

All that we are able to give is an average over-all of the elements in the emulsion, calculated by using the total number of atoms per cc. The number of atoms per cc, as found from the chemical composition of the NTA emulsion, is shown in Table I. The figures given in Table I apply to the dry emulsion, no correction having been made for moisture picked up by the plates. The average cross section is shown in Table II and in Fig. 4.

IV. DEUTERON CONTAMINATION

One factor which prevented us from making a more accurate determination of the cross section was the presence of deuterons in the alpha-particle beam. Even after helium has been run into the ion source continuously for several days it is still possible to find deuterons in the beam. The number of deuteron tracks in the photographic plates varied from a few percent of the number of alpha-particle tracks to approximately as many as the number of alpha-particle tracks. Although deuteron tracks are not ordinarily seen at the energies at which we were working, they seemed to contribute enough developed grains so that there was some uncertainty in the count of the alpha-particle tracks. Different observers

counting the same tracks have reported alpha-particle track counts which differ by 30 percent. This introduces an uncertainty in the cross sections given in Table II and Fig. 4. There is little confusion between stars initiated by alpha-particles and stars initiated by deuterons since it is ordinarily easy to tell whether an alpha-particle track ends at the star.

V. ACKNOWLEDGMENTS

We wish to express appreciation to Professor Ernest O. Lawrence for his continued interest in this study. The program was greatly helped by discussions with Professors R. L. Thornton, R. Serber, E. M. McMillan, and L. W. Alvarez. We wish to thank Mr. D. J. O'Connell for making the alpha-particle track and star count, Mr. A. J. Oliver for the preparation of Fig. 1, Mr. Duane Sewell and the cyclotron crew for bombarding the plates, and the Eastman Kodak Company for information regarding Eastman NTA plates. This paper is based on work performed under contract No. W-7405-eng-48 with the Atomic Energy Commission in connection with the Radiation Laboratory, University of California, Berkeley, California.

Positive Mesons Produced by the 184-Inch Berkeley Cyclotron

JOHN BURFENING,* EUGENE GARDNER, AND C. M. G. LATTES**

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

(Received October 11, 1948)

Positive mesons produced by 380-Mev alpha-particles in the 184-inch Berkeley cyclotron have been detected by means of photographic plates. The experimental arrangement is similar to that used for detecting negative mesons except that the plates are placed in a position to receive positive instead of negative particles from the target. Heavy positive mesons are observed to decay into secondary mesons in the manner described by Lattes, Occhialini, and Powell. Relative numbers of positive and negative mesons coming from a target are found by placing plates symmetrically on opposite sides of the target. Preliminary results indicate that for a $\frac{1}{16}$ -inch carbon target there are about one-fourth as many heavy positive mesons as heavy negative ones for meson energies of 2-3 Mev in the laboratory system.

I. INTRODUCTION

THE mesons first observed¹ at the 184-inch Berkeley cyclotron² were known to be

* Lieutenant Colonel, U. S. Army. Present address: Sandia Base, Albuquerque, New Mexico.

** On leave of absence from University of São Paulo, Brazil.

¹ E. Gardner and C. M. G. Lattes, *Science* **107**, 270 (1948).

² Brobeck, Lawrence, MacKensie, McMillan, Serber, Sewell, Simpson, and Thornton, *Phys. Rev.* **71**, 449 (1947).

negatively charged, since the photographic plates used for detecting them were placed in a position to receive negative but not positive particles from the target. We have now detected positive mesons by placing plates in a position to receive positively charged particles from the target. As with the exposures to negative mesons, the target

was bombarded with the circulating beam of 380-Mev alpha-particles. Most of our work has been done with a carbon target $\frac{1}{8}$ -inch thick. The photographic plates which we have found to be most suitable for detecting positive mesons are Ilford C 2 and C 3, and Eastman NTB, each of emulsion thickness about 100 microns.

II. DESCRIPTION OF APPARATUS

Two methods of making exposures to positive mesons have produced plates suitable for study. The first method makes use of positive mesons which follow trajectories like the one illustrated in Fig. 1. Plates are placed below the circulating beam, as shown in Fig. 2. Mesons are received which leave the target moving at a small angle downward from the beam direction. Plates to receive negative mesons of about the same energy and angular range may be placed on the opposite side of the target, as shown in Fig. 2. Shielding is provided on the side from which the beam comes in order to prevent scattered beam particles from reaching the plates. For mesons which strike the plate at right angles to the edge, the energy range is about 2-5 Mev in the laboratory system. For meson trajectories at other angles the energy at a given point on the plate is larger, so that the energy range of the mesons counted on the plates is not very well defined.

