PHYSICAL REVIEW VOLUME 69, NUMBERS 9 AND 10 MAY 1 AND 15, 1946

A Cloud-Chamber Analysis of Cosmic Rays at 14,120 Ft.

WILSON M. POWELL
Department of Physics, University of California, Berkeley, California
(Received November 12, 1945)

Protons and mesotrons near the end of their ranges are distinguished from each other by a method involving the degree of ionization in the gas of the cloud chamber and the scattering in the lead plates in the chamber. Photographs are shown of the production of protons and mesotrons in the lead by non-ionizing and ionizing radiation. Evidence is presented for the presence of an extremely large number of neutrons. Both neutrons and protons are shown to be secondary particles with a maximum energy near 200 Mev. The conclusion is reached that this maximum energy arises from the large cross section of the atmosphere for the production of pairs of mesotrons. The value of this maximum energy can be used as a measure of the mass of the mesotron. Photographs are shown of cascade showers produced by knock-on electrons, stars produced in the lead and the gas of the chamber, and Auger showers filling the whole chamber.

INTRODUCTION

THE remarkable photographs of G. Herzog and W. H. Bostick[1,2] made with a Wilson cloud chamber between the altitudes of 20,000 and 30,000 feet and the great abundance of slow mesotrons found there both by this method and by Schein, Jesse, and Wollan[3] using counters at still greater heights made it seem advisable to take a large Wilson cloud chamber[4] to the top of Mt. Evans in the summer of 1940 with the hope of discovering the abundance of slow protons and mesotrons and other phenomena occurring there. About 2400 photographs were made, part of them with random expansions and part with counter control. The data obtained were of sufficient value to warrant a second expedition in 1941. This time 20,000 photographs were made of random expansions of the large Wilson cloud chamber, and the two sets of photographs form the subject of this paper.

APPARATUS

Figure 1 shows a side view of the cloud chamber. The front glass Q is 0.5-inch "Tufflex" plate glass. The walls are made of 0.5-inch cold-rolled steel. The lead plates A measure $1\times 9.4 \times 30$ cm. The area photographed was 42 cm high. Compressed air from a paint-sprayer compressor was introduced through six ports, one of which is shown at P. This forced the neoprene diaphragm J against the hole plate K when the chamber was compressed. When expanded, the diaphragm rested against the hole plate D. Nine bolts like those shown at E and F held the plate D in place and permitted the expansion ratio to be adjusted to the proper value. One side of the chamber N was $\frac{3}{8}$-inch "Tufflex." The light entered the chamber through this window and was reflected back by a sheet of chromium plated ferrotype plate on the far side of the chamber. This obviated the necessity for a window and light on the other side. Five lead plates, each one cm thick and spaced six cm apart, traversed the chamber. Small rubber tubes, OO, were placed around the edges making each compartment somewhat airtight. The plates were sheathed in thin chromium-plated ferrotype plates so as to improve the illumination and prevent glare from the surfaces of the lead plates.

The cloud chamber was filled with argon and a small amount of air. The tank argon had been in the tank for more than a year, so that very few alpha-particles from radon appeared in the gas. The liquid was normal propyl alcohol, and no particular precautions were taken about the presence of small amounts of water in the alcohol. Every other one of the lead plates was charged positively to 250 volts, and the rest were at ground potential. The field was removed at the instant of expansion. It was impossible to use any water in the chamber because the insulation of the alternate plates was insufficient.

[1] G. Herzog, Phys. Rev. **57**, 337 (1940).
[2] G. Herzog and W. H. Bostick, Phys. Rev. **58**, 278 (1940).
[3] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940).
[4] W. M. Powell, Phys. Rev. **57**, 1061 (1940).

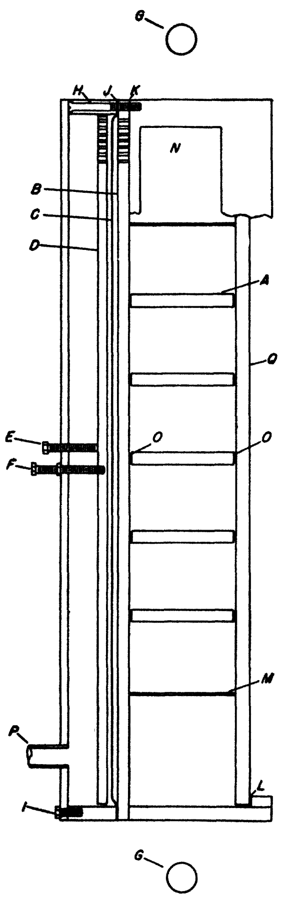


FIG. 1. Cloud chamber.

In 1940 eight coil-coil filament 60-watt, 115-volt clear Westinghouse bulbs with reflectors and condenser lenses were used for illumination. They were run at 240 volts d.c. from 40 second-hand car storage batteries purchased at junk price. The batteries were charged continuously at 125 milliamperes. The lamps were turned on at the moment of expansion and remained on for about 0.1 sec. The camera shutters remained opened continuously. In 1941 an Edgerton "flash lamp" 24 inches long and 0.5 inch in diameter with a cylindrical reflector behind and five double condenser lenses in front formed the source. Horizontal mirrors at the top and the bottom of the lamp-condenser unit gave even illumination at the two ends as well as the middle of the chamber. The lamp was flashed by the discharge of an electrical condenser of 250-microfarad capacity which was kept at 2000 volts by a voltage-controlled rectifier. This light was considerably brighter than the other, and consequently it was possible to use the cheaper DuPont Superior #3 film instead of the Agfa Ultra-Speed film.

The cameras were placed 30 degrees on either side of the normal to the chamber. In 1940 an F number of 3.5 was used for both cameras. In 1941 the camera on the left side nearest the light source used a lens with an F number of 2.5 while the other camera was the same as before.

The counter had a sensitive area of one by eleven inches. Two counters were placed above the chamber and one below, the three being in triple coincidence. In 1940 the cameras were reset by hand. In 1941 everything was operated automatically, and photographs were taken night and day except for about 14 hours during the week. All power was supplied by a 1000-watt 110-volt a.c. gasoline generator.

In 1940 the work was done in the laboratory of the University of Denver and Massachusetts Institute of Technology on the summit of Mt. Evans. In 1941 the apparatus was installed in a house-trailer. The trailer served as living quarters as well as laboratory and could be completely darkened for developing photographs. The walls were of sheet steel which covered the roof except for a small section in the top. Two 30-foot cables were attached to opposite corners of the trailer and buried a foot below ground as a protection from lightning. The generator was outside of the trailer.

DISCUSSION

There are three properties of the cosmic rays which permit identification of the rays with a Wilson cloud chamber containing five lead plates. First, there is the fact that electrons penetrating one cm of lead have a high probability of radiating and producing pairs, whereas protons and mesotrons have a very small probability of producing energetic secondaries. Second, the rate of change of the velocity of protons and mesotrons near the end of their range is quite different, and sufficiently so that they can be distinguished from each other by the appearance of the track just before stopping. Third, the scattering of mesotrons and protons is a function of their momentum and is greater for mesotrons having the same range as protons.

It is generally agreed that the probability of an electron penetrating a lead plate one cm thick without producing secondaries is small. Owing to the mathematical difficulties encountered in fluctuation problems in shower theory,[5] it has been impossible to calculate this directly. If a particle passes through two or more lead plates without producing secondaries, it is extremely unlikely to be an electron. This criterion is an excellent one for distinguishing between electrons and heavier particles.

The second and third properties can be combined to give a means of distinguishing mesotrons and protons which are near the end of their ranges. All singly charged particles possessing high velocities produce tracks with nearly the same ionization per unit length of track. There is a particular velocity where this ionization reaches a minimum, I_{min}. The ionization I increases quite rapidly as the velocity decreases. For all subsequent calculations the mesotron is assumed to have a mass of 200 times that of the electron.

Figure 2 shows the relative ionization I/I_{min} of protons and mesotrons plotted against the range in centimeters of lead. A proton with a range of 1.75 cm in lead will have a relative ionization of 3.25. This will be recognizable from inspection alone. Furthermore, when it leaves the next lead plate with a range of 0.75 cm, its relative ionization will be 4.65, and it will appear distinctly heavier than the section of track just above. A proton of shorter range will show a more marked change. A mesotron will have an entirely different appearance. If it has a range of more than 0.2 cm in lead, it will show no appreciable increase in ionization. Mesotrons then can be expected to stop in a lead plate without showing increase in ionization. Some will penetrate the last plate and leave it with less than 0.2 cm range. These will show a heavier track, but there will be no increase in ionization above this plate.

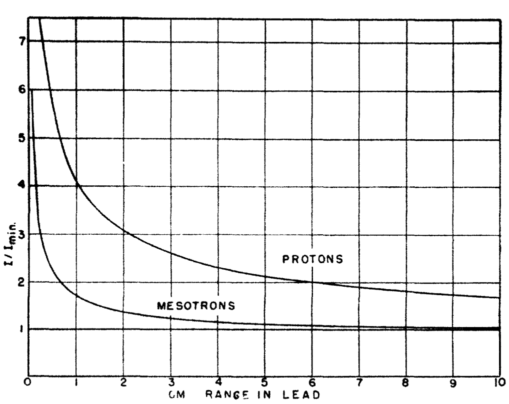


FIG. 2. Relative ionization of protons and mesotrons against range in cm lead.

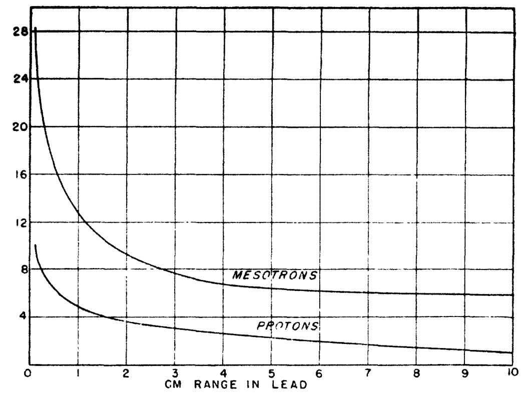


FIG. 3. Average projected angle of scattering in degrees for one cm of lead plotted against the range the particles have in cm of lead on leaving the plate.

There are occasions when the illumination of the track above and below a lead plate is not uniform, and there is some doubt about the proper interpretation. It is here where the use of scattering properties comes to the rescue and extends the data for mesotrons to much higher energies. Range and relative ionization were calculated from the paper by J. A. Wheeler and R. Ladenburg.[6]

IDENTIFICATION OF MESOTRONS AND PROTONS BY THEIR SCATTERING AND IONIZATION

Figure 3 is a graph of the average projected angle in degrees of scattering of mesotrons and protons through one cm of lead against the range in lead possessed by the particle on leaving the lead plate. It is calculated from the expression[7]

$$\bar{\theta} = (19.5 - 3.1 \log_{10} Z)^{\frac{1}{2}} \frac{600Ze}{\beta E} (Nt)^{\frac{1}{2}}, \qquad (1)$$

where Z is the atomic number of the scatterer, e the charge on the electron, N the number of

[5] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 305 (1941).

[6] J. A. Wheeler and R. Ladenburg, Phys. Rev. **60**, 754 (1941).

[7] E. J. Williams, Proc. Roy. Soc. **A169**, 548 (1939).

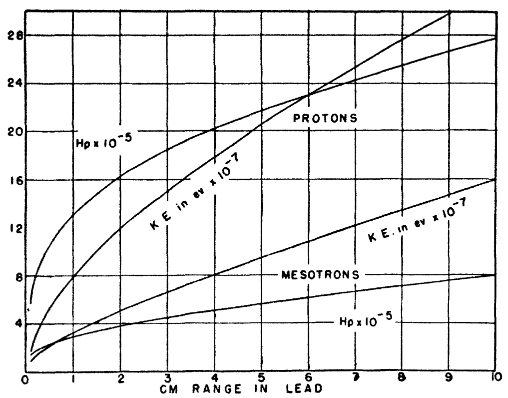


FIG. 4. Kinetic energy and magnetic rigidity ($H\rho$) of protons and neutrons.

atoms per cm^3, and t the thickness in cm. This reduces to

$$\bar{\theta}=3\times10^6/H\rho\times\beta, \qquad (2)$$

where $H\rho$ is the magnetic rigidity and β is the velocity of the particle divided by the velocity of light.

Figure 4 gives the values of the magnetic rigidity and the kinetic energy for protons and mesotrons as a function of their range in lead.

In calculating the angle of scattering it is necessary to use the average value of the magnetic rigidity for the plate. This is a very uncertain quantity near the end of the range of a particle, owing to the rapid change of $H\rho$. For this reason the plates were divided into sheets one mm thick and the corresponding angles calculated. The angle for a one-cm plate was calculated by taking the square root of the sum of the squares of the ten angles for the corresponding ten sheets. This was done up to a range of 1.5 cm. From there on the average value of the magnetic rigidity is sufficiently definite to permit the use of Eq. (2) directly.

The cameras were situated at 30 degrees on either side of a normal to the chamber. If this angle had been 45 degrees, the angle between the cameras would have been 90 degrees, and the scattering angles observed by each camera would have been independent of each other. As it is, there is a small dependence, but for the sake of argument the two sets of angles are assumed to be independent of each other. If this is assumed, then each traversal gives two observations of the projected angle of scattering. Since there are five lead plates in the chamber, as many as ten angles appear for those rays which penetrate all five plates.

