Penetrating Showers in Lead*

W. B. FRETTER
Department of Physics, University of California, Berkeley, California
(Received September 16, 1947)

Production of penetrating showers in lead has been observed in a cloud chamber containing eight ½-inch thick lead plates. In over half of the 53 examples of penetrating showers photographed high, energy electronic radiation was simultaneously produced. Many examples of mesons accompanying air showers were observed, but no production of penetrating particles in lead by electronic radiation was observed. The pictures taken give general support to recent theoretical speculations that the primary radiation produces penetrating particles and electronic radiation in the same event.

I. INTRODUCTION

THE production of penetrating showers by cosmic rays has been observed by means of counters[1–9] and cloud chambers.[10–31] Only with a cloud chamber can any identification of individual particles be made. Since the processes involved in penetrating showers in lead may be similar to those occurring in the production of penetrating particles such as mesons in the upper atmosphere, it is of considerable interest to make some attempt at identification and analysis. Protons and mesons can be distinguished if they are near the end of their range, while high energy electrons make cascade showers in lead. Protons and mesons of high energy may act differently in one respect: Protons may make meson showers.

It is desirable to be able to trace the shower of penetrating particles from the beginning to the end, and observe the entire event in a cloud chamber. In practice, the high energies of the particles created make this impossible in many cases. The present experiment was designed for observation of the initial event, with as much lead as possible in the cloud chamber for identification of the particles. All pictures were taken at sea level with only a thin roof of sheet metal and wood over the cloud chamber.

II. APPARATUS

The cloud chamber was 16 inches in diameter, 9 inches deep, and contained eight ½-inch thick lead plates, 8 inches wide. These were supported from ⅛-inch slabs of Lucite and were tilted so that the camera viewed them all end-on. One of the difficulties with multi-plate cloud chambers has been the lateral displacement of tracks in the chamber because of irregular motion of the gas during expansion. The Lucite side plates seemed to prevent this effect, and removed one source of confusion in the analysis of showers. The plates

* This work was supported in part by the Office of Naval Research.
1 L. Janossy and P. Ingleby, Nature **145**, 511 (1940).
2 G. Wataghin, M. D. de Souza Santos, and P. A. Pompeia, Phys. Rev. **57**, 61 (1940).
3 M. D. de Souza Santos, P. A. Pompeia, and G. Wataghin, Phys. Rev. **59**, 902 (1941).
4 L. Janossy, Proc. Roy. Soc. **A179**, 361 (1942).
5 P. Auger and J. Daudin, Phys. Rev. **61**, 549 (1942).
6 L. Janossy and G. D. Rochester, Nature **150**, 633 (1942).
7 L. Janossy, Phys. Rev. **64**, 345 (1943).
8 L. Janossy and G. D. Rochester, Proc. Roy. Soc. **A182**, 180 (1943).
9 L. Janossy and G. D. Rochester, Proc. Roy. Soc. **A183**, 181 (1944).
10 H. J. J. Braddick and G. S. Hensby, Nature **144**, 1012 (1939).
11 W. Powell, Phys. Rev. **58**, 474 (1940).
12 J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).
13 L. Janossy, C. B. McCusker, and G. D. Rochester, Nature **148**, 660 (1941).
14 G. Herzog and W. H. Bostick, Phys. Rev. **59**, 122 (1941).
15 D. J. Hughes, Phys. Rev. **60**, 414 (1941).
16 W. Powell, Phys. Rev. **60**, 413 (1941).
17 E. O. Wollan, Phys. Rev. **60**, 532 (1941).
18 W. H. Bostick, Phys. Rev. **61**, 557 (1942).
19 L. Seren, Phys. Rev. **62**, 204 (1942).
20 W. E. Hazen, Phys. Rev. **64**, 257 (1943).
21 W. E. Hazen, Phys. Rev. **63**, 213 (1943).
22 J. Daudin, Ann. de physique **18**, 217 (1943).
23 D. M. Bose, B. Choudhuri, and M. Sinha, Phys. Rev. **65**, 341 (1944).
24 J. Daudin, Ann. de physique **19**, 10 (1944).
25 W. E. Hazen, Phys. Rev. **65**, 67 (1944).
26 L. Janossy, G. D. Rochester, and D. Broadbent, Nature **155**, 142 (1945).
27 W. Powell, Phys. Rev. **69**, 385 (1946).
28 R. P. Shutt, Phys. Rev. **69**, 261 (1946).
29 G. D. Rochester, Proc. Roy. Soc. **A187**, 464 (1946).
30 W. B. Fretter and W. E. Hazen, Phys. Rev. **70**, 230 (1946).
31 G. D. Rochester, C. C. Butler, and S. K. Runcorn, Nature **159**, 227 (1947).

