Auger and Bertein,[35] Auger and Meyer,[37] Auger and Rosenberg,[36] Barnóthy and Forró,[37] Clay and Clay,[35] Ehmert,[37] Grivet-Meyer,[38] Pickering,[35, 37] Schwegler,[35] Watase and Kikuchi,[36] and Wilson[38] have used counters to study showers below sea level. The results are extremely difficult to interpret quantitatively because of the complicated transition effects usually involved. The increase in counting rate produced by the presence of a metal scatterer under several feet of water, stone or concrete, is not comparable with the increase produced by the same piece of metal in air. However, Pickering has found, that as the depth below sea level is increased, this increase in counting rate decreases very rapidly compared with the vertical intensity. Auger and Meyer have found a shift of the optimum thickness of lead to smaller values as the depth is increased. Grivet-Meyer has obtained an interesting difference between the rates of production of two-particle showers and larger showers at considerable depths in caves. She found that, under depths of earth equivalent to 10, 30 and 75 meters of water, the counting rate was increased by a factor of 2 or 3 by the presence of a thin lead scatterer, when the counters were arranged to detect two or more particles; whereas the same scatterer caused an increase of some 15 times in the counting rate when the counters were arranged to detect a minimum of three particles.

If we consider the total coincidence counting rate of a set of counters arranged out of line as a measure of the shower intensity, it is found that this intensity is approximately proportional to the vertical intensity down to depths of a few hundred meters of water. In fact Ehmert[37] finds that between depths of 35 and 240 meters of water the shower intensity does not decrease quite as rapidly with depth as does the vertical intensity. This result is supported to some extent by Clay, van Gemert and Wiersma,[36] and by Wilson[38] who gives some data on showers at various depths from sea level to 1000 meters of water. The studies of showers at great depths indicate that the penetrating component of the cosmic rays can give rise to showers.

In 1932 Compton[32] found that the frequency of occurrence of bursts increased with altitude. Compton and Stevenson[34] gave some additional observations on this point. Extensive study of the relationship of burst frequency with altitude was begun in 1935 by Bennett, Brown and Rahmel[35] and Montgomery and Montgomery.[35a, c] More recently Böggild,[38] Clay *et al.*,[37] Korff,[38] Messerschmidt,[36] and Young[36, 37] have given attention to this question.

The results of these investigations can be summarized, for altitudes less than 4300 meters, as follows:

(i) The frequency of all detectable bursts increases with altitude roughly in proportion to the square of the total ionization.

(ii) The rate of increase of burst frequency with altitude is greater for large bursts than it is for small bursts.

(iii) Below sea level both the frequency and mean size of bursts decrease with depth.

(iv) The size of the largest bursts observed increases with elevation faster than the total ionization.

Messerschmidt, who consistently finds a maximum in the frequency-size distribution, finds that this maximum shifts to greater sizes as the altitude increases. Montgomery and Montgomery, and Korff are not in agreement with (ii); they find that all sizes of bursts increase at approximately the same rate with altitude. This discrepancy may depend to some extent upon the thickness of the burst-producing layer. Young[37] found that the increase of burst frequency with altitude is a marked function of the thickness of lead above the chamber: the frequency increased by a factor of 10.6 from sea level to an altitude of 4350 meters with 0.64 cm of lead, whereas these factors were 9.4 for 1.3 cm, 8.9 for 3.2 cm, 6.5 for 6.7 cm, and 6.0 for 19.4 cm of lead. For larger bursts the Montgomerys, using a 4 cm lead shield, found a factor of 26.6; Bennett *et al.*, with a 12 cm shield, found a factor of 5.4 for all bursts, and 11.5 for bursts of the largest group. Woodward[36] reported a similar, but less marked, tendency for the change of shower frequency with altitude to depend on the thickness of the scatterer, and Stearns and Froman[38] found that the frequency of showers from 1.5 cm of lead increases much faster with altitude than the frequency from 19.4 cm.

From observations made during the flight of the *Explorer II*, Swann, Montgomery and Montgomery[36] found the frequency of bursts recorded at an altitude of 22 kilometers to be much less than would be expected, if this frequency increased with altitude according to the same function of the total intensity that it follows from sea level to an altitude of 4300 meters.

The burst frequency transition curves found by Young[37] at sea level, and at altitudes of 3250 meters and 4350 meters, have their maxima at the same thickness of lead. They are all very similar to the examples shown for 4350 meters in Fig. 11. The curves fall off, past the maximum, somewhat more rapidly at the higher elevations.

The change of burst frequency with barometric pressure is so small that precise estimates of the barometer effect are difficult to make from observations of the comparatively rare burst events. Montgomery and Montgomery[35a, c] find the frequency to be decreased about 0.5 percent per mm Hg at sea level and (7±2.3) percent at an altitude of 4300 meters. Steinke, Gastell and Nie[33] find 5 percent per mm at sea level. Doan[35, 36] finds no barometer effect within 0.8 percent per mm at sea level for large bursts. Messerschmidt[36] finds a value of 2 percent per mm at sea level. Gastell's[35a] analysis of his extensive data shows a 5 percent per mm barometer effect for the smallest bursts he can detect, but no variation of the frequency of large bursts. If this result is correct, it may be that much of the discrepancy in the results of others is due to differences in the size range of bursts considered. On the whole, the existing data do not give an effect differing significantly from the barometer effect with showers.

Scholz[35] reported an increase in ionization with increased atmospheric density for constant barometric pressure. Mott-Smith and Howell[33] observed the variation in the ordinary transition effect with altitude. Clay and van Alphen,[35] Young and Street,[37] and many others have given special attention to this variation because of its effect on the ionization depth curves.

The curvature of the paths of charged particles incident through the earth's magnetic field gives rise to measurable effects. If the rays contain more charged particles of one sign than of the other there will be a difference in the number of rays incident from easterly and westerly directions. This east-west asymmetry for cosmic rays is about 11 percent at the magnetic equator. The earth's field also prevents low energy charged particles from reaching the earth's surface. This gives rise to a variation of intensity with latitude called the latitude effect which is measured with both counter telescopes and ionization chambers. Because of atmospheric absorption the magnitude of the latitude effect is a function of altitude. Compton and Turner[37] find the sea-level intensity of cosmic rays by means of ionization chambers, to be constant at latitudes greater than about 50°, but reduced by some 10 percent of this value at the magnetic equator. When changes in temperature are considered this value becomes about 7 percent. Johnson and Read,[37] using a G-M counter telescope, found the latitude effect for vertical rays to be between 12 and 20 percent.

Johnson[34a, 35a, b] has measured the east-west effect for showers by placing a lead scatterer somewhat above and successively eastward and westward of a set of counters in triangular formation. In the earlier experiment Johnson found some indication of a predominance of showers with the scatterer in the westerly position but, on repetition of the experiment with higher precision, he found nearly the same counting rates for both positions of the scatterer. In contrast with total cosmic radiation, the measurements on showers indicate only a very slight westerly excess at sea level and no excess at high altitudes. On the present theoretical views of shower formation by successive radiation and pair production, it would be expected that sufficient angular divergence would be introduced to obviate the small collimation of the incident beam. If showers above sea level are produced mainly by the electron-photon component, there would be several interactions with nuclei in the atmosphere before the shower-producing ray arrived at the scatterer. These rays would have nearly equal probabilities of arriving from the east or west, even if the rays incident on the atmosphere contain an excess of a few percent from the west. If, however, penetrating rays such as heavy electrons are incident on the atmosphere, or are formed near the top of the atmosphere, their direction effects would be more likely to show up at sea level. The relative importance of the penetrating component in shower production increases with depth in the atmosphere. We might expect, then, a greater east-west effect for showers near sea level than at high altitudes.

The variation of shower intensity with latitude, however, is appreciable. Johnson,[34a, 35a, b, 37] Johnson and Read,[36, 37] Pickering,[36] and Neher and Pickering[38] have made extensive measurements of this effect. It is found that at sea level the shower intensity is constant at latitudes greater than 29°, and the equatorial decrease is 6 percent or 7 percent of the high latitude value. Thus at sea level, the constant intensity plateau extends to lower latitudes for showers than it does for the total radiation. The magnitude of the effect is approximately the same as, or slightly less than, that given by ionization chamber measurements, but it is considerably less than the effect on the vertical intensity. At an altitude of 4300 meters, however, the latitude effects on the shower and vertical intensities are nearly the same. Since most of the sea level ionization is produced directly by electrons, the latitude effects on showers and total ionization chamber intensity are about equal. The penetrating particles play a relatively more important role in the counter telescope. The average energy of the rays incident on the top of the atmosphere is greater at low latitudes since the earth's field excludes the less energetic rays. Probably the average energy of the rays remains higher in equatorial than in polar regions throughout the atmosphere. Since, on prevalent theory, high energy electrons are more efficient shower producers than those of low energy, we would expect the latitude effect to be less pronounced for showers than for the vertical rays, both in extent and magnitude.

Extensive data on the change of burst frequency with latitude are not available. Young[37] finds a latitude ratio of 1.34 at an altitude of 4350 meters between 49°N and 1°S magnetic latitudes. This value is determined from a single set of observations and its precision is not high. The value is very close to the corresponding ratio for total ionization.

4. Angular divergence

The use of counters in the study of showers is made possible by the divergence of the rays in a shower. Although cloud chamber observations give more complete data on angular divergence in showers, counters can be used for this study. Measurements of the angular divergence can be made with two counters arranged as *i*, Fig. 7, with a narrow scattering block. The counting rates are observed for various values of the angle θ subtended by the centers of the two counters at the middle of the scatterer. Similar measurements can be made with other arrangements of counters such as *j*, Fig. 7. The counter system is kept symmetrical about the vertical line through the center of the scatterer.

Figure 17 shows the results of such measurements made by several observers. The ordinates of the curves have been made to agree at $\theta = 22°$.

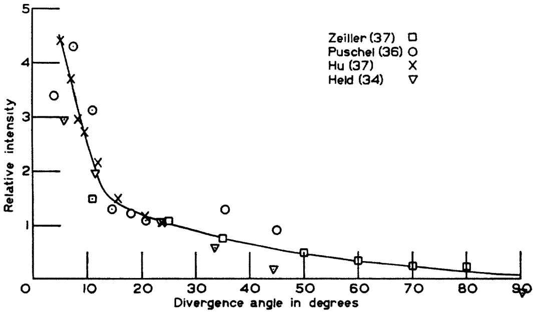


FIG. 17. Some results of counter measurements on the angular divergence of shower particles. The data from the different sources have been made to agree at 22°.

The number of coincidences tends to be greatest for small angles.

Geiger[35] has pointed out that the ordinates in Fig. 17 do not represent the probability of pairs being formed with an angular separation corresponding to the abscissae. For a given angular separation of the counters only a fraction of the shower rays diverging at this angle is detected, and another fraction of rays having larger divergence angles is recorded. Each of the fractions is a function of the angular separation of the counters and of the geometry of the arrangement. Held[34] has used an arrangement whereby the divergence angle between the counters is the same for each point on the scattering block. He has attempted to treat his observations so that the results represent the true number of showers for each divergence angle. The exact manner in which the data were corrected is not stated. Held's experimental arrangement and the plot of the corrected results are given in Fig. 18. The curve shows a maximum near 20°.

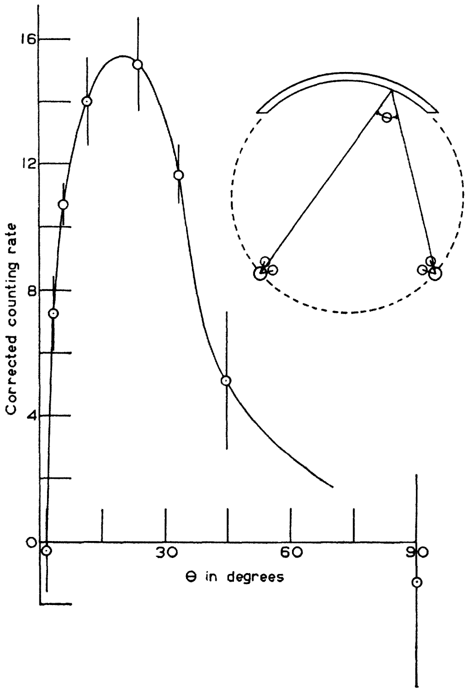


FIG. 18. A plot of corrected counting rate per hour against the divergence angle. (Held.[34])

Geiger and Zeiller,[37] using arrangement *i*, Fig. 7, found that the mean angle of divergence increases with increased thickness of the scatterer. This result is to be expected on the multiplicative shower-production hypothesis, and the effect would be accentuated if the more penetrating rays produced the less collimated type of shower.

Rossi[32a] mentions the existence of "back rays," i.e., shower rays moving upward from a scatterer. Quantitative measurements of these rays have been made by Fünfer,[33] Gilbert,[34] Zeiller,[35] Heidel,[35] and Geiger and Fünfer.[35] Some of these results are shown in Fig. 19. From these curves it is evident that about 6 mm of lead are sufficient to produce the maximum number of back rays.

Hoseman[36] has shown that many back rays are very easily absorbed. They are produced most copiously by scatterers of high atomic number, and the frequency of production is increased if a thin scatterer is placed above the system. Evidently shower particles are effective in generating back rays, for it is seen, from Gilbert's results (Fig. 19), that the maximum number of back rays appears when the scatterer above the system is of the optimum thickness for shower production.

With 1 cm of lead at *S*, Fig. 19, Heidel found that the presence of *R* increased the counting rate by 8, 15 and 52 percent when *R* was a thick sheet of aluminum, iron and lead, respectively.

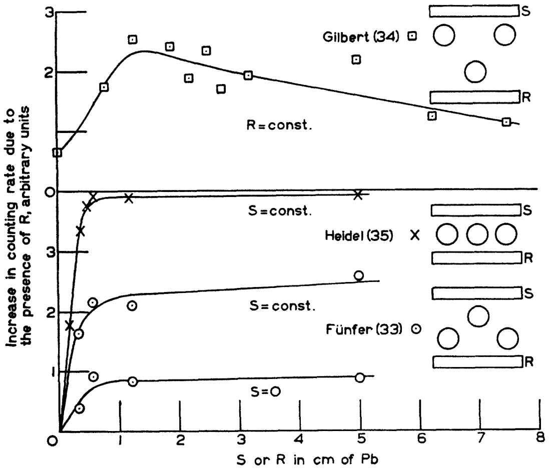


FIG. 19. Graphs showing the variation of "back ray" showers with the thickness of the scatterers.

Before the expansion of cloud chambers was controlled by counters, Anderson[33c] observed a shower of 12 particles in a random expansion. Seven of the rays diverged from one point and five from another. Blackett and Occhialini,[33] Locher,[33a] Anderson *et al.*,[34] Auger and Ehrenfest,[37] and others have found many cases in which shower particles diverge from more than a single center. Examples of such cases are shown in Fig. 20*a*, *b*, *c*, *e* and *f*, and in Fig. 21*f*. Since showers commonly diverge from more than one point the angle of divergence has no very precise meaning. The size and general divergence are influenced, markedly, by the kind and distribution of the shower-producing material. Adam[37] has found that the angle of separation of cosmic-ray pairs seldom exceeds 30° which is about the mean angle of separation of the pairs formed by Th C″ γ-rays. This result is to be expected from momentum considerations, since the mean energy of the cosmic-ray photons is greater than that of the γ-rays.

From observations of showers at an altitude of 3500 meters, Auger and Ehrenfest[36] estimated that the mean angle of divergence of the extreme rays in a shower was about 36°. Street and Stevenson[36a] have measured the angular deviation from the direction of the incident ray for some 560 shower electrons occurring in 107 showers. Their results are shown in Table II. The mean semi-angle of divergence is 10° or 12° which is in approximate agreement with counter results.

TABLE II. *Angular divergence of shower electrons.*

DIVERGENCE ANGLE IN DEGREES	0–10	10–20	20–30	30–45	45–90
Fraction of shower electrons per unit solid angle	0.71	0.12	0.09	0.07	0.01

We have seen that ionizing rays moving upward are commonly found with counters. In determining the sign of a charged particle it is necessary to know its direction of motion, and it is not at all safe to assume that all cosmic-ray particles are moving downward. As long ago as 1932 Skobelzyn[32a] observed back rays in his cloud chamber. An example of back rays is shown in Fig. 20*d*.

5. Absorption

The absorption of shower particles can be determined with counters by using some such arrangement as shown in Fig. 7*e*, *f* or *h*. Readings are taken with various thicknesses of the absorber above one of the lower counters. Although the absorption is not truly exponential, it has been the practice to calculate an effective absorption coefficient for the shower rays. Zeiller[35] has found that the calculated "exponential absorption coefficient" for the shower rays varies from 0.2 to 0.5 per cm of lead for different arrangements of the absorbing sheet and counters. Similarly, Hu *et al.*,[37] and Stearns and Froman[36b] have found values varying from 0.2 to 0.7 and from 0.4 to 0.8, respectively. Furthermore, Barschauskas,[37] Hu *et al.*,[37] Morgan,[36] Morgan and Nielsen,[36] and Püschel[36] have observed that the rays near the vertical are usually the most penetrating, a result which is consistent with cloud chamber observations. However, if the counter arrangement be kept constant, variations in the penetrating power of the shower rays produced in different materials, at different altitudes or under other varying conditions, can be measured.

Woodward and Street,[35] using Johnson's method, calculated an absorption coefficient for shower rays from an air-to-lead transition curve. The absorption coefficient obtained in this way is not in agreement with that which they obtained by placing an absorber above one of the lower counters.

It has been shown from the shape of the transition curve, and by direct absorption experiments, that the mean penetrating power of shower rays decreases with increasing atomic number of the scatterer; that absorption varies roughly in proportion with the atomic number of the absorber; and that the mean number of particles per shower increases with the atomic number of the scatterer. Evidence pertaining to these questions has been given by Auger and Rosenberg,[35] Clay,[36] Fünfer,[33] Hu *et al.*,[37] Rossi,[32b, 33b] and Sawyer.[33] Valkó[38] found that shower rays from carbon, as measured by absorbers less than 1 cm in thickness, are more penetrating in lead than are the shower rays from lead. For thicker absorbers no difference could be found in the absorption. Woodward,[36] Woodward and Street,[36] and Stearns and Froman[36b] established that the penetrating power of the shower rays is independent of the thickness

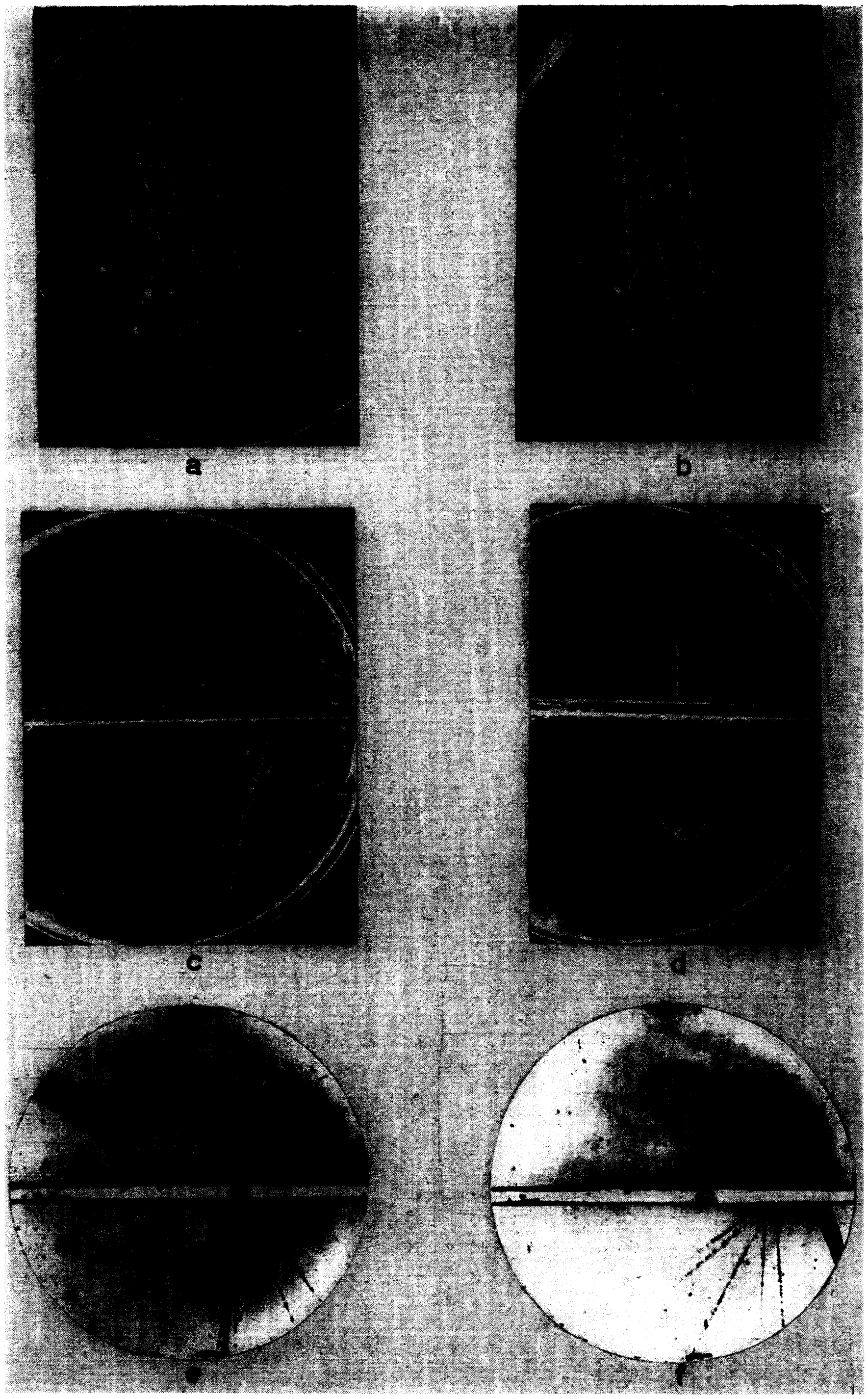


FIG. 20 (*a*) and (*b*). A pair of photographs showing a typical shower containing both positrons and negatrons. The nearly straight tracks seem to diverge from one point and the more curved tracks from a lower point. (Blackett and Occhialini.[33]) (*c*) A shower enters the chamber from above and a second shower is produced in the lead plate, probably by a photon since stereoscopic examination indicates that none of the ionizing rays above the lead is incident at the point of production of the second shower. (Blackett and Occhialini.[33]) (*d*) A shower showing two negatrons projected downward and at least one electron projected nearly vertically upward. If the shower was produced by a non-ionizing ray two particles were projected upward. (Blackett and Occhialini.[33]) (*e*) and (*f*) Two showers both of which have two distinct points of origin. An ionizing ray is incident to one of the points in both cases. (Auger and Ehrenfest.[37])