Williams' formula was checked for protons by the following method. Fifteen proton tracks were measured. The particles were identified by the increases in ionization after traversals of the lead plates. All fifteen tracks passed through two plates, seven through three plates, five through four, and two through five. The averages of the angles starting with the plate nearest the end of the range of the particles are 10.1, 5.3, 2.4, 1.1, and 1.2 degrees. This is in reasonably good agreement with the curve for protons. If anything, it indicates that the scattering of protons decreases more rapidly with increase in range than the theory would predict.

Figure 5a shows a proton track. Figure 5b is undoubtedly a mesotron track. It shows no increase in ionization. Therefore, if it were a proton, it would have to have a range greater than 1.75 cm when it leaves the last plate, for otherwise it would show an increase in ionization. The average projected angles p_i for a proton would be less than 3.7, 3.1, 2.7, and 2.4 degrees for the successive traversals, whereas the observed angles Θ_i are very much larger than this. There is a finite chance that a proton would stagger through the lead as shown. This chance can be calculated from the X^2 function where

$$X^2=\frac{2}{\pi}\sum_{i=1}^{n}\theta_i^2/p_i^2.$$

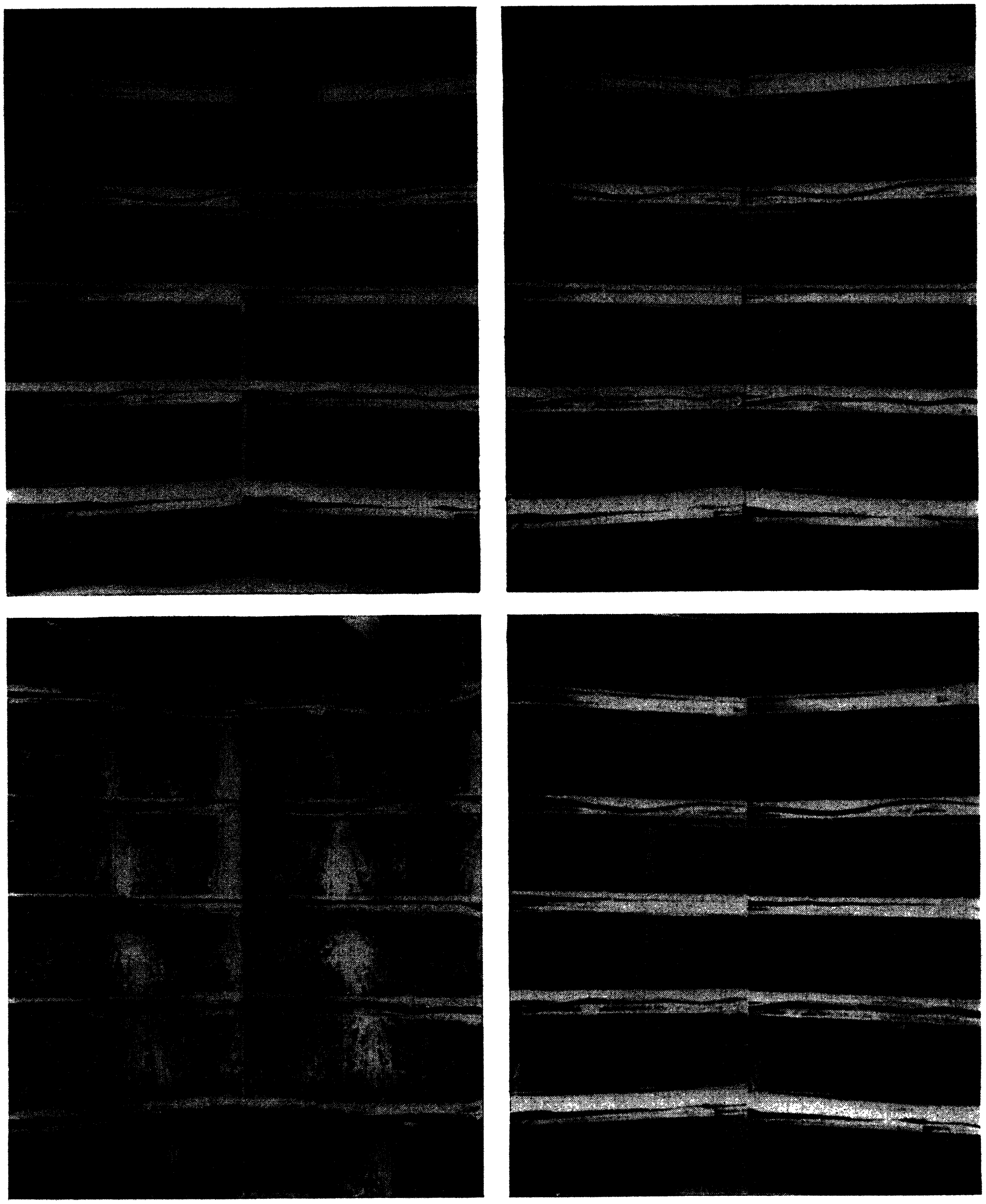
A table for the X^2 function gives the proportion P of protons of range greater than 1.75 cm that will show scattering angles equal to or greater than the observed angles.

The particle in Fig. 5b shows such large scattering angles that the value of P is extremely small. Since other evidence shows that there is an abundance of mesotrons, this small value of P indicates that the particle is *extremely unlikely* to be a proton and therefore must be a mesotron.

METHOD OF COUNTING PICTURES

Since approximately seventeen rays appear in each picture, it is very worth while to use a method which will depend upon counting only conspicuous events. For this reason a basis for

a b



c d

FIG. 5. a. A proton penetrating five plates and showing two increases in ionization at the end. b. A typical mesotron track identified by its large scattering. c. A cascade shower obtained with counter control. d. A cascade shower obtained in a random expansion.

all phenomena was taken as the number of particles penetrating two or more lead plates without producing secondaries. An exception was made to this rule if a particle penetrated two or more plates in a nearly straight line but had a secondary particle appearing with it. The secondary particle was interpreted as a knock-on electron instead of an electron resulting from radiation.

In general the heavy penetrating particles produce tracks showing light ionization. If the cloud chamber was operating poorly or with insufficient illumination, some of these tracks might have been missed while heavily ionizing tracks would continue to be counted. A careful comparison of pictures made with entirely different illuminating systems showed this not to be the case. Runs made in 1940 were compared with pictures made in 1941, and no appreciable difference appears. There is evidence that the sensitive time of the chamber varies from one set of pictures to another. Over a group of 100 pictures made in 1940 the average number of rays excluding the very large showers was 11 per picture. A run of 200 pictures made in 1941 showed an average of 21 rays per picture. This high number does not persist throughout all the 1941 pictures and in some cases drops to values in the neighborhood of six per picture. Nevertheless the relative number of different kinds of events remains unaffected by this change in the sensitive time of the chamber.

PROTONS, MESOTRONS, AND THE DISINTEGRATION ELECTRON

Table I is a collection of data on heavy particles identified by the three methods mentioned above. The top row entitled "Penetrating rays" refers to all rays traversing two or more plates without producing secondaries.[8] Column N_2 gives the percentage of penetrating rays traversing two plates and not more than two plates. Column N_3 gives the percentage of penetrating rays traversing three and not more than three plates, etc. From these values we get a distribution of penetrating particles which in itself means little. However penetrating rays have been chosen as the basis for counting phenomena of all sorts, therefore this analysis is fundamental for what follows. Actually from this analysis it will be shown that the protons in cosmic rays at this altitude are secondaries with a limited range of energy.

[8] See further qualifications above.

TABLE I. Compilation of data.

	Total	N_2	N_3	N_4	N_5	Pen. rays	Pictures
Penetrating rays	6918	51.9	24.1	12.4	11.1	6918	21,885
Mesotrons	312	49	24	17	10	4775	14,525
Mesotrons stopped	53	53	25	9.4		4775	14,525
Mesotrons*	12					4775	14,525
1 plate mesotrons	7					4775	14,525
Heavy I mesotrons	17					4775	14,525
2 plate protons	72	75	19.5	4.1	1.4	4775	14,525
1 plate protons	202					4775	14,525
Scattered rays	738					4775	14,525
Heavy I particles	2984					6918	21,885

* This group of mesotrons showed evidence of the disintegration electron. "Heavy I mesotrons" means mesotrons showing heavy ionization. "Heavy I particles" means tracks showing heavy ionization.

The row in Table I indicated at "2 plate protons" refers to particles identified as protons which penetrate two or more plates. A comparison of the percentages of protons penetrating different numbers of plates with those for penetrating rays or mesotrons shows at once that protons have a limited range. The proportion of protons traversing a few plates is considerably greater while the proportion traversing all five plates is *seven times smaller*. This means that at energies necessary to penetrate five lead plates the energy distribution curve for identifiable protons is falling off very much more rapidly than for all the penetrating rays. The identifiable mesotrons (see "Mesotrons" Table I) do not show this falling off in energy. Their distribution is identical with that of the penetrating rays. Therefore we can state that the protons are dying out at energies around 200 Mev. On the other hand at low energies they are very much more abundant. In the same group of penetrating particles 202 protons were observed which penetrated one plate only. In a group of 100 penetrating particles passing through two or more lead plates, there were 72 particles penetrating only one plate which could be interpreted by their lack of scattering and lack of accompanying secondaries as penetrating particles. This proportion is again smaller than that for protons.

This anomalous behavior of the protons is in agreement with the work of G. D. Rochester and M. Bound[9] who found a marked decrease in the number of slow protons at sea level when ten cm of lead were placed over their cloud chamber. They concluded that the protons have a short range less than ten cm of lead and that either more protons are produced in the air outside the chamber than in the lead or that the radiation producing the protons is filtered out by the lead. The fact that equilibrium is not established follows from the observation that only 4.7 percent of the protons are created in the lead plates of the chamber. There is no positive indication that the rest are not created in the walls of the chamber, but this seems unlikely in view of the fact that so much of the available material is concentrated in the lead plates. Furthermore, the creation of slow protons is always accompanied by other penetrating particles when it occurs in the lead, and these would be likely to show up with the protons from the walls. One case of this was observed, and that proton was included in the number created in the chamber. If we include all the penetrating particles created in the chamber with a range of more than one cm of lead and not identifiable as mesotrons, this amounts to only 12.2 percent of those stopped in the chamber. There seems to be no way of looking at the facts which is consistent with the assumption of equilibrium. We are forced to the conclusion that there is a group of protons of energy less than 200 Mev amounting to about 3.3 percent of the penetrating rays and that their number decreases very rapidly with increasing energy.

In this same group of particles there appeared 738 particles which showed at least one scattering angle of more than four degrees. Out of this group 312 particles could be identified as mesotrons by using the X^2 criterion. (Fig. 5b shows a typical scattered mesotron. It passes out of the back of the chamber.) Twenty-four percent of the mesotrons satisfied the condition that P is ten percent. This means that only ten percent of a group of protons which left the last plate with a range of 1.75 cm in lead would give angles equal to or greater than those observed. Because protons were scarce compared to mesotrons, this low value of P means that the particles in this group were very likely to be mesotrons. Thirteen percent of the particles gave a P equal to five percent, and the remaining 63 percent gave a P less than one percent. The distribution of the 312 particles matches that of the penetrating rays within the statistical error (see "Mesotrons," Table I). This indicates that the maximum in the energy distribution curve for mesotrons is well above 200 Mev in line with the majority of the penetrating rays.

Fifty-three mesotrons in this group stopped in the chamber. Ten of these passed through only one plate and identified themselves by large scattering angles and heavy ionization on one side of the plate. When the number of mesotrons which passed through two or more plates and showed heavy ionization were compared with those which failed to show heavy ionization, the proportion showing heavy ionization was found to be 22 percent. This is about the proportion which would be expected. The maximum range for a mesotron leaving a lead plate and showing heavy ionization is approximately 1.75 mm, which would indicate that about 18 percent of the rays stopping should show heavy ionization.

The cloud-chamber technique used here does not permit positive identification of the disintegration electron produced from a decaying mesotron. The following events, however, can be interpreted as mesotron disintegrations though the evidence that they are disintegrations cannot be conclusive.

In eight pictures a thin track appeared at the end of a mesotron track. The thin track was considered not to be the mesotron itself because of the very large angle it made with the mesotron track. In some of these cases the end of the mesotron track showed heavy ionization and then came a thin track at a large angle. Because of the presence of these thin tracks, it is possible to say that there is not negative evidence of the disintegration electron. Figures 6a and b show examples of this. In b the track occurs some

[9] G. D. Rochester and M. Bound, Nature **146**, 745 (1940).