were covered with very thin aluminum foil for reflection of light. The light for photography was at right angles to the line of sight and was provided by G.E. flash tubes FT-422 flashed on 220 mfd, 1700 volts. The illuminated depth was five inches. The chamber was counter-controlled with various arrangements of counters, but was always selective for showers.

Several different counter arrangements were used during the course of the experiment. In order to increase the yield of usable pictures there was always a counter below the cloud chamber. Since it was necessarily some distance below the lowest lead plate and no other lead shielding was used, low density side showers often tripped the counters and were not recorded in the cloud chamber. Most of the pictures were taken with one of the following arrangements: (1) Selective for air showers. Counters in triple coincidence, one above the chamber, one below, and one at a distance of one meter horizontally from the upper chamber. (2) Selective for narrow air showers. Same as (1) except the distance was 20 cm. (3) Selective for showers produced in the chamber. Counters in triple coincidence, two side by side just below the chamber, with the third 18 inches below these two.

With arrangements (1) and (2) most of the pictures showing counter-controlled tracks were those of electron air showers. With arrangement (3) a large fraction of the pictures with counter-controlled tracks showed single penetrating particles making knock-on electrons in the last lead plate.

III. THE ELECTRON SHOWERS

Approximately 1000 pictures of electron showers were obtained, the particles of which penetrated three or more lead plates. Over 500 more were observed penetrating two plates or less, the identification being uncertain because of the low particle density in low energy air showers. The total number of electron showers incident on the apparatus was probably about 2000. One hundred and one of these penetrated all of the eight lead plates. An example of a high energy electron shower, several particles of which penetrated the eighth plate, is shown in Fig. 1a.

In 52 pictures of electron showers, penetrating particles associated with the shower (tracks of about the same age) and moving parallel to it were observed. This amounts to 2.5 percent of the pictures of air showers showing parallel penetrating particles. The counter experiments of Cocconi, Loverdo, and Tongiorgi[32] on penetrating particles in air showers are thus supported by cloud-chamber observations of air showers.

In no case were penetrating particles observed produced in an air shower by electronic radiation. Production of penetrating particles by electronic radiation would, of course, be of great interest, and the electron showers were examined carefully for evidence of this type of reaction. Penetrating particles made in high energy electron showers might be masked by the high density of particles, and there were many pictures in which the existence of penetrating particles could not have been observed. There were a great many more favorable cases, however, and the usually large angle of deviation of penetrating particles in the true penetrating showers (see below) makes detection of these particles fairly easy.

Heavy tracks, presumably protons, were observed in only 24 electron showers. Thus, it seems that the cross sections for production of penetrating particles (mesons or fast protons) and slow protons by electrons or γ-rays must be extremely small.

IV. ELECTRON BURST PRODUCTION BY PENETRATING PARTICLES

In 93 pictures an ionizing particle, after traversing three or more of the lead plates without any interaction, created an electron shower that penetrated at least two plates. These are probably mostly examples of radiation by mesons, with the γ-ray creating an electron shower. Seventy-five percent of these occurred with counter set-up 3) which was, of course, more favorable to this sort of event. Twenty-two of the bursts penetrated four or more of the lead plates, indicating that the energies involved in such electron showers may be 500–1000 Mev, and might have been a considerable fraction of the energy of the incident meson.

---

[32] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 852 (1946).