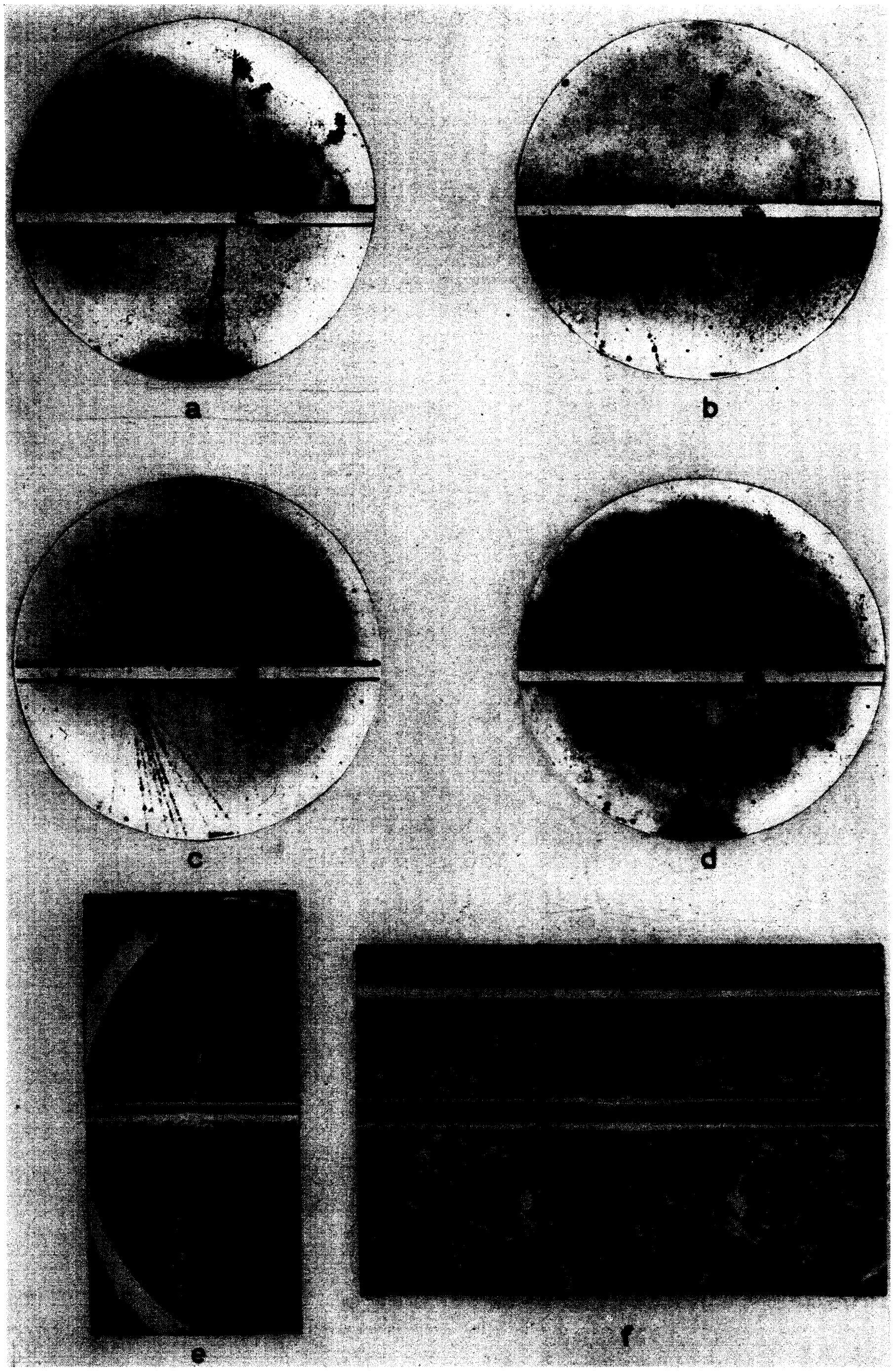


FIG. 21 (*a*), (*b*), (*c*) and (*d*). Photographs illustrating various types of showers. (*a*) and (*c*) are showers produced by ionizing rays and (*b*) and (*d*) by non-ionizing rays, probably photons. The shower of 10 rays (*c*) diverges considerably more than the smaller showers (*a*) and (*d*) but hardly more than the single pair in (*b*). (Auger and Ehrenfest.[37]) (*e*) The production of a single secondary by a high energy ionizing ray. (Blackett and Occhialini.[33]) (*f*) A shower of many very low energy electrons with no common origin. These rays were probably produced by many quite soft photons from a shower above the chamber. (Anderson, Millikan, Neddermeyer and Pickering.[34])

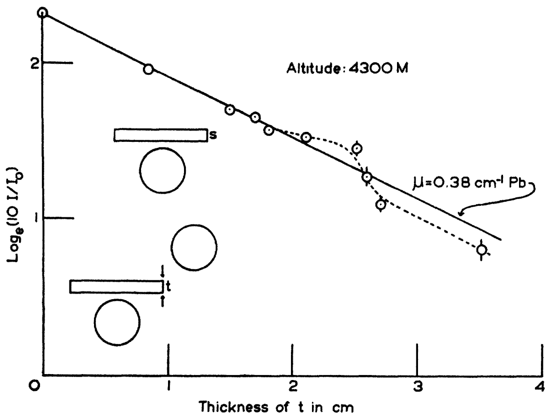


FIG. 22. An example of a shower absorption curve which indicates that shower rays from the scatterer may produce new shower particles in the absorber.

of the scatterer up to the thicknesses well beyond the optimum. Woodward reported no change in the penetrating power of the shower rays with altitude, whereas the writers have found the shower rays somewhat more penetrating at high altitudes than at sea level.

An inflection point occurs in the absorption curve at a thickness of absorber about equal to the optimum thickness for shower production. An example of such a curve, obtained by Stearns and Froman,[36b] is shown in Fig. 22. This result is to be expected if the shower particles arriving at the absorber are capable of multiplying, for in that case the counter beneath the absorber will have the greatest chance of being excited by rays produced in the absorber, if it is at the optimum thickness for shower production. The fact that the inflection occurs very near the optimum thickness is consistent with the view that there is no fundamental difference between the shower rays and the rays which produce them. Zeiller,[35] using counters arranged as at *e*, Fig. 7, placed an absorber above the lower counter. An increase in the width of this absorber showed a very significant increase in triple counting rate. No doubt this increase was caused by shower rays which had excited the upper counters but which would miss the lower counter, causing the emission of new shower rays from the absorber.

Montgomery and Montgomery[36a, e] have suggested that the proper procedure for describing the absorption of showers is to express the probability that the shower will be detected through any thickness of absorber as a function of the thickness. They have found this probability, measured by means of two ionization chambers and also by means of counters, to be a linear function of thickness, becoming zero at about 11 cm of lead.

Other reports on absorption of showers, not mentioned above, have been given by Auger,[35a] Auger and Rosenberg,[35] Clay,[36] and Trumpy.[37]

Cloud chamber experiments dealing with the absorption of showers have taken the form of energy loss measurements on single particles. These measurements are discussed in another section.

6. Atomic disintegration

A few heavy particles associated with cosmic rays were observed in cloud chambers as long ago as 1932 by Anderson[32a] and by Millikan and Anderson.[32] In 1933 Anderson,[33a] and Blackett and Occhialini[33] observed heavy tracks which could be interpreted as the tracks of protons from nuclear disintegrations. Similar phenomena were found by Reider and Hess[34] and by Anderson and Neddermeyer.[34b, c]

In 1935 Street, Schneider and Stevenson[35] observed a few long range heavy particles produced in a lead block in the cloud chamber. These rays were not coincident in time with showers but their ranges were too long for them to have been produced by radioactive contaminations. Herzog and Sherrer[35, 36] made similar observations at a high altitude. The frequency of occurrence of these heavily-ionizing rays increases rapidly with altitude.

Locher[36] observed several rays from disintegrations in the walls of the chamber and a few which occurred in the gas (argon) with which it was filled. By comparing the number of disintegrations observed when the expansions were controlled by counters arranged to detect showers, with the number observed when expansions were made at random, Locher was able to show statistically that the disintegrations were associated with the showers and were not due to radioactive contaminations. Moreover, he found that the disintegrations occurred more frequently when the counters were arranged to detect larger showers, or showers having abnormally wide divergence.

Anderson and Neddermeyer,[36] and Brode, MacPherson and Starr[36] have divided the showers they observed into two classes. In the more common case the showers are fairly well collimated and seldom contain heavily-ionizing rays. The other, rare type of shower often contains heavy recoil atoms and the rays diverge through a wide angle, some particles having momenta transverse to the incident ray corresponding to as much as 10^8 ev of energy. The photograph of one of these rare showers is shown in Fig. 23.

Veksler and Isajev[37a] have taken data, at an altitude of 4250 meters with a linear amplifier arrangement, which indicate the occurrence in showers of heavy particles ionizing 10 or 15 times as much as electrons. They find these particles ejected from iron and lead but not from aluminum. Anderson and Neddermeyer[36] obtained 123 tracks of heavy particles in 9188 expansions of their counter-controlled chamber at an altitude of 4300 meters. In one of these cases a disintegration occurred in which six positive and no negative particles appeared. One of the positives had range and $H\rho$ values corresponding to an e/m ratio much greater than the e/m ratio for a proton. Protons and electrons often arose at the same point, but the direction of emission of a proton was not dependent on the direction of the incident ray. Protons were observed in disintegrations caused by both ionizing and non-ionizing rays. The energies of these protons were usually much greater than those found in radioactive disintegrations. Practically all the heavy particles observed might easily have arisen as secondaries from materials close at hand.

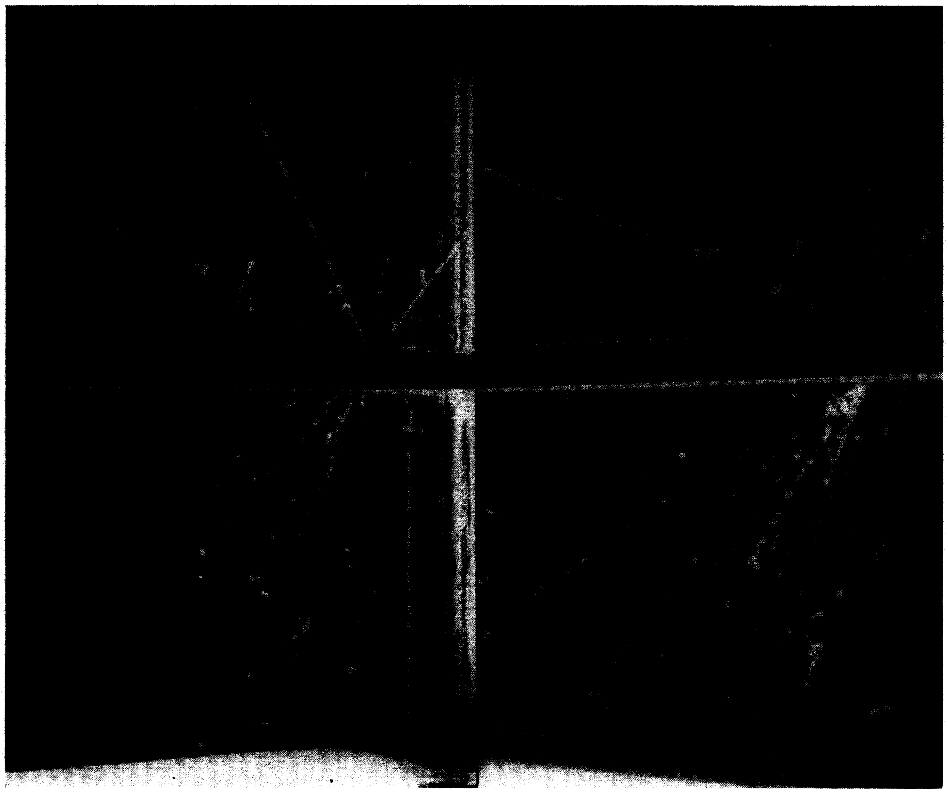


FIG. 23. A photograph of one of the rare type of shower where the particles are not well collimated and tracks are denser than those due to electrons. This was furnished by the courtesy of Messers Fussell and Street.

Brode and Starr[37, 38] obtained 215 cases of heavy particles associated with showers in 20,500 expansions. In 10 of these cases the heavy particle originated in the walls of the chamber or in the lead scatterer contained in it. Nishida,[37] and many others have observed some cases of dense tracks due to disintegrations. An example of disintegration by a non-ionizing ray in argon is shown in Fig. 24*a*. The two long tracks may be those of either protons or α-particles and the short one is probably due to the recoil of the remainder of the argon atom. Since the three particles diverge within a hemisphere, either the ray causing the disintegration carried considerable momentum, or one or more non-ionizing rays, probably neutrons, were ejected from the atom on disintegration. Fig. 24*b* shows a track whose curvature and ionization are consistent with the assumption that the ray is a proton. It is not common to find protons traversing the chamber nearly vertically.

In 1933 Locher[33] and Curie and Joliot[33] observed small blobs of ionization in their cloud chambers which, they suggested, were due to atoms recoiling from neutrons. Bonner[34] suggested that the anomalous absorption of neutrons in lead might account for the production of bursts. Locher[34, 36, 37b] has given considerable attention to the question of the occurrence of neutrons associated with cosmic rays and has

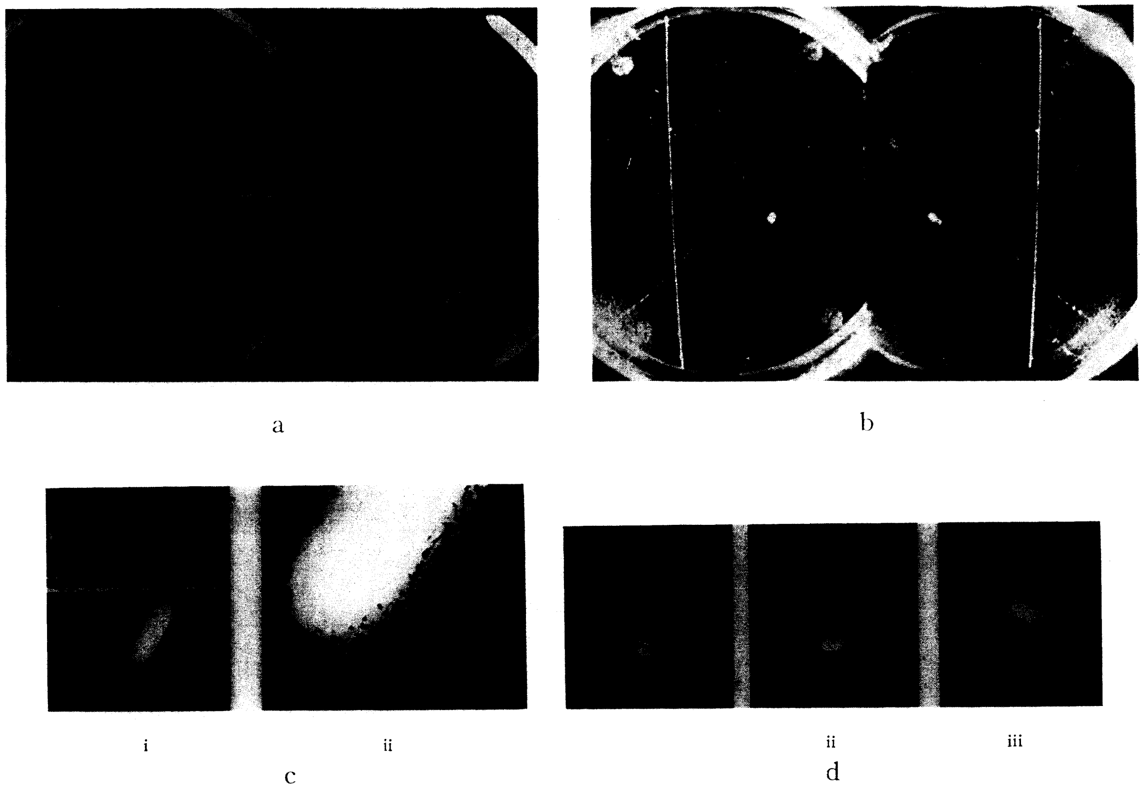


FIG. 24 (*a*). A disintegration in the gas (argon) of the chamber which is apparently simultaneous with the shower. The shower of several particles is barely visible in the reproduction. The three heavy particles diverge within a hemisphere. The disintegration was caused by a non-ionizing ray, possibly a neutron, or possibly the momentum is conserved by one or more neutrons ejected on disintegration. (Anderson and Neddermeyer.[36b]) (*b*) A strongly ionizing ray traversing the whole chamber with $H\rho = 1.8 \times 10^6$ gauss cm. The density of ionization is consistent with the assumption that the particle is a proton. (Anderson and Neddermeyer.[36b]) (*c*) (i) A typical broad track often observed in cloud chambers. (ii) The same track enlarged so that the distribution of droplets near the edge of the track can be determined. The distribution agrees with the theoretical predictions for the diffusion of ions before the expansion. (Blackett.[34]) (*d*) (i) A neutron recoil track. (ii) and (iii) Similar tracks found on photographs of cosmic rays. Although (ii) is very similar to (i), it may easily have been produced by an α-ray some time before expansion. In (iii) both positive and negative ion groups are present and the time of the ionization is calculated to be $\frac{1}{5}$ sec. before the expansion. (Blackett.[34])

reported[34] that neutrons arising in aluminum appear to be more energetic than those arising in lead. Anderson and Neddermeyer[34b] tested for the presence of neutrons by looking for the tracks of carbon atoms projected from graphite. They concluded that neutrons were not present in appreciable numbers in the energy range where the usual tests apply. Anderson *et al.*[34] found no evidence for the presence of neutrons associated with showers observed in their counter-controlled chamber at sea level.

