III. Composition of Cosmic Rays

Nature of Cosmic-Ray Particles*

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The first section of this report contains a brief summary of those experiments which have made substantial contributions to our knowledge of the nature and mode of absorption of cosmic-ray particles. Included is a discussion of the difficulties which inhere in the attempts to interpret the observed cosmic-ray phenomena in terms of the assumption that the cosmic-ray particles are practically all protons and positive and negative electrons. These difficulties are resolved by demonstrating that in the same momentum range there exist two types of particles, one of which is highly absorbed in a heavy material, mostly through radiation, while the other is relatively penetrating. Behavior of the first kind is typical of shower particles in general, and of all single negatron secondaries, which are presumably produced in elastic collisions with atomic electrons. This group is therefore to be identified with electrons. As it can be shown that particles of the penetrating group cannot be of protonic mass, it follows that they must be neither electrons nor protons. The simplest assumption is that their distinguishing property is a mass intermediate between the electron and proton. Confirmation of this view is found in the observation by other writers and by ourselves of particles whose range, ionization and curvature relations are such that they demand a mass in this region. The best range and ionization data seem to give mass determinations in the neighborhood of 200 electron masses. A discussion is given of certain difficulties which exist in the interpretation of cosmic-ray particles as electrons and mesotrons of a unique mass.

INTRODUCTION

THE dominating characteristic of the cosmic radiation which was brought out by all of the early investigations and which was in fact responsible for the discovery of the radiation is its great penetrating power. Later researches showed that there were also present relatively less penetrating parts both of primary and secondary origin, and subsequent detailed investigation of the properties of the two kinds of rays brought out serious difficulties in the identification of the penetrating component with any particles or radiations then known to physics. These difficulties were felt very strongly even as early as 1934. The object of the present paper is to discuss the experimental results which serve most clearly to bring out the nature of the difficulties, and to present experimental data (part of which have been given in previous papers and notes and part of which are new) which lead to their resolution by demonstrating the existence of charged particles with a mass intermediate between the masses of the proton and the electron.

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I. HISTORICAL SUMMARY

The first experimental evidence that the penetrating power of the sea-level cosmic rays is a property of the particles themselves which are directly responsible for producing the ionization observed in electroscopes, was provided by Bothe and Kolhörster[1] in 1929. They were the first to utilize for the study of cosmic rays the coincidences between the discharges of tube-counters arranged in a vertical plane. Their results were extended and improved upon by Rossi[2] in 1932, who was able to show, by an arrangement of three counters in a vertical plane with as much as a meter of lead placed between them, that about forty percent of the charged particles coming down vertically at sea level are able to penetrate this amount of material. That most of these coincidences observed with a meter of lead between the counters are actually produced by single charged particles traversing the whole thickness, Rossi demonstrated by showing that when the middle counter was displaced just outside the geometrical beam defined by the two outer ones the number of coincident dis-

[1] Bothe and Kolhörster, Zeits. f. Physik **56**, 751 (1929).
[2] Rossi, Naturwiss. **20**, 65 (1932); Zeits. f. Physik **82**, 151 (1933).

charges fell to about one-sixth its original value. This conclusion was later verified by experiments[3]) of Street, Woodward and Stevenson, Auger and Ehrenfest, and Leprince-Ringuet, in which one or two cloud chambers were interposed between counters and large thicknesses of lead, the cloud chambers being operated by the coincident discharges of the counters. It was found in practically all instances that the track of a single particle appeared in the cloud chamber as was to be expected from Rossi's results. These experiments by themselves, however, could not give any information concerning the mass of the particles which were capable of penetrating the large lead absorbers, in particular they could not serve to distinguish electrons from protons.

Cloud tracks of cosmic-ray particles were first observed by Skobelzyn[4] in 1929. These with much more extensive observations made by Millikan and Anderson who initiated, in 1931, the technique of the vertical cloud chamber for the specific purpose of studying the cosmic-ray particles, and by Kunze, established the following main facts:

(a) That with minor variations nearly all the cosmic-ray particles produce about the same density of ionization as found along the tracks of fast electrons, and since for a given velocity the density of ionization should be proportional to the square of the charge, this means that the particles presumably have a charge of one electron;[5]

(b) That the energies of the particles found by magnetic deflection extend from the energies of γ-rays up to at least 5000 Mev;[5, 6] this limit was later extended to about 20,000 Mev by Blackett and Brode,[7] and by Leprince-Ringuet and Crussard;[8]

(c) That positive and negative particles are roughly equal in number;[5, 6, 9]

(d) That the ionization exhibited by the particles makes it unlikely that any appreciable fraction of those whose curvatures correspond to electron energies less than 500 Mev could be of protonic mass[9, 10] (although until the existence of the positron was established the positives were assumed to be protons in spite of the discrepancy in the ionization; this was in fact the crucial point which subsequently led to the discovery of the positive electron);

(e) That there sometimes occur groups or showers of time-associated tracks representing both positive and negative particles.[11] These were most beautifully emphasized in the early photographs of Blackett and Occhialini who introduced the technique of counter control;[10]

(f) That the few direct measurements of energy loss in lead which were made up to 1934 could be understood in terms of ordinary collisions with atoms involving the ejection of extranuclear electrons, although the mean of the first few observations (35 Mev/cm of Pb) was somewhat higher than was to be expected theoretically from energy loss by ionization alone.[12]

The foregoing facts represent the situation about as it stood at the end of 1933. The experiments so far as they went seemed reasonably consistent with the assumption that the sea-level cosmic-ray particles consisted predominantly of positive and negative electrons which were presumably produced largely by photon absorption in the atmosphere. The application of the quantum theory of radiation to high energy electrons had not yet been made, although on simple classical grounds such particles must have radiated away their energy at a much more rapid rate than was observed. It was therefore tacitly assumed by most people at that time that radiation for some reason or other played no important part in the absorption of high energy electrons. The shower phenomena were still completely obscure and were thought to involve entirely unknown mechanisms.

New data taken during 1934, however, made apparent for the first time fundamental difficulties with the above point of view which later

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[3] Street, Woodward and Stevenson, Phys. Rev. **47**, 891 (1935); Ehrenfest and Auger, J. de phys. et rad. **7**, 65 (1936); Leprince-Ringuet, J. de phys. et rad. **7**, 67 (1936).

[4] Skobelzyn, Zeits. f. Physik **54**, 686 (1929).

[5] Millikan and Anderson, Phys. Rev. **40**, 325 (1932). C. D. Anderson, Phys. Rev. **41**, 405 (1932).

[6] Kunze, Zeits. f. Physik **80**, 559 (1933).

[7] Blackett and Brode, Proc. Roy. Soc. **A154**, 573 (1936).

[8] Leprince-Ringuet and Crussard, J. de phys. et rad. **8**, 207 (1937).

[9] Anderson, Phys. Rev. **44**, 406 (1933).

[10] Blackett and Occhialini, Proc. Roy. Soc. **A139**, 699 (1933).

[11] Anderson, Phys. Rev. **43**, 368 (1933).

[12] Reference 9, p. 409.

were resolved only in terms of the existence of a new kind of elementary particle. These data comprised the following principal facts:

Additional direct measurements of energy loss in lead of particles mainly below 250 Mev showed in some cases anomalously large losses, and proved beyond a doubt that the emission of radiation is an important mechanism of energy loss by electrons in a heavy material like lead,[13] although the mean experimental value was still lower than the value given by theory, which by then had been worked out in its preliminary form by Heitler and Sauter.[14] These experiments then, although showing definitely the existence of large losses which were almost certainly radiative, showed equally clearly the presence of particles which were more penetrating than electrons should be if the radiation theory were valid at these energies, *but whose specific ionization was too low to permit their identification with particles as massive as protons* (see for example Figs. 8 and 9, Phys. Rev. **44**, 412 (1933)).[15] Therefore as a result of these experiments it was still generally believed by most people at the end of 1934 that the quantum theory of radiation was inapplicable to electrons of high energy and that radiation was not an important factor in the absorption of such electrons. The highly penetrating particles were then actually assumed to be very energetic positrons and negatrons.

In an attempt to reconcile the discrepancy between experiment and the Bethe-Heitler theory[16] which resulted if the penetrating particles were identified with electrons, an alternative point of view had been suggested by Williams[17] who assumed that the electron component of the cosmic rays was highly absorbable as demanded by theory, but that the penetrating component consisted of particles of protonic mass. Evidence against this point of view lay in the examples referred to above of particles which could not be protons but which were more penetrating than electrons in terms of the Bethe-Heitler theory. Additional evidence opposed to this point of view lay in the fact that heavily ionizing particles which would correspond to protons near the ends of their ranges where their velocity would be appreciably less than the velocity of light were not observed in the abundance that one would expect if all the penetrating particles had protonic mass.[18] Moreover, statistical data on the number and distribution in energy of the secondary negative electrons arising from elastic collisions with atomic electrons in absorbing plates of lead and carbon provided further evidence against the possibility that a large fraction of the penetrating particles can be as massive as protons. These data consisted of observations made on 2439 traversals of singly occurring particles in the higher energy group (>300 Mev) through plates of carbon and lead, from which the numbers and energies of the particle secondaries produced in the plates by the passage of the incoming particles were noted. Negatron secondaries were found to occur in much greater abundance than positrons (71 single negative and only 3 positive secondaries were produced) and could practically all be ascribed to simple elastic collisions with atomic electrons in the plates. This conclusion was based upon the fact that the absolute number and the distribution in energy of the negatron secondaries observed agreed well with the number and distribution to be expected theoretically from close encounters with extranuclear electrons if the high energy particles producing them were assumed to be of electronic mass. If, however, the primary particles traversing the plates were assumed to have protonic mass the agreement between theory and experiment did not then obtain. These data could not serve to measure the mass of the incoming particles except insofar as to provide evidence against the possibility that a large fraction of them could have protonic mass, since the expected energy distribution of the negative electrons resulting from close elastic encounters with atomic electrons is approximately the same for all incident particles whatever their mass, so long as the maximum kinetic energy which can be transferred to an electron is somewhat larger than the maximum secondary

[13] Anderson and Neddermeyer, Int. Conf. on Phys., Lond., p. 171 (1934).
[14] Heitler and Sauter, Nature **132**, 892 (1934).
[15] Experiments of a similar type and leading to the same result were reported by Street and Stevenson, Washington Meeting Am. Phys. Soc. April 1937, Phys. Rev. **51**, 1005 (1937).
[16] Bethe and Heitler, Proc. Roy. Soc. **A146**, 83 (1934).
[17] Williams, Phys. Rev. **45**, 729 (1934).
[18] Reference 13, p. 182, also see footnote.

energy considered in the observations. (The condition is more precisely stated in Section II-*b*).

If then the bulk of the penetrating particles are not protons, this left but one other alternative in terms of particles known to physics, namely to identify them with electrons and to assume that the Bethe-Heitler theory of absorption of electrons becomes completely invalid at energies above a few hundred million electron-volts.