V. THE PENETRATING SHOWERS

Fifty-three pictures were obtained in which one or more penetrating particles were produced in the cloud chamber. The energy released in these events varied widely, from low energy events in which a penetrating particle created one or two other penetrating particles and usually a few heavy tracks, to extremely high energy

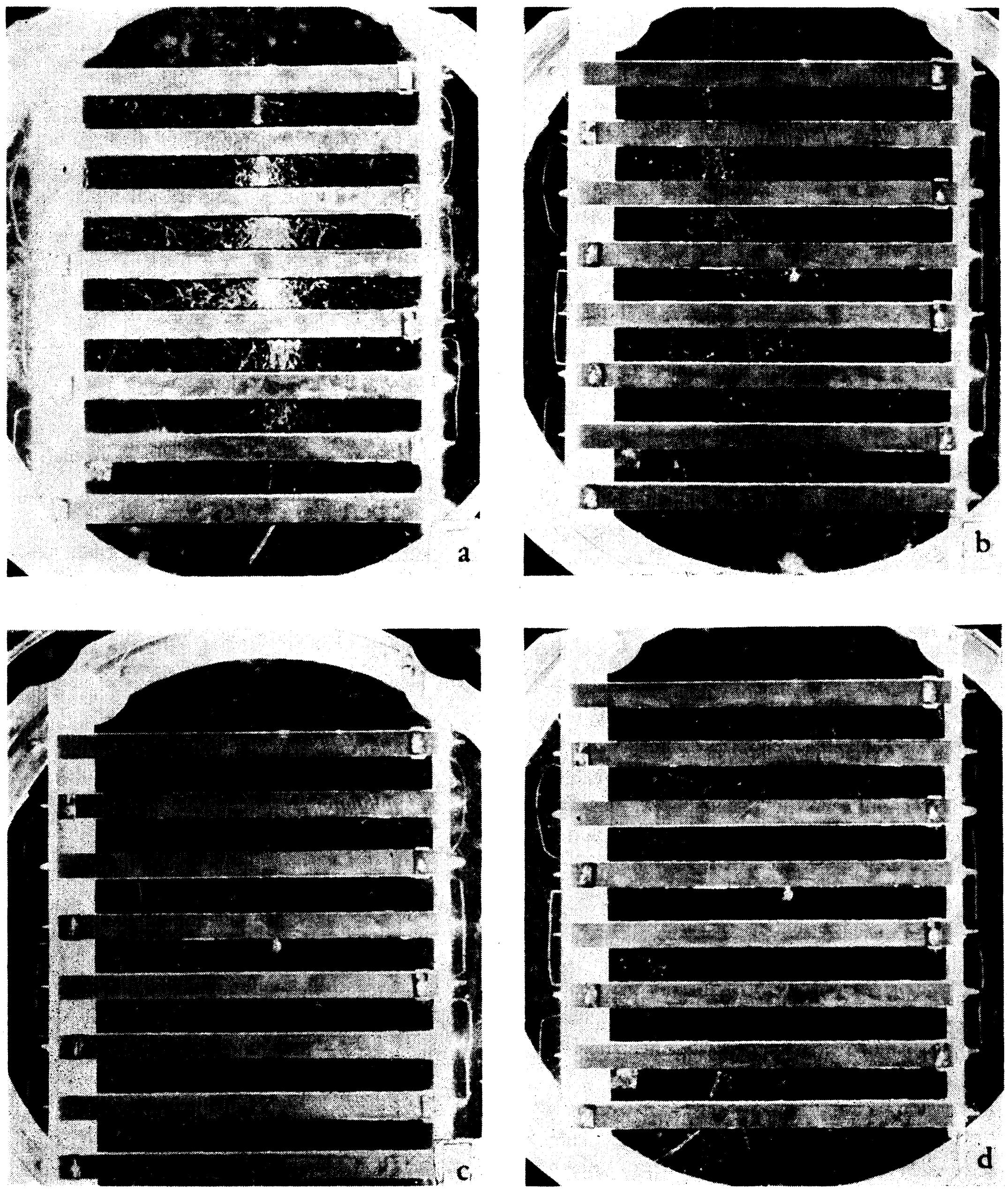

FIG. 1. a. Electron shower penetrates 10 cm of lead. b. Penetrating shower possibly made by neutral radiation. Conservation of momentum in such a high energy event makes it unlikely that the heavy track above the top plate produced the shower. The particle making this heavy track was probably a slow particle produced in the event. c. An air shower of five penetrating particles is incident on chamber, with penetrating particles produced in the fourth and possibly the seventh plate. d. An air shower with a penetrating particle that produces a penetrating shower in the seventh plate.

events in which many penetrating particles and electrons were created. Analysis of the pictures reveals several characteristic properties of penetrating showers.