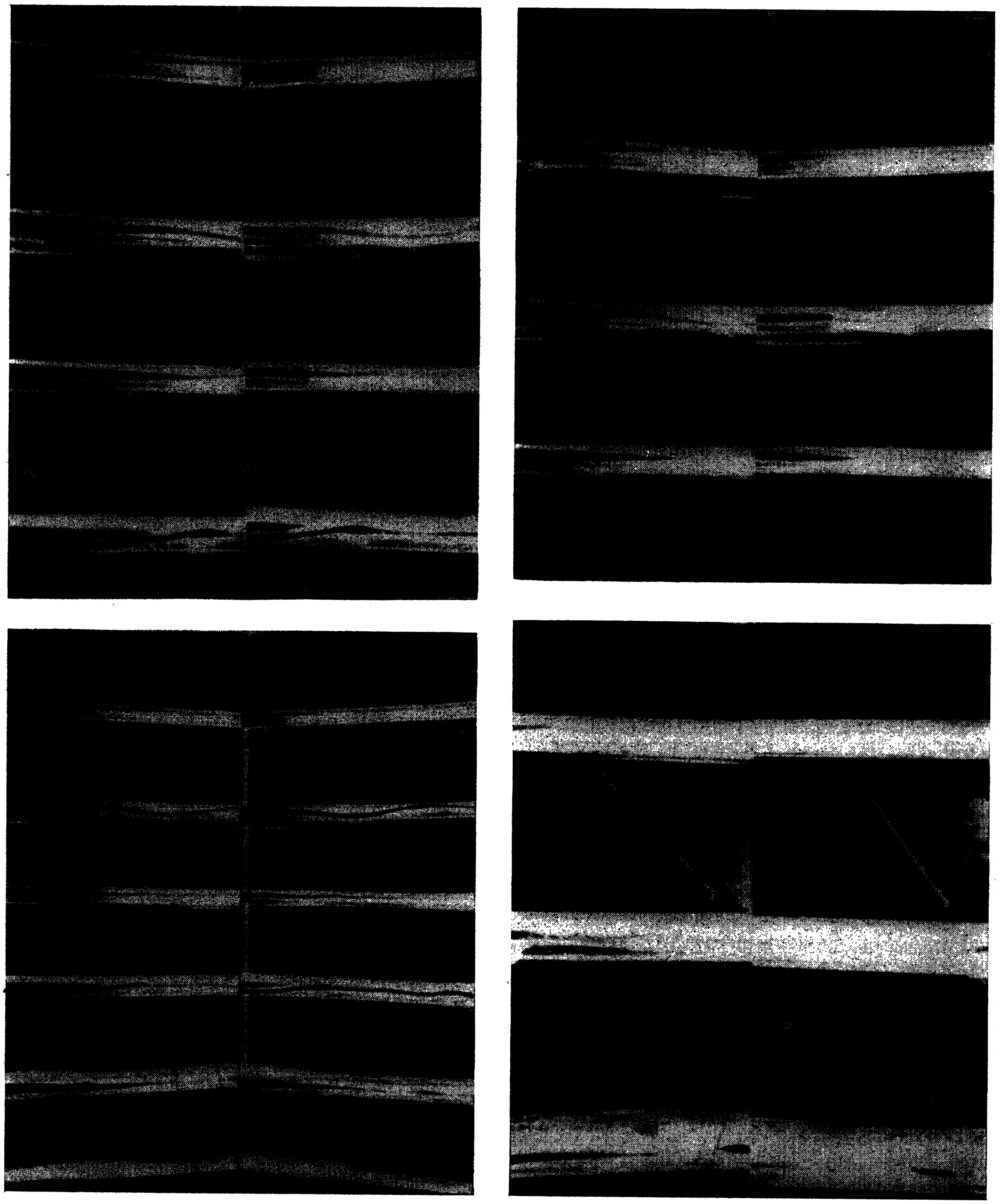


FIG. 6. a. A mesotron showing heavy ionization after the last traversal and a particle below the last plate which can be interpreted as the disintegration electron. b. A mesotron stopping in the bottom plate identified by its stopping and by the delta-ray. The particle going upwards near the end of the mesotron track may be the disintegration electron. c. A mesotron identified by scattering and a single increase ion ionization. d. Probably a mesotron disintegrating in the gas of the chamber and showing the disintegration electron.

distance to the right of the mesotron. The mesotron so near the end of its range could scatter sideways in the lead and then shoot the disintegration electron upwards.

Figure 6d shows a heavy track ending in the gas of the chamber with a thin one leaving the end. This photograph is the nearest approach to a proof of the existence of the disintegration electron that has been obtained with this chamber. It fails to indicate the direction of the particles except for the fact that the end of the heavy track is slightly kinked. This kink would indicate that the particle producing the heavy track stopped or nearly stopped and then produced the electron track. On the other hand, the two particles might have been ejected from an atom excited by a neutron or a photon, or the electron itself might have caused an atom to eject a neutron and the heavy track. The picture of the disintegration electron by E. J. Williams[10] has the same appearance at the end of the heavy track. It must be emphasized that all of the pictures shown here can be interpreted only as negative evidence that there is no disintegration electron.

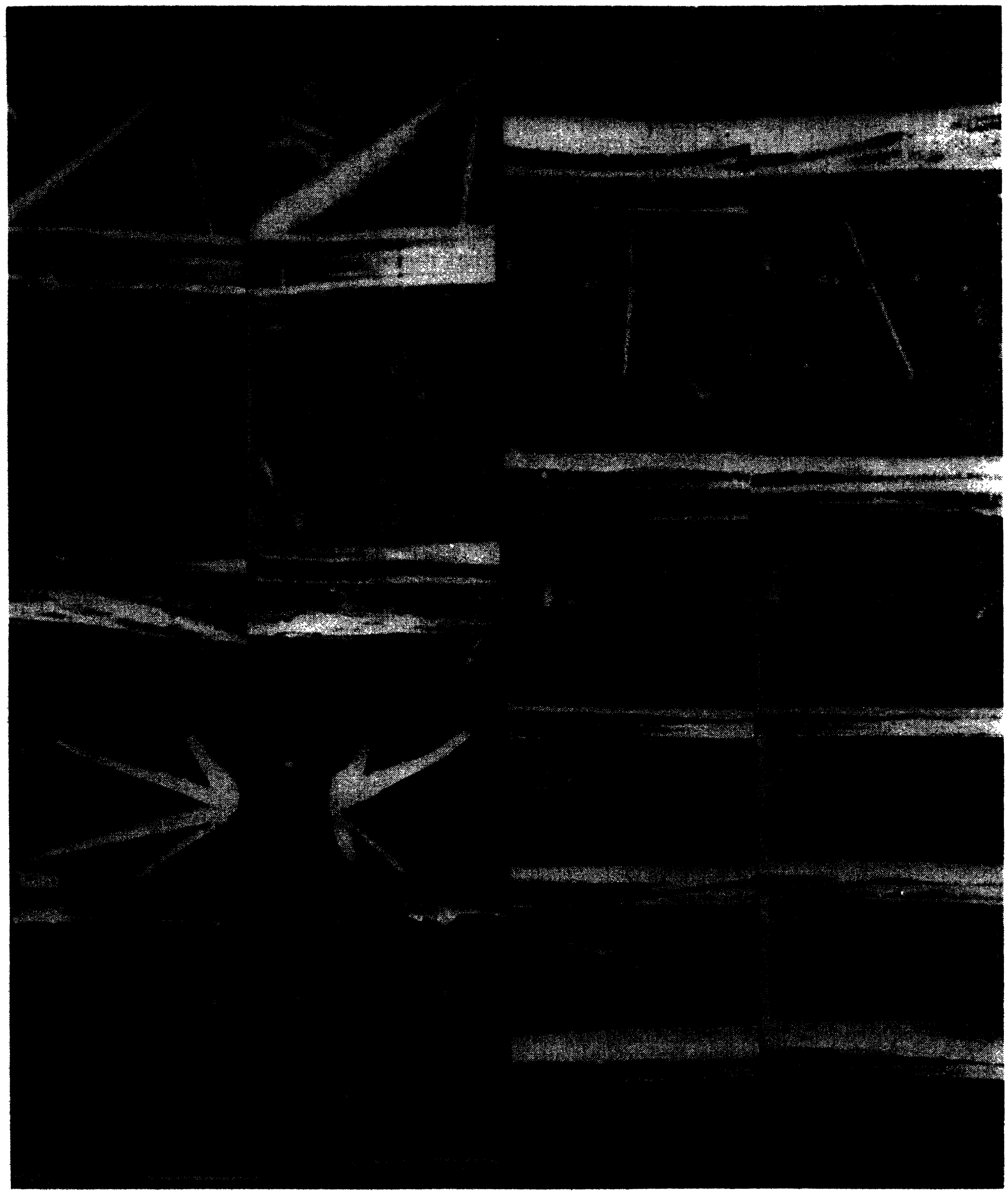
In a group of 9500 pictures containing 1413 heavy tracks 75 of these heavy tracks ended in the gas of the chamber. These were not alpha-particles. This means that approximately 360 heavy particles stopped in the gas out of the 6918 penetrating particles appearing in the chamber. Figure 6d is the only case of its kind. The extreme scarcity of this phenomenon leads to two possible conclusions. First, that the production of a disintegration electron by a mesotron is very unlikely; second, that most of the particles stopping in the gas are protons. Nothing much can be said about the first, but there are two pieces of evidence which contradict the second. First there is the discovery of D. M. Bose and B. Choudhuri[11] that most of the particles appearing in stars in photographic plates left at altitudes of 12,000 ft. and 14,500 ft. are mesotrons, and second, the fact discussed below that when the reaction is energetic enough for the particles to be identified, there are at least three cases where both protons and mesotrons are produced simultaneously, and at least four cases where a mesotron is created by itself. Of the 52 penetrating particles which passed through two or more plates and were created in the chamber, 8 could be identified as mesotrons, 17 as protons, and the remaining 27 could not be identified. There is one more fact which can be interpreted as an indication that more of these particles are mesotrons. The range of a proton is about ten times greater than the range of a mesotron with the same ionization. This means that mesotrons showing the same ionization as protons are ten times more likely to stop in the gas. Opposing these two arguments there is the fact noted above that the number of slow protons increases very rapidly as their energy decreases. An extrapolation of this behavior to very low energies would indicate that most of the particles in the gas were protons. Then there is the

TABLE II. Data on heavily ionizing rays.

	Total	Heavy I rays	Per-cent of heavys	S_2	S_3	S_4	S_{5-6-7}	Pene-trating rays	Pic-tures
Heavy I rays	2050	2050	100					4775	14,525
All stars	156	2428		103	27	19	5–1–1	5629	18,909
Air stars	13	2984		6	4	2	1–0–0	6918	21,885
Stars upwards	16	2428		12	3	1	0–0–0	5629	18,909
Heavys in stars	358	2428	14.7					5629	18,909
2 plate protons	72	2050	3.5					4775	14,525
1 plate protons	202	2050	9.8					4775	14,525
Heavy I mesotrons	17	2050	0.8					4775	14,525
Stopped mesotrons	53	2050	2.6					4775	14,525
Alpha-particles	208	2050	10.1					4775	14,525
Unidentified heavy I	1541	2050	75.2					4775	14,525
Single unidentified heavy I	1254	2050	61.2					4775	14,525
Created mesotrons	8	2984	0.29					6918	21,885
Created protons	17	2984	0.63					6918	21,885
Created unidentified penetrating particles	27	2984	1.0					6918	21,885
Total created	52	2984	1.92					6918	21,885
Heavy I particles stopped in gas	75	1413	5.3					3186	9,500

[10] E. J. Williams, Nature **145**, 102 (1940).
[11] D. M. Bose and B. Choudhuri, Nature **148**, 259 (1941).

a b



c d

FIG. 7. a. A star in the gas of the chamber showing evidence that the left-hand particle was emitted a few thousandths of a second after the right-hand particle. b. The old horizontal track removed the water vapor from its neighborhood so that a gap appears in the vertical heavy track formed after expansion of the chamber. c. A star in the gas of the chamber showing evidence of neutrons. d. A star in the gas of the chamber with a thin track passing obliquely through the plate just below.

observation of C. D. Anderson and S. H. Neddermeyer[12] that "wherever the direction of the particles is definitely known (as for particles produced by a disintegration occurring inside the chamber), the sense of curvature in the magnetic field is such as to indicate a positive charge." Furthermore, if the assumption is made that the 38 tracks appearing singly in A. and N.'s pictures are going down, then 33 of them are positively charged and five are negatively charged.

In conclusion it can be said that the only strong argument in favor of the slow particles being mesotrons is the one advanced by D. M. S. and B. C. If the particles are all positive and are mesotrons, they are sure to show disintegration electrons. The almost complete absence of the disintegration electron, the increase in the number of protons at low energies, and the strong likelihood that they are all positive give almost overwhelming evidence that the slow particles are protons.

HEAVILY IONIZING RAYS

In a series of 14,525 photographs containing 4775 penetrating particles which pass through two or more plates, there appear 2050 tracks showing heavy ionization. Protons and mesotrons penetrating two or more plates and showing heavy ionization account for 89 of these. The heavy particles can be divided into the following categories (see Table II). Ten percent are alpha-particles, 3.5 percent are protons passing through two or more plates, 9.8 percent are protons passing through only one plate, 0.8 percent are mesotrons passing through one or more plates. This leaves 75 percent of the heavy particles unidentified. The particles in stars coming from either the gas or the lead amount to 14.7 percent. The remaining 61 percent appear singly, starting in the lead and stopping in the next piece of lead or the gas or leaving the chamber. It is open to conjecture as to how many of these are slow mesotrons.

In Table II the columns marked S_2, S_3, etc. give the number of stars with two, three, etc. particles per star. All the stars produced in the gas except the one of five particles appear to be excited by non-ionizing radiation. This star is shown in Fig. 7d. It is probably excited by non-ionizing radiation, but it might be interpreted as being excited by the thin ray passing through the bottom lead plate. This ray is evidently a heavy particle traveling very fast as there is very little scattering in the bottom lead plate. (The reproduction fails to show the thin ray on the far side of the plate.) However, it may perfectly well be coming from the star itself with the star being exited by non-ionizing radiation, as is usually the case.

Two of the stars have the appearance of the one shown in Fig. 5a. A small gap appears at the intersection of the two particles. Figure 7b shows how this might have happened. Here a sharp heavy track evidently laid down after the expansion of the chamber crosses an old diffuse track. The formation of the droplets along the old track robbed the gas of alcohol vapor and heated it with the heat of condensation so that when the vertical track formed conditions for droplet formation were unfavorable at the intersection. The left-hand track in the star appeared first and was followed after a very short time by the right-hand particle. The heavy ionization indicates that the particles were probably alpha-particles.