The whole question of the interpretation of the small ionization blobs has been discussed most carefully by Blackett.[34] He showed that the distribution of droplets near the edge of these thick tracks, Fig. 24*c*, agrees with the theoretical expectation for the diffusion of ions, if the ionization occurs an appreciable time before the expansion. In some of these tracks, Fig. 24*d* (iii), the two ion groups are distinctly separated before the clearing field is removed from the chamber. In this case the time of the ionization before expansion can be estimated with fair precision. Blackett believes that many of the cases showing a single, nearly round, blob are due to ions of one sign only, the other group having been swept out of the field before expansion. Both methods of estimating the time of ionization lead to three alternative conclusions, of which only the last is tenable: (i) if the tracks are due to neutrons associated with showers, the neutrons appear several tenths of a second before the other rays of the shower; (ii) there is some mechanism in a shower which is capable of ionizing over an extended volume; and (iii) the tracks are due to radioactive contaminations of the materials of the chamber. Blackett showed, too, from Beardon's[33] values of the radioactive contamination of common materials, that the number of blobs of varying breadths observed were consistent with conclusion (iii). It is thought that there are very few neutrons associated with cosmic rays at sea level. However, there is some evidence in the work of Rumbaugh and Locher,[36] and Wilkins[36] that neutrons appear in appreciable numbers at very great altitudes. These experimenters detected the tracks of protons, supposedly expelled from paraffin by neutrons, in photographic emulsions. Regener and Auer[34] found that lining an ionization chamber with paraffin did not increase the current perceptibly even at very great altitudes.

In 1935 Cairns[35] suggested that two very large bursts occurred very close together more often than would be expected fortuitously, and that this could be explained on the basis of cosmic-ray-induced radioactivity. However, Alvarez[35] was able to show that Cairns' data were consistent with the expectation for random events.

Some indications of cosmic-ray-induced radioactivity from lead with a half-value period of about 9 minutes have been reported by Clay and Jonker[38] using a single counter, and by Clay and v. Tijn[37] using an ionization chamber. Reboul and Reboul[37] also believe that they have detected induced radioactivity in several elements, and they give some absorption coefficients for the induced radiation.

Bramley[37d] has given some theoretical discussion on the question of disintegrations associated with showers. Blackett[34] has discussed critically the question of negative protons, concluding that there was no evidence for their existence. There seems to be nothing in subsequent work to alter this view.

7. Shower production and growth

Early counter experiments by Street and Johnson[32b] indicated that ionizing particles could give rise to showers. This result has been confirmed by Geiger and Fünfer,[35] Johnson,[34] Sawyer[33, 35] and Street.[33] The usual method of study is to compare the counting rates with the apparatus arranged first as *d*, then as *g*, Fig. 7. As pointed out in the section on instruments, the probability of discharge in a counter is very much greater on the passage of an ionizing particle through it than on the traversal of a non-ionizing ray. Hence, coincident discharge of the counters in arrangement *g* is almost always caused by a shower generated by an ionizing ray which has passed through the upper counter. The relative number of showers produced by ionizing and non-ionizing rays cannot be measured accurately by experiments of this type, because of the differences in the geometry of the two arrangements, and the differences in the limitations in the directions and paths of the incident rays. However, the indications are that, very roughly, half of the showers are produced by incident ionizing rays.

Geiger and Zeiller[38] have made some measurements with counters on the relative numbers of photons and ionizing rays in showers. Although counters are not easily adapted to this kind of study, these measurements indicate that the numbers of photons in the showers are in excess of the number of ionizing rays.

Auger and Leprince-Ringuet[34] believed that most of the showers they observed were induced by photons. Anderson[33a] found many cases of showers with no track above the scatterer, and Anderson and Neddermeyer[34b] found that a small fraction of the pairs they observed were produced by electrons. The arrangement of the counters around the cloud chamber may bias the system in favor of recording showers produced by ionizing rays. Stevenson and Street[35, 36] used one counter above, and two below a chamber containing a 1.3 cm lead scatterer. With this arrangement about 75 percent of the single-centered showers were produced by ionizing rays passing through the upper counter. In the other cases the upper counter may have been discharged by a back ray scattered upward from the lead or by an ionizing particle, which missed the chamber, but which was associated with the photon causing the shower. The number of showers of this type observed was too great to be accounted for by accidental coincidences. If absorption is neglected, the multiplicative shower production theory suggests that electron-produced showers would contain odd numbers of electrons, and photon-produced showers, even numbers. This relation cannot be expected to hold for showers emerging from a lead scatterer as thick as 1.3 cm, but it is interesting to note that, in the data of Stevenson and Street, 41 percent of the electron-produced showers contain odd numbers of particles and 36 percent of the photon-induced showers contain odd numbers. Although this difference is hardly significant on the 107 showers observed, it is in the expected direction. Showers of even numbers of particles predominate in both classes because of the large numbers of pairs observed.

Fussell[37] has found that about 36 percent of ordinary showers are produced by electrons. Auger and Ehrenfest[37] have controlled their cloud chamber with four counters placed below it. With this arrangement the system was much more sensitive to large than to small showers, but it was independent of the type of ray generating the shower. Auger and Ehrenfest found equal numbers of electron- and photon-produced showers. This result is in agreement with the work of Brode and Starr[37] who found that the optimum thickness of scatterer for the production of pairs is the same for both electrons and photons. Starr[38] has obtained a similar result. He found that 8 percent of the electrons incident on a 7 mm lead plate produced showers, and that electron- and photon-produced showers were of the same character.

Examples of showers produced by ionizing and non-ionizing rays are shown in Fig. 21. The first four photographs show typical showers, whereas the phenomena illustrated in *e* and *f* are rather rare.

Soon after the discovery of bursts, Steinmauer[30] and Pforte[31] investigated the sudden variations of ionization taking place in each of two ionization chambers placed near each other. They found no correlation between the apparently random fluctuations in the two chambers.

In 1933 Swann and Montgomery[33] arranged three coincidence counters around an ionization chamber. The chamber was divided into halves by a lead partition, and, as the ionization could be measured in each half, it really constituted two chambers. They found that bursts were recorded simultaneously in both halves of the chamber very frequently, and that the triple coincidence counter system was actuated in about half of these cases. The probability of these coincidences being fortuitous is very small.

Ehrenberg[36] arranged three counters below an ionization chamber which recorded only on the simultaneous discharge of the counters. He found, consistently, that bursts are registered on the discharge of the counters and he estimated that, on the average, about 30 rays pass through the chamber when the counters are discharged. A burst of 30 rays in an ionization chamber of medium size is by no means small.

Nie[36b] has found that bursts observed in one ionization chamber are capable of producing bursts in a second chamber separated from the

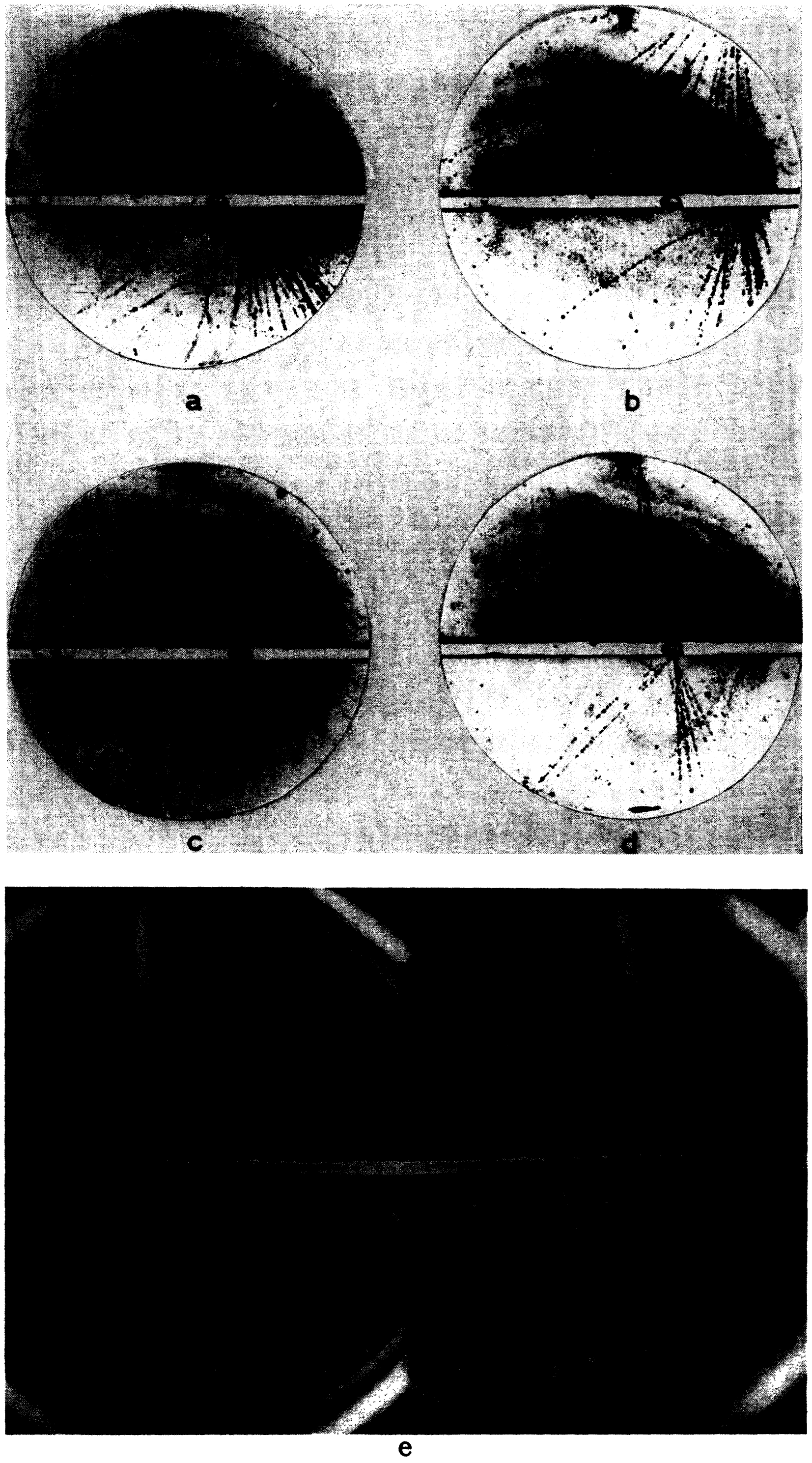


FIG. 25. Typical photographs showing the building up of a shower in the lead plate across the center of the chamber. The shower in (*b*) is an excellent illustration of the common observation that rays diverging at wide angles from the axis of the shower are easily absorbed. [(*a*), (*b*), (*c*) and (*d*), Auger and Ehrenfest[37]; (*e*), Anderson and Neddermeyer.[36b]]

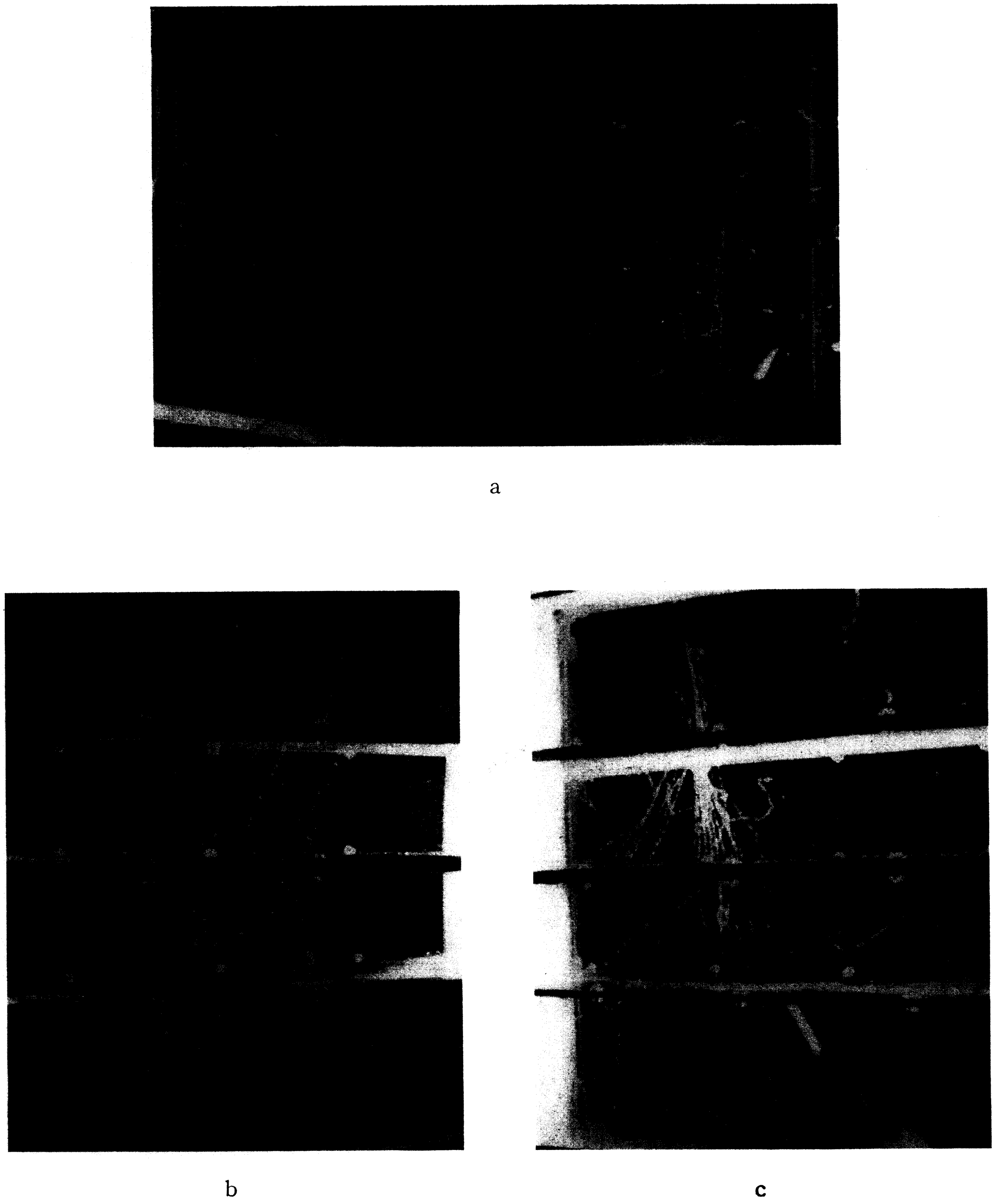


FIG. 26 (*a*). One of the first cases in which definite shower rays from above the chamber were observed to produce more shower rays in the lead plate. (Stevenson and Street.[35]) (*b*) and (*c*) Interesting cases showing the growth and absorption of showers in divided scattering blocks. The showers originate in 2.5 cm of iron above the chamber. Photographs by the courtesy of Messers Fussell and Street.

first by a few centimeters of lead. Hilgert and Bothe[36] have used an arrangement of four counters. Their results give some indication that all of the rays of a shower do not arise at a single point.

We have seen that counter experiments indicate that shower rays are capable of inducing new showers, and that showers often diverge from more than one point. These facts support the multiplicative shower production hypothesis.

In discussing their photographs of showers, Blackett and Occhialini[33] remarked that ". . . when one shower occurs there is a surprisingly large chance that another will occur a short way below it." Evidence of the same kind can be found in the work of Anderson and Neddermeyer[34b] and others. Auger and Ehrenfest[37] found that they could account for practically all of the showers they observed, at an altitude of 3500 meters, by assuming that they were produced by shower rays arising in the atmosphere. Starr[38] found that the mean size of showers increased with increased thickness of the scatterer, in conformity with the multiplicative hypothesis. Figure 25 shows examples of the enhancement of showers by a lead sheet. Auger *et al.*[36a] used two semi-cylindrical lead scatterers above a cloud chamber to show this enhancement. One of the scatterers was placed just above the apparatus and the other, larger scatterer was placed a considerable distance above the first. For thicknesses of the small one up to 1 cm, the presence of the large scatterer produced a large increase in the rate of observation of showers in the counter-controlled chamber, although the large scatterer alone was very inefficient.

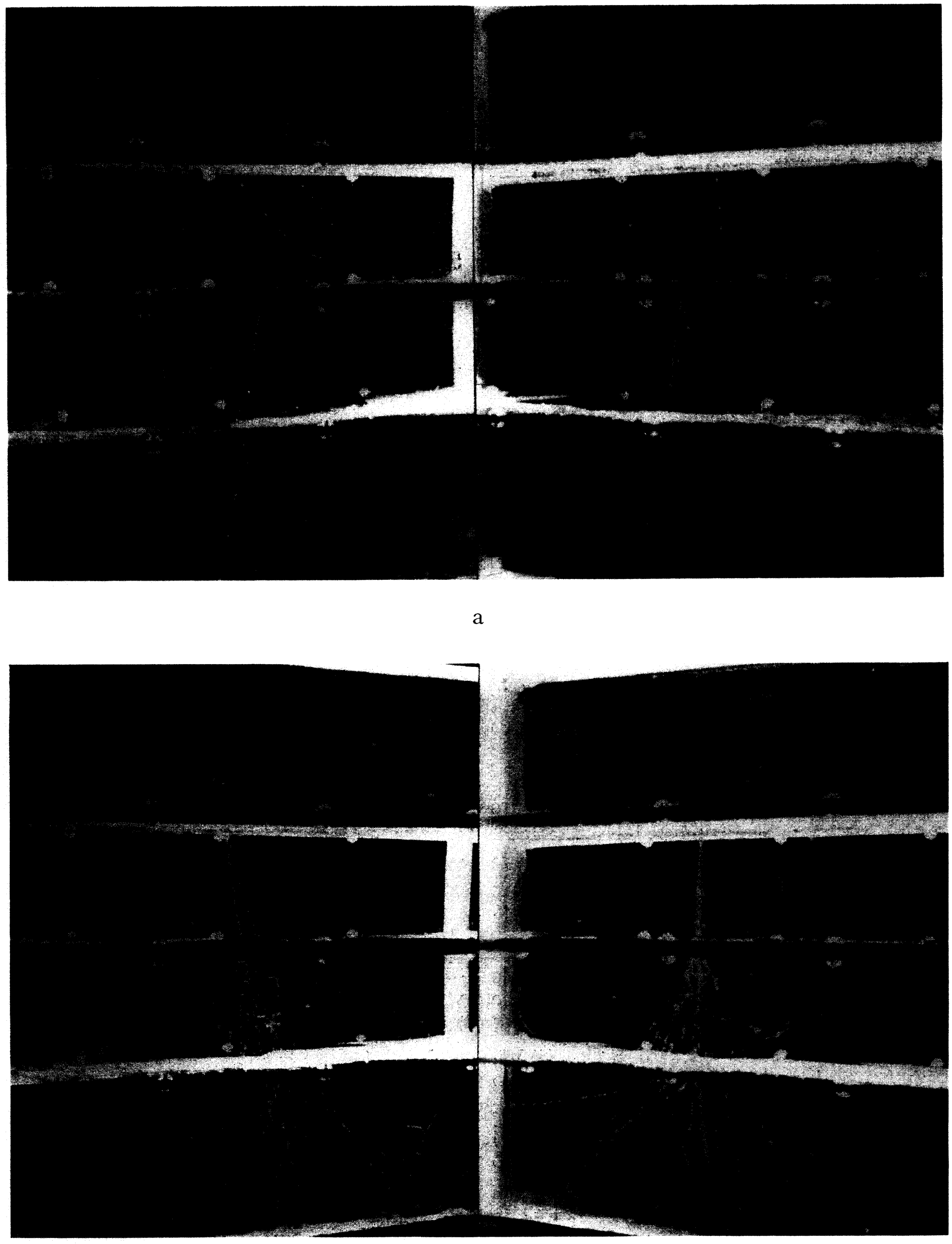
The use of divided scattering blocks in the cloud chamber provides an excellent method of studying the growth and absorption of showers. Fussell[37] used three lead sheets, the upper two 0.63 cm thick and the lower one 0.07 cm thick in such a study. Out of 500 showers observed with this arrangement only 3 were found to diverge from a single point. The second scattering block increased the number of shower particles by a factor of 1.7 on the average. No case of production of a shower greater than a pair was observed from the 0.07 cm sheet. Figures 26, 27 and 28 show several cases illustrating the growth and absorption of showers.

In the photographs shown there are several cases in which it is evident that the shower rays, diverging at a large angle from the axis of the shower, are quite easily absorbed. This is typical of most showers. In some cases the energies of the individual rays are reduced so much that the shower begins to be absorbed in the cloud chamber. Figure 26*c* is an excellent illustration of the absorption of the shower. A similar case is shown in Fig. 29*c*. When the energy of the ray originating the shower has become divided among a sufficient number of rays, the energies of the individual electrons and photons becomes so small that energy loss by ionization greatly exceeds loss by radiation, or pair formation, and the rays are rapidly absorbed.

8. Energy loss measurements

Charged particles in passing through matter are known to lose energy in the following ways: (i) by excitation and ionization of atoms near their paths; (ii) by transfers of large amounts of energy by close collisions with electrons in the matter traversed; (iii) by disintegration of nuclei; and (iv) by radiation excited during close nuclear encounters. In addition, two other processes, not definitely known to occur, are conceivable: (v) direct production of electron pairs without a photon intermediary; and (vi) change in kinetic energy due to a change in proper mass with or without a change in total energy.