(1) Many of them are created by ionizing penetrating particles. Thirty such showers were observed, with 7 others created in the top plate by ionizing particles so that the penetrating power could not be observed. Six showers were believed to be initiated by neutral radiation, and in 10 others the initiating particle was uncertain. It seems clear, however, that neutral radiation can create penetrating showers, but the selectivity of the first two counter arrangements for ionizing particles excluded neutral radiation for part of the time. One could not say that the results of this experiment were in disagreement with Janossy and Rochester,[8] who found that the penetrating showers are produced almost equally by ionizing and nonionizing particles. In 60 percent of the showers the initiating particle was not accompanied by other particles, but in most of the very high energy events the initiating particle was accompanied by other particles.

(2) Heavy tracks of protons or slow mesons were observed in 70 percent of the pictures, and often several were seen scattered throughout the shower. The presence of heavy tracks is in distinct contrast to the case of electron showers, where heavy tracks were relatively rare, and may be due to neutrons produced in the initial event or accompanying the shower-producing radiation. In the high energy events heavy tracks were almost always produced in the initial event, sometimes upwards, and may have been the debris from the original nuclear explosion.

(3) The penetrating particles produced had usually a rather wide angular deviation from the direction of the initiating particle, and the shower continued to fan out from the initial point. This is in contrast to the behavior of electron showers where the angular spread is due primarily to multiple scattering and the wide-angle particles do not usually penetrate the next plate.

(4) The number of identifiable penetrating particles produced in a given event varied from 1 to 15, according to the energies involved. The multiplicity in the high energy events may have been even higher, but the particles could not be counted in the core of the shower.

(5) Showers started with almost equal probability in any one of the lead plates, except the seventh plate, in which almost twice as many were observed as in any other. This is very likely due to the geometry of the counter set-up which would be selective for showers produced near the bottom of the chamber. The amount of lead in the chamber would have to be increased considerably in order to measure an absorption coefficient by counting events occurring in each plate.

(6) In three pictures successive production of penetrating particles was observed. This indicates that some particle like a negative proton or antimatter is not responsible for the event, for if an explosive action such as an annihilation of a negative proton had to occur to make a penetrating shower, it could only occur once, and successive events such as observed here and in a previous experiment[30] would not occur.

(7) Sixty percent of the pictures showed clear evidence that electronic radiation was simultaneously produced having energies large enough to create an electron shower. In many of the high energy events the electron shower produced was very large and made observation of the penetrating component difficult. One shower (Fig. 2d), although obviously a nuclear event because of the multiple production of heavy tracks in the initial event, contained no identifiable penetrating particles, although it is possible that the core of the shower consists of both electrons and penetrating particles.

(8) In only six pictures was it possible to identify any one of the penetrating particles as mesons, although the identification by ionization and scattering in these cases was quite clear.

(9) The frequency of penetrating showers with counter arrangement (3) was 0.035 per hour.

VI. DISCUSSION

Events in which high energy penetrating particles and high energy electrons occur simultaneously have been observed in cloud chambers by Rochester[29] and Daudin,[24] although the initial event was not seen in these cases. Rochester shows that the electrons cannot have been produced by knock-ons or decay electrons of ordinary mesons, but that if they are decay products, the lifetime of the mesons producing them must be extremely small. Recently J. R. Oppenheimer has suggested that in these nuclear events not only charged mesons may be produced, but also uncharged mesons. The neutral mesons are calculated to have an extremely short life ($\sim 10^{-15}$ sec.). Thus, even if the neutral