Photographs similar in appearance to Fig. 7a appear when actinium A is formed and decays in a cloud chamber.[13,14] In W. E. Bennet's paper, Fig. 4b, Plate 1, and in C. T. R. Wilson's paper, Fig. 1, photographs appear which show the gap placed in an exactly similar manner. The mean lifetime of actinium A is 0.0019 sec. In its formation and decay alpha-particles are ejected with ranges longer than the tracks appearing here.

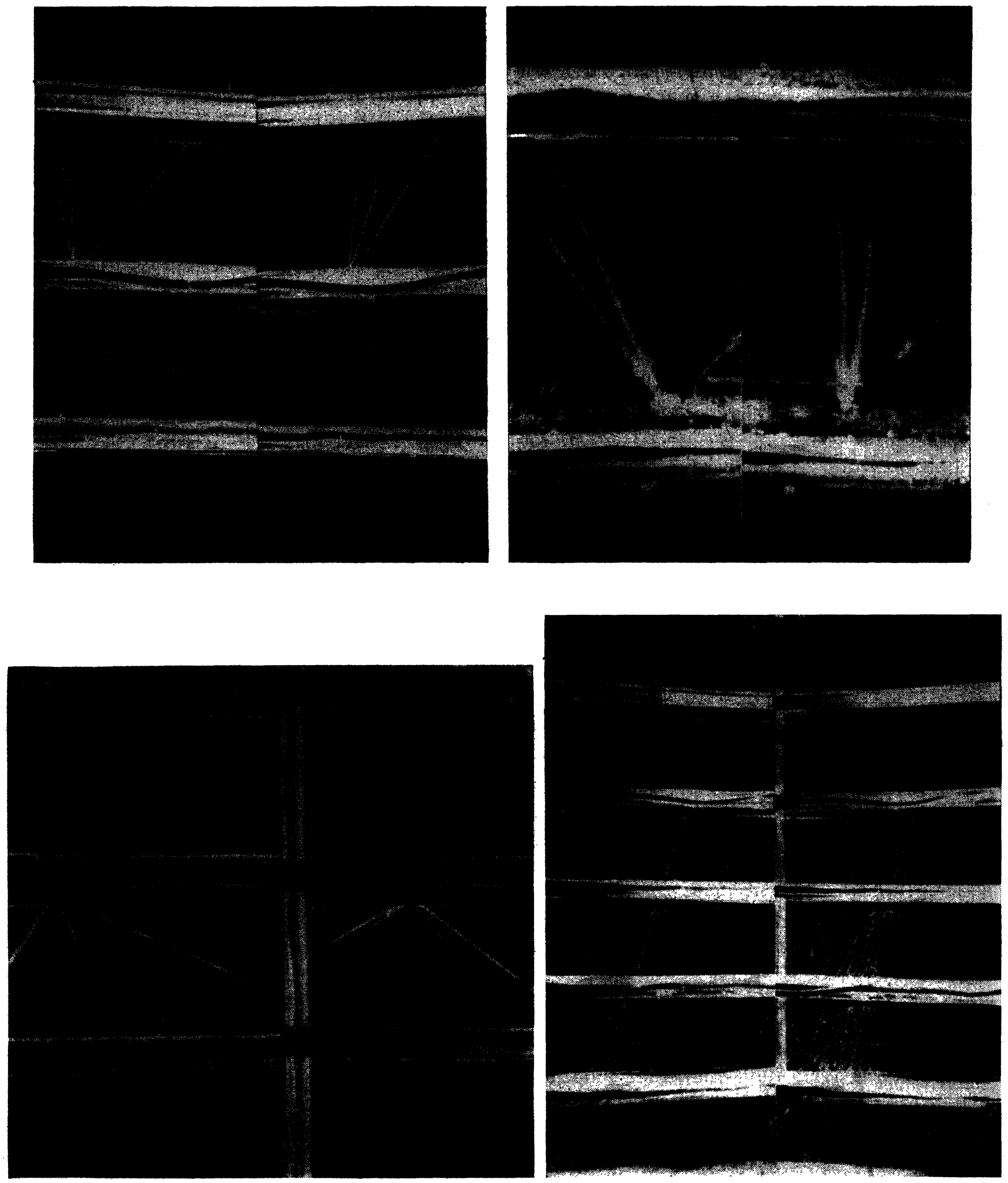
There are difficulties in assuming that actinium A is responsible for these tracks. The argon gas was prepared by distillation from liquid air but had been in its container for over a year. Even if the walls of the chamber were very radioactive, which they do not appear to be, it is difficult to see how enough of the parent gas actinon could leave the walls so as to produce these stars in the middle of the gas. We can conclude that these stars indicate the presence of an atom which may be excited by non-ionizing

[12] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).

[13] C. T. R. Wilson, Proc. Camb. Phil. Soc. **21**, 405 (1923).

[14] W. E. Bennet, Proc. Camb. Phil. Soc. **34**, 282 (1938).

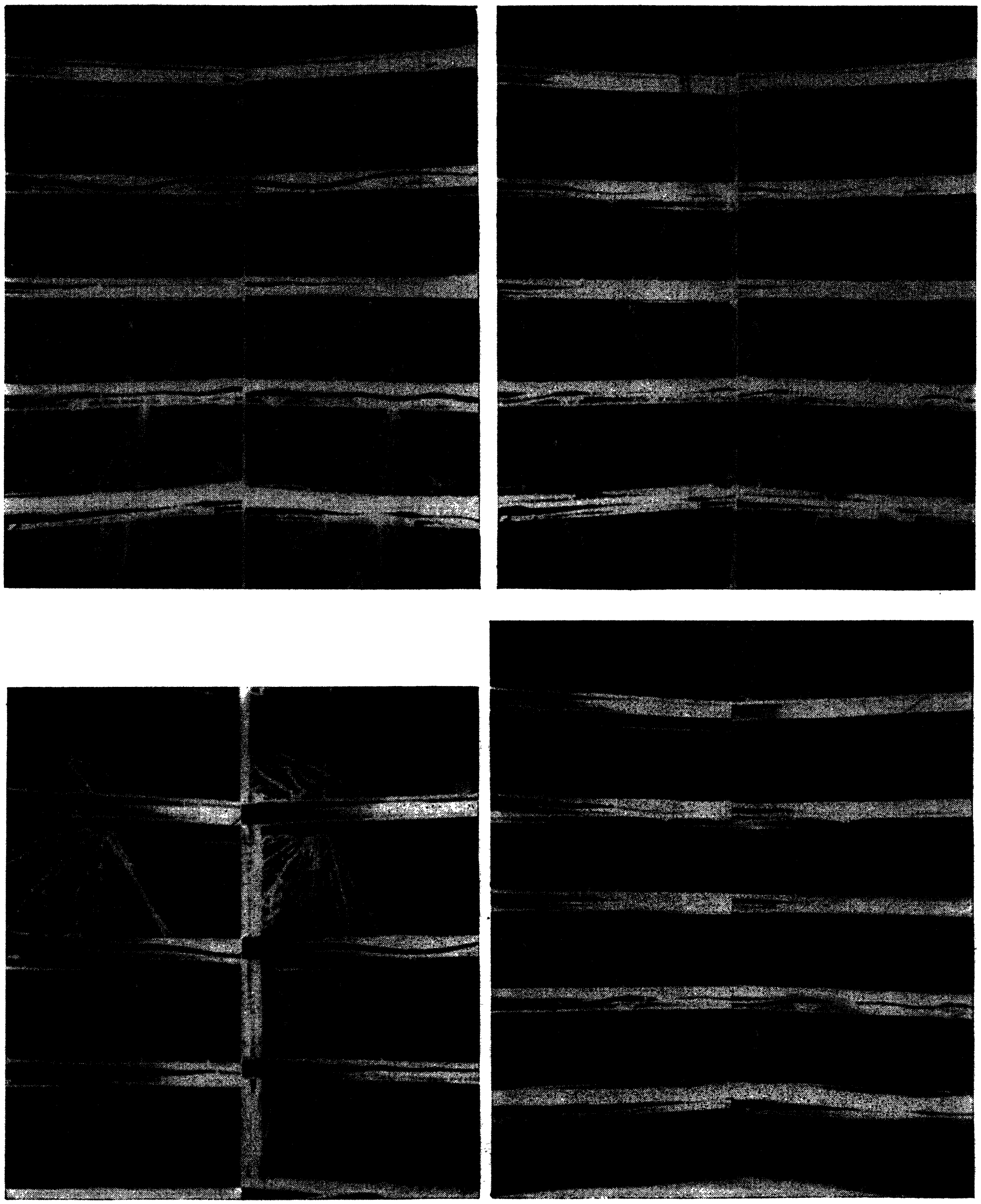
a b



c d

FIG. 8. a. A disintegration in the lead showing no thin tracks. b. A disintegration in the lead. c. A disintegration in the lead. d. A cascade shower produced by a penetrating particle.

a b



c d

FIG. 9. a. The only case where a heavy particle and a cascade are associated. The right-hand particle above probably initiates the cascade and the particle above to the left which shows by its ionization that it is going up is a proton. b. A penetrating particle produces a proton (lower left) and a particle which may be a mesotron (lower right). c. Two particles enter above and produce one mesotron which penetrates the lower plate, shows scattering and increase in ionization. There are three heavy tracks and at least fifteen thin tracks. d. A penetrating particle produces one heavy track and five thin tracks.

radiation so that it ejects an alpha-particle, has a lifetime in the neighborhood of 0.002 sec., and then ejects another particle.

The four-particle star shown in Fig. 7c on reprojection is found to be going back into the chamber. The star initiates near the middle of the chamber, and two of the particles strike the back of the chamber. One stops in the gas, and one hits the lower lead plate. In order to satisfy the law of the conservation of momentum, it is necessary to assume that neutrons are taking part in this event, either initiating it or pouring out of it or both.

Typical examples of stars originating in the lead plates are shown in Figs. 8a, b, and c. Most of the particles in the stars showed heavy ionization, the number being 358 particles. There were 43 particles accompanying these stars which appeared thin. Not more than one thin track appeared in most stars. No event was called a star if there were no heavy particles in it. Practically all stars were initiated by non-ionizing radiation.

CASCADE SHOWERS PRODUCED BY PENETRATING PARTICLES

There are fifteen cases where cascade showers are produced by penetrating rays. There are five where the penetrating ray traverses one plate, six where it traverses two plates, and four where it traverses three plates. In one case shown in Fig. 9a a proton was ejected upwards and a cascade appeared below. Since there were 19,436 traversals of one cm of lead by penetrating particles which passed through two or more plates the cross section per electron is about 2×10^{-28} cm^2. Figure 8d shows the largest shower produced by a penetrating ray. Its energy is about 1000 Mev. A close inspection of the rays at the top of the picture shows that all but one of the tracks are older (more diffuse) than those appearing in the shower. It seems very unlikely that an electron with sufficient energy to produce this large cascade shower could have passed through the top lead plate without producing secondaries. The particle is undoubtedly heavier than an electron.

PENETRATING PARTICLES PRODUCED BY IONIZING RADIATION

There are twenty-seven events in which penetrating particles are produced by ionizing radiation, and in all cases but one there is no evidence whatsoever that they are associated with cascade showers. The exception to the rule is shown in Fig. 9a. A proton is ejected upwards as is indicated by the increase in ionization of the left-hand ray. The right-hand ray is distorted by turbulence in the chamber but is uniformly thin. It is probably the ray which initiates the cascade shower and the proton. There is always the possibility that any ray appearing above any of these events may be traveling upwards with sufficient velocity to show no change in ionization. It seems to be more likely that the thin particle appearing above is the cause of the event.

Figure 9b shows a penetrating particle which passes through two plates and then produces at least four heavy particles. The lower left-hand one is identifiable as a proton both from its ionization which is obviously heavier than the thin tracks present, and by the delta-ray which indicates a velocity for the particle for which a mesotron would show very large scattering. The long ray on the right side is both thin and scattered. It is probably a mesotron though the scattering is insufficient to determine this with assurance. The two heavy tracks are unidentifiable except for the fact that they must be either either mesotrons or protons.

Figure 9c shows two particles coming into the top plate. Two heavy tracks appear which stop in the next plate. One particle penetrates through two plates and appears heavy under the last plate and markedly scattered. This is a mesotron. Two of the thin tracks can be identified as electrons because of their scattering in the gas. The remainder are probably electrons but might be mesotrons.