However, as early as 1934, the writers recognized that this view was not entirely consistent with all the available experimental data on the properties of the cosmic rays.[18]

For example, Bowen, Millikan and Neher[19] by ionization experiments had measured the total intensity of the cosmic radiation as a function of height above sea level at San Antonio and in Peru. From their measurements, at these two stations, which at that time extended to heights of 22,000 feet above sea level, it was possible by taking the difference between the intensities measured at corresponding heights to show that those particles which are removed by the earth's magnetic field at Peru but are able to reach the earth at the latitude of San Antonio have an apparent absorption coefficient equal to about 1.0 per meter of water. An absorption coefficient as large as this corresponds to an energy loss much higher than that due alone to ionization along the paths of the particles, and implies therefore the existence of some mechanism which will rapidly dissipate the energy of the incoming particles. Such an absorption mechanism should then evince itself in the cloud-chamber observations, for example, by the frequent appearance of showers from the plates. Altogether we had observed 2439 traversals through lead and carbon plates corresponding to a particle passage through an equivalent thickness of at least 76 meters of water or more than seven times through the earth's atmosphere. Since these observations showed that only an insignificant number of the penetrating particles produced showers or gave other evidence of a large absorbability, in their passage through either carbon or lead plates, it was clear that most of the incoming particles constituting the magnetic field sensitive portion of the cosmic rays incident on the earth interact with matter to a much higher degree than do the bulk of the particles found at sea level. And furthermore this difference in behavior could not be ascribed to a difference in energy of the two groups of particles since the energies of the two groups lay in overlapping ranges. The earth's magnetic field served to measure the energies of the particles in the one group, and the magnetic field of the cloud chamber those of the other.

These data and arguments were presented by the writers[18] in 1934 to show that difficulties arose in attempts to interpret the penetrating particles either as (+ and −) electrons or as particles of protonic mass. An exceedingly interesting aspect of the cosmic-ray problem then lay in this apparent paradox. Further experimental and theoretical work carried out subsequent to 1934 has contributed new data bearing directly on its solution.

In 1935 some 10,000 cloud-chamber photographs made on the summit of Pikes Peak[20] at an elevation of 14,100 feet above sea level provided hundreds of new examples of electron showers. Comparison with photographs made at Pasadena near sea level showed that the ratio of the frequency of occurrence of showers per unit time on Pikes Peak to the frequency of occurrence of showers at Pasadena was greater than the corresponding ratio for the frequency of occurrence of single particles at the two locations. This is in qualitative agreement with other experiments previously made by Rossi[21] and others[22] using counters and ionization chambers.

The many photographs of showers obtained on Pikes Peak also made possible direct energy loss measurements in lead of those particles which occur exclusively in showers. These measurements, extending up to electron energies of 400 Mev, brought out the surprising result that so long as the measurements were restricted to

[19] Bowen, Millikan and Neher, Int. Conf. Phys., London 219 (1934).

[20] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).

[21] Rossi, Int. Conf. Phys., London, 233 (1934).

[22] C. and D. Montgomery, Phys. Rev. **47**, 429 (1935); Young, Phys. Rev. **49**, 638 (1936); Johnson, Phys. Rev. **47**, 318 (1935); Woodward, Phys. Rev. **49**, 638 (1936); Bennett, Brown and Rahmel, Phys. Rev. **47**, 437 (1935); Street and Young, Phys. Rev. **46**, 823 (1934); **47**, 572 (1935).

particles occurring in showers the experimental values of energy loss were found to agree within observational uncertainty with the requirements of the Bethe-Heitler theory. Several shower particles of even higher energy ($E>400$ Mev) were also measured, some of which showed absorption values greater than 1000 Mev/cm. *The behavior of these higher energy shower particles was then apparently shown to be quite in accord with the general requirements of the Bethe-Heitler theory, but not at all like that of the bulk of the single particles occurring at sea level which, as pointed out above, are of the penetrating type.* Furthermore in these observations the total number of small showers produced in the lead plate by the passage through it of the electrons whose energy loss was measured was shown by approximate calculations to be about the number one could expect from the absorption in the plate of the photons produced by the incoming particle. These measurements then, in contrast with those previously reported which included singly occurring particles, showed no certain disagreement between experiment and the theory. *With these data at hand, we were then in a position to speculate on the implications of the theory if it were assumed to be valid up to indefinitely high electron energies. Rough calculations showed that the theory, if its validity were assumed, was itself capable of providing a natural explanation of the electron showers, the transition effects, etc. in terms of a chain of successive processes of photon production and their subsequent absorption to produce new electron pairs.*[23] Once it has been shown that electrons are highly absorbable in a heavy element, the penetrating particles discussed above must be assumed to be other than normal electrons. Since the observations also gave evidence that the penetrating particles were not as massive as protons, a new type of particle was indicated.

Some evidence of a much more direct nature[20] was provided by the observation of particles whose range, ionization and curvature relations were such that they could not very well be interpreted either as protons or electrons.

Further evidence on the nature of the penetrating component was contained in a set of photographs taken with a 1-cm plate of platinum placed across the center of the cloud chamber. It was found that shower particles (by definition those entering the chamber accompanied by others) possessed an enormously greater probability of producing a shower in the platinum plate than did those particles entering singly, and it seemed reasonably certain that this difference in behavior existed because of a fundamental difference in the character of the particles, and not merely because of a difference in energy. The results for 1833 primary traversals through the platinum of particles with momenta greater than 500 'Mev'[24] are listed in Table I. Part of these results were reported in a colloquium in November 1936 and interpreted in terms of a new kind of particle with a mass intermediate between the proton and electron. This interpretation seemed unavoidable particularly in view of the other difficulties referred to above which were encountered in attempts to explain cosmic-ray phenomena in terms only of electrons and protons. A brief report of this appeared in 1936 in *Science*.[25] The results for the shower particles are quite similar to those found by Stevenson and Street,[26] who worked

TABLE I. *Showers produced in 1 cm of platinum by "single" and shower particles.*

	No. of primary traversals	Produce showers Number	Produce showers Proportion	Mean number in shower
Singles	1795	12	0.0067	5.0
Pri. accompanied by one	33	7	0.21	3.3
Acc. by >1	33	12	0.36	4.3

[23] Reference 20, p. 268.

[24] For a given charge $H\rho$ is proportional to momentum independently of mass, that is $p=eH\rho/c$, and since it is momentum and not energy that is measured by the radius of curvature the result of a curvature measurement should be expressed as momentum when there is doubt about the mass. We may express the momentum in terms of the energy an electron would have if its track curvature were the same as that of the particle considered. This is not very good usage, but because so many data have been recorded in terms of electron energies it is convenient for avoiding unnecessary explanation or lack of precise statement. Thus an electron with a momentum of 100 'Mev' has an energy of this value, while a heavier particle with the same momentum would have a lower energy depending on its mass. The natural electron unit, mc, is also convenient, the momentum μmc being connected to the mass km and the kinetic energy ϵmc^2 by the relation $\epsilon=(\mu^2+k^2)^{\frac{1}{2}}-k$.

[25] Science, p. 9 of supplement, Nov. 20, 1936.

[26] Stevenson and Street, Phys. Rev. **49**, 427 (1936).

without a magnetic field and therefore had no evidence that the difference in behavior between shower particles and single ones was not due simply to a difference in energy.

By the close of 1936, then, data from two types of observations had been reported, firstly, from determinations of the penetrating power and of the production of secondaries by cosmic-ray particles, and secondly, from observations of heavily ionizing particles under conditions where their curvatures and their ranges could be measured, both of which seemed to require for their explanation the existence of particles of intermediate mass. To eliminate any remaining uncertainty that the main facts could not be understood in terms of some peculiar kind of breakdown of the radiation theory for electrons, measurements were made, from the same set of photographs, of the change in curvature of 15 shower particles and 40 single ones which traversed the platinum plate, all of them with momenta below about 500 'Mev.' It was found that the shower particles in nearly all cases lost more than three-fourths of their initial momentum as they should be expected to do if our previous measurements of energy loss of shower particles in a thin lead plate were correct.[27] The particles occurring singly, however, were found

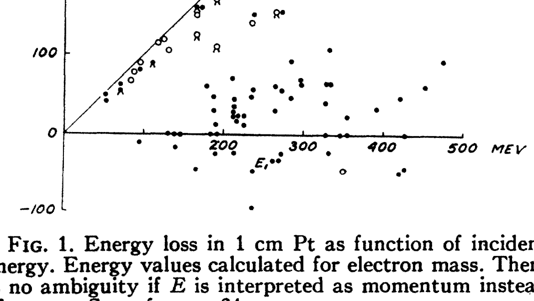


FIG. 1. Energy loss in 1 cm Pt as function of incident energy. Energy values calculated for electron mass. There is no ambiguity if E is interpreted as momentum instead of energy. See reference 24.

[27] Neddermeyer and Anderson, Phys. Rev. **51**, 884 (1937).

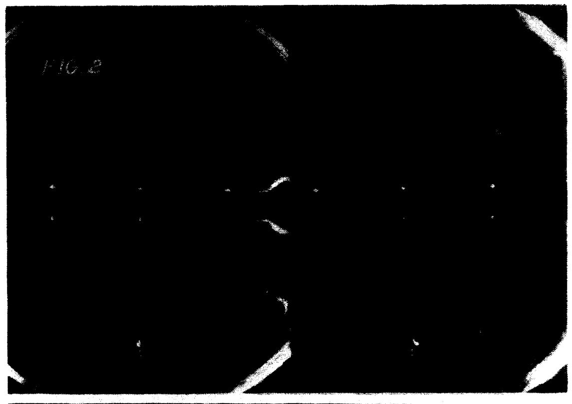
in general to be much less absorbable, exhibiting a behavior shown by the very earliest measurements which were made before enough showers had been observed for it to be possible to see clearly in more than two or three cases just what happened to the individual particles. The above results with an additional 39 measurements taken under somewhat improved conditions are plotted in Fig. 1. From these measurements it was clear that the absorbable shower particles were to be identified as electrons and if this were so the penetrating particles must have a property which distinguishes them from electrons; that they could not be protons moreover was clear from the observed ionization which is characteristic of a light particle and very much smaller than that to be expected from protons of the same momentum. We have adopted the assumption of a mass intermediate between the proton and electron as the best working hypothesis for understanding their behavior. Examples of energy loss and shower production are shown in Figs. 2–10.

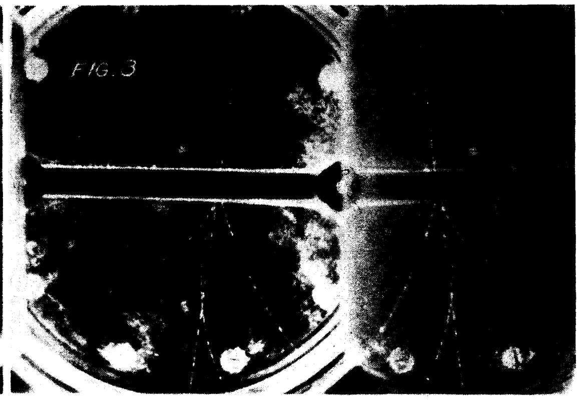
Early in 1937 Carlson and Oppenheimer, and Bhabha and Heitler[28] reported detailed calculations of the effects to be expected from the passage of very high energy electrons and photons through matter. Their calculations assumed the validity of the present quantum dynamics up to extremely high electron and photon energies and gave a satisfactory interpretation of large electron showers and electroscope bursts, and the transition effects observed with counters and electroscopes.