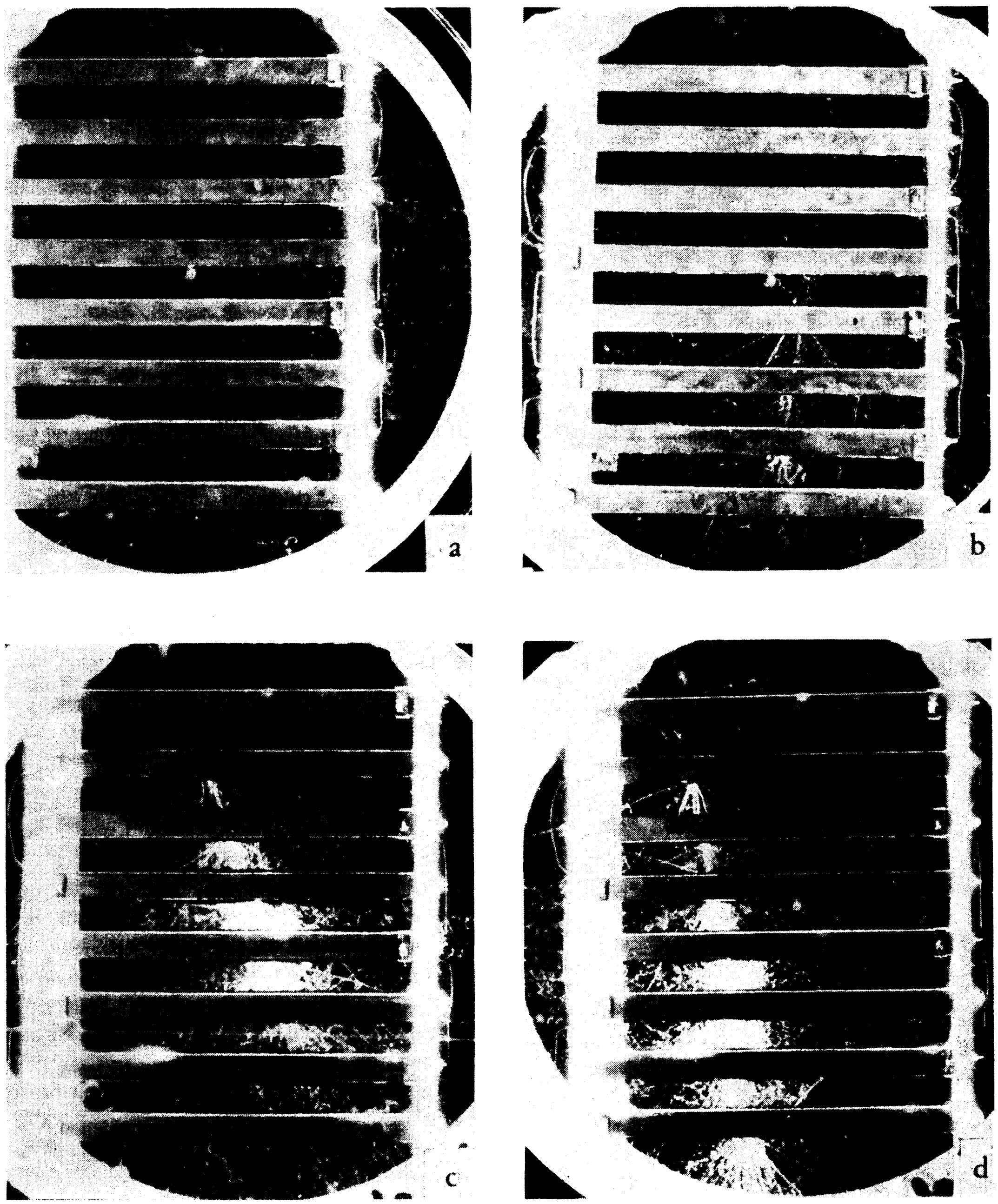

FIG. 2. a. Penetrating shower in which mesons can be identified by scattering and ionization. b. Penetrating particle makes a shower of electrons, slow heavy particles, and fast penetrating particles. c. High energy event with many high energy electrons and penetrating particles. d. Nuclear event in which seven slow heavy particles and high energy electrons are produced. Continued production of heavy tracks throughout the chamber is characteristic of penetrating showers, but no penetrating tracks are observed.

mesons were given a large amount of energy in the initial event they would decay almost immediately and produce a pair of γ-rays, which would then create the electron shower. Recent calculations by Heitler and Power[33] indicate that "transverse" mesons of short lifetime may be responsible for the production of electron showers.