In Fig. 9d the penetrating particle is without question coming from above as is indicated by the knock-on electron under the second plate. The heavy particle ejected upwards stops in the gas. The particle starting just above the fourth plate on the left passes down through the fourth and fifth plates and produces a knock-on electron which is the track farthest to the right below the fifth plate. It is just a coincidence that this particle with its knock-on happens to be in the picture. The left-hand particle passing through the fifth plate may very well be a penetrating

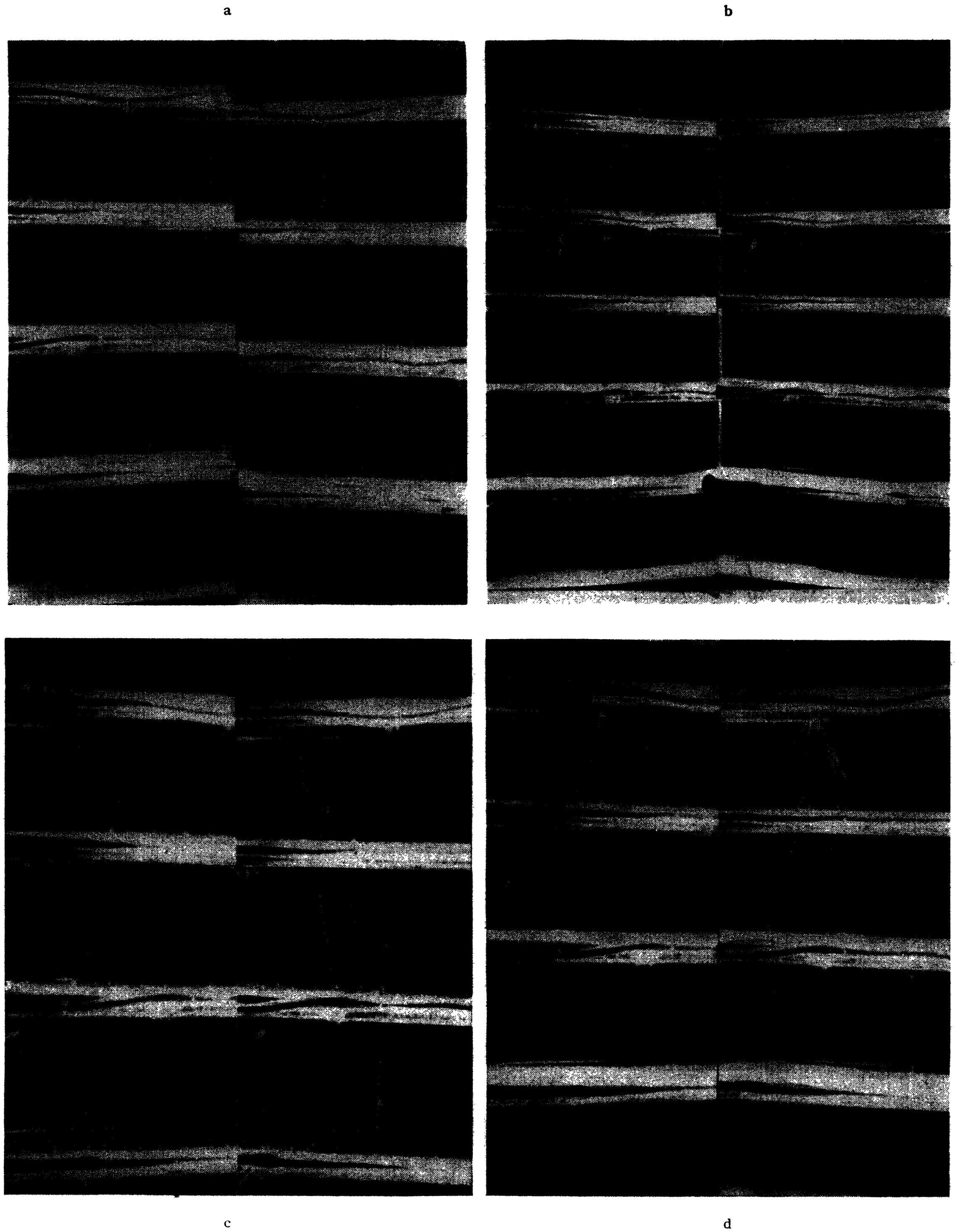
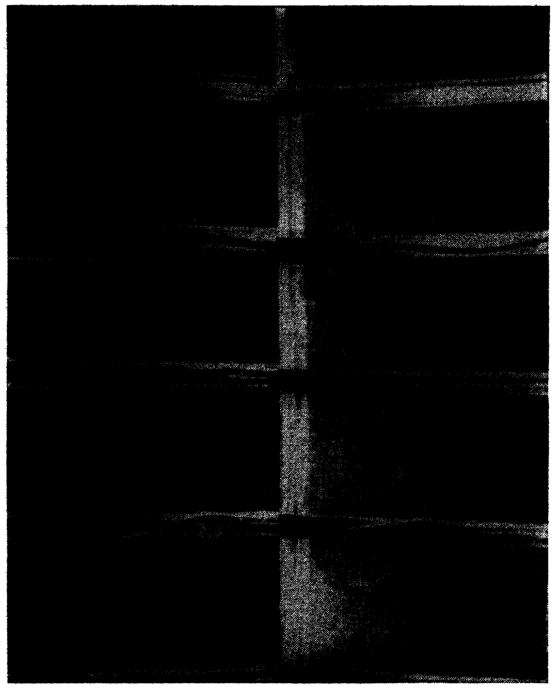
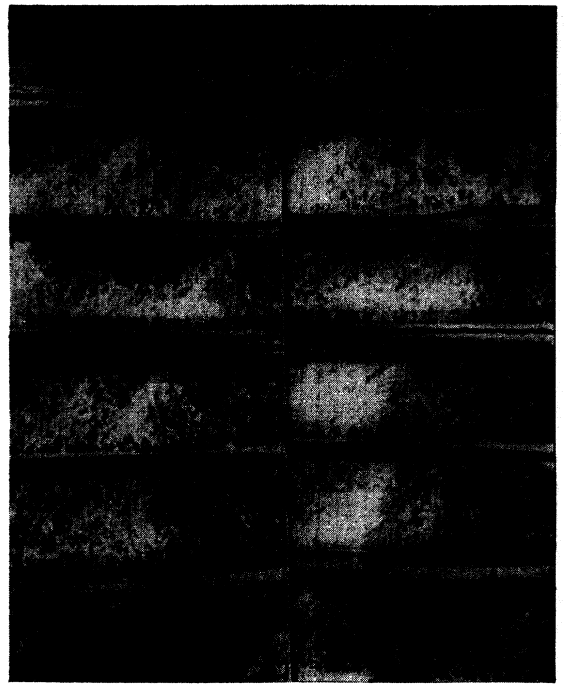


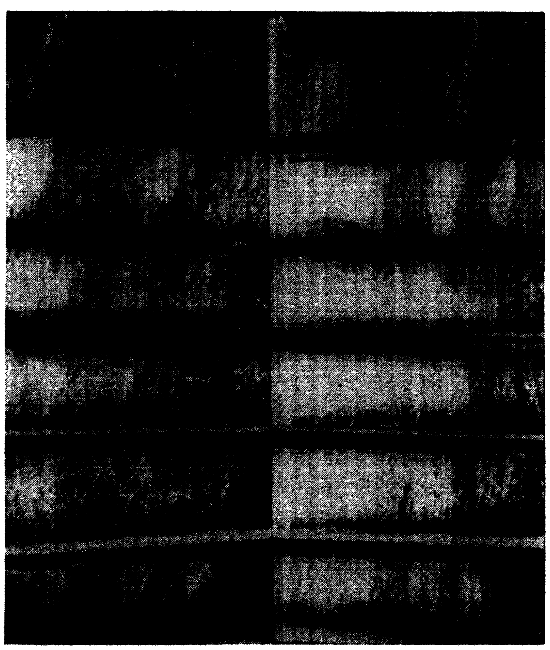
FIG. 10. a. A penetrating particle produces one heavy track and five thin ones. b. A penetrating particle produces at least four heavy particles, one of which is a proton and one a mesotron. c. Non-ionizing radiation produces two protons. d. Non-ionizing radiation produces one proton (lower right) and one mesotron (lower left), the latter stopping in the lead plate.

a



b





c

FIG. 11. a. Non-ionizing radiation creating a mesotron which stops in a lead plate and shows a track at the end which can be interpreted as the disintegration electron. b. Auger shower coming in at an angle of about 45 . It appears to be made up of many cascade showers. c. Huge Auger shower going straight down.

particle. It shows some scattering and may be a mesotron.

Figure 10a shows a penetrating particle producing two heavy tracks and a number of thin tracks in the bottom plate. It is not at all unlikely that this event would show other penetrating particles if the rays below had had the opportunity to pass through additional pieces of lead.

Figure 10b has appeared before[15] and further study has led to the definite identification of two of the particles. The track which penetrates the second plate and then becomes very thick is without doubt a proton. A study of tracks appearing in the same part of the chamber in other photographs on the same film show that the apparent greater density of the track before it passes through the second plate is real. This alone makes it impossible for the particle to be a mesotron. No additional argument is needed, but the average scattering angle for a mesotron so near the end of its range is very large, and the photograph shows that both scattering angles give an average of only two degrees. The track which penetrates three plates presents scattering angles that only one proton in twenty would show. There is little doubt that this is a mesotron. The particle which penetrates two plates presents angles that only one proton in eight would show. This picture affords unmistakable evidence for the *simultaneous production of mesotrons and protons*. Still another picture appears of this process. The event takes place in front of the chamber, so that it is impossible to identify the incoming ray. A proton penetrates one plate and shows increase of ionization on both sides of the plate. The mesotron penetrates two plates with such large scattering that there is practically no chance that the particle is a proton.

There are altogether 19,438 traversals of the one-cm lead plates by penetrating particles. These 27 cases of the production of heavy particles give a neutron-proton cross section of 1.8×10^{-28} cm^2 for this process. This is of the same order of magnitude as the neutron-proton cross section[16] given by R. P. Shutt of 4×10^{-28} cm^2.

HEAVY PARTICLES PRODUCED BY NON-IONIZING RADIATION

Figure 10c shows the production of two protons by non-ionizing radiation. The upper section of the two proton tracks are obviously heavier than the single track which appears to the right and then between the two tracks. Figure 10d shows another case of the simultaneous production of a mesotron and a proton. The left-hand particle shows small scattering but stops near the middle of the bottom plate. Only a mesotron can do this without showing heavy ionization. The right-hand track is distinctly heavy and also stops in the bottom plate. It is a proton. Still another photograph not reproduced shows two heavy tracks going down and stopping in the next plate while one proton goes up through one plate.

Figure 11a shows a mesotron created in a lead plate. It stops two plates away and a particle comes back from the end. This might very well be the disintegration electron. There are three photographs like this except for the fact that the other two show no disintegration electron. There are four photographs where the appearance is the same except that the particle shows no scattering, and one photograph where only one particle is emitted by the plate. It passes through two plates and then leaves the chamber.

Altogether there are sixteen occasions where a non-ionizing radiation produces penetrating particles which pass through at least one lead plate. Five particles are protons, four are mesotrons, and the remaining eleven particles cannot be identified. This does not count the particles that show heavy ionization but fail to penetrate a plate. Practically all the stars in the gas of the chamber and appearing from the lead are initiated by non-ionizing radiation.

There are six events where it is impossible to determine the type of initiator. Their appearance is essentially similar to those above. Five protons, one mesotron, and five unidentified penetrating particles appear in these.

In all of these events there are seventeen protons, eight mesotrons, and twenty-seven penetrating particles going too fast to be identified. Simultaneous production of mesotrons and protons appears in all three types. Three of the protons are going up. The fact that so many protons are produced in the chamber coupled with the falling off in the number of protons with the number of plates they penetrate indicates again that the protons result from secondaries produced in the atmosphere around the chamber, and that very few, if any, of the primary protons appear in the energy range above 200 Mev.

[15] W. M. Powell, Phys. Rev. **60**, 413 (1941).
[16] R. P. Shutt, Phys. Rev. **61**, 6 (1942).

COUNTER CONTROLLED PHOTOGRAPHS

A total of 1628 pictures were made with counters above and below the chamber. The efficiency of the counters was not known. The counter cylinders were 2.54 cm in diameter and 28 cm long and were placed 80 cm apart above and below the chamber. A third counter was placed between them solely for the purpose of reducing accidental counts. A coincidence occurred once in 45 seconds on the average. Five hundred and ninety-two pictures gave evidence of having been counter-controlled. Of these 411 showed a penetrating particle passing through five plates, 33 showed cascade showers (Fig. 5c), 138 showed numerous thinly scattered particles, and ten showed giant Auger showers two of which passed through the chamber at an angle of about 45 degrees. (Fig. 11b and 3) It is apparent that the Auger showers are made up of huge cascade showers mixed into each other. There is no evidence whatsoever that they include heavily ionizing particles. The confusion is too great to follow through penetrating particles which do not show an increase in ionization. About 100 counter-controlled pictures were made with the counters all above the chamber. In only one case did a ray stop in the chamber.

THE ELECTRON COMPONENT

During 19,438 traversals of the lead plates by penetrating particles 666 electron showers containing more than six particles were observed. These were all random expansions. No large Auger showers were seen in this group.

A careful study was made of the particles appearing between the upper two plates of the chamber. In 200 photographs 985 particles appeared there. If two or more particles started from one point in the lead and failed to penetrate one of the plates or passed out of the chamber they were called electrons. Tracks showing marked scattering in the gas were called electrons. These two classes accounted for 546 particles. There were five knock-on electrons. There were 14 particles which were in groups coming from points in the back or front of the chamber. These were classified as electrons. There were 263 particles which occurred singly and failed to pass through any plates. Fifty-one of these passed through the gas without touching the lead plates. They were unidentified. Seventy-two particles passed through one plate only showing very little scattering and producing no secondaries. Most of these probably were penetrating particles. There were 100 particles which penetrated more than one plate. These were classified as penetrating particles. Of the 710 tracks which could be identified 565, or 80 percent, were electrons. The remainder were heavy particles.

For a cosmic ray to get into this section of the chamber from above it must pass through 1.27 cm of iron and one cm of lead. If we assume that the number of electrons is increased by a factor of ten in passing through the lead and iron, then 29 percent of the incoming rays must be electrons.