Ionization energy losses have not been measured directly for very energetic electrons. Probably the best value of this kind of loss is 32.2 volts per primary ion in normal air given by Eisl.[29] Eisl found this value to be constant for electron energies from 9×10^3 to 59×10^3 ev. Although these energies are far below those usually encountered in the cosmic rays, the value is very probably applicable to cases of high energy because the energy involved in secondary ionization along the cloud chamber track of an electron must be practically independent of the electron's energy, since the secondary electrons have an apparently constant short range in all cases, and, obviously, the ionization potentials of the atoms are independent of the electron's energy. The number of primary ions formed per



a

b

Fig. 27. Photographs showing the growth of showers in divided scattering blocks. In (*a*) the energy is transferred from the first to the second block by a non-ionizing ray. Photographs by the courtesy of Messers Fussell and Street.

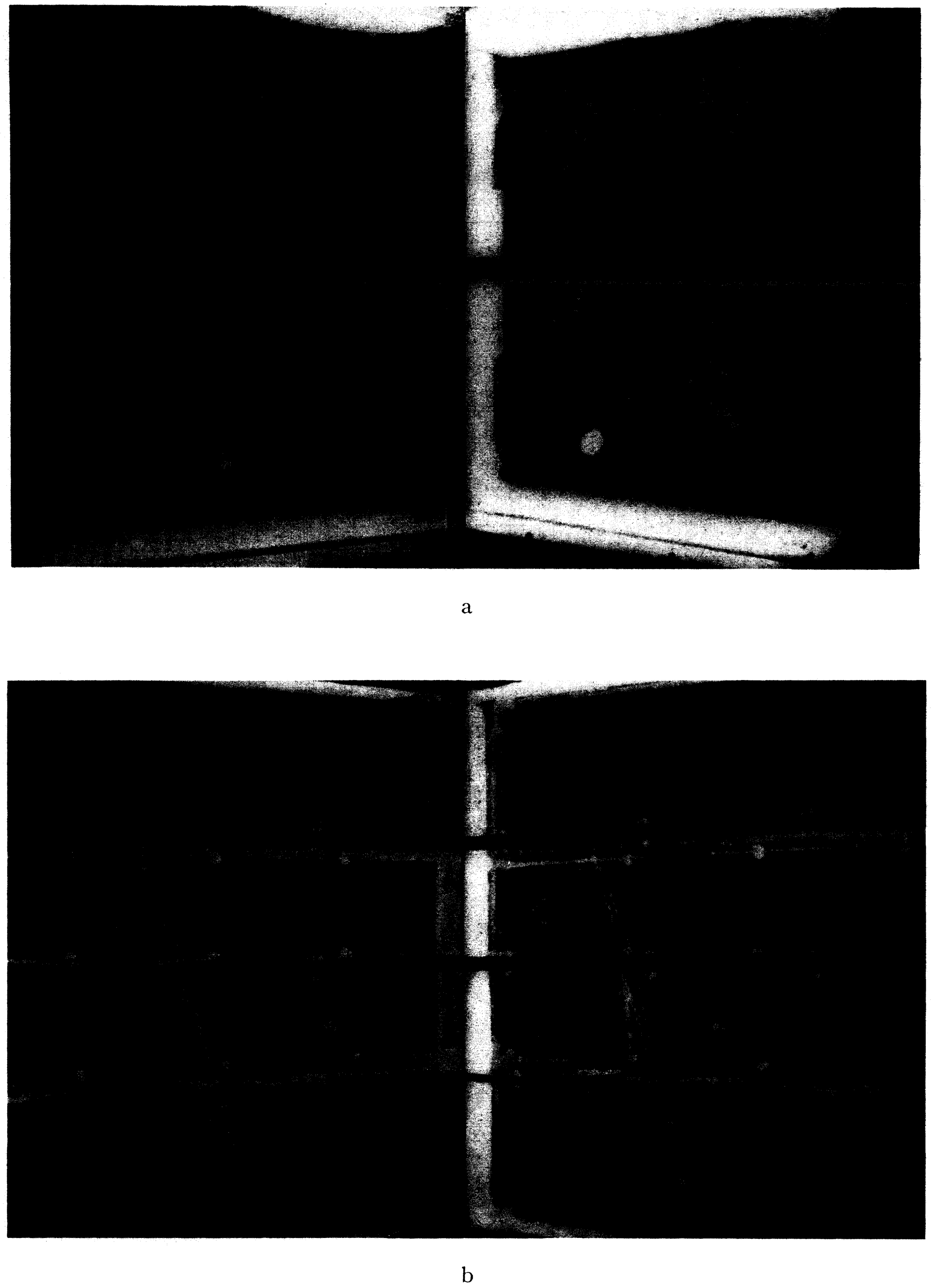
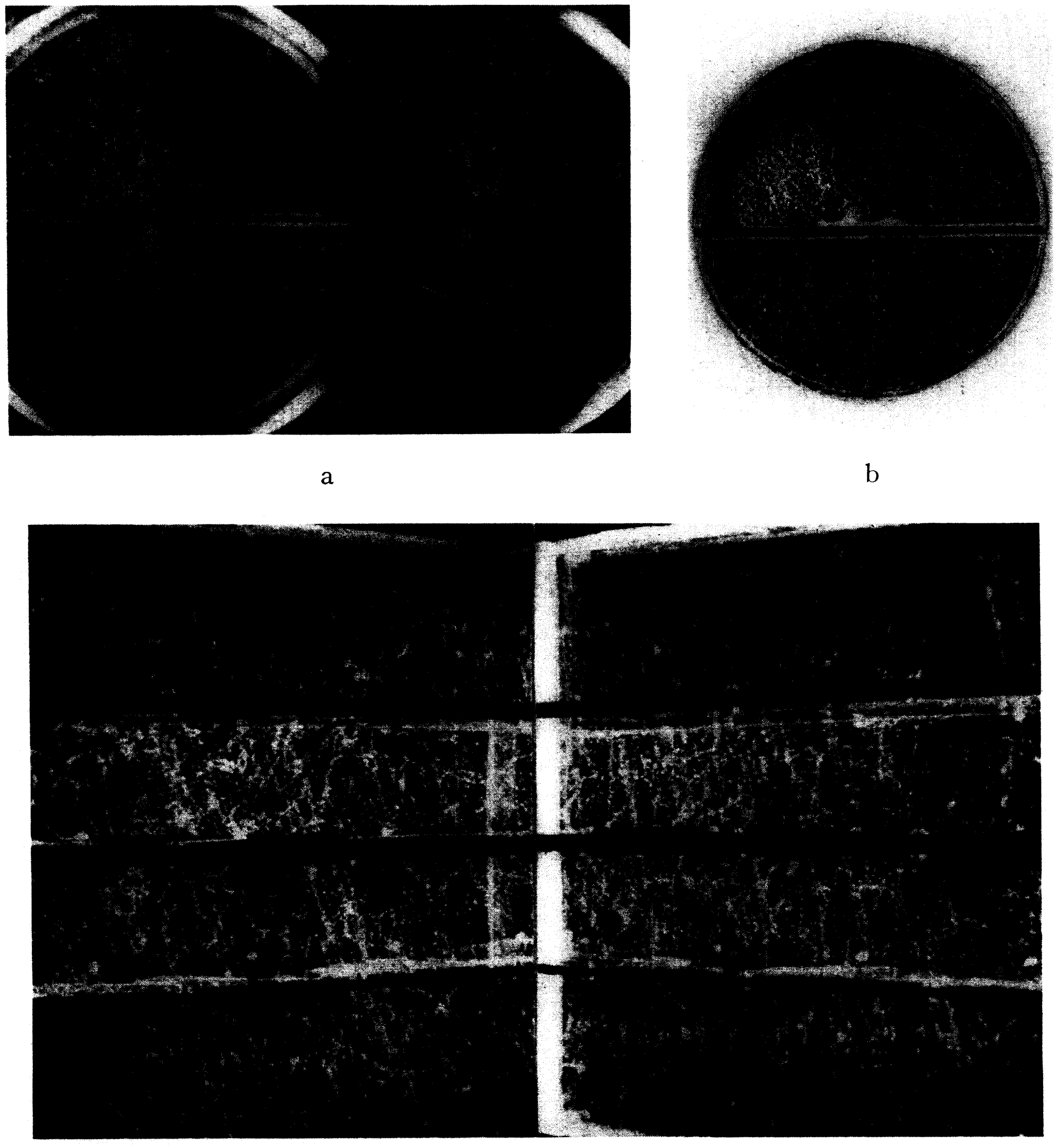


FIG. 28. Examples of shower growth. In (*a*) are shown several cases of pairs and more complicated phenomena produced by non-ionizing rays. Photographs by the courtesy of Messers Fussell and Street.

cm can be found most directly by counting droplets. This method gives a lower limit to the number and is probably not more than 50 percent too small. The number of primary ions formed in normal air has been determined by droplet counting for high energy electrons by Anderson,[33d] Kunze,[33] Locher,[32] and Williams and Terroux.[30] If we take 30 ion pairs per cm for the specific ionization, we find that a cosmic-ray electron loses at least 10^3, probably nearer 2×10^3, ev per cm of air under standard conditions due to process (i).

Carlson and Oppenheimer[32] have given theoretical formulae for calculating the probability


a

b

c

FIG. 29. Examples of very large showers of sizes quite sufficient to produce the ionization bursts observed. (*a*) A shower of more than 300 rays having a total energy probably exceeding 1.5×10^{10} ev. (Anderson and Neddermeyer.[36b]) (*b*) A very large shower. (Ehrenfest and Auger.[36]) (*c*) A shower in which more than 100 electrons enter the chamber. The total energy may be well over 10^{12} ev. Photograph by the courtesy of Messers Fussell and Street. In these large showers, especially in (*c*), the multiplication and absorption of the shower rays is evident.

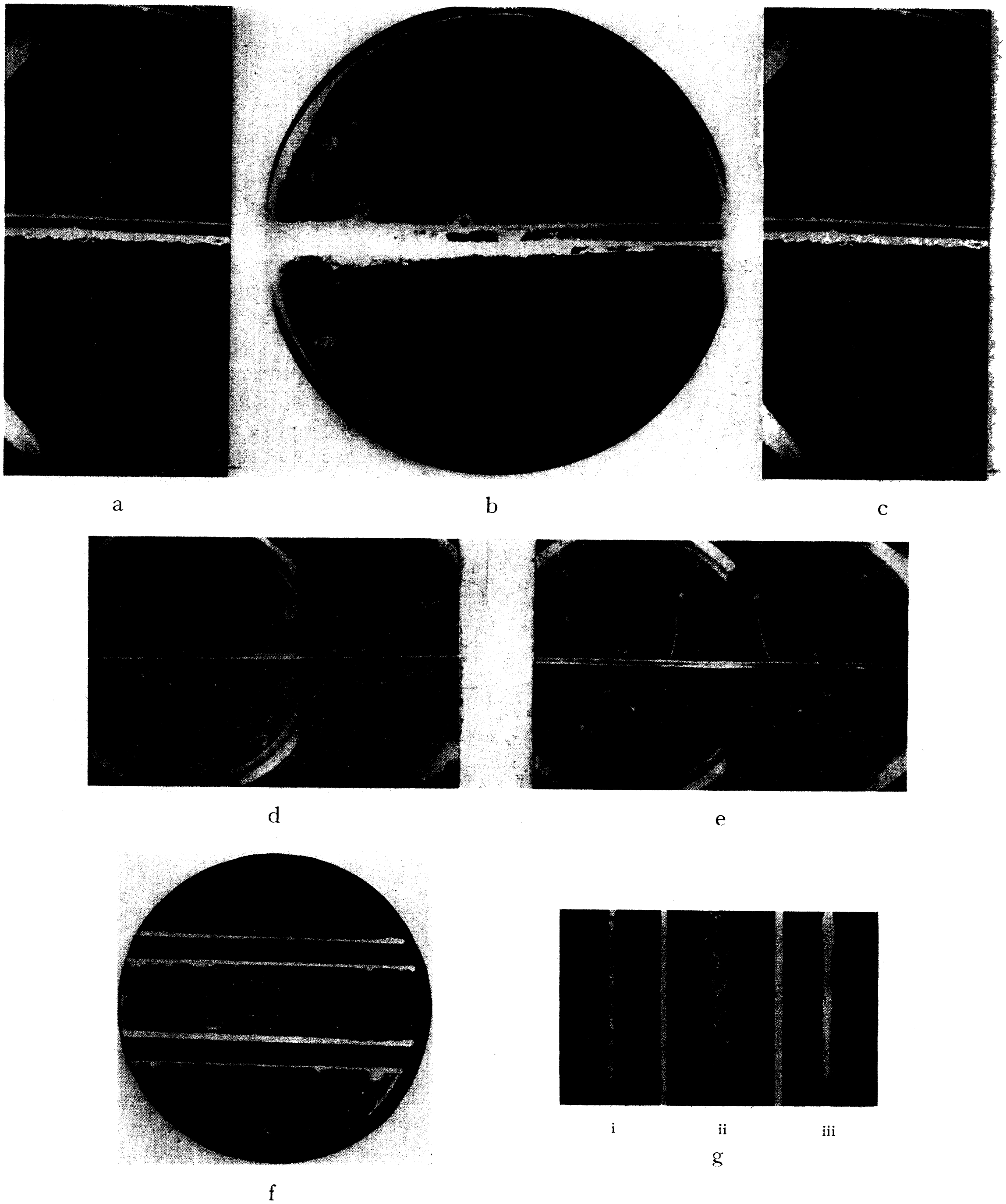


FIG. 30 (*a*). A 60×10^6 ev positive electron penetrating a 4 mm lead plate with an energy loss of 38×10^6 ev. (Blackett and Occhialini.[33]) (*b*) The positive electron. (Anderson.[33b]) This photograph, showing ionization and energy loss for an electron but a positive curvature, was the first one recognized as an unambiguous case of a positron track. (*c*) A negatron, on passing through the 4 mm lead plate, loses at least 70×10^6 ev. (Blackett and Occhialini.[33]) (*d*) The heavy, nearly vertical track near the center of the chamber is an early example of a penetrating ray which has a range much greater than would a proton with the same $H\rho$. Above the lead plate the particle ionizes like an electron. (Anderson and Neddermeyer.[36b]) (*e*) An example of a heavily-ionizing ray ejected upward from the lead plate by a non-ionizing ray. The ray is coincident with the shower and, again, the range is much greater than the range of a proton with the same $H\rho$. (Anderson and Neddermeyer.[36b]) (*f*) A 2.4×10^8 ev particle which loses 2×10^6 ev in the upper 11 mm lead plate and 6×10^6 ev in the lower one. Energy values on the basis that the particle is an electron. (Anderson.[33a]) (*g*) (i) An electron track in oxygen, (ii) an electron track in hydrogen and (iii) a proton track in oxygen. (Blackett.[34])

of electron energy losses by process (ii). This theory, naturally, gives a definite energy distribution for the secondary electrons, and this energy distribution agrees well with the experimental distribution found by Anderson and Neddermeyer.[34a, c] Hence we can be fairly confident of the theoretical value of energy loss by this process. Processes (i) and (ii) together account for losses of the order of 2×10^7 ev per cm of lead for the usual cosmic-ray electrons.

The disintegration of atoms giving rise to highly ionizing particles is an extremely rare event. We can neglect the mean energy loss per cm by process (iii) in comparison with other types of losses.

Quantum theory has been applied to the calculation of energy loss by electrons making radiative collisions, process (iv). Heitler and Sauter[34] derived an approximate result in which they neglected the electron screening of the nucleus, and Bethe and Heitler[34] have given a detailed theory in which they included corrections for screening. The Bethe-Heitler theory predicts that radiative energy losses will increase with energy and amount to well over 10^8 ev per cm of lead for energies exceeding 10^8 ev. For example a 3×10^8 ev electron incident on a 1 cm lead plate would be expected to lose 2.5×10^8 ev of energy.

The contributions to energy losses by processes (v) and (vi) are probably small. Practically no information on change of proper mass is available on either theoretical or experimental grounds, although we shall see later that there is some evidence that such a process may occur.

It is well known that the observed energy losses of β-rays, of energy about 10^7 ev, are usually slightly greater than the theoretical losses, but the difference is often of questionable significance. The energy losses of electrons in cosmic-ray showers are also usually slightly in excess of the theoretical predictions. Cloud chamber photographs of electrons losing energy in transmission through lead plates are shown in Fig. 30*a*, *b*, *c* and *f*.

Cloud chamber energy loss measurements, made on the assumption that all the thinly-ionized tracks are due to electrons, have been made on cosmic-ray particles by Anderson,[33a, b, c] Anderson and Neddermeyer,[34a, c, 35, 36, 37] Blackett,[37a, b, 38] Blackett and Wilson,[37] Crussard and Leprince-Ringuet,[37] Leprince-Ringuet,[37] and others. Lenz[35] has made energy loss measurements with counters and an electric field. Street, Woodward and Stevenson[35] have compared the absorption in very thick lead with cloud chamber energy distributions to find specific energy losses. For cosmic-ray particles of high energy, calculated on the hypothesis that the particles are electrons, the measured energy losses are very frequently much less than expected on the Bethe-Heitler theory. For energies less than 10^8 ev rough agreement is found between the theory and observation. The simple assumption that the theory breaks down at high energies is untenable if, as Neddermeyer and Anderson's[37] results indicate, the particles can be divided into two groups, one of which agrees with theoretical predictions and the other contains particles whose energy losses are much too small. The grouping was not done by a mere separation of the particles into two classes, one of which gave agreement with theory, but by classifying the particles into shower and nonshower groups. Not only do the shower particles obey the Bethe-Heitler law fairly well while the others do not, but the shower particles frequently initiate new showers whereas the others do so very rarely indeed. There is good reason to believe that the shower rays are electrons and are fundamentally

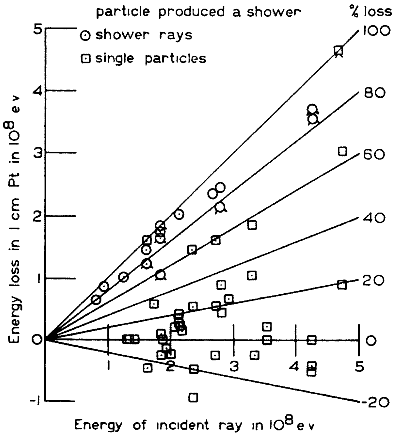


FIG. 31. Energy loss measurements as a function of initial energy for shower rays and single rays. (Neddermeyer and Anderson.[37])

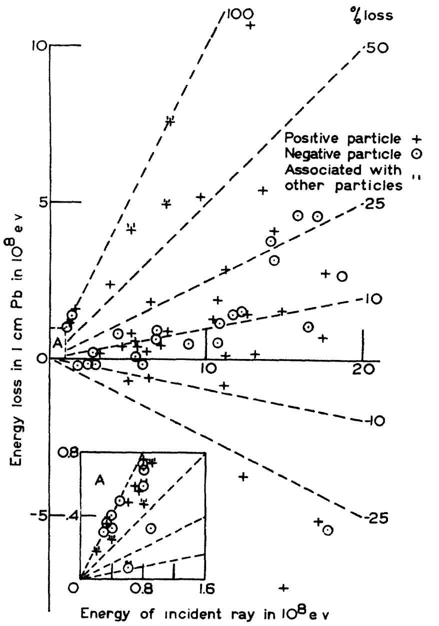


FIG. 32. Energy loss measurements as a function of initial energy for rays appearing in a cloud chamber. (Blackett.[38])

different from most of the rays of the other group which almost always appear singly in cloud chambers. Some of the singly-occurring rays appear to be electrons for they are strongly absorbed and produce showers. The observations on energy loss by particles penetrating 1 cm of platinum, given by Neddermeyer and Anderson,[37] are shown in Fig. 31. Both types of particles occur with both signs of charge, negatives and positives being about equally frequent. Most of the cases of apparent gains in energy shown in Fig. 31 are probably due to distortions produced by gas currents in the chamber, although there is always the chance that the particle was moving upward, which is probably the case for the particle represented by the lowest point on the graph.

Very recently Blackett[38] has made further energy loss measurements some of which are shown in Fig. 32. In agreement with the results of Blackett and Wilson[37] it was found that nearly all rays of energy less than 2×10^8 ev showed losses in agreement with theory, whereas half of the particles in this energy range observed by Neddermeyer and Anderson showed abnormally low losses. On the other hand, there seems to be universal agreement that there are a few very energetic particles which show the energy losses predicted by theory for electrons, but that most of the high energy rays do not. Blackett has concluded by indirect argument from the energy spectrum, and from direct experiment, that at least some of the penetrating rays become indistinguishable from electrons when their energies fall much below 2×10^8 ev. The hypothesis that electrons have variable, possibly quantized, masses seems to explain the appearance of particles which do, and particles which do not, follow the predictions of electron theory for both high and low energies. This hypothesis would also account for changes in the behavior of the particle, for, as Blackett has suggested, it might have its mass suddenly altered during collisions with nuclear fields.