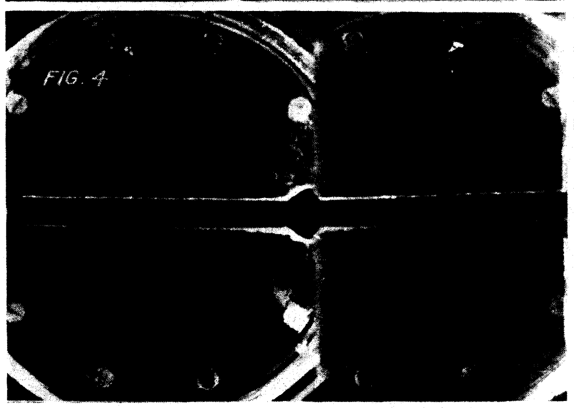
The most striking verification of the essential correctness of this theory even for extremely high energies is contained in the data of Bowen, Millikan, and Neher,[29] who have reported ionization chamber measurements of cosmic-ray intensities made in India up to a depth below the top of the atmosphere corresponding to only 20 cm of water equivalent. Comparison of the

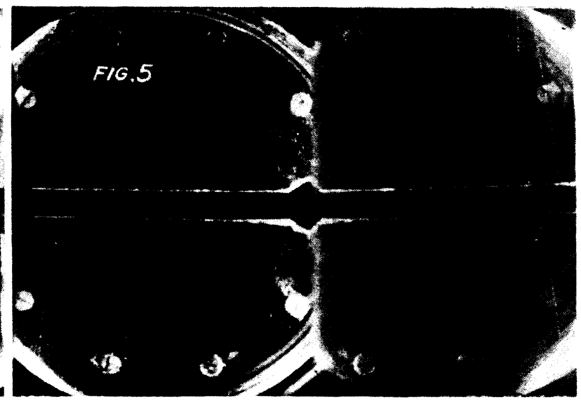
[28] Carlson and Oppenheimer, Phys. Rev. **51**, 220 (1937); Bhabha and Heitler, Proc. Roy. Soc. **A159**, 432 (1937). Preliminary reports of these calculations were published by Oppenheimer, Phys. Rev. **50**, 389 (1936) and by Bhabha and Heitler, Nature **138**, 401 (1936) in August and September, 1936, respectively. The results of our energy loss measurements which showed no disagreement with radiation theory had been privately communicated to these authors in May 1936.

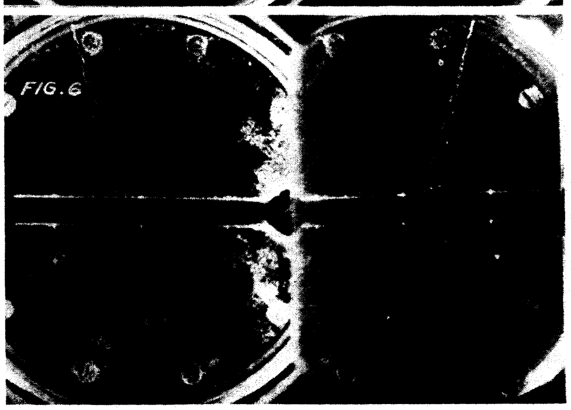
[29] Bowen, Millikan and Neher, Phys. Rev. **52**, 83 (1937); **53**, 219 (1938).











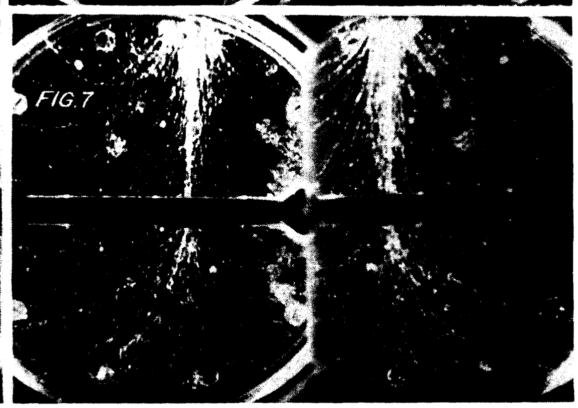


FIG. 2. The field is 7900 gauss for all photographs except Fig. 17. The left-hand view is the direct image of the chamber. A negative particle of $H\rho = 7.1 \times 10^5$ gauss cm and therefore momentum of 213 'Mev' passes through a 1-cm Pt plate and emerges with an $H\rho = 6.3 \times 10^5$ gauss cm and momentum of 190 'Mev' (see reference 24 for definition of momentum units). This particle is clearly not of protonic mass because a proton of momentum 213 'Mev' has an energy of only 19 Mev. It could not traverse the Pt plate and would have a specific ionization at least 10–15 times that of a fast electron. The particle is not easily interpreted as an electron because statistical data have shown that the probability of an electron losing less than three-fourths of its incident momentum in 1 cm of platinum is very small. The assumption that the mass of the particle is intermediate between that of an electron and a proton makes the observations consistent. If its mass were 200 m_e the incident energy would be 134 Mev, the emerging energy 113 Mev, and the specific ionization of the lower track should be almost the same as that of a fast electron. The energy loss would be 21 Mev/cm instead of the 23 calculated from the curvatures on the basis of electronic mass, which is within experimental error equal to the expected loss by ionization.

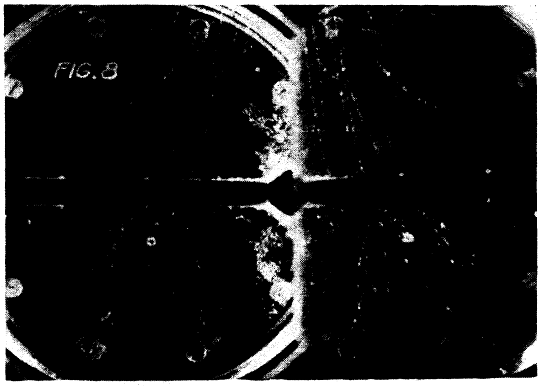
FIG. 3. An example of a small electron shower produced by a high energy single particle ($H\rho > 1.5 \times 10^6$ gauss cm). A discussion of these showers with a table of their frequency of occurrence is given in the text, Section II-*b*.

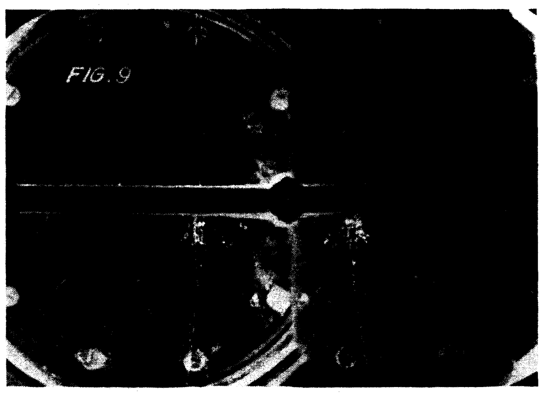
FIG. 4. The negative component of an electron pair ($E = 160$ Mev) is completely absorbed in the platinum, only a 3.5-Mev positron emerging below.

FIG. 5. A negatron secondary produced in the material above the chamber ($E = 210$ Mev) is completely stopped in the platinum. 80 Mev of the incident energy appears in the two positrons emerging below.

FIG. 6. Another example of a negatron secondary which is almost completely absorbed. Incident energy, 190 Mev; emerging, 5 Mev. This is typical of the behavior which has so far been shown without exception by all negatron secondaries. As most of such single negatrons presumably arise from elastic collisions with atomic electrons, this provides an independent experimental identification of the highly absorbable particles with ordinary electrons.

FIG. 7. Example of a shower of high energy electrons incident nearly normally on a 1-cm plate of Pt. Most of the energy is degraded into relatively low energy electrons.





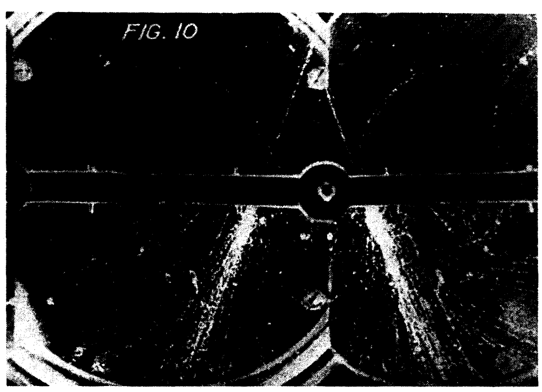


FIG. 8. A simpler case showing the behavior of shower particles in the intermediate energy range.

FIG. 9. A group of three shower particles with momenta greater than 500 'Mev' each incident on the upper surface of the platinum produces a shower of more than twenty positrons and negatrons.

FIG. 10. A well-collimated group of three high energy shower particles incident on the upper surface of the Pt plate produces a large shower. A second shower arising in the Pt just to the left of the main group of particles is presumably generated by photons accompanying the incident particles. Occasionally penetrating particles of high energy occur in showers. At the extreme right of the left-hand image are examples of two such particles, which traveling nearly parallel to one another, both pass through the plate without producing secondaries. It is likely that they are mesotrons.

ionization-depth curve obtained in the equatorial regions with those they had obtained previously at more northerly latitudes (Texas and North Dakota) confirmed the result discussed in a previous section of this paper, that a large fraction of the incoming particles are so highly absorbed in the atmosphere that they must lose energy at a rate many times greater than they should by direct ionization alone. Bowen, Millikan, and Neher, by comparing the observed intensities of ionization at various depths in the atmosphere, with the results of the Carlson-Oppenheimer calculations, assuming the incoming particles to be electrons, have shown that both the observed and theoretical ionizations at first increase and then rapidly decrease as one goes down from the top of the atmosphere. Although the agreement is not exact, the theoretical and observed ionization-depth curves are quite similar for the first three or four meters of water equivalent. Lower in the atmosphere the observed ionization becomes increasingly greater than the theoretical until at sea level the disagreement amounts to a factor of about twenty. This result, that the cosmic-ray particles observed at sea level are for the most part much less absorbable than electrons obeying the Bethe-Heitler theory, is quite in accord with the results of the other experiments on the sea-level particles discussed in the first part of this paper.

From these high altitude observations it became clear that the incoming cosmic-ray particles are very highly absorbed in the atmosphere even up to energies exceeding 10,000 Mev, which is the minimum energy of an electron which can penetrate the earth's magnetic field and reach the earth at its equator. These experiments offer confirmation of the validity of the Bethe-Heitler theory as previously found in our direct energy loss measurements, and provide for the first time definite evidence that the range of approximate validity of the theoretical formulae extends in a substance of low atomic number such as the air to electron energies greater than 10,000 Mev.

Although the theory of cascade showers seems capable of describing well the main mode of absorption of the soft component of the cosmic rays, it cannot as yet account for the presence of the penetrating particles which occur in abundance in the lower regions of the atmosphere and below sea level. These particles presumably are mesotrons, and as pointed out by Bowen, Millikan and Neher,[29] they must arise for the most part as secondaries produced in the atmosphere or other absorbing material by the incoming primaries. The precise nature of the mechanisms which give rise to the mesotrons, and most of the properties of the mesotrons themselves are as yet quite obscure. The remainder of this paper deals mainly with our own data and the information they give about the nature of the mesotrons.[30]

II. Determination of Mass

The principal means by which mass determinations may be made (assuming the charge to be known) are the following: (1) Measurement of range and curvature in a magnetic field, (2) ionization and curvature, (3) ionization and range, (4) close elastic collisions with electrons, (5) deflection by electric and magnetic fields. The first three methods involve essentially the same things and require a knowledge of the relationship between ionization or energy loss and the velocity of the particle. As the theoretical relations for these have been only partially checked by experiment, these methods suffer somewhat on this account. They are also subject to rather large experimental uncertainties, which vary widely with the velocity and proper mass of the particle. The last two methods are less open to objections of the first kind because they depend only on the most fundamental laws of mechanics and electricity. The fourth is perhaps the most powerful method of all because it should be applicable over a wide range of momenta and masses where the other methods either break down completely or are of extremely uncertain applicability. It has however the experimental disadvantage that data of the right kind are extremely rare and under the best conditions only slowly obtainable.