In a second method of detecting positive mesons, the photographic plates are placed in a position to receive mesons which leave the target in a direction opposite to the beam direction. The arrangement is shown in Fig. 3. Plates exposed in this way have tracks of negative mesons along one edge, and tracks of positive mesons along the opposite edge. In this method, as in the preceding one, the energy range of the mesons received by the plates is not well defined.

In addition to the meson tracks found on the plates there is a "background" of tracks caused by protons and alpha-particles. Some of the background tracks are attributed to stars and recoils produced by neutrons, and some to low energy protons and alpha-particles from the target. Neither of the methods for making exposures to positive mesons gives as high a ratio of meson tracks to background tracks as that obtained in exposures to negative mesons.¹

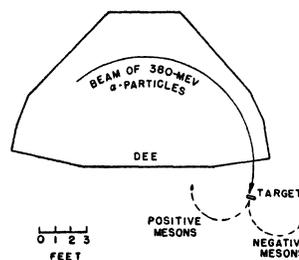


FIG. 1. Plan view of cyclotron showing direction in which positive and negative mesons are deflected by the magnetic field.

III. DESCRIPTION OF THE POSITIVE MESON TRACKS

The appearance of the positive meson tracks under the microscope is similar to that of negative meson tracks.¹ They have a characteristic grain density change along the track and a characteristic wandering associated with small-angle scattering. For mesons which come from the target a measurement of the mass can be obtained by measuring the bending in the magnetic field of the cyclotron and the range in the emulsion. The radius of curvature of the trajectory is calculated from the position on the plate at which the track is found and the angle which the track makes with the edge of the plate. The mass determination has not yet been made with any precision; however, preliminary measurements indicate that there are two groups of mesons having masses of about 300- and 200-electron masses, respectively. It is presumed that they are the same as the π^- and μ^- -mesons described by Lattes, Occhialini, and Powell.² The total number of light and heavy mesons observed so far is about 200.

Neither the heavy nor the light positive mesons initiate stars. Most of the heavy positive mesons disintegrate to give observable secondary mesons, as shown in Figs. 4-6. Figure 4 is taken from an Eastman NTB plate, Fig. 5 from an Ilford C 2, and Fig. 6 from an Ilford C 3. In each case the heavy positive meson enters from the bottom left. At the point at which the heavy positive meson stops a secondary meson is initiated, moving toward the right. It is thought that all, or almost all, of the heavy positive mesons give secondaries; but in some cases the secondaries

² C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, *Nature* **160**, 453, 486 (1947).

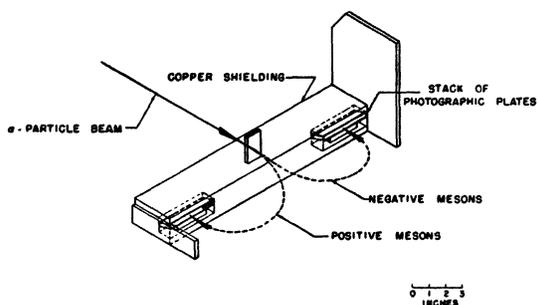


FIG. 2. Apparatus used for placing photographic plates below the circulating beam for exposure to both positive and negative mesons.

move up or down at a steep angle through the emulsion, and the tracks are not seen. The fraction of the heavy mesons which are observed to give secondaries depends on the thickness and sensitivity of the emulsion and on the background of other tracks in the vicinity. Of the emulsions which we have used, the Ilford type C 3 seems to be best for showing secondaries.

For all of the secondary mesons which stop in the emulsion the range is about 600 microns, corresponding to an energy of about 4 Mev. Table I gives the ranges of five secondary mesons which stopped in the emulsion (Ilford plates).

In addition to the light meson tracks which start at the ends of heavy positive meson tracks, other tracks are found which have a grain density change characteristic of light mesons. It is assumed that they are positively charged and that they come from heavy mesons which disintegrate at positions other than in the emulsion. There are two groups: (a) Tracks with random orientation, found in all regions of the plate where heavy positive meson tracks are found. These mesons