Crussard and Leprince-Ringuet[37] found that negative particles lost roughly twice as much energy as positives on the average. This result is not in agreement with the work of others. Blackett and Wilson[37] could detect no difference in energy loss dependent on the sign of the charge. The latter workers found that the specific energy loss in lead was about five times as great as in aluminum.

Measurements on atmospheric absorption also indicate that there must be a penetrating ionizing ray component of the cosmic rays other than electrons. Further discussion of this question is given in the section on the barytron.

9. Discovery of the positron

In 1932 Anderson[32b] obtained the cloud chamber photograph shown in Fig. 30b. If the central curved track represents the passage of a single particle through the 6 mm lead plate, the particle must be positive. The curvature on one side of the plate corresponds to an energy, assuming the particle is an electron, of 63×10^6 ev, and on the other side to 23×10^6 ev, and is in the proper direction for a positive particle if it lost energy in the plate. A similar energy consideration on any assumption of the particle's mass leads to the conclusion that the charge is positive. It is inconceivable that a negative electron in passing through the lead would have its energy tripled. Even if there is a minute probability of such an event, the comparatively frequent occurrence of the phenomenon subsequently found, rules out the suggestion.

There is the bare possibility that the tracks on the two sides of the plate are made by two independent negative electrons. The sharpness of the tracks shows that they were both made within about 0.02 second of each other, and they are practically collinear. It is obvious that the probability of such an event is negligibly small, especially when subsequent observations are considered. There is also the possibility that a non-ionizing ray caused the simultaneous ejection of two rays from the lead. If so, the direction of curvature shows that one of them must be positive. That the track could not have been made by a proton can be seen from several considerations. If the particle is a proton the curvatures give its kinetic energy as 2×10^6 ev on one side of the lead, and 3×10^5 ev on the other. The specific ionization produced by a proton of the latter energy is much greater than that of an electron, but the track shows the characteristic thin ionization exhibited by electrons. The range of a 3×10^5 ev proton is about 0.5 cm in normal air, while the track of this particle is visible in the chamber for ten times this distance from the lead and, indeed, shows no measurable loss of energy over the whole 5 cm. The particle cannot be a proton. In fact if the particle has unit charge, its mass must be less than twenty times the mass of the electron if the energy loss in the lead is to be consistent with known values for electron energy losses. Both the specific ionization and the energy loss in the lead fix an upper limit of about $2e$ for the charge on the particle. It is legitimate to conclude from this single photograph that a particle of charge $<2e$ and mass $<20m_e$ exists. All of the data are consistent with the assumption that the particle has a charge $+e$ and mass m_e. Another unambiguous case of a positron is shown in Fig. 30*a*.

In 1933 Anderson[33a, b] found several other positive electrons. Kunze,[33] Blackett[33b] and Blackett and Occhialini[33] also found many cases which checked the existence of this particle. The ionizing rays in a shower are approximately half positive and half negative electrons.

The positive electron is usually called a *positron*, the negative electron a *negatron*, and the term *electron* is used for either.

Since 1933 an overwhelming mass of evidence in support of the positron's existence has been built up in both cosmic-ray and disintegration studies.

10. Discovery of the barytron

The hypothesis of the existence of a new type of elementary particle is a favored method of explaining experimental results difficult to interpret on the basis of the properties of the well-known particles. In addition to the classical proton and electron, the existence of the neutron and, as we have just seen, the positron is well established. The concept of the neutrino plays an important part in modern thought even if direct experimental evidence has not proved its existence. The concept of a particle with charge e and a proper mass intermediate between the electron's mass, m_e, and the proton's mass, m_p, is not new. Bothe,[25] in discussing Compton collisions, suggested that an electron might absorb a fraction of a photon's energy in the form of additional rest mass. Jauncey[37] has suggested that this concept might be applicable to the explanation of the great penetration of some of the cosmic rays.

Yukawa[35] has pointed out that the assumption of particles of intermediate mass offers a more natural explanation of the exchange forces between protons and neutrons than does Fermi's[34] theory of the electron-neutrino field. However, as Oppenheimer and Serber[37] have indicated, this does not constitute contributary evidence for the existence of such particles. Stueckelberg[37] has predicted the existence of "Bose" electrons with proper mass exceeding $m_e+$the mass of the neutrino. The "Bose" electrons would be unstable, secondary particles. Yukawa and Sakata,[37] Bhabha,[38] and Kemmer[37] have discussed, theoretically, the possibility that these intermediate particles, obeying "Bose" statistics, constitute the penetrating component of the cosmic rays. These particles are now frequently called "dynatons" (Bethe,[38] Primakoff,[38] and Serber[38a]). Bethe[38] finds that dynatons of neutral charge are needed to explain the forces between like and unlike heavy particles. Kobayasi and Ozaki[38] have deduced, theoretically, the energy losses in the direct production of pairs by ordinary electrons and by the heavier particles. They find that, for particles of mass $\gtrsim 10m_e$ almost all the energy lost is of this kind and that the loss on pair formation is the same as for an electron of the same velocity. Nordheim and Teller[38] have calculated the probability of emission of heavy electrons of mass $\sim 137m_e$ by the passage of energetic protons and neutrons through matter. The probability seems to be too low to account for the large number of apparently heavy particles observed in the cosmic rays. They have also estimated the life of these particles, from β-decay data, to be the order of 0.5×10^{-3} sec. If this estimate is reliable and the particles do appear in the sea level cosmic rays, they must be produced in the atmosphere. Wentzel[36] has introduced a particle of mass $\gtrsim m_p$ for theoretical considerations.

In quantum mechanics an electron is defined by its charge and mass. It is conceivable that some additional fundamental property associated with an electron is needed to explain its complete behavior. Crane[37] has suggested that the collision cross section might depend upon the length of the de Broglie wave train associated with an electron, and Bramley[37a] has suggested that the distribution of an electron's charge throughout space might affect its penetrating properties. Bramley[37a, 38] pointed out a result from the work of Dirac[36] that if an electron's spin exceeds $\frac{1}{2}$, the probability of its radiating in nuclear fields is reduced. Pauli and Weisskopf[34] have postulated particles of zero spin and Carlson[38] has compared the theoretical energy losses of heavy Pauli-Weisskopf particles with the losses of particles of spin $\frac{1}{2}$, i.e., particles obeying the Dirac equation. These points should be kept in mind during the following discussion. However, if we find it necessary to postulate the existence of particles different from electrons as we know them, and if we can account satisfactorily for observed facts on the hypothesis of intermediate mass, it would seem that such an explanation should not be less acceptable than an explanation, probably less convincing, which requires some other alteration of the electron's fundamental properties.

In the following discussion evidence favoring the existence in the cosmic-ray complex of particles possessing unit charge and intermediate mass, is presented along three main lines: (i) experimental observations which would be explained satisfactorily by this hypothesis, (ii) evidence to show that certain theoretical laws are obeyed by electrons but not by all of the cosmic-ray particles, and (iii) direct observations on energy loss, specific ionization and range of cosmic-ray particles. These particles have been called penetrating particles, X-particles and heavy electrons. They are now commonly called barytrons.

The exceedingly low absorption coefficient for cosmic rays at great depths is well known. Rossi,[33a, 34, 35] Rossi and Bottecchia,[34] Auger and Ehrenfest[34] and Schwegler[35] have used counters separated by great thicknesses of lead, to show that there are ionizing rays incident at sea level capable of penetrating at least one meter of lead. Street, Woodward and Stevenson[35] have checked this result by placing a cloud chamber in the path of the ray. Leprince-Ringuet and Crussard[37] have used a cloud chamber in a magnetic field to show that penetrating rays of energy less than 10^9 ev, calculated on the assumption that the particles are electrons, can produce coincidence in counters after penetrating 14 cm of lead. It is well established that there are ionizing rays of energy of the order of 10^9 ev which penetrate to great depths.

A study of the latitude effect on the ionization-depth curve in the atmosphere gives much information on the question of penetration. We will not discuss this very important problem in detail here, but merely mention those results useful in our discussion of heavy electrons. The intensity-depth curve obtained with a single counter by Curtiss *et al.*,[38] shows good agreement with the ionization curve. The blocking effect of the earth's magnetic field prevents the incidence of charged particles of energy less than a definite minimum depending upon the magnetic latitude. From observations of the ionization at various altitudes for different latitudes it is possible to construct an ionization-depth curve for the field-sensitive portion of the rays. For examples of such curves and a more complete discussion see Bowen, Millikan and

Neher.[37, 38] Near the equator rays of energy less than about 1.7×10^{10} ev are excluded, yet in higher latitudes these rays apparently penetrate the whole atmosphere for their ionization effects are easily measurable at sea level. Air-depth curves taken with counters by Pfotzer[36] and by Pfotzer and Regener[35] indicate the presence of two major components of the cosmic rays in the same energy range, one component being much the better shower producer. We may confidently conclude that there are existent ionizing rays of high penetration even when their energies are limited. We have seen that energy loss measurements strongly support this finding. On the purely empirical basis of energy losses experienced by shower particles, which we have reason to believe are electrons, we cannot account for the high penetration of the singly-occurring particles on the assumption that they are electrons. If we assume that the particles are protons, we can account for their penetration but, as roughly half of these rays are negatively charged, it becomes necessary to postulate the negative proton. This was done by Williams.[34]

We have seen that, above sea level, the frequency of shower production varies with altitude in approximate proportion to the intensity of the soft component of the cosmic rays. Below sea level, and under thicknesses of material greater than some 200 g per sq. cm, the frequency of occurrence of showers is proportional to the total intensity which, in this case, consists mainly of the penetrating component. Thus we have evidence that the penetrating rays can initiate showers. Alocco[35] and Rossi and Alocco[35] measured the relative efficiency of lead and aluminum for shower production when the whole apparatus was, and was not, shielded by 7.5 cm of lead. Since the relative efficiency of the aluminum was much greater in the shielded case, they concluded that there are both penetrating and soft shower-producing rays. Stearns and Froman[38] have shown that the percentage increase of shower frequency with altitude is much greater for showers produced in thin scatterers than for those produced in thick ones. This also suggests two components. Schwegler[35] studied shower production with a 10 cm lead absorber above a lower counter. This absorber should remove practically all shower electrons. Schwegler found the Rossi transition curve for this case to resemble the transition curve taken under several meters of water. We suggest that the showers detected may have been produced in the scatterer by a penetrating ray which continued through the thick absorber to discharge the shielded counter. In fact Ehrenfest[38] has obtained a cloud chamber photograph of a shower containing three positrons and two negatrons which was produced apparently by a penetrating ray. This ray continued through the chamber with very little loss of energy. Anderson and Neddermeyer[36] and Brode, MacPherson and Starr[36] have, in fact, noticed that showers fall into two groups. In the more frequently occurring type the particles are well collimated and heavy particles are rare. In the other, very rare, type, heavy particles are common and the angular divergence of the shower is great. An example of the rare type of shower is shown in Fig. 23. Nielsen and Morgan[38] have found that the soft component of the cosmic rays at sea level, about 30 percent, is reduced to only about 25 percent by absorption in 75 ft. of rock. This indicates that the penetrating component produces soft radiation and that equilibrium is nearly established at sea level. All of these observations on shower production are consistent with the hypothesis of heavy electrons, but might be explained equally well by a proton hypothesis if protons are capable of initiating showers. However, Bhabha[38] has applied the quantum theory to a calculation of the transition effects expected with thick scatterers for particles of intermediate mass. The theoretical predictions agree reasonably well with observations if masses of some tens or a few hundred times m_e are assumed. The few estimates of masses available are from 100 to $300m_e$.

In 1934 Bethe and Heitler[34] developed the quantum theory of radiation by electrons in nuclear fields and of pair formation by γ-rays. Since it was thought that this theory gave incorrect results for high energy rays, its application to the problem of multiplicative shower production was not made for some time. However, three years later Bhabha and Heitler[37] and Carlson and Oppenheimer[37] independently applied the theory to the problem of shower production. According to the theory, energy carried by electrons and photons would, on the average, be about equally divided between the two forms. Montgomery and Montgomery[38a, c] have made calculations to show that considerably less than half the total cosmic-ray energy at sea level is carried by photons. Ramsey and Danforth[37] have shown that the frequency of showers produced at sea level is less than expected on the theory if all the ionizing rays are electrons. If the theory is obeyed by electrons, the sea level cosmic rays must contain a component other than electrons and photons.

We have seen already that the measurements of energy losses, when low energy ionizing particles penetrated matter, gave results in approximate agreement with the Bethe-Heitler theory, but that the deviation from the predictions of the theory for high energies was great. Although Williams,[34] Weizsaeker[34] and others gave theoretical reasons to expect a breakdown of the theory for very high energies, we have seen that in the energy range of shower electrons the theory is valid for the shower electrons but probably not for the singly-occurring particles. Oppenheimer[35a] and Williams[34, 35] have given clear analyses of the validity of the quantum mechanics formulae for the absorption of high energy rays, which were in use at the end of 1934. Recently the ionization-depth curves, for both the latitude-sensitive and nonsensitive rays, have been extended to great heights. On the assumption that the primary rays consist almost entirely of electrons and photons, a direct test of the applicability of the theory up to energies of about 2×10^{10} ev is possible. As applied to cosmic rays near the top of the atmosphere the theory gives results which agree closely with observations, and, in fact, there is strong evidence that the theory is accurately applicable to electrons of this energy. Actually the absorption at very great altitudes is slightly in excess of the theoretical predictions.* This may be connected with a peculiar fact found by Auger *et al.*[37a] that atmospheric absorption, as measured by change of zenith angle, is not the same as measured by change of depth. Until recently it was thought that evidence from the ionization-depth curve definitely contradicted the theory. (See Bowen, Millikan and Neher,[34, 37] and Millikan, Neher and Haynes[36].) Critical accounts of the applicability of the theory at high altitudes is given by Bowen, Millikan and Neher,[38] and by Nordheim.[38]

Now the theory gives very nearly the correct intensity variation in the upper layers of the atmosphere on the assumption that the incident cosmic rays are made up of electrons and photons, but on the electron-photon basis, it predicts an absorption at greater depths in the atmosphere markedly greater than that observed. Obviously this deviation from theoretical prediction cannot be accounted for by the high energy of the rays, since they must lose energy in penetrating the atmosphere. The frequency of large bursts increases rapidly with altitude in the same way as the soft component. Since the energy expended in a large burst is high, it is obvious that, even for very high energies, those rays which produce bursts are much more easily absorbed than are the penetrating rays. Moreover, the agreement between theory and experiment at great heights is evidence against the hypothesis that the primary rays contain a large percentage of heavy particles. Bhabha and Heitler[37] have shown that, if the Bethe-Heitler theory is applicable to electrons, we would find no sea level latitude effect for electrons. If the theory is applicable up to energies of 10^{10} ev, as we believe it to be, the electron latitude effect would not extend above 35°. It is well known that the sea level effect extends to 50°. The only tenable conclusion would seem to be that secondary penetrating rays are produced in the atmosphere. There is, however, evidence from counter telescope measurements that incident photons do not produce appreciable numbers of penetrating rays in lead.† Moreover, Nordheim[38] has shown that the intensity-depth curves can be fitted well by assuming a mixture of soft and penetrating rays incident on the atmosphere.

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* *Note added in proof.* Serber[38b] has shown recently that a refined calculation of the multiplication of the soft component of the cosmic rays in the upper atmosphere, based on exact high energy radiative formulae, leads to excellent agreement between theory and experiment on the position of the maximum.

† *Note added in proof.* This conclusion must now be reversed. The measurements mentioned were made near sea level. Very recently Schein and Wilson[38] have obtained good evidence that penetrating ionizing rays are produced by non-ionizing rays in considerable numbers at altitudes between 20,000 and 25,000 ft. above sea level.

Compton and Bethe,[34] Compton[35] and others have used a proton (and sometimes an α-ray) hypothesis to explain the low absorption in the atmosphere. It is, however, very difficult to explain why so few of these particles are observed in cloud chambers. Although very high energy protons cannot be distinguished from electrons and the depth of the atmosphere is not nearly as great as the range of high energy protons, we would expect a considerable number incident at large zenith angles to be near enough the ends of their ranges to make identification as protons easily possible. Blackett and Occhialini,[33] Blackett,[37a, b] Brode, MacPherson and Starr,[36] Montgomery, Montgomery, Ramsey and Swann[36] and others find too few protons at sea level to account for the discrepancy between theory and experiment. Brode, MacPherson and Starr estimate, from a consideration of the data from 8500 cloud-chamber photographs, that not more than 1 percent of the sea level ionization is produced by particles ionizing heavily. Montgomery and Montgomery[36d] estimate from this data that protons constitute less than 1.4 percent of the penetrating component at sea level. Anderson and Neddermeyer[36] took 1500 exposures with a cloud chamber controlled by a counter telescope. The telescope was turned through as much as 70° from the vertical, and lead absorbers up to 1 meter in thickness were used, in an effort to find protons near the ends of their ranges. They found no protons, but they did find a case or two of particles with e/m apparently greater than $(e/m)_p$. Although Blackett and Brode[36] found more positive than negative penetrating rays, there are certainly a great many negatives. If the penetrating rays are protons, the negative proton must exist. Although there are several cases on record of particles which have been identified definitely as protons, none of these particles have been charged negatively. Another strong point of evidence against the proton hypothesis is the fact that the energy distribution of single secondary negatrons, ejected from plates of material by cosmic rays, is not consistent with the energies of the incident rays measured on the assumption that they are protons. This energy distribution indicates a much smaller mass. This was pointed out by Anderson and Neddermeyer[34c] several years ago. At the same time they showed that the available data on the latitude-sensitive-air-depth ionization curves indicated a difference in character between the penetrating rays observed in cloud chambers at sea level, and the rays in the same energy range responsible for the latitude effect.

It would seem that, if the penetrating rays consist mainly of particles of intermediate mass, many of these should be found near the ends of their ranges, and that the absence of many heavily-ionizing rays is evidence equally applicable to intermediate masses and to protons. However, the ionization produced by a particle of intermediate mass will differ from that of an electron less than does the ionization by a proton. Moreover, the heavy particles may be electrons with variable mass. If this is true, we would expect the mass to be less, on the average, for those particles of low kinetic energy and many of the heavy corpuscles may lose mass by radiation or other processes when nearing the ends of their ranges.

We have seen that the quantum theory gives results for shower production which agree very well with experiment if the scatterers are not too thick. This comparison of theory with experiment gives strong indications that the penetrating component of the cosmic rays is made up of particles heavier than electrons, and probably not as heavy as protons.

Before the quantum theory of radiative energy loss was developed sufficiently to give very precise values for the energy losses to be expected when electrons traversed matter, Anderson[33a] had observed several cases of energy loss which were too small to agree with modern theory. The cloud chamber photograph showing one of these cases is reproduced in Fig. 30*f*. On the assumption that the particle is an electron, its energy changes in the upper 11 mm lead plate from 24×10^7 to 22×10^7 ev, and in the second plate from 22×10^7 to 16×10^7 ev. In particular, the former loss of 2×10^7 ev is much smaller than is expected on the basis of modern theory, or on the basis of the more recent measurements of losses by shower particles of the same energy. The low specific ionization produced by this corpuscle precludes the assumption that it is a proton. Evidence of the same nature has been given by Street and Stevenson.[37]

In 1936 Anderson and Neddermeyer[36b] obtained a disintegration by a non-ionizing ray shown in Fig. 30*e*. The heavily-ionizing ray ejected upward from the plate obviously ionizes much more copiously than an electron. On the assumption that it is a proton, its range in the argon of the chamber gives a value of 1.5×10^6 ev for its energy, whereas its curvature in the field of 7900 gauss gives an energy of 1.6×10^5 ev. This difference of a factor of nine is well outside the errors of curvature measurement, but there is a possibility that multiple scattering has so altered the curvature that its measurement is unreliable. In view of this fact and, especially, in view of the radical assumption needed to explain the observations, Anderson and Neddermeyer tentatively identified this particle as a proton, although the data strongly indicate an intermediate mass. This particle is of special interest since it arises in the lead plate, showing directly that such particles can be produced in matter. Another similar case given by the same authors is shown in Fig. 30*d*. In this case the particle is incident on the top of the lead plate and, on emergence, ionizes very appreciably more heavily than do the shower electrons shown in the same photograph. The curvature of this track corresponds to a 10^6 ev proton. Such a proton has a range of 2 cm in the chamber while this track is more than 5 cm long. As pointed out by Neddermeyer and Anderson[37] the apparently high value of e/m (on the proton basis) cannot be due to a large value of e, because the particle does not ionize appreciably faster than an electron in the upper part of the chamber where its kinetic energy is high. Similar results have been obtained by Street and Stevenson[37a] who, incidentally, obtained only one shower in 500 traversals of a 1-cm lead plate by penetrating rays.