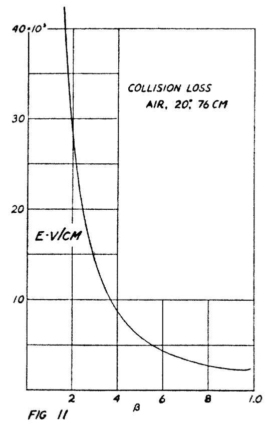
[30] Reviews and discussions of the experimental data have been given by Euler, Physik. Zeits. **23**, 943 (1937); Stearns, Rev. Mod. Phys. **10**, 133 (1938); Wentzel, Naturwiss. **26**, 273 (1938); Euler and Heisenberg, Ergeb. d. Exacten Naturwiss. **17**, 1 (1938), and by Bhabha, Proc. Roy. Soc. **A164**, 257 (1938). Part of the following discussion overlaps that given by Corson and Brode, Phys. Rev. **53**, 773 (1938).

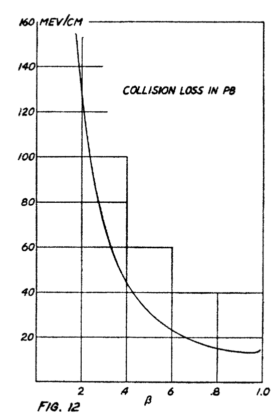
a. Range and ionization methods

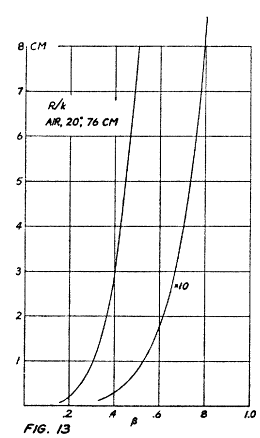
The energy loss by atomic collisions depends essentially only on the charge and velocity of the particle. The usual theoretical formula for this may be written[31]

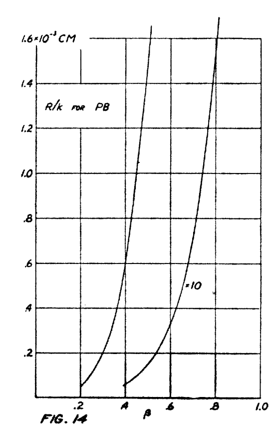
$$-\frac{dE}{dx}=\tfrac{3}{4}NZ\varphi_0 mc^2\frac{1}{\beta^2}\left\{\ln\frac{mc^2\beta^2W}{(1-\beta^2)I^2Z^2}+1-\beta^2\right\}. \quad (1)$$

The gamma-function derivative does not contribute essentially and has been omitted. $\varphi_0 = 8\pi e^4/3m^2c^4$; IZ = an average ionization energy and according to Bloch is $13.5Z$ volts. W is the maximum energy that can be transferred to an electron in an elastic impact. This depends only









Figs. 11 and 12. Theoretical collision loss as a function of v/c for air and Pb.

Figs. 13 and 14. Theoretical range divided by mass number for air and Pb. k is mass number in terms of electron rest mass. These curves are valid for $k \gg 1$.

[31] Heitler, *Quantum Theory of Radiation* (Oxford, 1936), p. 218.

on the velocity of the impinging particle provided that $m_{pri}/m \gg 2/(1-\beta^2)^{\frac{1}{2}}$. With this restriction $W=2mc^2\beta^2/1-\beta^2$. The other letters have their usual significance. For air at 20°, 76 cm (effective $Z=7.25$) (1) becomes

$$-\frac{dE}{dx}=\frac{0.91\times10^{-4}}{\beta^2}\left\{2\ln\frac{\beta^2}{1-\beta^2}+1-\beta^2+17.8\right\}.$$

Mev/cm.

The results of the calculation for air and lead are plotted in Figs. 11 and 12 and the corresponding range curves found by graphical integration are plotted in Figs. 13 and 14.

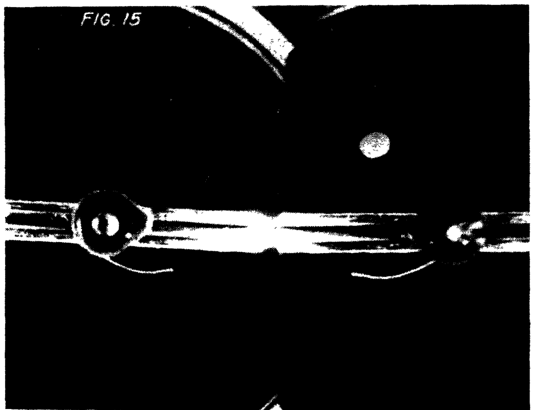
As the energy loss is a function of velocity only, it follows that the range has the form $R=kg(\beta)$ where k is the mass number of the particle in terms of the electron mass, m; $g(\beta)$ is the function plotted in Figs. 13 and 14. The $H\rho$ value measures the momentum directly independently of the mass, thus $p/mc\equiv\mu=eH\rho/mc^2$ and it is therefore convenient to use the relation $\mu=k\beta/(1-\beta^2)^{\frac{1}{2}}$. Then $\mu/R=\beta/(1-\beta^2)^{\frac{1}{2}}g(\beta)\equiv\varphi(\beta)$; and if μ and R are known from the measurements, the value of β can be picked off from a plot of φ, and the mass is then just $R/g(\beta)$. A mass determination can also be made from the above relations and the observed change in momentum on passage through a known thickness of material. The mass has then to be found by a process of trial and error.

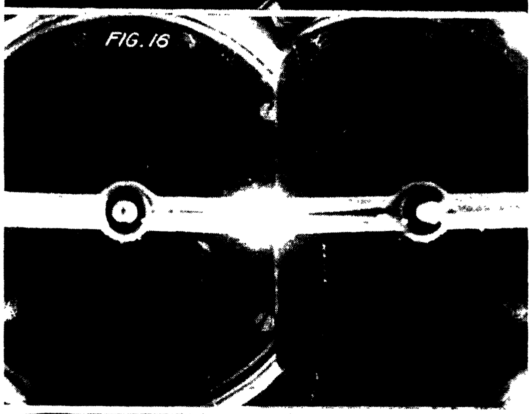
If the velocity of the particle lies in the region from about 0.25 c to 0.7 c, so that the ionization produced is appreciably greater, but not too much greater than the minimum value, then a mass determination can be made from the measured $H\rho$ and the number of ion pairs produced per cm of path, as determined by counting droplets along a diffuse track. The energy expended per ion-pair in air is known to be approximately constant (32 ev) and the total ionization should therefore vary with velocity in the same way as the energy loss. The ionization found by drop counts along diffuse tracks, as has been pointed out, is not the total ionization, but something less than this. The theoretical dependence of energy loss on velocity may be corrected to take this into account by leaving out of consideration in the theory those primary ions which are capable of producing clusters of secondary ions too large to be counted on the photographs. The ionization fixes the velocity, and the mass is then just $\mu(1-\beta^2)^{\frac{1}{2}}/\beta$. This method can be quite accurate over its restricted range of applicability. The uncertainty in μ is greater, however, than for sharp tracks and the same uncertainty as to the validity of the energy loss-velocity relation exists as in the first method.

When the velocity is very small it is known that the theoretical collision loss departs strongly from experiment. To get the correct dependence of range on energy we may take the energy loss to be proportional to about the inverse first power of the velocity, thus $-dE/dx\backsimeq az^2/\beta$ where z is the charge number and a a constant. This leads to the form $R=bE^{\frac{3}{2}}/z^2\sqrt{M}$. If M is the mass in terms of the proton mass and E the energy in Mev, then $b=8/3$ gives $R=\frac{1}{3}E^{\frac{3}{2}}$ for α-particles and $R=(8/3)E^{\frac{3}{2}}$ for protons, both formulas agreeing approximately with experiment over a considerable range of energies.[32] By expressing E in terms of mass and $H\rho$ we obtain for a particle of unit charge $R=7.9\times10^{-16}(H\rho)^3/M^2$. Since this formula is derived on largely empirical grounds from experiments with protons and α-particles it may be quite invalid when applied to low energy mesotrons. The curvatures of particles also apparently do not seem to vary with their residual ranges in the way the formula would indicate. It is however sufficiently good in some cases to rule out protons, although the masses found in this way have tended to be considerably higher than those found by other methods. Examples of mass determinations are given in the captions of Figs. 15–18.

The only direct experimental check of the collision energy loss formula by curvature measurements in a magnetic field appears to be the data of Turin and Crane[33] and the writers[13] on the energy loss in carbon. The former have found 3.4 Mev/cm as the mean of over 100 measurements of the energy loss in 0.5 cm of carbon for electrons with initial energies from 4 to 6 Mev. We had previously made only five measurements on particles (presumably elec-

[32] For more accurate treatment of range relations see Livingston and Bethe, Rev. Mod. Phys. 9, 261 (1937).
[33] Turin and Crane, Phys. Rev. 52, 610 (1937).





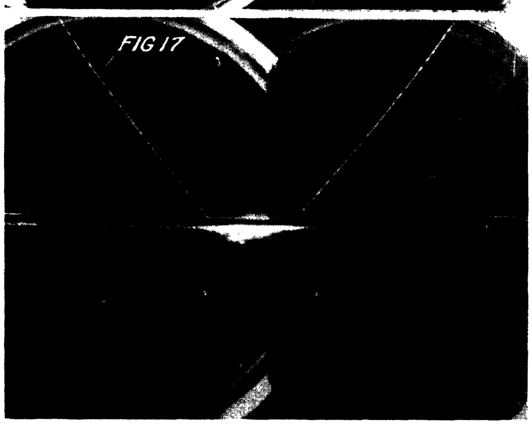


FIG. 15. Photograph already published, reference 45, showing a mesotron which passes through a Geiger counter placed inside the cloud chamber, then comes to rest in the gas ($\frac{2}{3}$ atmos. He; $\frac{1}{3}$ atmos. argon). The counter consists of a flattened copper cylinder 85 mm long, 18 mm wide and 7 mm high, enclosed in a glass tube whose upper and lower surfaces are flat and parallel to one another. The glass walls have a total surface density (measured after breaking the counter) of 0.687 g/cm^2, the copper cylinder 0.226 g/cm^2. The total, 0.913 g/cm^2, corresponds in electron density to 0.825 g/cm^2 of air. The actual thickness traversed is somewhat uncertain, but is about 1.2 times the normal thickness, or 0.99 g/cm^2 of air. With an $H\rho$ $=1.74\times10^5$ gauss cm, this gives a mass 220. A reasonable limit of error, allowing only for the (*experimental*) uncertainties of the $H\rho$ and the thickness traversed, should be about ±35.

FIG. 16. A positive particle enters the counter with a momentum of 75 'Mev,' emerging with a momentum of 50 'Mev.' The mass traversed is 0.82 g/cm^2 air equivalent, and if the whole energy loss is assumed to result from ionization alone this corresponds to a mass $\sim 360m$, and ionizations above and below the counter of 4 and 7 times the minimum for a fast particle. The ionization produced is quite certainly greater than the minimum, but probably not by so big a factor. A mass 220 gives factors 2.3 and 3.5, but to have the observed curvatures such a particle should have to traverse a mass of 2.4 g/cm^2 air equivalent. Even if the particle went through the tungsten wire in the counter (one chance in fifty) the mass traversed could be only 1.5 g/cm^2. It appears probable that the mass of this particle is smaller than the computed value and that the curvature change is to be explained in terms of an abnormal energy loss other than from ionization and radiation.