A rather surprising discrepancy from theory was found in a comparison of the number of photon-produced and electron-produced pairs. Where theory predicts a ratio of about 1.6 in favor of photon-produced pairs the actual number was 72 photon-produced pairs against 16 electron-produced pairs. J. R. Oppenheimer called attention to the fact that the electrons and photons involved being of low energy it would be expected that the electrons would be absorbed out more readily than the photons because the loss by ionization becomes appreciable. This effect should be less at the top of the chamber and if we compare only those pairs produced in the top lead plate, this is found to be true. There are 30 photons-produced pairs to 10 electron-produced pairs. Agreement with theory is better in the case of three-particle showers. There are 16 photon-produced against 7 electron-produced showers in this group.

NEUTRONS AND THE MASS OF THE MESOTRON

The data given in Table II can be interpreted so as to indicate the presence of a very large number of neutrons. It will be shown that these neutrons have an average energy of 100 Mev, and that probably they have a maximum energy of 200 Mev. It is quite probable that the similarity between this maximum energy of 200 Mev and the mass equivalent of two mesotrons of weight 200 times that of the electron is not fortuitous. This similarity was pointed out by L. W. Alvarez.

Stars arise in the lead and in the gas of the chamber. The particles in the stars frequently come out of one plate and stop in the next. Occasionally a few stop in the gas of the chamber. If the radiation in the chamber has reached equilibrium then the following condition should hold:

$$\frac{\text{Stars produced in the lead}}{\text{Stars produced in the gas}} \cong \frac{\text{Heavy particles stopped in the lead}}{\text{Heavy particles stopped in the gas}}.$$

Putting in the figures shown in Table II, this becomes

$$\frac{156/5629}{13/6918} \cong \frac{1338/3186}{75/3186} \quad \text{or} \quad 14.7 \cong 17.8.$$

This agreement is well within experimental error, so it can be said that equilibrium has been reached.

The average path of a particle in the gas is approximately seven cm, the space between the plates. By multiplying this path length by the ratio above we obtain the average range of a particle in the gas. This amounts to about 120 cm in air. A particle with this range in air would have a kinetic energy of approximately 12 Mev, which agrees closely with the maximum in the energy distribution curve for particles appearing in photographic emulsions left at high altitudes.[17]

It is obvious that many stars are formed inside the lead with insufficient energy to appear in the gas of the chamber. The range of a 12-Mev proton in lead is about 0.02 cm. Since the plates are one cm thick, this means that fifty stars are created inside the lead for one appearing leaving the plates. Now if we assume that it takes about eight Mev to eject a nuclear particle from the nucleus, then one particle would take a total of 20 Mev. The average number of ionizing particles appearing in a star in the gas is three. It is reasonable to assume that one neutron is ejected for every proton. This leaves a total of six particles and a total energy of 120 Mev for the average star. Table II shows one air star of five particles and five stars leaving the lead of five particles. There were no stars of more than seven particles. This is an indication that the maximum energy for stars amounts to about 200 Mev.

Above it was shown very conclusively that the high speed protons had a maximum energy of 200 Mev. This means that the protons are of secondary origin. They would be expected to be in equilibrium. However, the ratio of high speed protons created in the chamber to those stopped instead of being one as it should be for equilibrium is one to twenty. We are forced to conclude that for this group of protons capable of penetrating one or more cm of lead equilibrium is not established.

[17] A. Widhalm, Zeits. f. Physik **115**, 481 (1940).

ENERGY CARRIED BY THE NEUTRONS

Practically all stars are produced by nonionizing radiation and since they are hardly ever accompanied by cascade showers, it seems reasonable to assume that the producing agent is neutrons. The number of neutrons can be estimated in the following manner. Table II shows 156 stars to occur while there were 5629 penetrating particles. The penetrating particles make slightly more than two traversals each on the average. During each traversal the loss in energy is about 13 Mev. The total energy lost by the penetrating particles is $5{,}629 \times 2 \times 13 = 1.7 \times 10^5$ Mev. The energy lost by the 156 stars is 156×120 Mev, but we have shown that for one star appearing outside of the lead there are fifty produced inside. Hence this number should be multiplied by fifty giving $156 \times 50 \times 120 = 9.4 \times 10^5$ Mev as the total energy for all the stars. The remarkable fact appears that the energy used in creating the stars is *five times greater* than the energy lost by the penetrating component in the same amount of material.

THE NUMBER OF NEUTRONS

We are now in a position to estimate the relative number of neutrons present. If we assume that their angular distribution is similar to that for the penetrating particles, then they will traverse two cm of lead on the average. A reasonable assumption for the cross section per lead atom is 3×10^{-24} cm^2. They pass 6×10^{22} lead atoms in penetrating two cm of lead. This means that approximately four out of five neutrons will pass through the lead without producing a star. The conclusions is that there are $156\times 50\times 5 = 3.9\times 10^4$ energetic neutrons accompanying 5629 penetrating particles or a ratio of *seven to one* in favor of neutrons.

PROTONS ARE RECOILS FROM NEUTRONS

Above we showed that the high speed protons were of secondary origin and not in equilibrium in the chamber. Inside the chamber there are no very light nuclei except for the small number of protons in the alcohol. The wood of the trailer and the protons in the observer were all available for collision with the abundant energetic neutrons indicated by the presence of the stars. The neutrons transfer their energy without degradation to the protons in the wood of the trailer. One cm of wood in the neighborhood of the chamber would be sufficient to produce the number of fast protons observed. This explanation accounts completely for the lack of equilibrium of the high speed protons found inside the chamber.

THE MASS OF THE MESOTRON

Most of the conclusions drawn in this paper were described in a preliminary letter to the editor in 1942.[18] In a recent discussion of these results L. W. Alvarez pointed out the equality between 200 Mev and the rest mass energy of two mesotrons of mass 200 each. There is little doubt that the mesotrons at this altitude have a mass very close to 200.[19] The explanation of the strong band of secondary neutrons follows directly. Apparently the atmosphere acts as a filter. Neutrons coming down and possessing energies greater than 200 Mev create pairs of mesotrons. If they have insufficient energy to do this, then they come on through and produce the stars and protons described above. An accurate determination of the cut-off with rising energy of the secondary neutrons would yield a minimum value for the mass of the mesotron.

CHANGE OF INTENSITY WITH ALTITUDE

In the 1942 expedition to Mt. Evans[19] the number of heavily ionizing particles was observed to decrease to about half when the apparatus was moved from the peak at 14,100 ft. to Summit Lake at 12,700 ft. This reduction is consistent with the assumption that the particles are produced by the neutrons observed at the summit.

The number of atoms per cm^3 of air at 13,400 ft. is 3×10^9. The average cross section for neutrons in 21 percent oxygen, and 79 percent nitrogen is 8×10^{-25} cm^2 per atom. The intensity I at 12,700 ft. becomes

$$I = I_0(\exp)(-3\times 10^{19}\times 8\times 10^{-25} \times 1400\times 12\times 2.54),$$

where I_0 is the intensity at the summit. The value of the exponent is approximately minus one. The predicted intensity lies between one-half and one-third the intensity at the peak. This agreement is well within the experimental error.

It is apparent that a large increase in the intensity of the neutrons can be expected for a small increase in altitude.

ACKNOWLEDGMENTS

I wish to thank the many organizations and individuals who made this work possible. The continued support of the Rumford Fund of the American Academy of Arts and Sciences was of the greatest help in initiating and sustaining this work. All the preparatory work was done at Kenyon College, Gambier, Ohio. The original grant for construction of the cloud chamber was made by Kenyon College. The Studebaker Corporation through Mr. Paul Hoffman contributed to the first expedition. The late Mr. Wilbur Cummings, trustee of Kenyon College, contributed materially to the initiation of the second expedition. The Fund for Astrophysical Research gave the money for the Edgerton lamp and the power supply. The American Philosophical Society made major contributions toward the second and third[18] expeditions. The Cosmic Ray Committee of the Carnegie Institute of Washington gave the major portion of the funds for the third expedition. Dr. J. A. Fleming's continued interest in this work was of great value before this as well. The John Simon Guggenheim Memorial Fellowship Grant made it possible to carry out the interpretation of the

[18] W. M. Powell, Phys. Rev. **61**, 670 (1942).
[19] C. E. Nielsen and W. M. Powell, Phys. Rev. **63**, 384 (1943).

extensive data in the Department of Physics of the University of California, Berkeley.

Professor R. T. Birge's generous hospitality in extending the facilities of the Department of Physics was of the greatest assistance. Professor R. B. Brode did everything possible to forward the work. Professor J. R. Oppenheimer reviewed much of the data and made many valuable suggestions in its interpretation. Professor Bayes M. Norton of the department of Chemistry at Kenyon College took many of the first photographs made on the mountain.

Two Kenyon students, Richard W. Penn and Henry Meyers, each gave a summer of work on Mt. Evans. Their help was essential to the many things necessary to the success of the expeditions on the mountain. Professor J. C. Stearns, at that time in charge of the laboratory on Mt. Evans, was of great assistance to us while we were on the mountain.

PHYSICAL REVIEW VOLUME 69, NUMBERS 9 AND 10 MAY 1 AND 15, 1946

The Velocity Dependence of the Absorption of Boron for Slow Neutrons

J. H. Manley, L. J. Haworth, and E. A. Luebke
Department of Physics, University of Illinois, Urbana, Illinois
(Received October 27, 1941)*

Measurements of the slow neutron velocity distribution between 1 and 10 km/sec. from a 14-cm cube of paraffin, with a source of 2.5-Mev neutrons in the center, show the distribution to be approximately Maxwellian with $T=400°$K, but with an excess of fast neutrons for $V>3.5$ km/sec. Similar measurements of the distribution of neutrons transmitted through a boron absorber verify the assumed $1/v$ absorption law in this velocity range.

INTRODUCTION

Apparently a number of physicists[1–4] realized, about 1937, that the development of artificial neutron sources would lead to a method of measuring neutron velocities through modulation of the ion beam producing the neutrons. Previous to these electrical methods a mechanical velocity selector had been used to investigate the neutron distribution from paraffin[5] and the rotating wheel method for checking a $1/v$ absorption law had been applied to boron, cadmium, and silver.[6]

The velocity distribution of slow neutrons has been examined only by the mechanical method and by the electrical method of Fertel, Gibbs, Moon, Thomson, and Wynn-Williams[3] (FGMTW). In neither case was the resolution available particularly high. With a method available for determining velocity distributions, the distribution before and after passing through an absorber or scatterer may be measured and the cross section as a function of neutron velocity found. Only FGMTW have published results on both the distribution and absorption laws, the absorption being in boron. Their results on boron are in disagreement with a $1/v$ variation of cross section which has been assumed for slow neutrons producing an (n, α) reaction in such a light element. The validity of this assumption is of importance since many measurements of neutron energies depend upon it. In addition to the experiment of FGMTW, the rotating disk method has been applied to boron[6] as has been the electrical method of Alvarez.[1] Both indicate a $1/v$ dependence of cross section, but the disk method is not capable of large changes in relative speed and Alvarez assumed thermal equilibrium of the

* This paper was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] L. W. Alvarez, Phys. Rev. **54**, 609 (1938).

[2] J. M. W. Milatz and D. Th. J. ter Horst, Physica **5**, 796 (1938).

[3] Fertel, Gibbs, Moon, Thomson, and Wynn-Williams, Proc. Roy. Soc. **175**, 316 (1940).

[4] C. P. Baker and R. F. Bacher, Phys. Rev. **59**, 332 (1941).

[5] G. A. Fink, Phys. Rev. **50**, 738 (1936).

[6] Rasetti, Segre, Fink, Dunning, and Pegram, Phys. Rev. **49**, 104 (1936); Rasetti, Mitchell, Fink, and Pegram, Phys. Rev. **49**, 777 (1936).