The first estimate of the mass of one of the penetrating particles was made by Street and Stevenson.[37b] In order to increase the probability of getting a penetrating particle near the end of its range in the cloud chamber, the apparatus was arranged as shown in Fig. 33. The cloud chamber was expanded only when counters 1, 2 and 3 were discharged and set 4 was not. This scheme eliminated many penetrating rays not near the ends of their ranges. The 10-cm lead block removed most of the soft component. The expansion was delayed 1 second after the counters were tripped in order to facilitate droplet counting. Out of 1000 expansions Street and Stevenson observed two particles which ionized more heavily than the others. One of the particles was identified with a proton. An example of a proton track is shown in Fig. 34*b*. The track of the other particle is shown in Fig. 34*a*. The ionization density in this track is about six times as great as is found in the usual thin tracks. Its $H\rho$ value is 9.6×10^4 gauss cm. On the assumption that the specific ionization is inversely proportional to the square of the velocity, the mass of the particle is $130m_e$. Street and Stevenson estimate a probable error of 25 percent in this determination due to the difficulty in making a precise droplet count. They suggest that the only possible objection to the interpretation that this particle is of intermediate mass lies in possible distortion of its path. This is very improbable for the deflection is uniform and more than ten times the distortion usually observed.

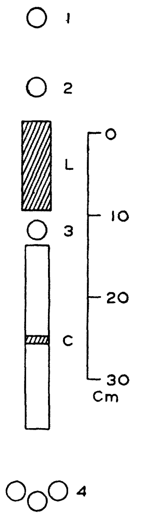
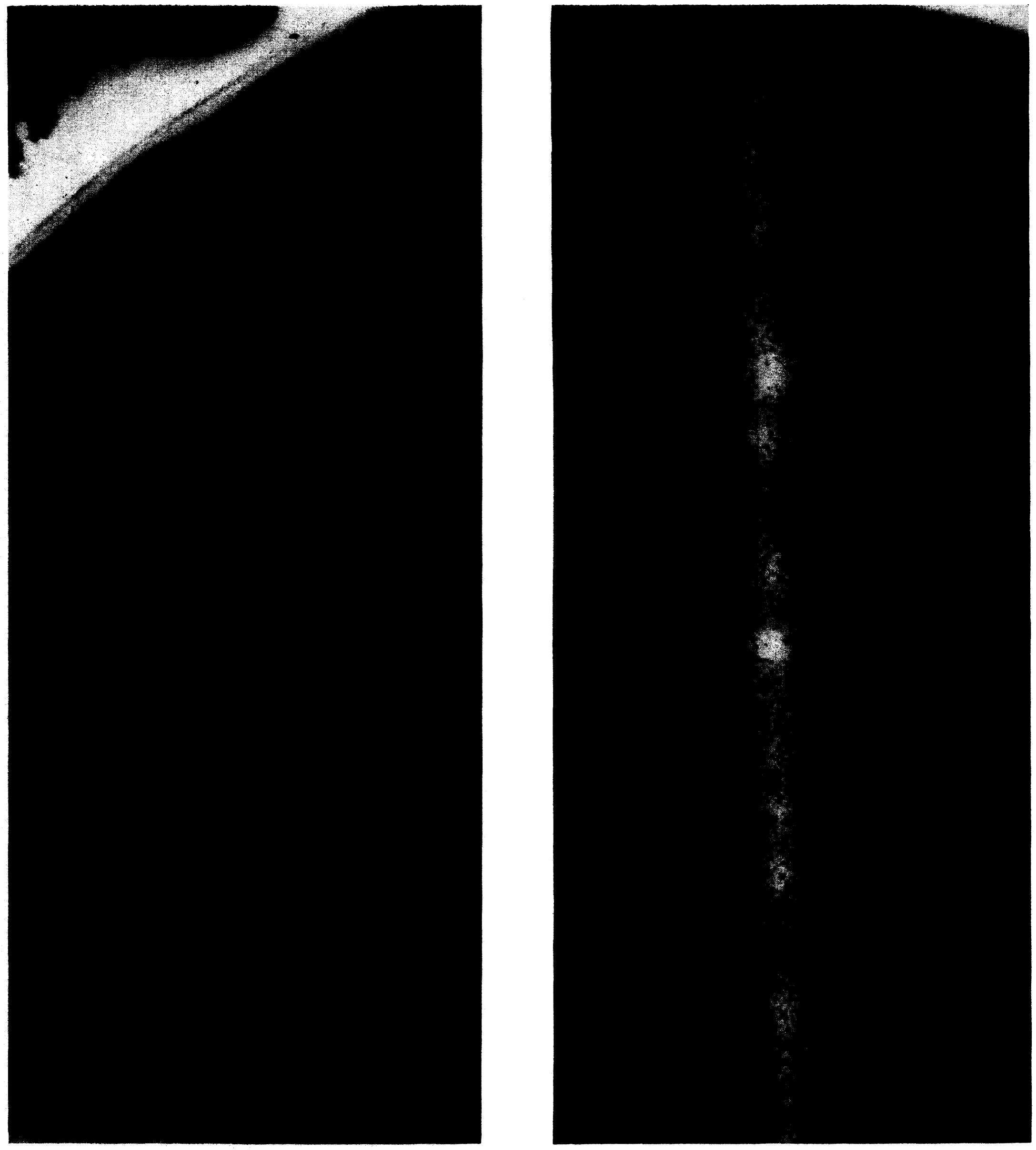


FIG. 33. The arrangement of apparatus used by Street and Stevenson [37b] for measuring the masses of the penetrating rays. *L* is a lead block and the cloud chamber *C* was expanded, after a delay of 1 sec., when counters 1, 2 and 3 were discharged simultaneously with no discharge in counter set 4.

Nishina, Takeuchi and Ichimiya[37] have measured the mass of one penetrating ray in a similar manner. They estimated that the mass was between 200 and $300m_e$. Auger[38] has found evidence for the intermediate mass at depths of



a b

FIG. 34 (*a*). A delayed photograph of the track of a ray whose specific ionization is estimated by different observers to be from 4 to 9 times that of an electron, with 6 times, the best value. $H\rho = 9.6\times10^4 \pm 5$ percent gauss cm. The range >6.0 cm of air. The range of a proton with this $H\rho$ is 0.9 cm. The estimated mass of the particle is 130 ± 25 percent times that of the electron. It was from this track that the first numerical estimate of the mass of the heavy penetrating particle was made by Street and Stevenson.[37b] (*b*) A ray, ionizing heavily, with $H\rho = 1.8\times10^6 \pm 10$ percent, and specific ionization 3 to 5 (best value 4) times that of an electron. These measurements were made before any calculations were done and they lead to an estimate of the mass at 1900 times that of the electron. The particle is obviously a proton and the excellent agreement of the estimated mass with that of the proton shows that the method of mass estimation is surely applicable to protons. The particle in (*a*) cannot be a proton. Photograph by the courtesy of Professor Street.

several meters of water below sea level. He estimated the mass in one case as approximately $100m_e$. Ehrenfest,[38] using two cloud chambers, estimated the mass of a particle at roughly $200m_e$. Corson and Brode[38] have made an estimate of $350m_e$ for a penetrating ray observed near the end of its range. Ruhlig and Crane[38] have observed a similar ray so near the end of its range that the change in curvature along the track could be measured. They estimate the mass to be $(120\pm30)m_e$. There was a short section of another similar track in the chamber at the same time suggesting the possibility that the particles were associated as in a shower. Williams and Pickup[38] have obtained at least three excellent examples of heavy electrons in a cloud chamber expanded at random. In one of these cases the particle almost certainly passed through the chamber after the expansion and during the exposure. This eliminates the possibility of distortion by currents in the gas, and it also allows for an exceptionally good determination of the primary specific ionization. Hydrogen was mixed with the air in the chamber to increase the diffusion and thus enable the observers to estimate primary ionization with greater precision. The three values of the mass, in terms of m_e, are 220 ± 50, 190 ± 60, and 160 ± 30. They found one other of $m>430m_e$ but they could not set a reliable upper limit on its value. On the basis of preliminary considerations of the data obtained in a recent experiment, Neddermeyer and Anderson[38] estimate $m=240m_e$. The paucity of estimates on the mass follows from the very low probability that a penetrating ray will be near the end of its range in passing through a cloud chamber. The variations in the mass estimates are no indication of inaccuracy of determination, for we have no reason to assume a unique value. On the contrary, there is some reason to believe that the mass is variable, and if this is true it explains, in part, the low number found ionizing heavily near the ends of their ranges.

Direct measurements of energy loss, atmospheric absorption, and shower production with thin scatterers provide sufficient evidence for us to conclude that the Bethe-Heitler theory is applicable to electron energies at least as great as 10^{10} ev. If this is true we must assume another, more penetrating, ionizing particle to account for the observed absorption at great depths, the production of showers under thick scatterers and the sea level latitude effect. Even if we assume that the Bethe-Heitler theory breaks down at high energies we still cannot explain why the latitude effect extends to 50°, nor explain the shape of the transition curve for large showers and bursts which show high absorption in the high energy range. If the penetrating rays are protons, the negative proton has been discovered, the new protons react with extra-nuclear electrons differently from all other protons, they do not follow the predictions of quantum theory in the matter of shower production, and they have a range and specific ionization at variance with their fellows. We can see no alternative to the conclusion that positive and negative particles of approximately electronic charge, but of masses intermediate between the masses of electrons and protons exist. Evidence as to whether they are produced to a large extent in the atmosphere is, at present, somewhat conflicting and inconclusive. The only objection to this conclusion lies in our desire to keep the number of fundamental particles small. The suggestion that the heavy particles are electrons with additional mass energy in a quasi-stable form may satisfy this objection. This suggestion has been made in somewhat different forms by Neddermeyer,[38] Langer,[38] Freeman[38] and others. Indeed, the recent energy loss measurements of Blackett[38] tend to confirm this view, for he has found evidence that penetrating rays may behave as ordinary electrons when the energies are reduced sufficiently. If the heavy particles are electrons in excited mass states, this result is to be expected. It appears that the hypothesis of variable mass states for electrons will explain all observations satisfactorily.

Theoretical discussions of these problems based on the assumption of a high energy breakdown of the Bethe-Heitler theory have been given by Nordheim[36, 37, 38] and Heitler.[37] It appears to be impossible to explain the shape of the intensity-depth curve on the assumption that the theory breaks down for high energy electrons. Nordheim, Nordheim, Oppenheimer and Serber[37] have discussed, theoretically, the production of showers at great depths by a proton-nucleus reaction giving a positron and a neutrino. Swann[37a] has suggested the possibility that the electrodynamic force equation in common use is not correct, and has indicated a method of checking it. The applicability of equations of electrodynamics in the energy ranges of the cosmic rays should certainly be assured before any final conclusions dependent on these equations are made. Landau and Rumer[37] have done theoretical work on the emission of quanta by heavy electrons. An excellent discussion of the whole problem of the heavy electron has been given by Bhabha.[38]

IV. SUMMARY

Throughout this paper we have seen that the measured properties of bursts and showers, such as the variation of frequency with altitude and latitude, the specific ionization of their respective rays, and the form and magnitude of their transition effects, are strikingly similar. Fig. 29 shows examples of cumulative showers large enough to be detected by ionization chambers as large bursts. There is evidence (Ehrenfest and Auger,[36] Montgomery and Montgomery[35b, 38d]) that such showers occur with sufficient frequency to account for most bursts.

In conclusion, some of the important theoretical and experimental findings regarding the two types of cosmic-ray showers are presented below in tabular form.

	FREQUENT TYPE	RARE TYPE
Composition	Negatrons, positrons and photons.	Heavy particles, electrons and photons.
Size	Definite relationship of the number of rays with the atomic number and thickness of the shower-producing material, and the energy of the incident radiation.	No known relationships.
Geometry	Well collimated, often no definite point source.	No collimation, apparent point source.
Penetration	Widely divergent rays most easily absorbed. Varies inversely with the atomic number of the scattering block.	Unknown.
Dependence on latitude and altitude	Frequency of occurrence increases rapidly with altitude, and decreases near the magnetic equator.	Unknown.
Origin and growth	Cumulative process of radiation and pair production initiated by an electron or photon, at great depths indirectly by the penetrating component.	Apparently cataclysmic, directly or indirectly by the penetrating component.
Relation to other cosmic radiations	Shower rays identical with the soft component. Most bursts are large showers of this type.	Probably contains some particles (barytrons) found in the penetrating component.
Theoretical treatment by	Bhabha and Heitler,[37] Carlson and Oppenheimer,[37] etc.	Heisenberg,[36] Heitler,[38] etc.
General contributions of shower studies to science	The discovery of the positron. Very instrumental in the discovery of the barytron. Suggestions for new experiments and fruitful hypotheses (pair creation, quantization of mass). Means of studying interactions between high energy radiation and matter. Verification of theoretical predictions of energy losses and determination of specific ionization for high energy charged particles.	

V. BIBLIOGRAPHY AND ACKNOWLEDGMENTS

References from 1897 to 1923 deal with the discovery and early history of cosmic rays. These and a few others are not specifically referred to in this paper. While the bibliography is not exhaustive, it does contain representative articles dealing with the subject treated. The numbers following the references give the sections of this article in which the paper is mentioned.

Full references to the early work on bursts have been given by Hoffmann,[32] Messerschmidt,[32] and Steinke and Schindler.[32] Various summaries and reviews on cosmic-ray topics have been made by Auger,[36] Blackett,[33a, 35, 37c] Compton,[36] Corlin,[35] Geiger,[35, 36, 37] Johnson,[32b, 35c] Kolhörster,[33] Leprince-Ringuet,[33] Millikan,[33] Regener,[37] and Steinke.[34] These articles by Blackett are descriptive in nature; Geiger has paid special attention to secondary effects and showers, and sizeable bibliographies have been given by Corlin, Geiger[35] and Leprince-Ringuet.

The writers are indebted to Professor Hoffmann for the loan of the original record of the electrometer trace reproduced in Fig. 2, and to Messers Anderson, Auger, Blackett, Fussell and Street for providing the beautiful cloud chamber photographs appearing throughout the paper. They also wish to thank Ethel Froman for aid in compiling the bibliography and checking the manuscript.

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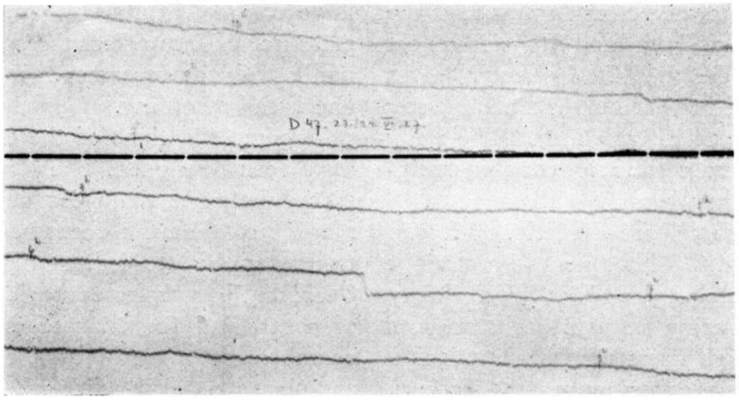


FIG. 2. Hoffmann's electrometer trace showing the first burst to be observed. The sharp deflection between 6h. and 7h. on the record of June 24, 1927, corresponds to a burst of 4×10^6 ions. Photograph by courtesy of Professor Hoffmann.

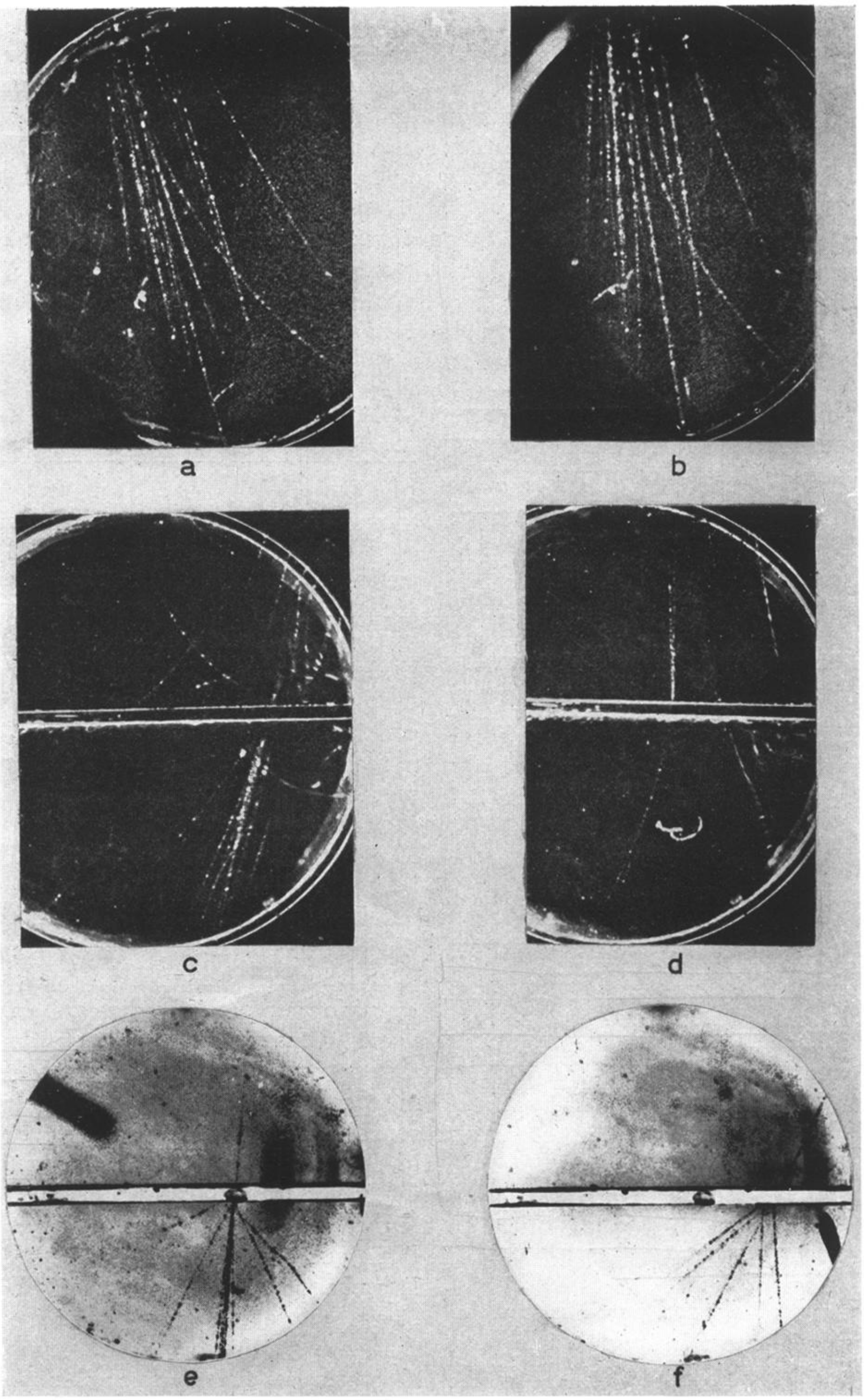


FIG. 20 (*a*) and (*b*). A pair of photographs showing a typical shower containing both positrons and negatrons. The nearly straight tracks seem to diverge from one point and the more curved tracks from a lower point. (Blackett and Occhialini.[33]) (*c*) A shower enters the chamber from above and a second shower is produced in the lead plate, probably by a photon since stereoscopic examination indicates that none of the ionizing rays above the lead is incident at the point of production of the second shower. (Blackett and Occhialini.[33]) (*d*) A shower showing two negatrons projected downward and at least one electron projected nearly vertically upward. If the shower was produced by a non-ionizing ray two particles were projected upward. (Blackett and Occhialini.[33]) (*e*) and (*f*) Two showers both of which have two distinct points of origin. An ionizing ray is incident to one of the points in both cases. (Auger and Ehrenfest.[37])