FIG. 17. Pikes Peak. Positive particle, momentum 235 'Mev,' which is stopped in a 0.32-cm copper plate. The maximum distance traversed is 0.42 cm Cu or roughly 0.39 cm Pb equivalent, which gives a lower limit of 1300 m for the mass. A proton of this curvature should have a range of 0.2 cm Pb and should ionize about 7 times the minimum for a fast particle, which seems reasonably consistent with the photograph. To get a range just equal to the maximum thickness traversed would require a momentum of 300 'Mev' for a proton, which should then ionize about 5 times the minimum. It seems reasonably certain, then, that this particle is to be identified as a proton.

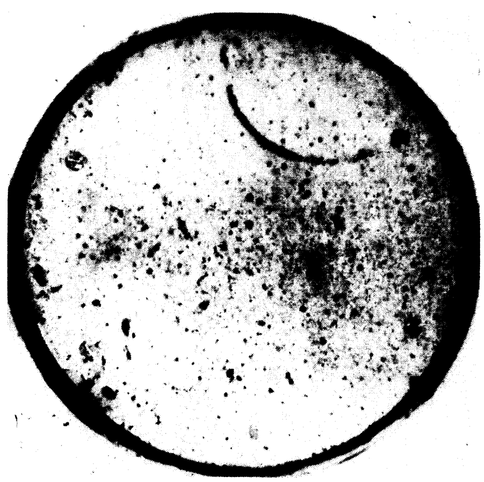
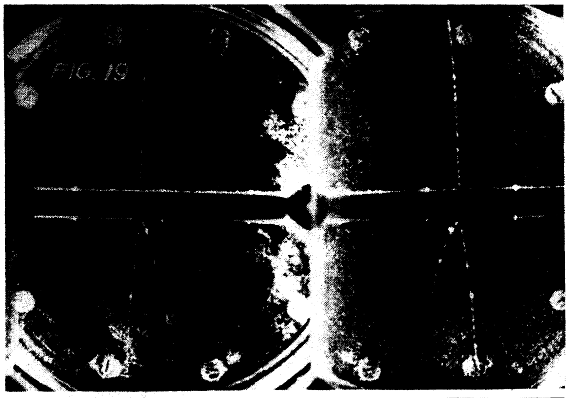
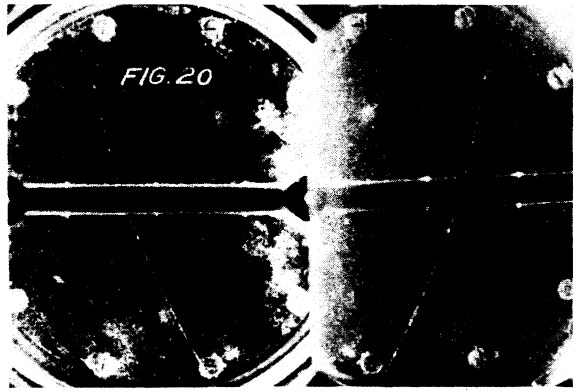
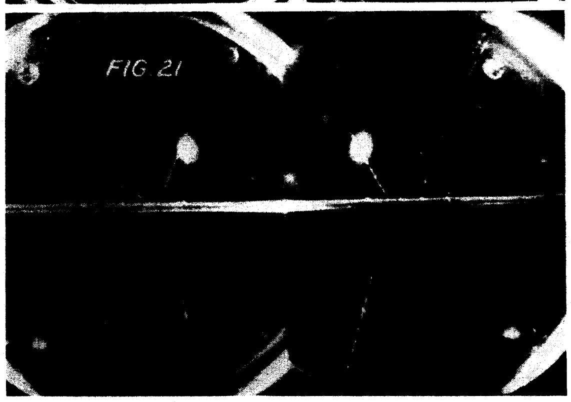


FIG. 18. 15,000 gauss. An early photograph (1931) of a particle with an $H\rho$ of 6×10^4 gauss cm, whose ionization quite certainly exceeds that of a fast electron. A value 10 times the minimum should correspond to a mass of 150, and 15.5 times the minimum to a mass 200. Either of these ionization values could be consistent with the photograph. Range and $H\rho$ give a rough upper limit of 300. (See also Fig. 5 by Kunze, Zeits. f. Physik **83**, 10 (1933).)







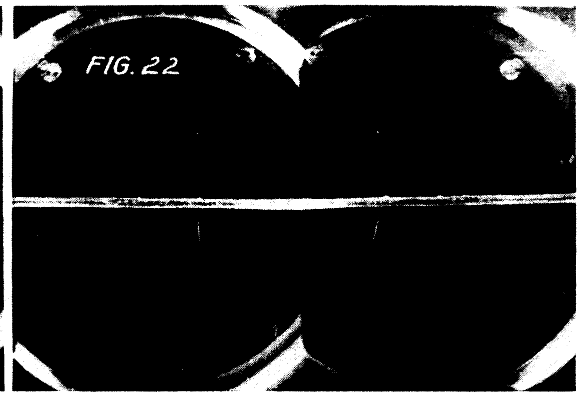


FIG. 19. Another example of a particle of positive charge too lightly ionizing to be of protonic mass but which loses only a third of its momentum in the 1-cm Pt plate. Its momenta above and below the plate are, respectively, 180 'Mev' (6×10^5 gauss cm) and 120 'Mev' (4×10^5 gauss cm). A secondary negatron of energy 16 Mev emerges from the lower face of the plate. Statistical studies have shown that such single secondary negatrons result in general from elastic impacts with atomic electrons in the plate. If such is the case in this photograph then it is possible to place an upper limit of 65 m to the mass of the incident positive particle (see Section IIb). If the incident particle is a positron the probability that the same one should emerge below with so much of its original energy should be of the order of a percent. The probability that the emerging particles are a pair of electrons resulting from a second-order process involving the complete absorption of an incident positron by emission of a single high energy photon may be somewhat greater than this.

FIG. 20. Positive particle showing an apparent gain in momentum (95 'Mev' above, 105 'Mev' below). As the upper segment of the track is much closer to the pole piece than the lower, part of the apparent gain can be attributed to the non-uniformity of the field, which varies over the whole chamber by about ten percent. This leaves no room, however, for energy loss by ionization. Motion of the gas may account for the remaining discrepancy. The difficulty of identifying this particle with a mesotron of mass 200 even if it is assumed to be moving upward is apparent because a momentum of 100 'Mev' would correspond to an energy of only 42 Mev and a range less than 1 cm of platinum. (See Section III.)

FIG. 21. Pikes Peak. A high energy particle produces a disintegration in a 0.35-cm Pb plate, similar to the disintegrations reported earlier (reference 20). The three particles expelled ionize somewhat more strongly than do fast electrons, and are consistent with a protonic mass.

FIG. 22. Pikes Peak. An interesting photograph which shows a negative particle, momentum 66 'Mev,' impinging upon a 0.35-cm Pb plate. The upper track may represent either an electron or a mesotron. The particle below is certainly not an electron but it may be a proton. The particle below could have a mass as low as 200 only if the curvature were somewhat modified by scattering in the gas. This might be an example of the absorption into a nucleus of a mesotron after it has been brought nearly to rest. If the incoming particle is a mesotron of mass 220 its theoretical range is about 0.37 cm Pb and its actual energy is 18 Mev.

trons), with a mean initial energy of 20 Mev, which gave a mean loss of 5.0 Mev/cm in a 1.5-cm plate. The corresponding calculated values are 3.7 and 4.3 Mev/cm, which are just about within the limits of experimental uncertainty. Further measurements of the energy loss in carbon are now being undertaken in this laboratory by Mr. Kuo to obtain more accurate values in the range above that covered by Turin and Crane, and to find out whether in a light material abnormal losses occur which are attributable neither to ordinary atomic collisions nor to radiating nuclear collisions of the usual kind. The existence of some abnormally high losses among the "penetrating" group in our platinum data could be attributed either to a phenomenon of this kind or to the presence of some particles with masses small enough so that ordinary *bremsstrahlung* would be an important mechanism of energy loss. Wilson[34] has found, however, in the region from about 1 to 3×10^9 ev, a large excess absorption of the penetrating particles in copper and lead which is much too large to be understood in terms of ionization and much too small for the particles to be radiating electrons. The fact that this loss does not follow a Z^2 law makes unlikely the possibility that it could be the *bremsstrahlung* of particles with masses only a few times as big as the electron mass, although this cannot be taken as strong evidence against the presence of such particles.

b. Method of elastic collisions.

If a particle whose momentum is $\mu_0 mc$ and whose mass is km collides elastically with a particle of mass m initially at rest, then the energy ϵmc^2 which is transferred to the second particle may be shown to be given by

$$\epsilon=2(\mu_0/k)^2\cos^2\vartheta/\{[(\mu_0^2/k^2+1)^{\frac{1}{2}}+1/k]^2 - (\mu_0/k)^2\cos^2\vartheta\},$$

where ϑ is the angle between $\boldsymbol{\mu}_0$ and the path of the secondary.

This relation when applied to collisions with electrons in which the angles and momenta are accurately measurable permits, in contrast to the ionization methods, mass determinations of particles whose total energies are quite large compared to their proper energies. An idea of how effective the method can be is given by the curves in Fig. 23 which show ϵ as a function of ϑ for a primary momentum of $400mc$ (200 'Mev'), and for masses 1, 20 and 80 electron masses. Leprince-Ringuet and Crussard[35] have observed one case of a secondary produced in the gas of a cloud chamber by a particle with a momentum $\sim10^{10}$ 'ev' from which it was possible to conclude, by measurement of the angle and energy of the secondary, that the mass of the primary was less than that of a proton. It is interesting that such a low energy secondary (33 Mev) can give even this much information about a primary with so high a momentum.

If only the energy of the secondary can be measured, and not its angle, it is still possible to place an upper limit on the mass of the primary, thus with $\cos\vartheta=1$, $\epsilon_{\max}\simeq2\mu_0^2/k^2$ provided $k\gg1$. This has been applied to place a limit on the mass of one particle which traverses 1 cm of platinum with only a small loss of energy and produces a secondary negatron. This case is discussed in detail in the caption of Fig. 19.