Whatever the actual mechanism for production of high energy electrons may be, it seems clear that they are produced simultaneously with penetrating particles and may absorb enough of the primary energy to account for the very energetic electron air showers observed by Auger and others. It seems likely that primary particles and possibly high energy neutrons created by them are responsible for the showers observed. The frequency of events observed is not inconsistent with the number of primaries expected at sea level as estimated from the somewhat uncertain values of primary intensity and absorption in the atmosphere.

I am indebted to Professor R. B. Brode for his friendly interest in this experiment and to Professor J. R. Oppenheimer and Professor W. E. Hazen for stimulating discussions.

[33] W. Heitler and S. Power, Phys. Rev. **72**, 266 (1947).

PHYSICAL REVIEW VOLUME 73, NUMBER 1 JANUARY 1, 1948

Energy Distribution of Photoelectrons from Polycrystalline Tungsten*

L. Apker, E. Taft, and J. Dickey
General Electric Research Laboratory, Schenectady, New York

(Received September 19, 1947)

Total-energy distributions of the photoelectrons from aged polycrystalline tungsten ribbons, with the usual rolling texture, were determined by applying retarding potentials to spherical collectors. Particular attention was paid to the region of low energy. When stray fields were eliminated, energy-distribution functions rose linearly with energy. The average work function was determined by extrapolation of (current)$^{\frac{1}{2}}$-voltage curves to the saturation line. The result agreed with the value 4.49 ev determined both from the spectral distribution and from the temperature variation of the photo-current. Application of spherical photo-cells to investigations of semiconductors is discussed briefly.

1. INTRODUCTION

Using simple assumptions about photoelectric emission from a Sommerfeld metal, Fowler[1] and DuBridge[2] developed graphical methods for analyzing photoelectric data. These techniques are convenient for determining the work functions of metals used as reference surfaces in studies of semiconductors.[3] This paper reports work done in preparation for such investigations.

The general theory of the photoelectric effect[4] has justified the assumptions of Fowler and DuBridge for a uniform, ideal metal surface with a potential barrier rounded by an image field. Faces of metallic single crystals approximate this ideal case. For such surfaces, Fowler's work provides a simple interpretation of the spectral distribution near the threshold. DuBridge's analysis treats the temperature variation of the photocurrent and the energy distribution of the emitted electrons.

These techniques had their original success, however, when applied to polycrystalline metals.

* Presented in part at the meeting of the American Physical Society, New York, New York, January, 1947.

[1] R. H. Fowler, Phys. Rev. **38**, 45 (1931).

[2] L. A. DuBridge, Phys. Rev. **39**, 108 (1932); **43**, 727 (1933); *New Theories of the Photoelectric Effect* (Hermann and Cie, Paris, 1935).

[3] R. A. Millikan, Phys. Rev. **18**, 236 (1921); E. U. Condon, Phys. Rev. **54**, 1089 (1938).

[4] K. Mitchell, Proc. Camb. Phil. Soc. **31**, 416 (1935); L. I. Schiff and L. H. Thomas, Phys. Rev. **47**, 860 (1935); R. D. Myers, Phys. Rev. **49**, 938 (1936); A. G. Hill, Phys. Rev. **53**, 184 (1938); R. E. B. Makinson, Proc. Roy. Soc. **A162**, 367 (1937); H. Y. Fan, Phys. Rev. **68**, 43 (1945).