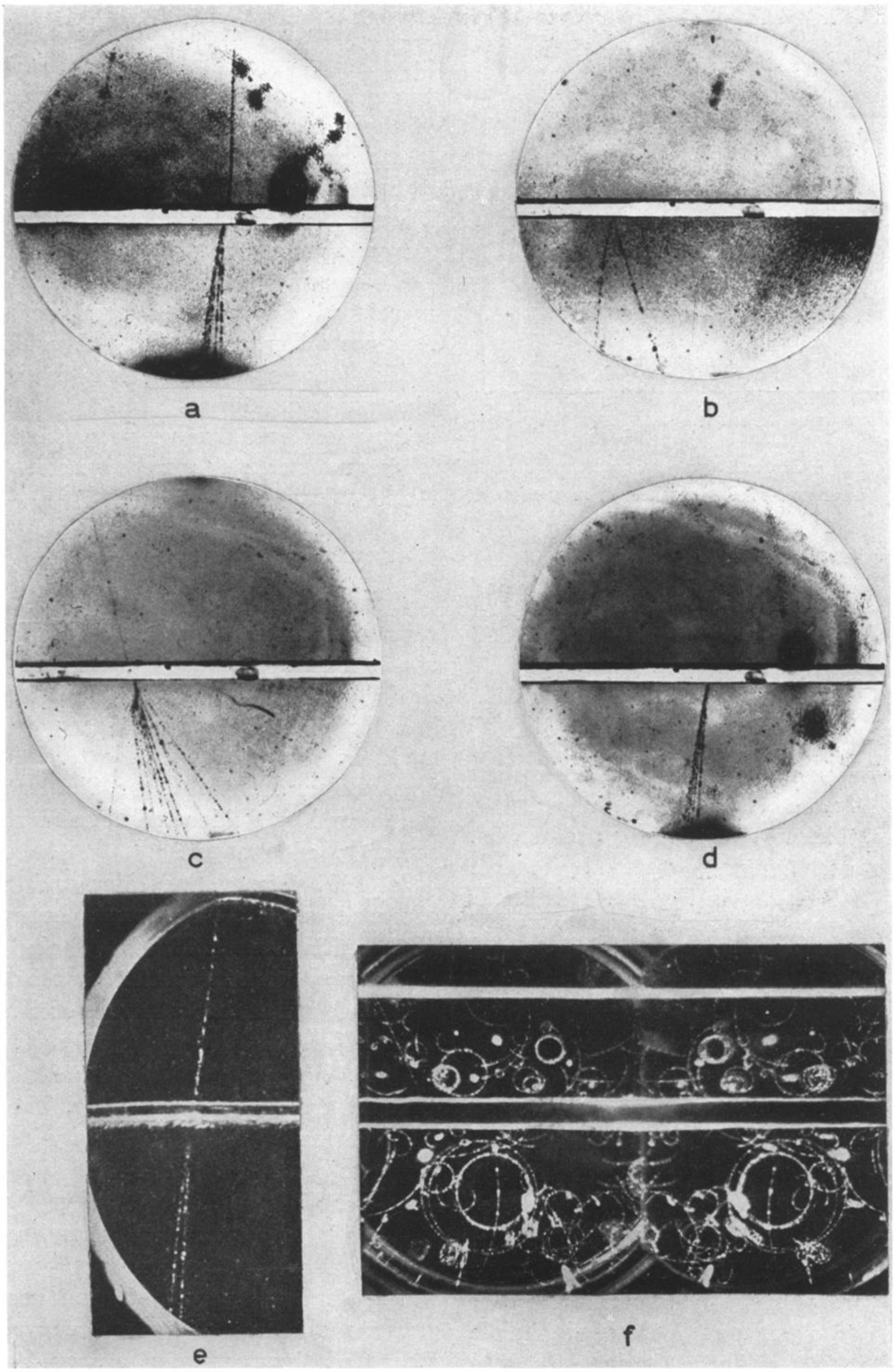


FIG. 21 (*a*), (*b*), (*c*) and (*d*). Photographs illustrating various types of showers. (*a*) and (*c*) are showers produced by ionizing rays and (*b*) and (*d*) by non-ionizing rays, probably photons. The shower of 10 rays (*c*) diverges considerably more than the smaller showers (*a*) and (*d*) but hardly more than the single pair in (*b*). (Auger and Ehrenfest.[37]) (*e*) The production of a single secondary by a high energy ionizing ray. (Blackett and Occhialini.[33]) (*f*) A shower of many very low energy electrons with no common origin. These rays were probably produced by many quite soft photons from a shower above the chamber. (Anderson, Millikan, Neddermeyer and Pickering.[34])

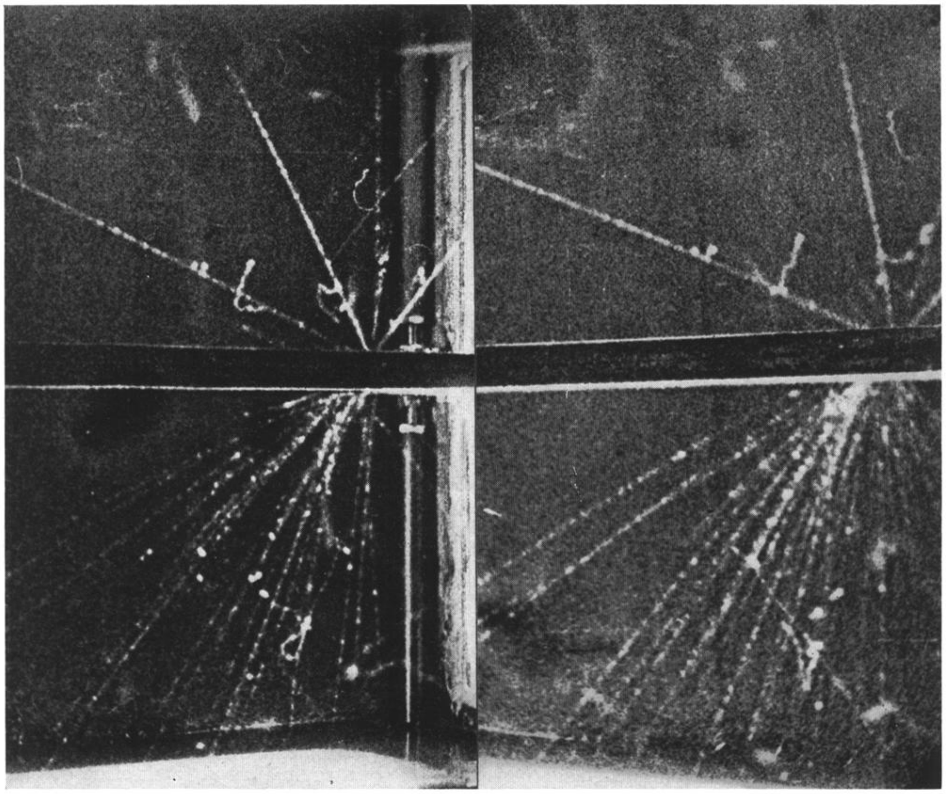
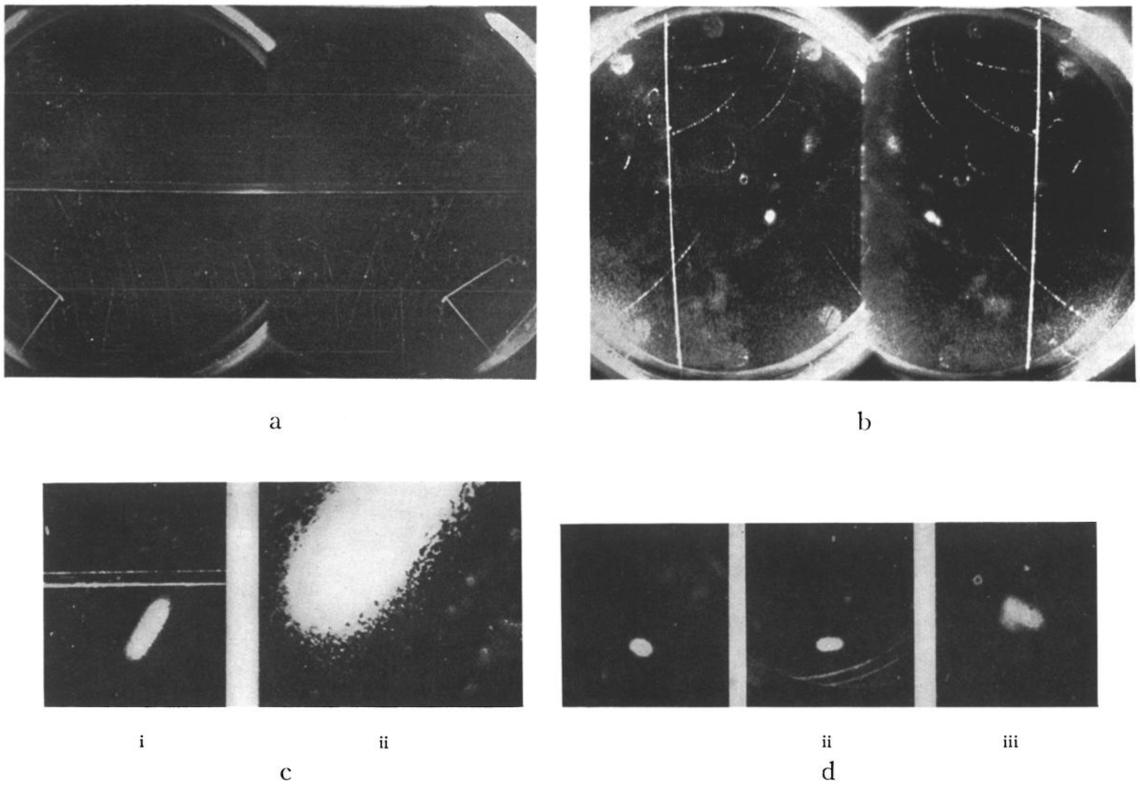


FIG. 23. A photograph of one of the rare type of shower where the particles are not well collimated and tracks are denser than those due to electrons. This was furnished by the courtesy of Messers Fussell and Street.



a

b

i

ii

c

ii

iii

d

FIG. 24 (*a*). A disintegration in the gas (argon) of the chamber which is apparently simultaneous with the shower. The shower of several particles is barely visible in the reproduction. The three heavy particles diverge within a hemisphere. The disintegration was caused by a non-ionizing ray, possibly a neutron, or possibly the momentum is conserved by one or more neutrons ejected on disintegration. (Anderson and Neddermeyer.[36b]) (*b*) A strongly ionizing ray traversing the whole chamber with $H\rho = 1.8\times 10^6$ gauss cm. The density of ionization is consistent with the assumption that the particle is a proton. (Anderson and Neddermeyer.[36b]) (*c*) (i) A typical broad track often observed in cloud chambers. (ii) The same track enlarged so that the distribution of droplets near the edge of the track can be determined. The distribution agrees with the theoretical predictions for the diffusion of ions before the expansion. (Blackett.[34]) (*d*) (i) A neutron recoil track. (ii) and (iii) Similar tracks found on photographs of cosmic rays. Although (ii) is very similar to (i), it may easily have been produced by an α-ray some time before expansion. In (iii) both positive and negative ion groups are present and the time of the ionization is calculated to be $\frac{1}{5}$ sec. before the expansion. (Blackett.[34])

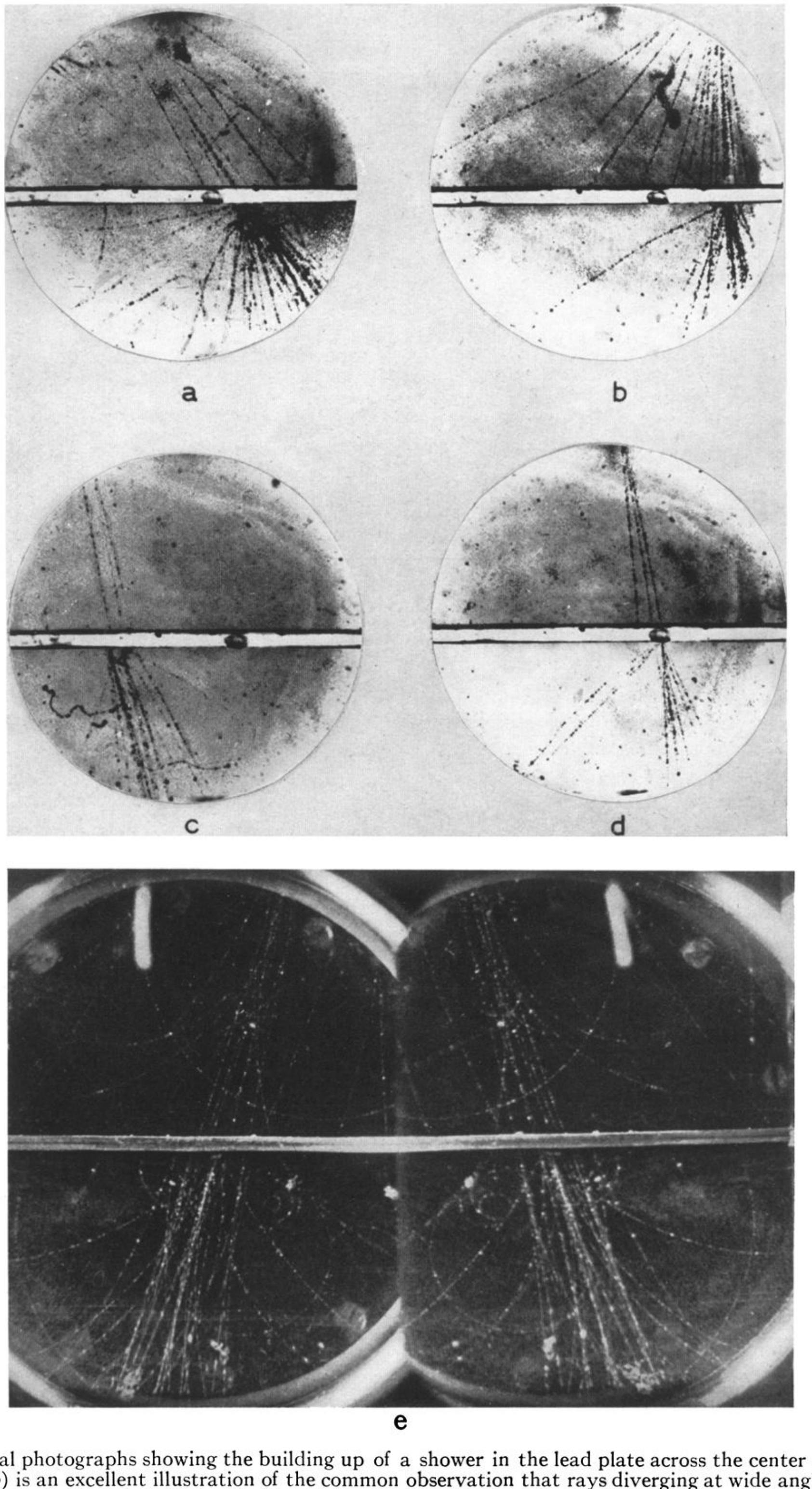
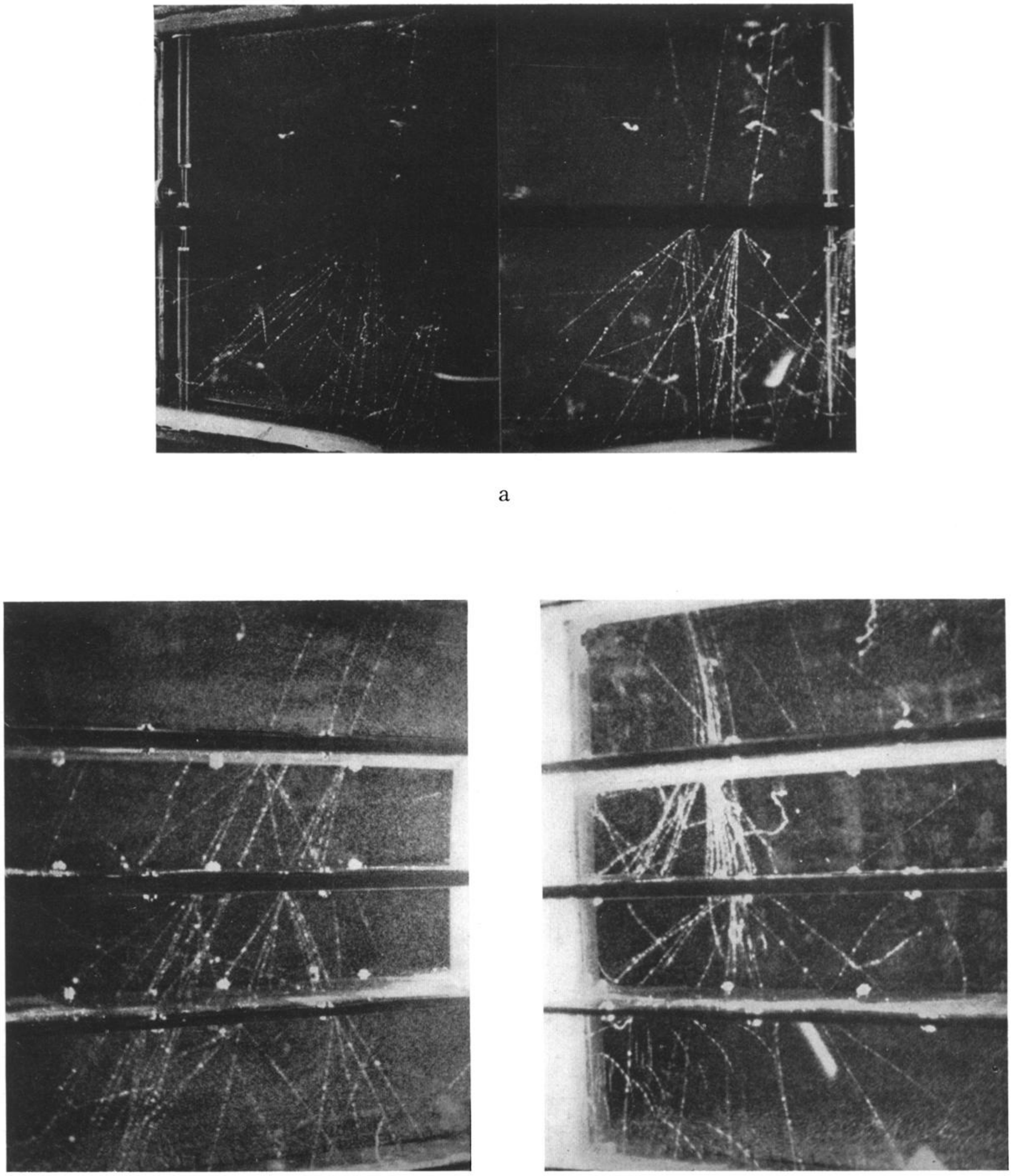


FIG. 25. Typical photographs showing the building up of a shower in the lead plate across the center of the chamber. The shower in (*b*) is an excellent illustration of the common observation that rays diverging at wide angles from the axis of the shower are easily absorbed. [(*a*), (*b*), (*c*) and (*d*), Auger and Ehrenfest[37]; (*e*), Anderson and Neddermeyer.[36b]]

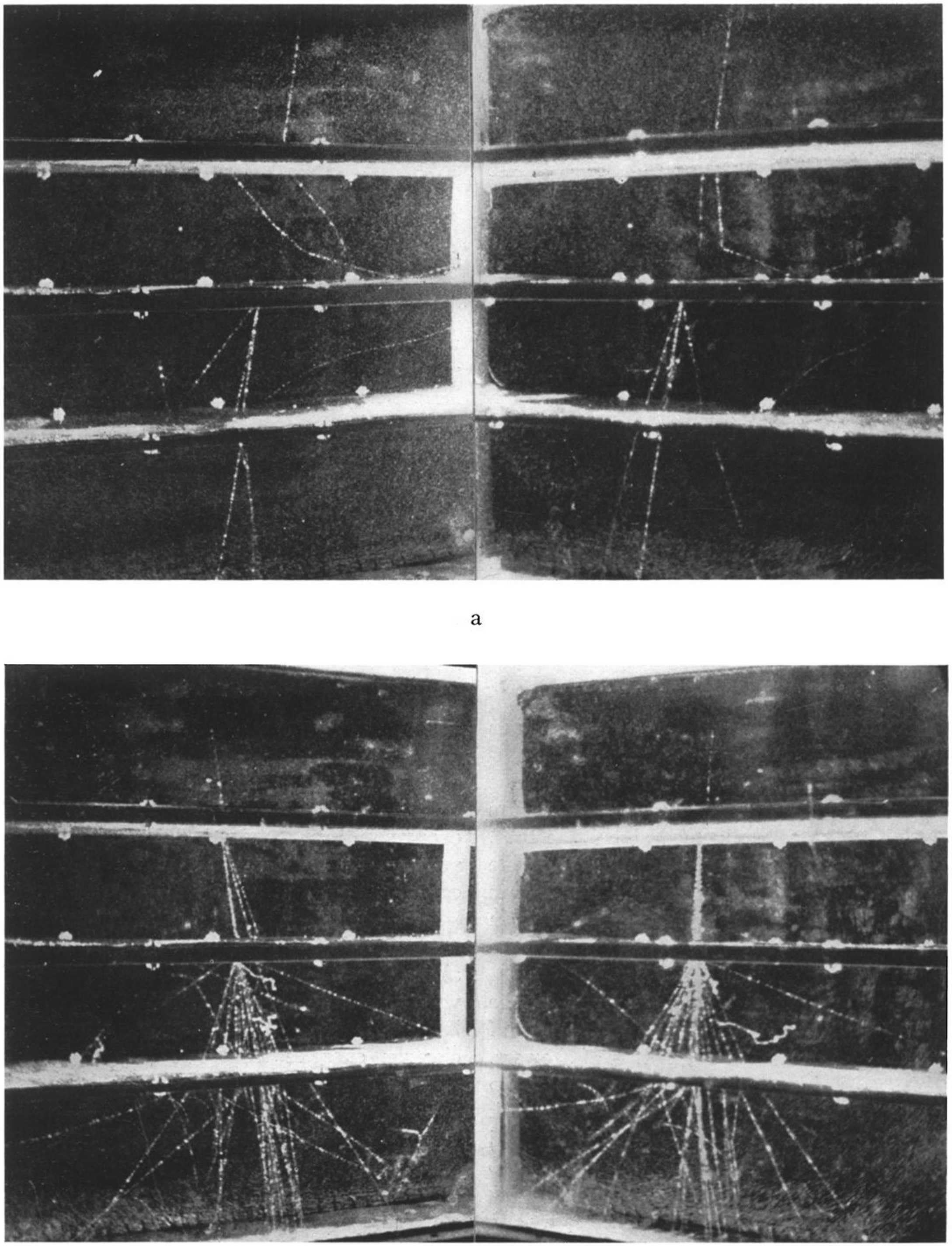


a

b

c

FIG. 26 (*a*). One of the first cases in which definite shower rays from above the chamber were observed to produce more shower rays in the lead plate. (Stevenson and Street.[35]) (*b*) and (*c*) Interesting cases showing the growth and absorption of showers in divided scattering blocks. The showers originate in 2.5 cm of iron above the chamber. Photographs by the courtesy of Messers Fussell and Street.



a

b

FIG. 27. Photographs showing the growth of showers in divided scattering blocks. In (*a*) the energy is transferred from the first to the second block by a non-ionizing ray. Photographs by the courtesy of Messers Fussell and Street.