On account of the impossibility of measuring energies above about 500 Mev with our chamber obstructed by a metal plate, the above argument cannot be applied in particular cases to secondaries produced by high energy primary particles. A statistical argument based on the energy distribution of the secondary negatrons, and the momentum distribution of the primaries as determined with an unobstructed chamber is, however, a very useful one, and has already been applied by the writers as evidence that the primary particles are not principally of protonic mass.[13] A more recent set of data from 2700 primary traversals of particles occurring singly through 1 cm of platinum provides a means (with certain assumptions) of placing somewhat stronger restrictions on the mass of the primary particles (Fig. 24). These data are summarized in Table II, in which are listed the numbers of showers and single secondaries produced in the platinum, with and without a 1″ Pb filter placed over the top of the cloud chamber. The large predominance of single negative secondaries over positives and showers means that they presumably must result from close impacts with atomic electrons. A few and perhaps most of the lower energy showers may be started by secondaries of this kind. The distribution in energy of

TABLE II. *Observed and calculated numbers of secondaries ejected from 1 cm of* Pt *by "single" primaries with momenta greater than 500 'Mev.'*

	With 1″ Pb filter 814 traversals		All data 2724 traversals	
Energy, Mev	*20–100*	*>100*	*20–100*	*>100*
Obs. no. of (−)	9	4	28	8
Calc. ($k=1$)	9.7	3.2	32	5.3
Calc. ($k=250$)	6.4	1	24	2
Obs. No. of (+) and showers	2	2	8	9

[34] Wilson, Proc. Roy. Soc. **A166**, 482 (1938).
[35] Leprince-Ringuet and Crussard, J. de phys. et rad. **8**, 212 (1937).

the emerging secondary negatrons, to be expected theoretically if they result solely from elastic impacts, has been calculated taking into account the energy lost by the secondaries before they emerge and using the alternative assumptions (1) that the primaries are of electronic mass, but do not themselves radiate, or (2) that the primaries all have a mass $250m$. In the latter case the primary momentum distribution must be taken into account, and has been assumed to be as given in an earlier paper.[13]

The cross section for production of a secondary of energy E in dE has been taken as before[13] to be $p(E)dE = AdxdE/E^2$ where $A = \pi e^4 n/m^2c^4 = 1.28$ for platinum when E is expressed in units of $2mc^2$, or approximately in Mev. n is the number of electrons/cm^3. The average energy loss of the secondaries is assumed to be $-dE/dx = aE + b$, and for N primaries of electronic mass and energy E_0 this leads to the theoretical distribution of emerging secondaries

$$f(E) = \frac{AN/a}{E + b/a}\left(\frac{1}{E} - \frac{1}{E_{\max}}\right),$$

where

$$E_{\max} = \begin{cases} (E + b/a)e^{at} - b/a \equiv E_1 & \text{when } E < E_1 < E_2 \\ E_0/2 \equiv E_2 & \text{when } E < E_2 < E_1 \end{cases}$$

We have taken for platinum $a = 3.2$ cm^{-1}; $b = 32$ Mev/cm and the thickness $t = 1$ cm. This makes $E_1 = 25E + 240 \gg E$. Moreover $E_2 \gg E$ for most of the primaries, so that in a first approximation the second term may be neglected altogether. The error thus made is ~ 10 percent at $E = 200$ Mev, which is of no significance because of the few secondaries with energies higher than this. Thus for electronic primaries the expected distribution of negative secondaries is

$$f(E) = 0.4N/E(E + 10)$$

which is independent of the thickness of the plate. For primaries of mass km we may find an upper limit to the expected distribution by using the same cross section as above and assuming it to cut off at an energy $E = \mu_0^2/k^2$, where $\mu_0 mc$ is the momentum of the primary particle. If the primaries are divided into groups of N_i particles with mean momenta $\mu_{0i} mc$, then the expected distribution may be written in the simple form

$$f(E) = \frac{0.4}{E + 10}\left\{ \sum_{E < E_1 < E_{2i}} N_i \left(\frac{1}{E} - \frac{1}{E_1}\right) + \sum_{E < E_{2i} < E_1} N_i \left(\frac{1}{E} - \frac{1}{E_{2i}}\right) \right\},$$

which is much less cumbersome to use than the integral form. The above calculated distributions are plotted in Fig. 24 along with the observed data. The necessity for taking into account the radiative loss of the secondaries is indicated by the upper curve, which represents the distribution that should be observed (from electronic primaries) if the secondaries lost energy by ionization only. The tabulated results of observation and theory (Table II) for the numbers of secondaries in the intervals 10–100 Mev and >100 Mev tend to favor an average primary mass small compared to $250m$. The data taken with a 1″ Pb filter above the chamber differ from the total mainly in that the proportion of showers is smaller. This probably means that some electronic primaries were removed by the filter, and that the few showers produced by the remaining primaries were generated by negatron secondaries. A crude estimate of the number of showers so produced is easily made if we observe that the total number of secondaries with energies $>E_1$, that should be produced anywhere in the plate is $\sim 3500/E_1$. The pairs and showers should be produced mainly by negatrons above 150 Mev (see Fig. 1), of which there should be 23. If half of these produced showers the expected number would be 12, or 3.5 for the filtered data. Observed were 17 and 4, respectively, so that the orders of magnitude are evidently right. Estimated on the same basis there should be about 5 and 1.5, respectively, for primaries of mass 250. As no account of shower production is taken in the calculation of the negatron secondary distribution, the number of single secondaries so calculated should be higher than the observed by roughly the number of showers produced by the negative secondaries. Actually the observed number of single negatives is about equal to the calculated in the low energy range (20–100 Mev), assuming light particle primaries, and higher than the calculated in the range >100 Mev.

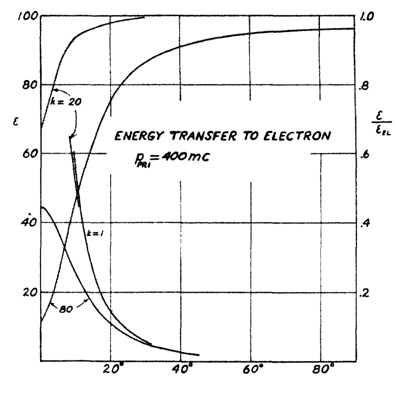


FIG. 23. Energy transfer (ε in terms of electron proper energy, mc^2) to an electron as a function of angle between incident momentum and the path of the secondary, calculated for a primary momentum $400mc$ and for primary masses 1, 20, and 80 electron masses. The two upper curves (right-hand ordinate) give the transfer relative to that for an electronic primary of the same momentum.

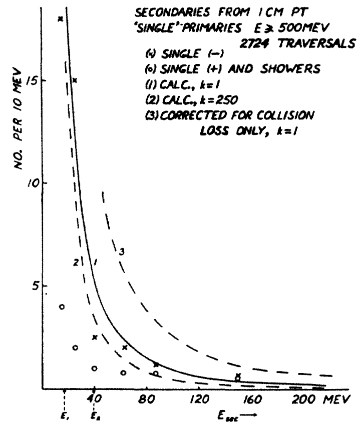


FIG. 24. Energy distribution of secondaries ejected from 1 cm of Pt. Showers are plotted as number of *showers* against total energy appearing per shower. Increasing intervals are chosen at the higher energies to smooth out fluctuations, each point being reduced to number of single secondaries (or showers) per 10 Mev. E_1 and E_2 indicate the maximum energy that can be transferred to an electron by a proton with an energy of 3000 or 5000 Mev (momenta about 3800 and 5800 'Mev'), respectively.

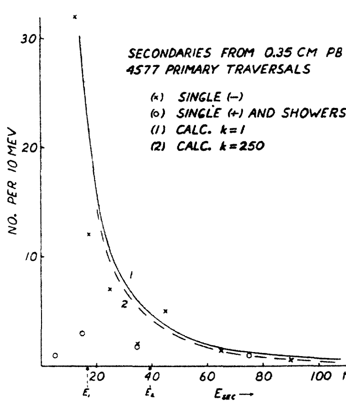


FIG. 25. Energy distribution of secondaries from 0.35 cm of Pb.

Thus counting the showers as produced by negative secondaries there is an excess of secondaries over that demanded by theory. The discrepancy is even worse for primaries more massive than electrons. However, a third set of old data (1935, unpublished) from 4577 traversals through 0.35 cm of Pb give no strong indication one way or the other (between primary particles of electronic mass or of mass $200m_e$), although these data do not provide as many high energy secondaries and are therefore not as critically dependent on the masses of the primary particles. They are also listed in Table II and plotted in Fig. 25. In plotting the experimental distributions progressively larger intervals have been taken with increasing energy to smooth out the fluctuations, each point having been reduced to number of secondaries per 10 Mev. It is to be pointed out that although these data do not so far serve to distinguish between incoming particles of mass 250 and particles of electronic mass, they do give strong evidence that not many of the incoming particles can be as massive as protons, for E_1 and E_2 indicated on the abscissae scales of Figs. 24 and 25 show the maximum energy that can be transferred to an electron in an elastic impact by protons with energies of 3000 and 5000 Mev (momenta about 3800 and 5800 'Mev'), respectively. Curvature measurements have shown that only a small fraction of the incoming particles have momenta above 5800 'Mev,' and hence if these particles are of protonic mass one could not then account for the observed energy distribution of the single negatron secondaries.

The various mass determinations[36–41] that have been made by ionization and range methods show a rather large spread from some 100 electron masses to over 400. As the errors involved are rather large and difficult to evaluate it is perhaps conceivable that these measurements could be consistent with a unique mass in the neighborhood of 200. Secondary data obtained by Wilson[42] from a 2-cm plate of gold appear to be consistent

[36] Street and Stevenson, Phys. Rev. **52**, 1003 (1937).
[37] Nishina, Takeuchi and Ichimiya, Phys. Rev. **52**, 1198 (1937).
[38] Ruhlig and Crane, Phys. Rev. **53**, 266 (1938).
[39] Ehrenfest, Comptes rendus **206**, 428 (1938).
[40] Corson and Brode, Phys. Rev. **53**, 773 (1938).
[41] Williams and Pickup, Nature **141**, 684 (1938).
[42] Wilson, Nature **142**, 73 (1938).

with a mass of this order of magnitude when all the observed showers and single secondaries produced by particle traversals are interpreted as arising through ordinary negatron secondaries. Our own secondary data, though not entirely self consistent, tend somewhat to favor a small average mass; and a case such as illustrated in Fig. 19 appears difficult to understand except in terms of a small mass.

III. Discussion

The evidence for the existence of the mesotron is then of two main types, (a) Observations involving range, curvature and ionization, and (b) Observations of penetrating power in a thick layer of heavy material, which reveal a duality in behavior in the same momentum range. Method (a) is by its character limited to particles of rather low energy, and the particles to which this method has been applied seem to be predominantly positively charged. At least one of these originated in a nuclear disintegration, in which there appeared five other unidentifiable positive particles of which one may have been a proton and the rest mesotrons. The penetrating component appearing in the platinum energy loss measurements consists, however, of roughly equal numbers of positives and negatives and suggests very strongly that they may be created in pairs by photons in a way analogous to the creation of electron pairs.[27] Whether these particles, which apparently have quite different origins, have the same properties is a question for future experiments to decide. Particularly in the penetrating group where the velocities are such that mass determinations by the ionization methods are not possible it is less certain that mass is the characteristic that distinguishes the mesotrons from electrons. That it is simply the mass, however, may be inferred on the general grounds (a) that this is the simplest way of accounting theoretically for their not radiating, and (b) that mass and charge are the only parameters which characterize the electron as a particle in the Dirac equation. As the available data (except Wilson's[42]) on the production of secondaries tend to indicate a smaller mass than do the range-ionization data, this still leaves open the possibility that the mesotrons in the penetrating group may be produced according to some such law as has been suggested by one of the writers.[43]

Blackett[44] has suggested, on the basis of his observation that very few penetrating particles exist with momenta below 200 'Mev,' that the particles at a critical energy either disintegrate or in some other obscure way become electronic in character. However there are many cases of mesotrons with momenta far below Blackett's critical value, and we have moreover observed one particle which probably comes to rest in the gas of the cloud chamber (Fig. 16), although there is some uncertainty as to whether it finally disintegrated within the time limit imposed by the photograph.[45]

It has been found by Ehmert[46] and Kulenkampff[47] that there is a higher absorption in air than in water at equivalent depths below the top of the atmosphere. This has been interpreted by Euler and Heisenberg[48] in terms of a spontaneous disintegration of the penetrating particles into electrons. Assuming that the apparent excess absorption is simply a consequence of the longer time taken to traverse the equivalent amount of the lighter material, they estimate from the experimental data a mean life of about 2×10^{-6} sec. This is about twenty times as big as the mean life estimated by Yukawa, *et al.*,[49] on the basis of Yukawa's theory.