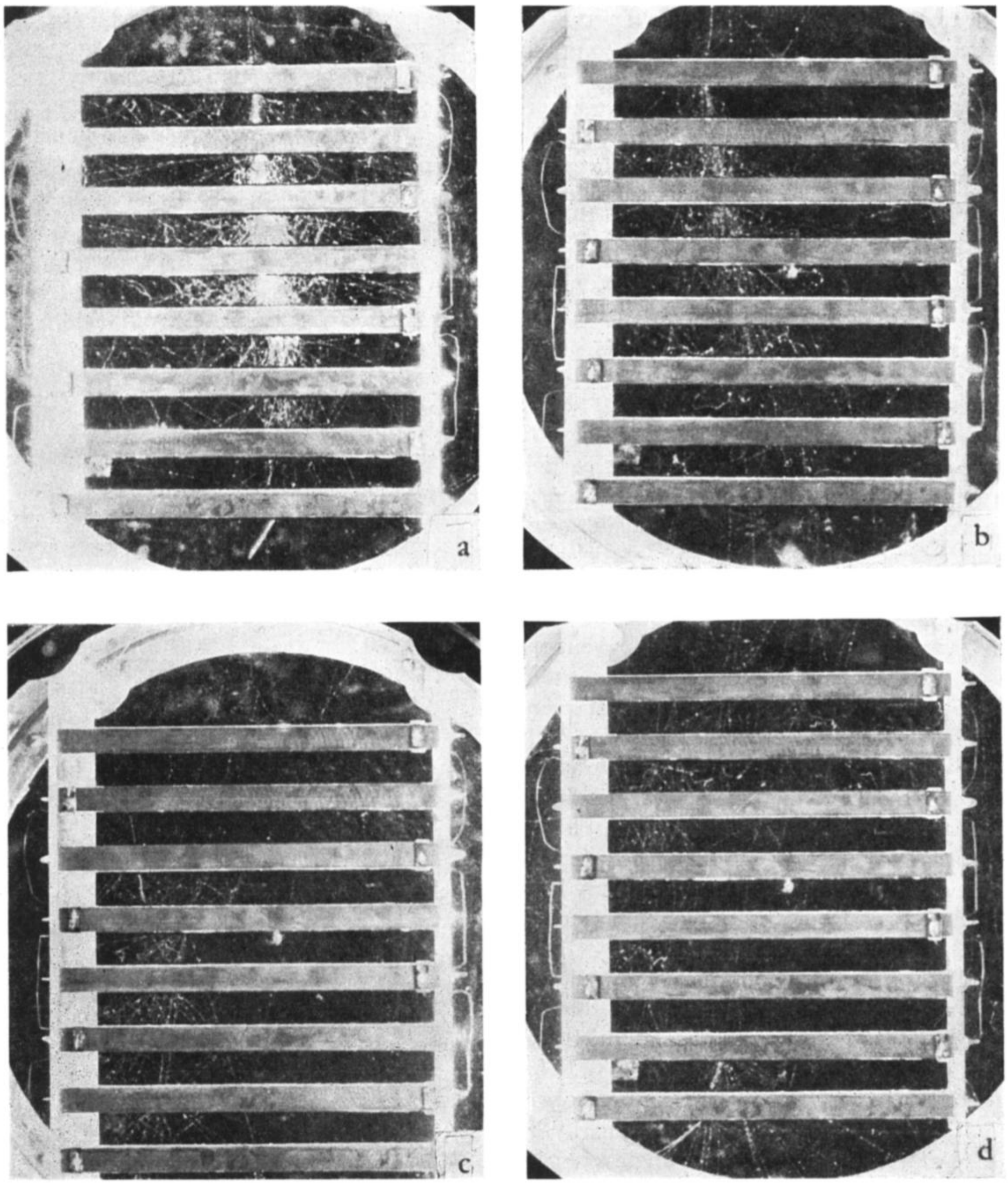

FIG. 1. a. Electron shower penetrates 10 cm of lead. b. Penetrating shower possibly made by neutral radiation. Conservation of momentum in such a high energy event makes it unlikely that the heavy track above the top plate produced the shower. The particle making this heavy track was probably a slow particle produced in the event. c. An air shower of five penetrating particles is incident on chamber, with penetrating particles produced in the fourth and possibly the seventh plate. d. An air shower with a penetrating particle that produces a penetrating shower in the seventh plate.