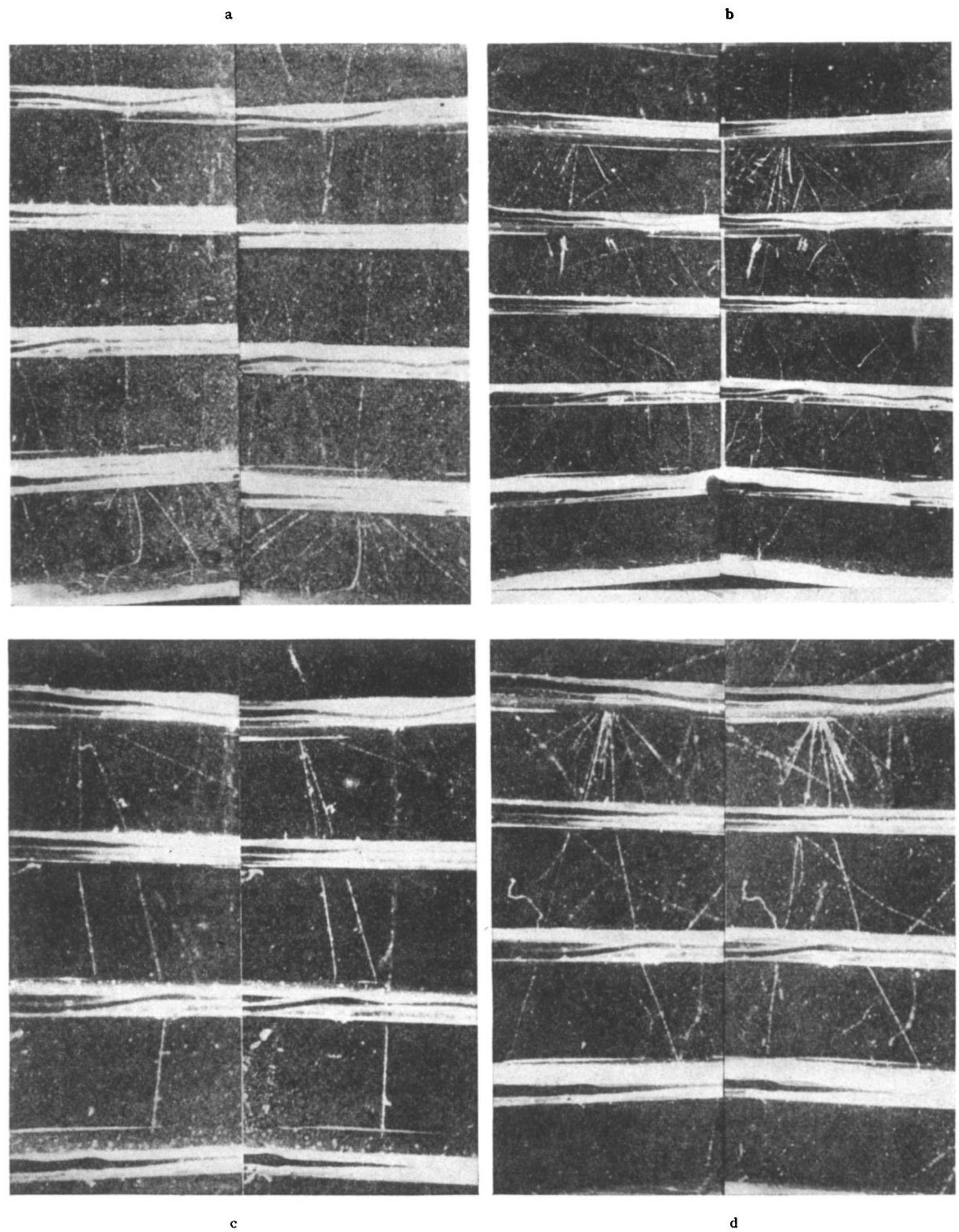
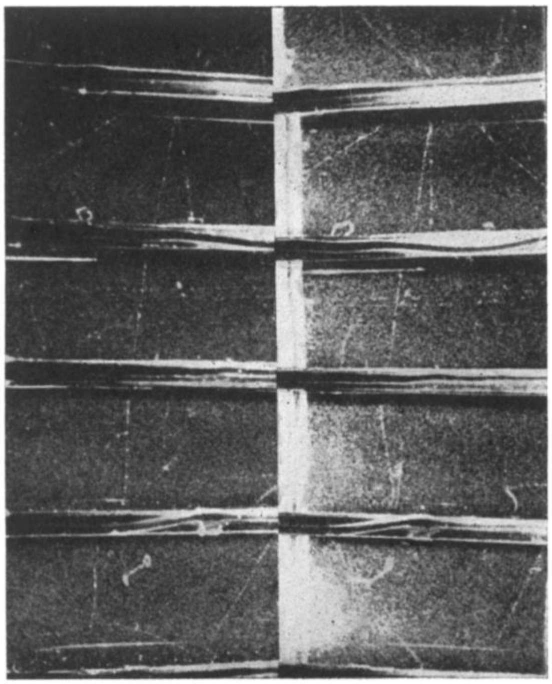
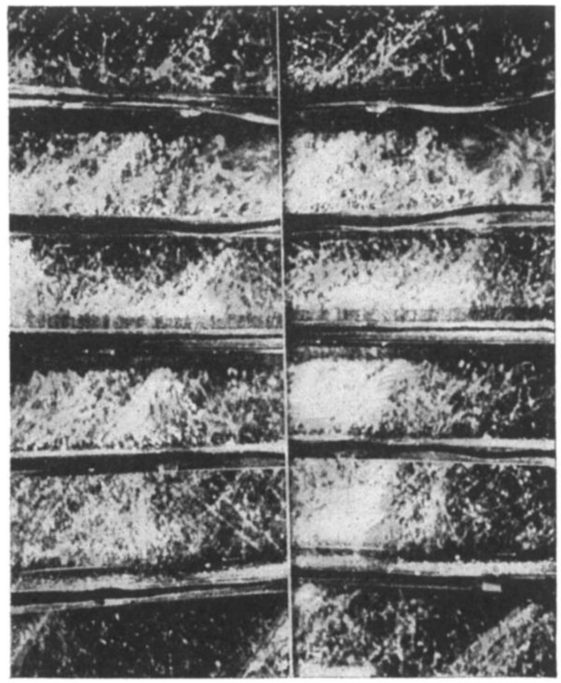


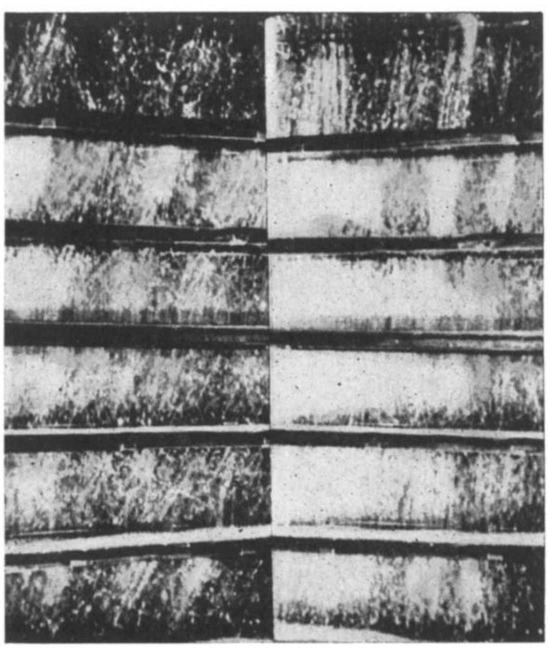
FIG. 10. a. A penetrating particle produces one heavy track and five thin ones. b. A penetrating particle produces at least four heavy particles, one of which is a proton and one a mesotron. c. Non-ionizing radiation produces two protons. d. Non-ionizing radiation produces one proton (lower right) and one mesotron (lower left), the latter stopping in the lead plate.

a



b

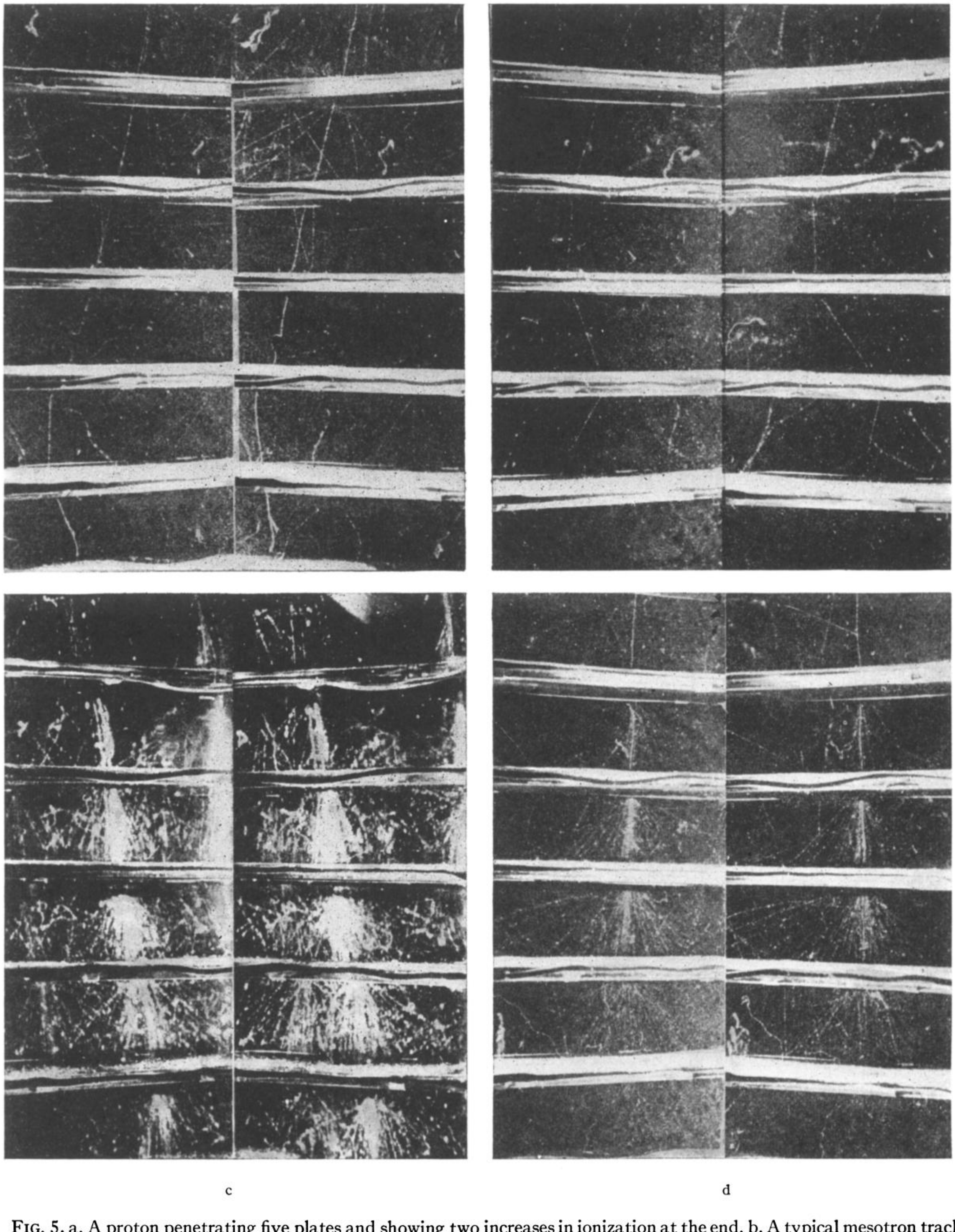




c

FIG. 11. a. Non-ionizing radiation creating a mesotron which stops in a lead plate and shows a track at the end which can be interpreted as the disintegration electron. b. Auger shower coming in at an angle of about 45 . It appears to be made up of many cascade showers. c. Huge Auger shower going straight down.

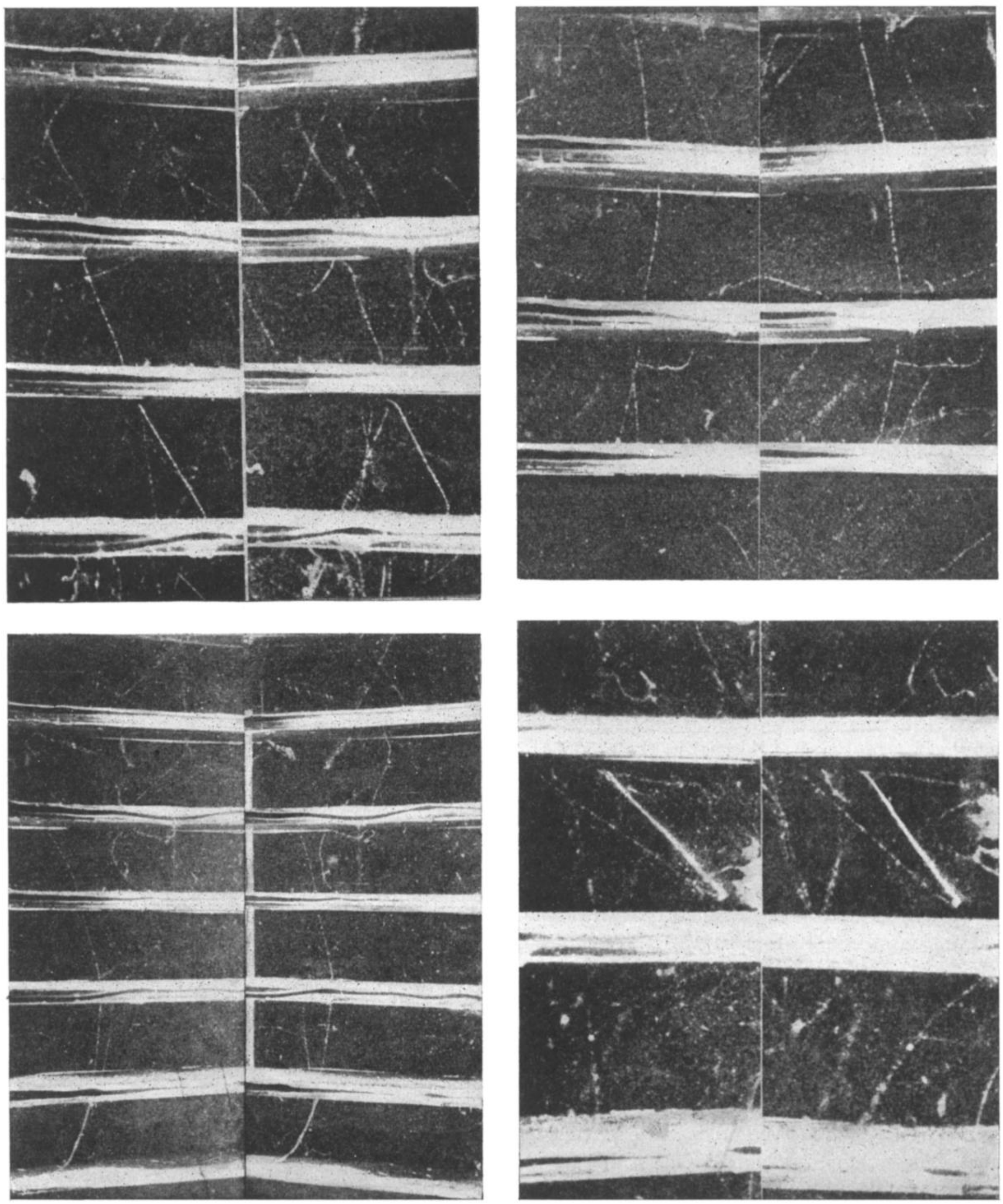
a b



c d

FIG. 5. a. A proton penetrating five plates and showing two increases in ionization at the end. b. A typical mesotron track identified by its large scattering. c. A cascade shower obtained with counter control. d. A cascade shower obtained in a random expansion.