Some difficulty exists in the interpretation of the few particles that we have found in our platinum measurements with momenta below 150 'Mev.' Some of the single particles in this region behave like electrons as has also been found by Blackett. The others, which seem to lose little or no momentum cannot be interpreted in terms of mesotrons as massive as $200m$ which traverse the plate and retain their identity. For example, with a mass 200 a 100-'Mev' particle

[43] Neddermeyer, Phys. Rev. **53**, 102 (1938). Some of the consequences of the mass quantization have been developed by Langer, Phys. Rev. **53**, 494 (1938).
[44] Blackett, Proc. Roy. Soc. **A165**, 11 (1938).
[45] Neddermeyer and Anderson, Phys. Rev. **54**, 88 (1938).
[46] Ehmert, Zeits. f. Physik **106**, 751 (1937); Physik. Zeits. **38**, 975 (1937).
[47] Kulenkampff, Verhand. d. deutsch. phys. Ges. (1938).
[48] Euler and Heisenberg, Ergeb. d. Exacten Naturwiss. **17**, 1 (1938).
[49] Yukawa, Sakata, Kobayasi and Taketani, Proc. Phys. Math. Soc. Japan **20** (Sept., 1938). Yukawa and Sakata, Nature **143**, 762 (1939), have shown that a lifetime $\sim10^{-6}$ sec. can be obtained by using a mass $100m$ instead of 200.

would have an actual energy of 42 Mev and should be stopped in the plate by ionization (see Fig. 20). A 150-'Mev' particle of this mass would have an actual energy of 80 Mev and should show a momentum loss of 45 'Mev.' While it is possible to obtain a gain in momentum by a process involving a change in mass and the ejection of a neutral particle or photon backward, this does not seem to be a likely interpretation because it usually should be associated with a very large scattering. A more likely one is that the masses of these particles are small enough so that the ionization loss is near the minimum for high velocities (in this event the actual energy loss will be given very nearly by the momentum loss in 'Mev'). This should have a value of 25–30 Mev/cm, and by making generous allowances for all possible errors in the measurements, might be made consistent with observation.

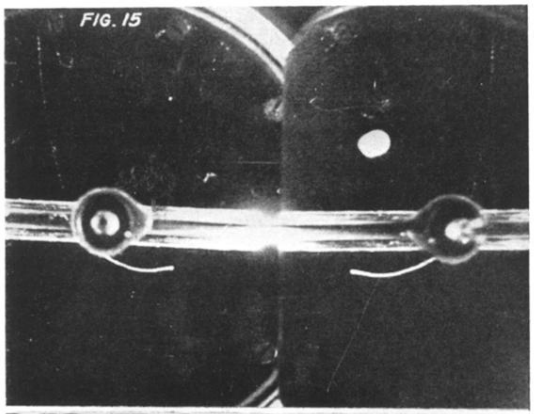
It has been found by the writers that heavily ionizing particles occur 12 times as frequently per exposure on Pikes Peak (4300 meters) as at Pasadena.[19] Atomic disintegrations produced by charged particles (in most cases unidentifiable except in having unit charge) as well as by photons or neutral particles also occurred much more frequently at the high altitude. It is an interesting fact that the number of disintegrations in lead produced by charged particles alone is also of the order of ten times as great *per particle traversal* at Pikes Peak as at Pasadena. This might be interpreted in several different ways, e.g., (1) the mesotrons have a lower most probable energy at the higher altitude, and therefore interact more strongly with nuclei than at sea level where the energy is high; (2) the mesotrons have a higher average mass at the higher altitude, or (3) the particles producing the disintegrations are mainly electrons or photons, which are relatively much more abundant than mesotrons at high altitudes.

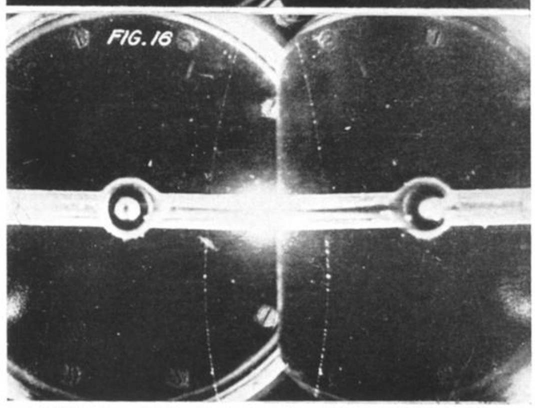
More high altitude observations are necessary to distinguish among the various interpretations. Further studies of the disintegrations should be especially helpful in attempting to find out whether the mesotrons can be identified with the particles postulated by Yukawa[50] to account for nuclear forces. Examples of disintegrations are shown in Figs. 21 and 22.

Although the reasonable certainty that the mesotrons exist clarifies many cosmic-ray observations whose interpretation on any other basis has been completely obscure, it has become increasingly likely that a complete interpretation of the experimental data is not to be found in the simple assumption of unstable particles with unit charge and a unique mass of the order of 200 electron masses. The experiments have not yet been carried far enough to indicate clearly what the nature of the final solution might be, nor to suggest an experimental approach other than to investigate further the modes of production and absorption of the particles and to attempt further mass determinations with the view of finding out whether a mass spectrum actually exists.

We wish to express our gratitude to Professor Millikan for his continued interest and help in these researches, and to Dr. J. K. Boggild and Mr. I. C. Kuo for their assistance in operating the apparatus and in making calculations. We are also greatly indebted to the Baker Company for the loan of the platinum for a period of over two years, and to the Carnegie Institution of Washington from which has come all of the financial support.

[50] Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1935).





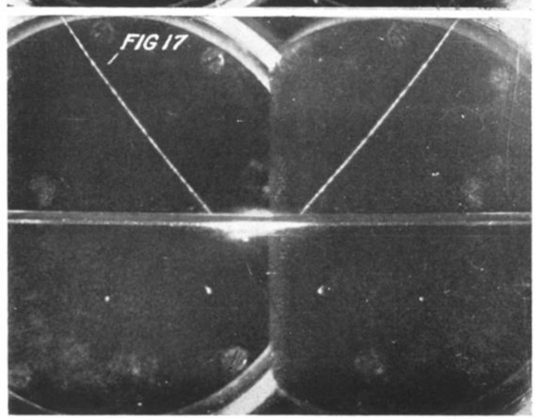


FIG. 15. Photograph already published, reference 45, showing a mesotron which passes through a Geiger counter placed inside the cloud chamber, then comes to rest in the gas ($\frac{2}{3}$ atmos. He; $\frac{1}{3}$ atmos. argon). The counter consists of a flattened copper cylinder 85 mm long, 18 mm wide and 7 mm high, enclosed in a glass tube whose upper and lower surfaces are flat and parallel to one another. The glass walls have a total surface density (measured after breaking the counter) of 0.687 g/cm^2, the copper cylinder 0.226 g/cm^2. The total, 0.913 g/cm^2, corresponds in electron density to 0.825 g/cm^2 of air. The actual thickness traversed is somewhat uncertain, but is about 1.2 times the normal thickness, or 0.99 g/cm^2 of air. With an $H\rho = 1.74\times10^5$ gauss cm, this gives a mass 220. A reasonable limit of error, allowing only for the (*experimental*) uncer-

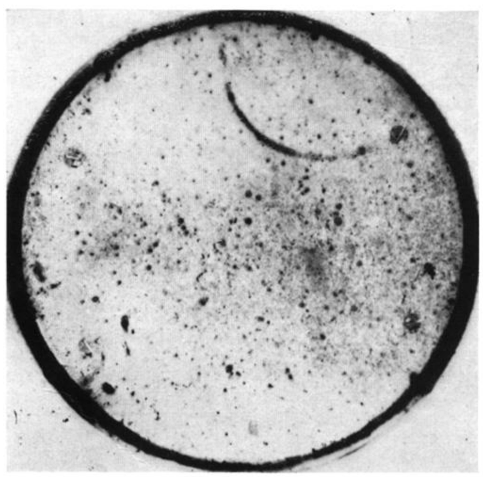
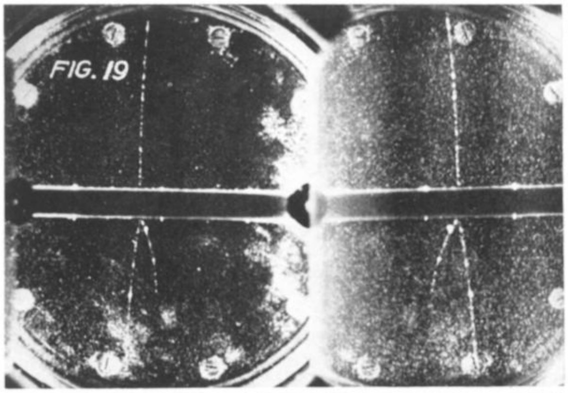
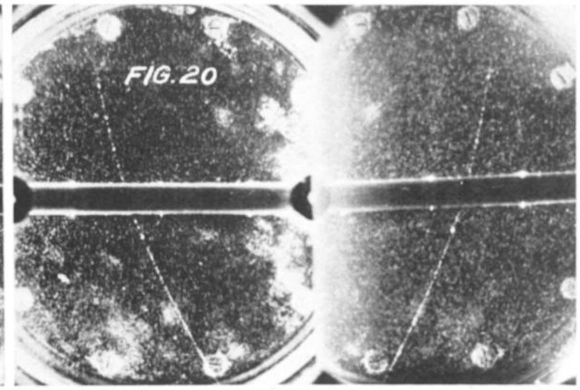
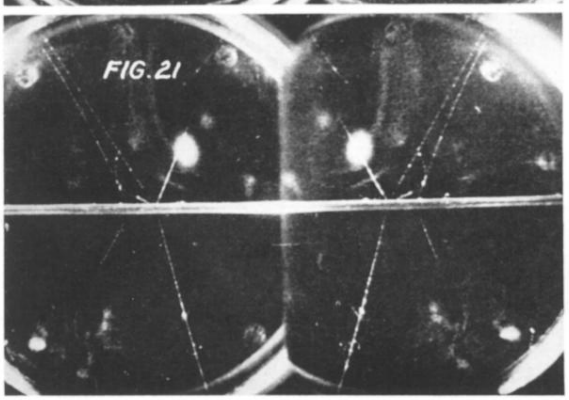


FIG. 18. 15,000 gauss. An early photograph (1931) of a particle with an $H\rho$ of 6×10^4 gauss cm, whose ionization quite certainly exceeds that of a fast electron. A value 10 times the minimum should correspond to a mass of 150, and 15.5 times the minimum to a mass 200. Either of these ionization values could be consistent with the photograph. Range and $H\rho$ give a rough upper limit of 300. (See also Fig. 5 by Kunze, Zeits. f. Physik **83**, 10 (**1933**).)