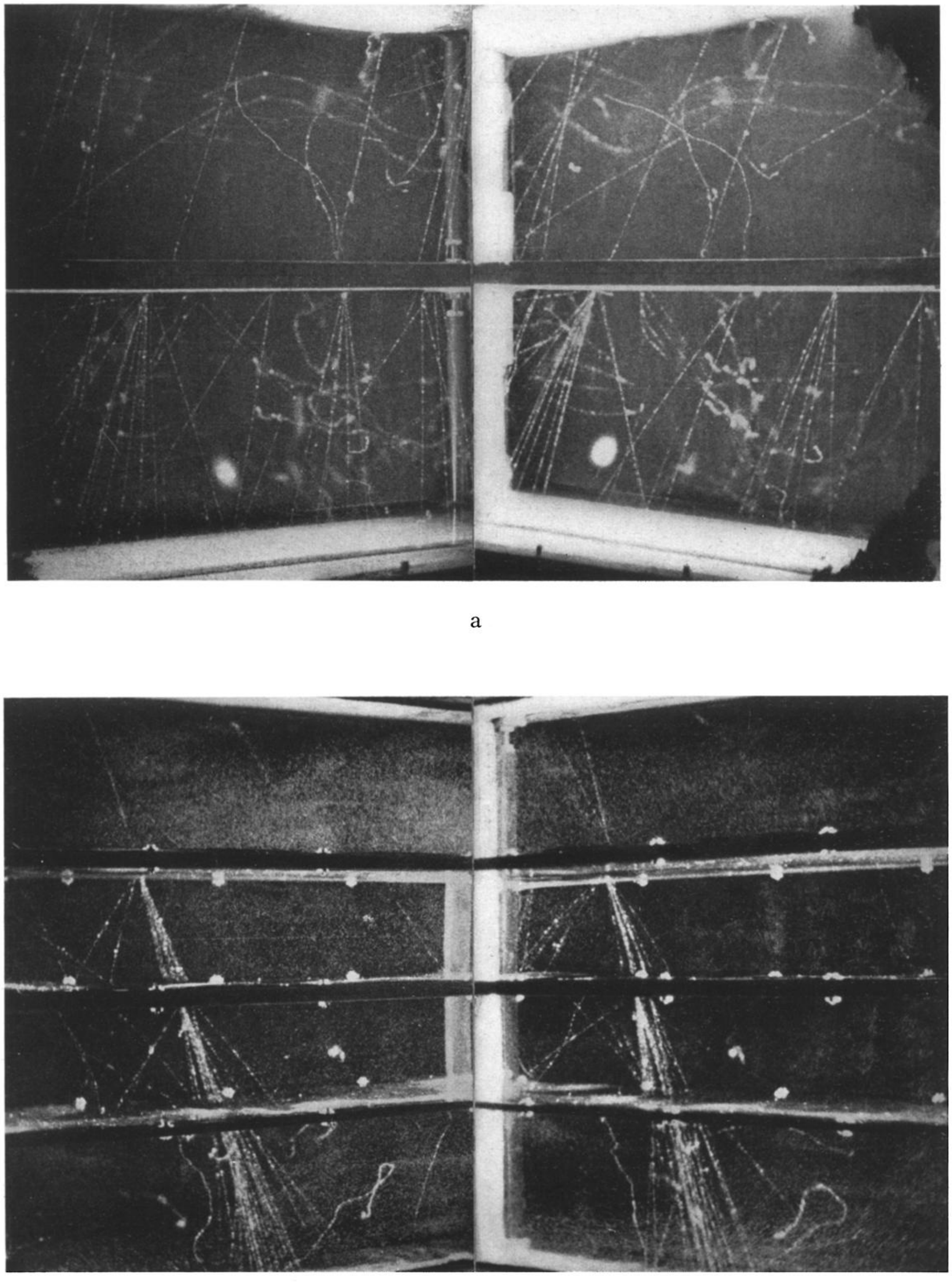
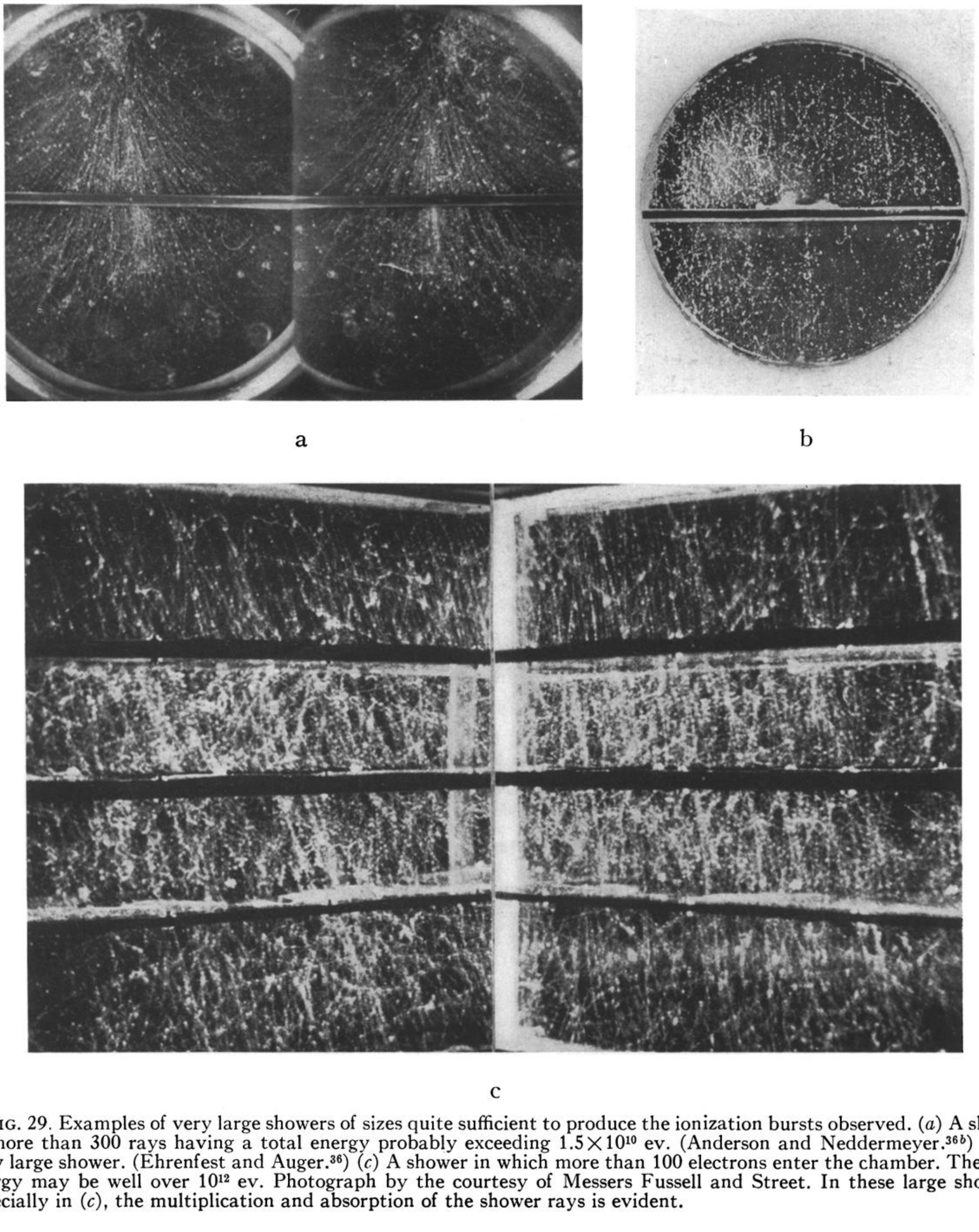


FIG. 28. Examples of shower growth. In (*a*) are shown several cases of pairs and more complicated phenomena produced by non-ionizing rays. Photographs by the courtesy of Messers Fussell and Street.


a

b

c

FIG. 29. Examples of very large showers of sizes quite sufficient to produce the ionization bursts observed. (*a*) A shower of more than 300 rays having a total energy probably exceeding 1.5×10^{10} ev. (Anderson and Neddermeyer.[36b]) (*b*) A very large shower. (Ehrenfest and Auger.[36]) (*c*) A shower in which more than 100 electrons enter the chamber. The total energy may be well over 10^{12} ev. Photograph by the courtesy of Messers Fussell and Street. In these large showers, especially in (*c*), the multiplication and absorption of the shower rays is evident.

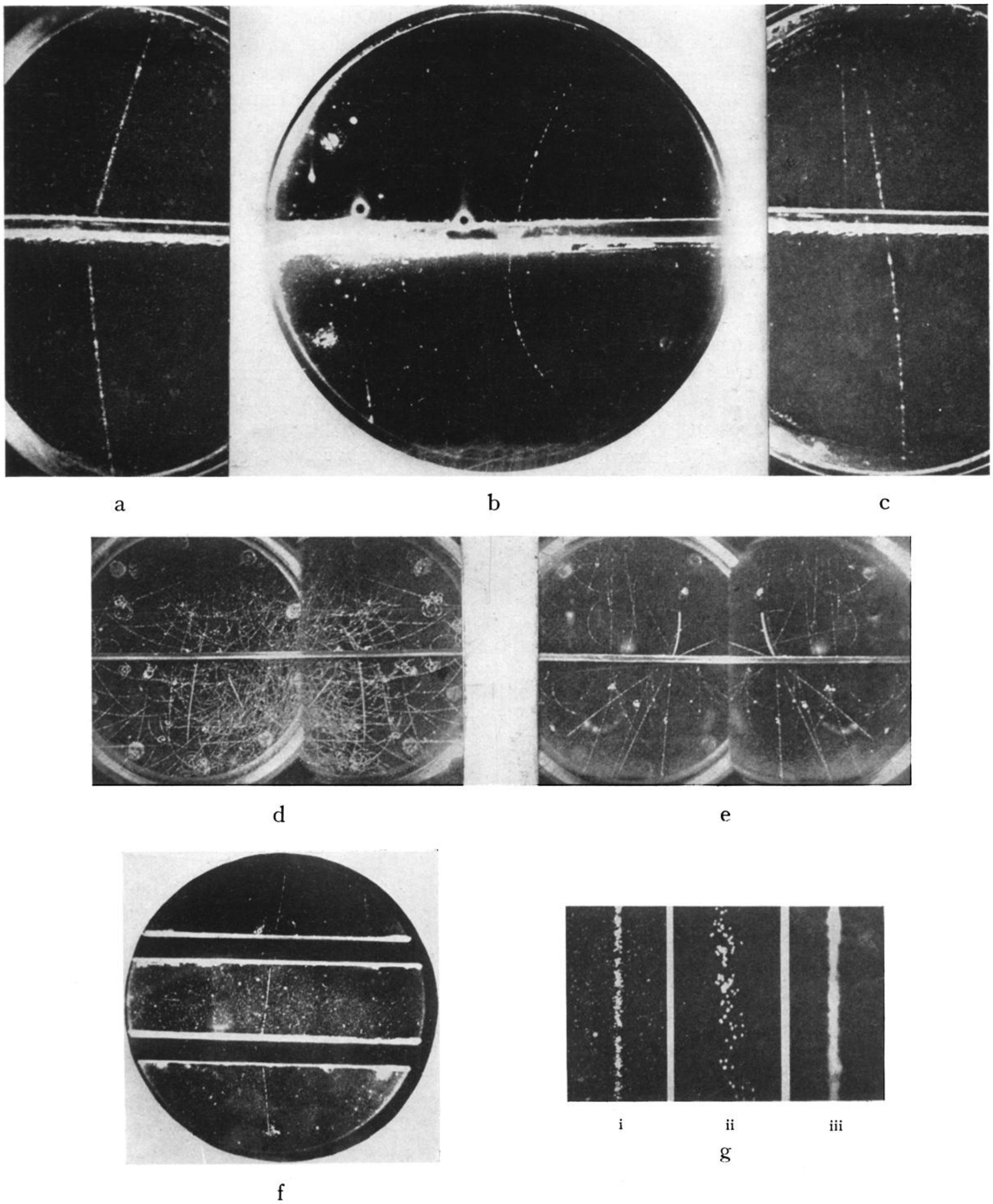


FIG. 30 (*a*). A 60×10^6 ev positive electron penetrating a 4 mm lead plate with an energy loss of 38×10^6 ev. (Blackett and Occhialini.[33]) (*b*) The positive electron. (Anderson.[33b]) This photograph, showing ionization and energy loss for an electron but a positive curvature, was the first one recognized as an unambiguous case of a positron track. (*c*) A negatron, on passing through the 4 mm lead plate, loses at least 70×10^6 ev. (Blackett and Occhialini.[33]) (*d*) The heavy, nearly vertical track near the center of the chamber is an early example of a penetrating ray which has a range much greater than would a proton with the same $H\rho$. Above the lead plate the particle ionizes like an electron. (Anderson and Neddermeyer.[36b]) (*e*) An example of a heavily-ionizing ray ejected upward from the lead plate by a non-ionizing ray. The ray is coincident with the shower and, again, the range is much greater than the range of a proton with the same $H\rho$. (Anderson and Neddermeyer.[36b]) (*f*) A 2.4×10^8 ev particle which loses 2×10^6 ev in the upper 11 mm lead plate and 6×10^6 ev in the lower one. Energy values on the basis that the particle is an electron. (Anderson.[33a]) (*g*) (i) An electron track in oxygen, (ii) an electron track in hydrogen and (iii) a proton track in oxygen. (Blackett.[34])

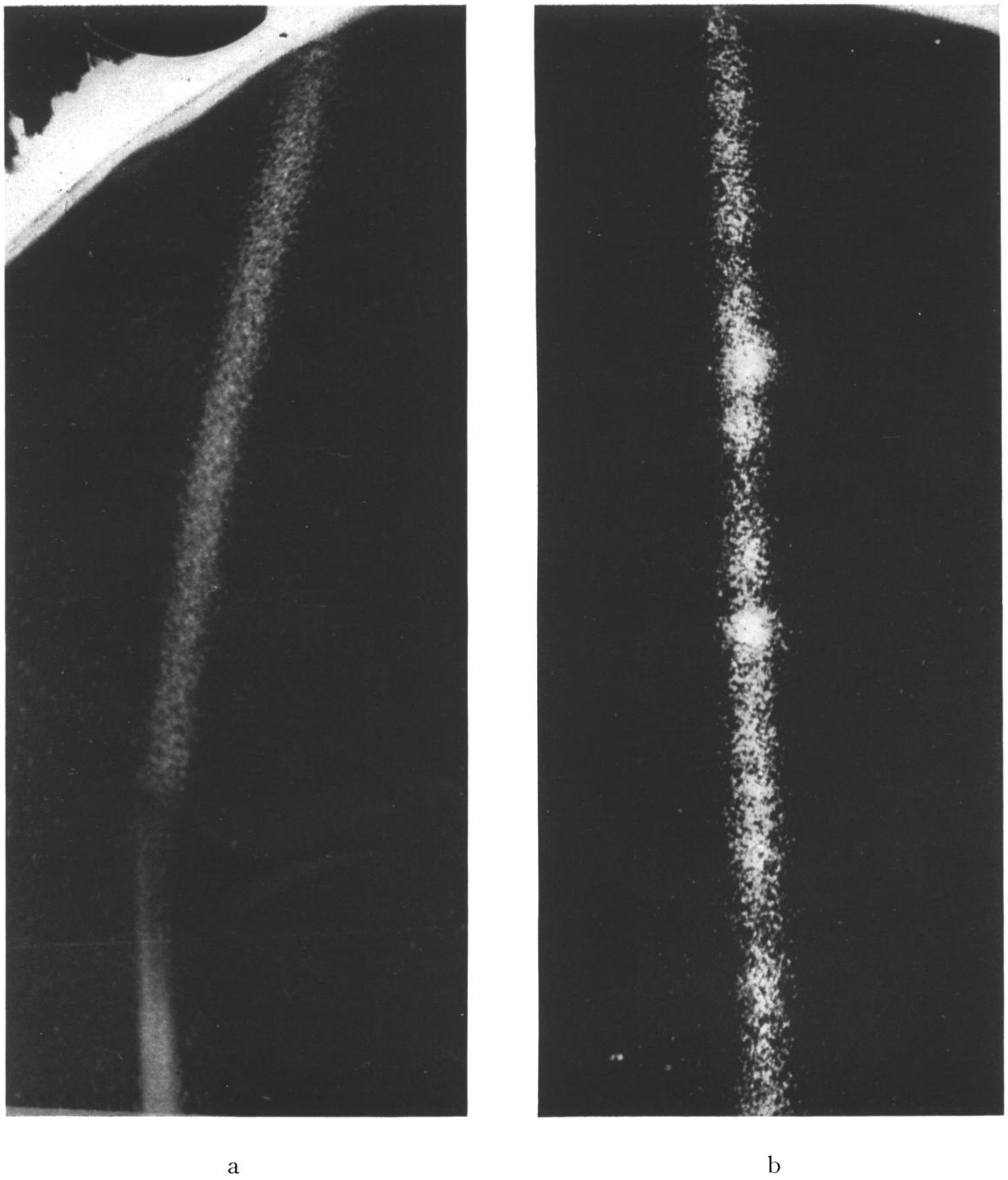


FIG. 34 (*a*). A delayed photograph of the track of a ray whose specific ionization is estimated by different observers to be from 4 to 9 times that of an electron, with 6 times, the best value. $H\rho = 9.6\times 10^4 \pm 5$ percent gauss cm. The range >6.0 cm of air. The range of a proton with this $H\rho$ is 0.9 cm. The estimated mass of the particle is 130 ± 25 percent times that of the electron. It was from this track that the first numerical estimate of the mass of the heavy penetrating particle was made by Street and Stevenson.[37b] (*b*) A ray, ionizing heavily, with $H\rho = 1.8\times 10^6 \pm 10$ percent, and specific ionization 3 to 5 (best value 4) times that of an electron. These measurements were made before any calculations were done and they lead to an estimate of the mass at 1900 times that of the electron. The particle is obviously a proton and the excellent agreement of the estimated mass with that of the proton shows that the method of mass estimation is surely applicable to protons. The particle in (*a*) cannot be a proton. Photograph by the courtesy of Professor Street.