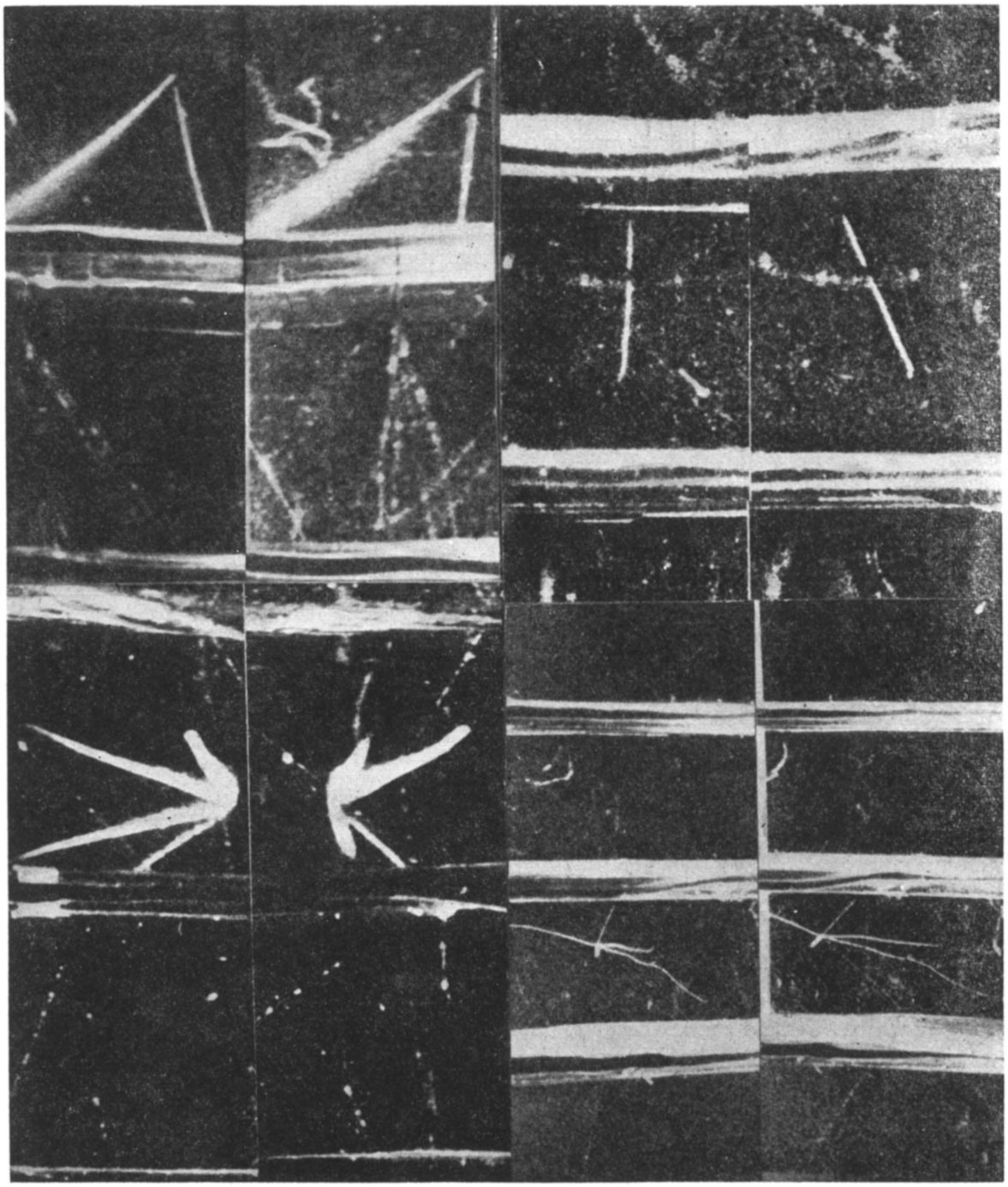
a b



c d

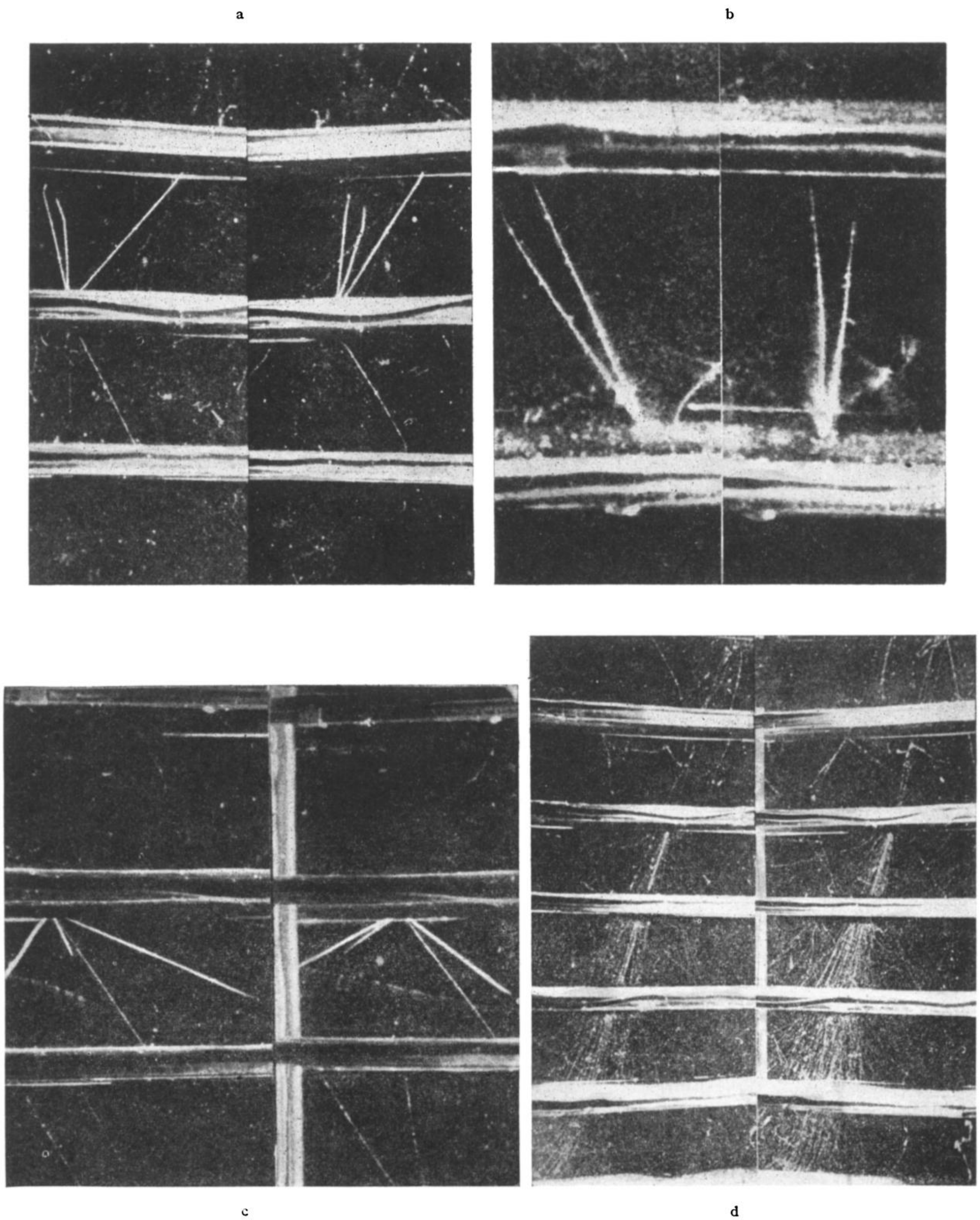
FIG. 6. a. A mesotron showing heavy ionization after the last traversal and a particle below the last plate which can be interpreted as the disintegration electron. b. A mesotron stopping in the bottom plate identified by its stopping and by the delta-ray. The particle going upwards near the end of the mesotron track may be the disintegration electron. c. A mesotron identified by scattering and a single increase ion ionization. d. Probably a mesotron disintegrating in the gas of the chamber and showing the disintegration electron.

a b



c d

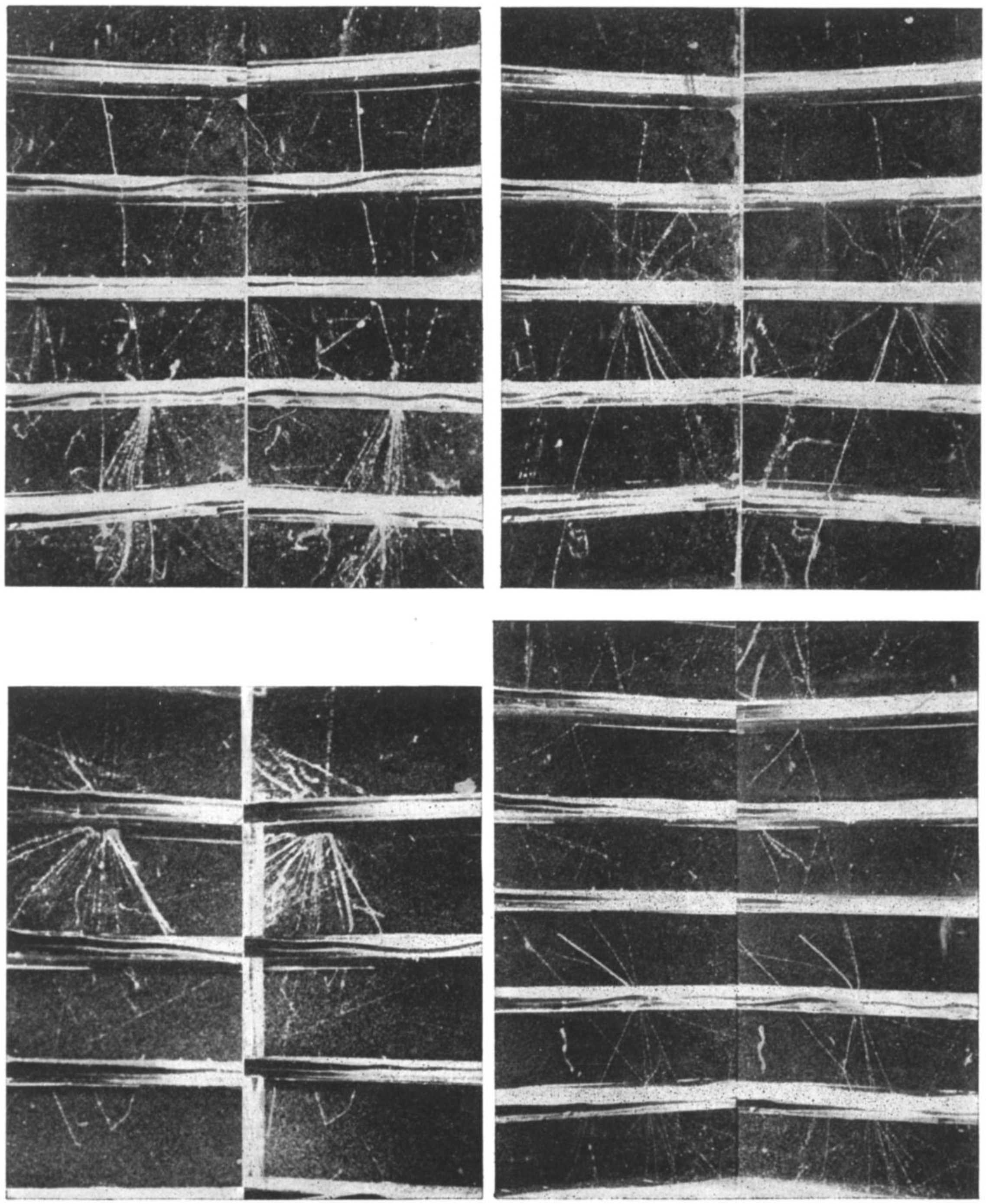
FIG. 7. a. A star in the gas of the chamber showing evidence that the left-hand particle was emitted a few thousandths of a second after the right-hand particle. b. The old horizontal track removed the water vapor from its neighborhood so that a gap appears in the vertical heavy track formed after expansion of the chamber. c. A star in the gas of the chamber showing evidence of neutrons. d. A star in the gas of the chamber with a thin track passing obliquely through the plate just below.



a b c d

FIG. 8. a. A disintegration in the lead showing no thin tracks. b. A disintegration in the lead. c. A disintegration in the lead. d. A cascade shower produced by a penetrating particle.

a b



c d

FIG. 9. a. The only case where a heavy particle and a cascade are associated. The right-hand particle above probably initiates the cascade and the particle above to the left which shows by its ionization that it is going up is a proton. b. A penetrating particle produces a proton (lower left) and a particle which may be a mesotron (lower right). c. Two particles enter above and produce one mesotron which penetrates the lower plate, shows scattering and increase in ionization. There are three heavy tracks and at least fifteen thin tracks. d. A penetrating particle produces one heavy track and five thin tracks.