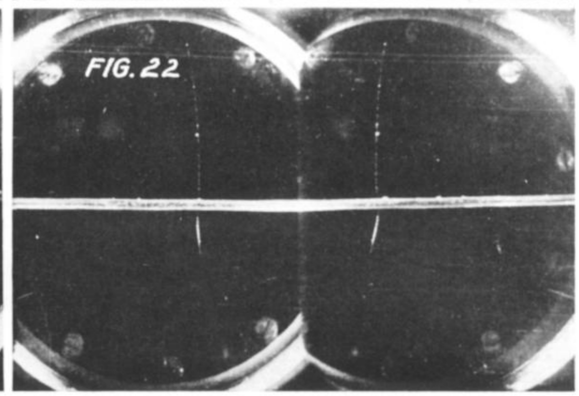
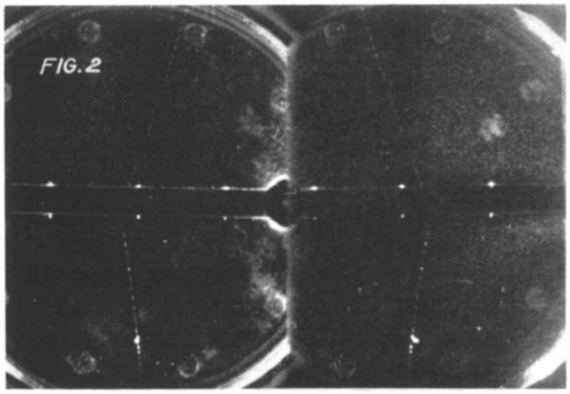


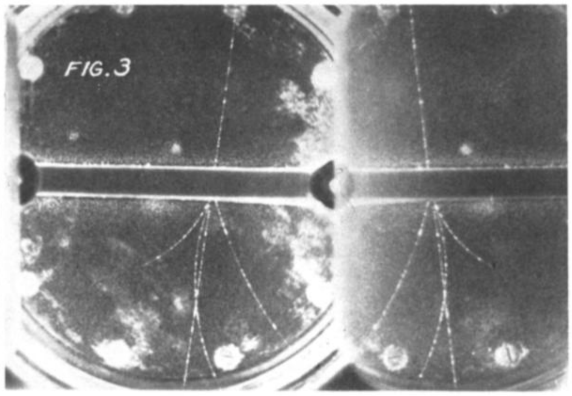
FIG. 19. Another example of a particle of positive charge too lightly ionizing to be of protonic mass but which loses only a third of its momentum in the 1-cm Pt plate. Its momenta above and below the plate are, respectively, 180 'Mev' (6×10^5 gauss cm) and 120 'Mev' (4×10^5 gauss cm). A secondary negatron of energy 16 Mev emerges from the lower face of the plate. Statistical studies have shown that such single secondary negatrons result in general from elastic impacts with atomic electrons in the plate. If such is the case in this photograph then it is possible to place an upper limit of 65 m to the mass of the incident positive particle (see Section IIb). If the incident particle is a positron the probability that the same one should emerge below with so much of its original energy should be of the order of a percent. The probability that the emerging particles are a pair of electrons resulting from a second-order process involving the complete absorption of an incident positron by emission of a single high energy photon may be somewhat greater than this.

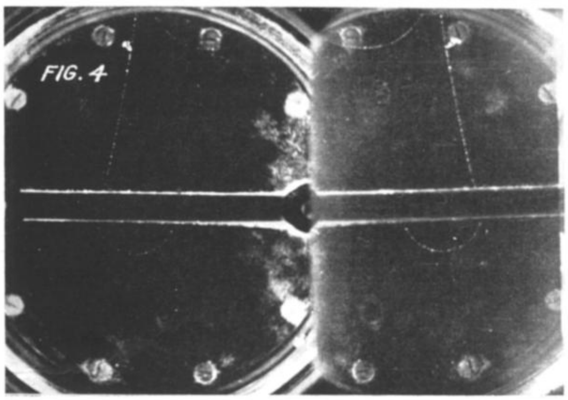
FIG. 20. Positive particle showing an apparent gain in momentum (95 'Mev' above, 105 'Mev' below). As the upper segment of the track is much closer to the pole piece than the lower, part of the apparent gain can be attributed to the non-uniformity of the field, which varies over the whole chamber by about ten percent. This leaves no room, however, for energy loss by ionization. Motion of the gas may account for the remaining discrepancy. The difficulty of identifying this particle with a mesotron of mass 200 even if it is assumed to be moving upward is apparent because a momentum of 100 'Mev' would correspond to an energy of only 42 Mev and a range less than 1 cm of platinum. (See Section III.)

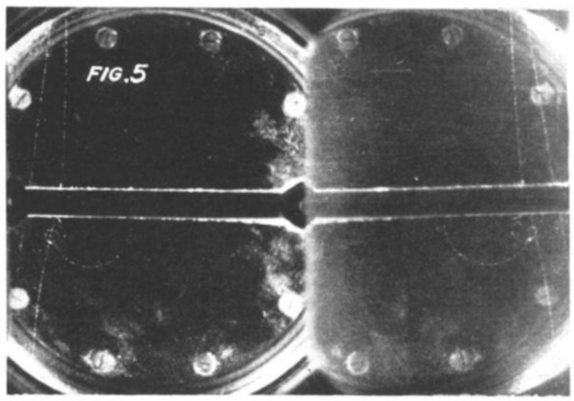
FIG. 21. Pikes Peak. A high energy particle produces a disintegration in a 0.35-cm Pb plate, similar to the disintegrations reported earlier (reference 20). The three particles expelled ionize somewhat more strongly than do fast electrons, and are consistent with a protonic mass.

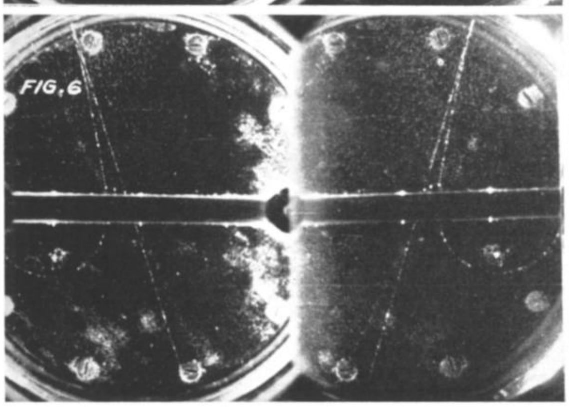
FIG. 22. Pikes Peak. An interesting photograph which shows a negative particle, momentum 66 'Mev,' impinging upon a 0.35-cm Pb plate. The upper track may represent either an electron or a mesotron. The particle below is certainly not an electron but it may be a proton. The particle below could have a mass as low as 200 only if the curvature were somewhat modified by scattering in the gas. This might be an example of the absorption into a nucleus of a mesotron after it has been brought nearly to rest. If the incoming particle is a mesotron of mass 220 its theoretical range is about 0.37 cm Pb and its actual energy is 18 Mev.











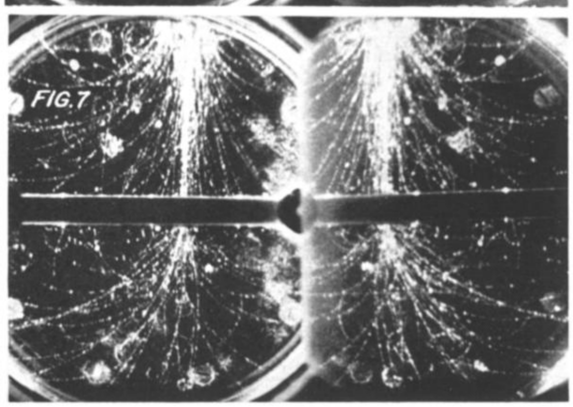


FIG. 2. The field is 7900 gauss for all photographs except Fig. 17. The left-hand view is the direct image of the chamber. A negative particle of $H\rho=7.1\times10^5$ gauss cm and therefore momentum of 213 'Mev' passes through a 1-cm Pt plate and emerges with an $H\rho=6.3\times10^5$ gauss cm and momentum of 190 'Mev' (see reference 24 for definition of momentum units). This particle is clearly not of protonic mass because a proton of momentum 213 'Mev' has an energy of only 19 Mev. It could not traverse the Pt plate and would have a specific ionization at least 10–15 times that of a fast electron. The particle is not easily interpreted as an electron because statistical data have shown that the probability of an electron losing less than three-fourths of its incident momentum in 1 cm of platinum is very small. The assumption that the mass of the particle is intermediate between that of an electron and a proton makes the observations consistent. If its mass were 200 m_e the incident energy would be 134 Mev, the emerging energy 113 Mev, and the specific ionization of the lower track should be almost the same as that of a fast electron. The energy loss would be 21 Mev/cm instead of the 23 calculated from the curvatures on the basis of electronic mass, which is within experimental error equal to the expected loss by ionization.

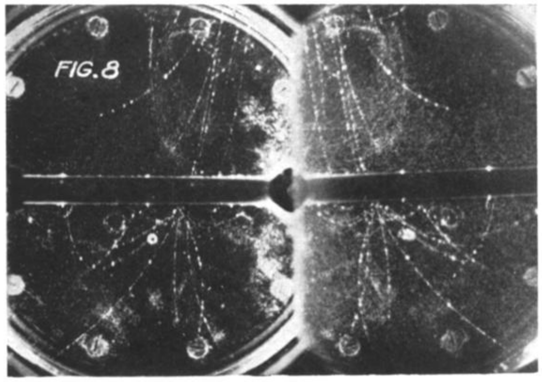
FIG. 3. An example of a small electron shower produced by a high energy single particle ($H\rho>1.5\times10^6$ gauss cm). A discussion of these showers with a table of their frequency of occurrence is given in the text, Section II-*b*.

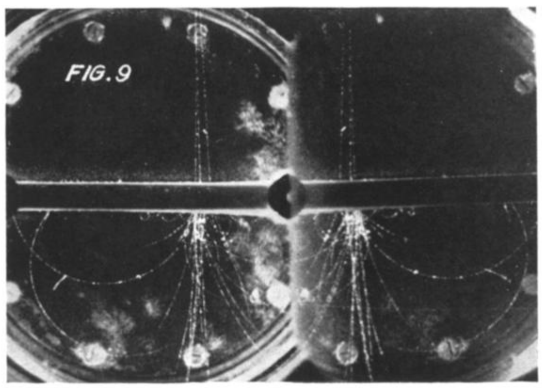
FIG. 4. The negative component of an electron pair ($E=160$ Mev) is completely absorbed in the platinum, only a 3.5-Mev positron emerging below.

FIG. 5. A negatron secondary produced in the material above the chamber ($E=210$ Mev) is completely stopped in the platinum. 80 Mev of the incident energy appears in the two positrons emerging below.

FIG. 6. Another example of a negatron secondary which is almost completely absorbed. Incident energy, 190 Mev; emerging, 5 Mev. This is typical of the behavior which has so far been shown without exception by all negatron secondaries. As most of such single negatrons presumably arise from elastic collisions with atomic electrons, this provides an independent experimental identification of the highly absorbable particles with ordinary electrons.

FIG. 7. Example of a shower of high energy electrons incident nearly normally on a 1-cm plate of Pt. Most of the energy is degraded into relatively low energy electrons.





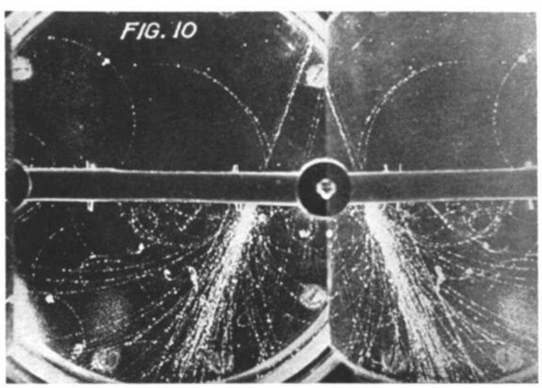


FIG. 8. A simpler case showing the behavior of shower particles in the intermediate energy range.

FIG. 9. A group of three shower particles with momenta greater than 500 'Mev' each incident on the upper surface of the platinum produces a shower of more than twenty positrons and negatrons.

FIG. 10. A well-collimated group of three high energy shower particles incident on the upper surface of the Pt plate produces a large shower. A second shower arising in the Pt just to the left of the main group of particles is presumably generated by photons accompanying the incident particles. Occasionally penetrating particles of high energy occur in showers. At the extreme right of the left-hand image are examples of two such particles, which traveling nearly parallel to one another, both pass through the plate without producing secondaries. It is likely that they are mesotrons.