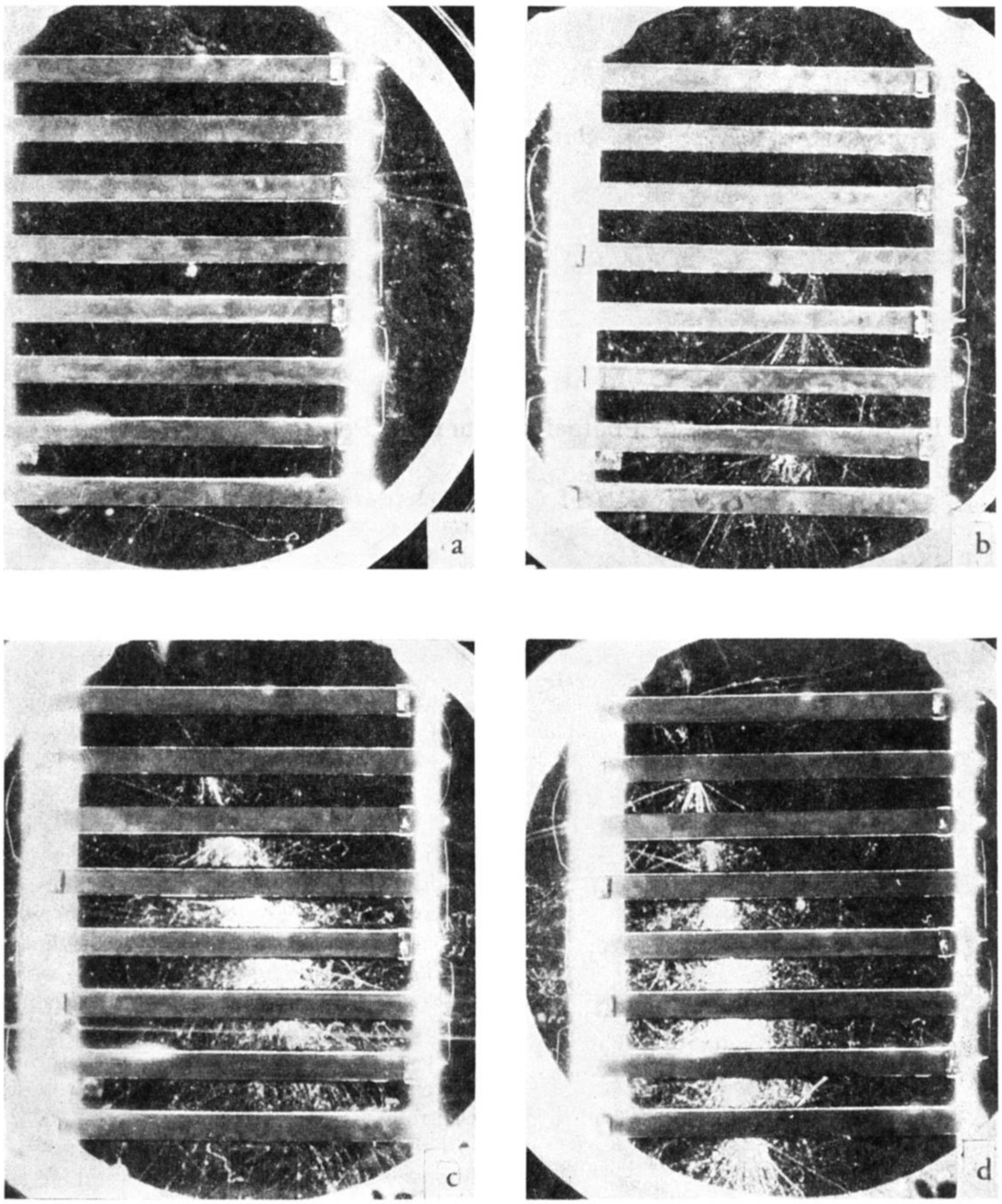

FIG. 2. a. Penetrating shower in which mesons can be identified by scattering and ionization. b. Penetrating particle makes a shower of electrons, slow heavy particles, and fast penetrating particles. c. High energy event with many high energy electrons and penetrating particles. d. Nuclear event in which seven slow heavy particles and high energy electrons are produced. Continued production of heavy tracks throughout the chamber is characteristic of penetrating showers, but no penetrating tracks are observed.