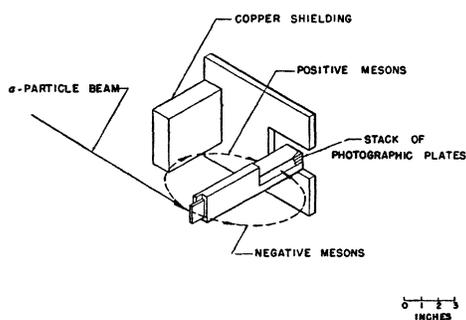


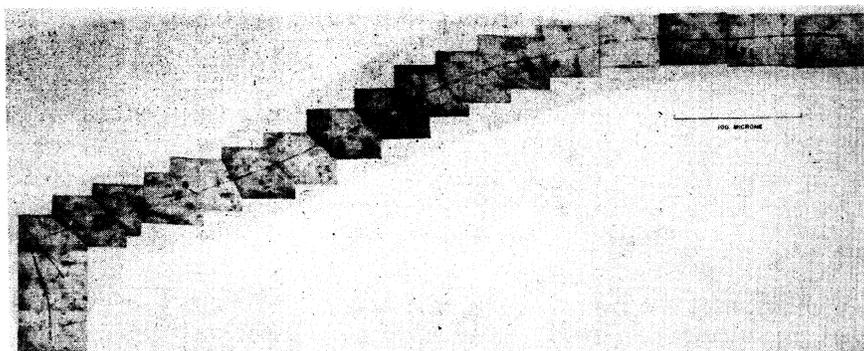
FIG. 3. Apparatus used for placing photographic plates in a position to receive positive mesons which leave the target in a direction opposite to the beam direction.

are presumed to arise from local disintegration of heavy positive mesons in the glass above or below the emulsion. For the disintegrations which are observed in the emulsion, the secondary mesons come off in random directions, so that some remain in the emulsion and some pass out of the emulsion into the glass. Similarly, it is to be expected that disintegrations above or below the emulsion would produce some secondaries which would enter the emulsion from the glass. (b) Tracks which start from the edge of the plate. These probably come from the target, or from some region not too far distant. The evidence for this is that if the masses are calculated by means of bending in the magnetic field and range in the emulsion on the assumption that the mesons come from the target, values are obtained which give an average of about 200-electron masses. The spread in mass values is rather large, suggesting that perhaps not all of the light meson trajectories originate at the target. If the energies of these mesons are calculated from their ranges, assuming a mass of 200-electron masses, almost all of the values found are less than 4 Mev. This suggests that most of them probably come from the decay of heavy mesons at rest, since 4 Mev is about the kinetic energy which a light meson receives from the disintegration of a heavy one.

The light mesons from the target may come from the decay of heavy ones which did not have enough energy to escape from the target. Another possibility is that a heavy meson goes through a 360° trajectory, as illustrated in Fig. 7, and then returns to the target, where it disintegrates into a light meson. It is probable that more light mesons arise from heavy mesons which decay without leaving the target than from those which return, because many of the 360° trajectories spiral up or down enough to miss the target.

Some of the light mesons may not come directly from the target but may come from heavy mesons which disintegrate in flight. Another possibility for a light meson trajectory which does not start at the target is illustrated in Fig. 8. Here a heavy meson from the target comes to rest in the copper of the plate holder in a position such that the secondary meson can reach the photographic plate.

FIG. 4. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Eastman NTB plate.

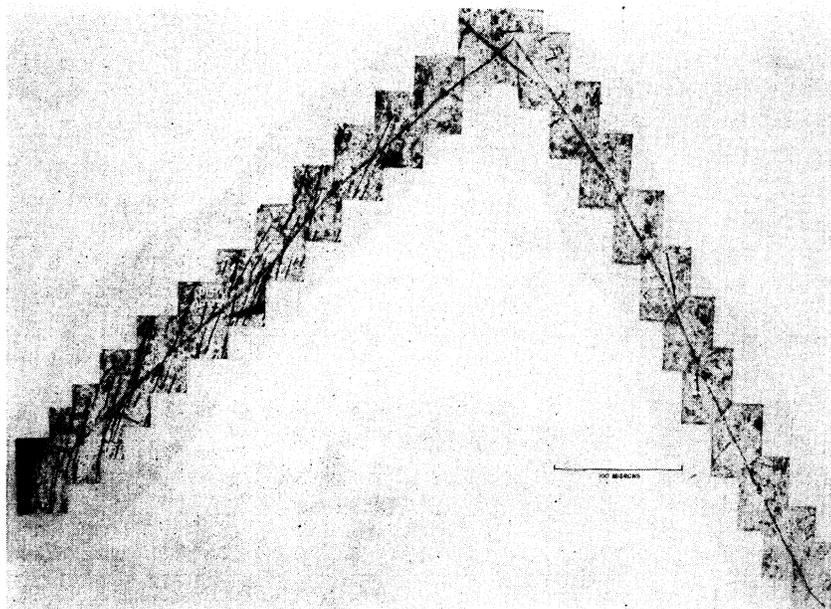


A rather hasty survey indicates that the numbers of light mesons found in various positions on the plate are about what would be expected from the decay of the heavy ones as suggested above. The relative numbers of light and heavy mesons may be illustrated by one group of mesons found in 100-micron Ilford C 3 plates. Of the 34 mesons in the group, 20 entered from the edge of the emulsion and 14 entered from the glass above or below the emulsion. For the 20 mesons which entered from the edge of the emulsion a measurement of bending in the magnetic field and range in emulsion showed that 16 had masses measured as greater than 260-electron masses. The remaining 4 had masses measured between 150-

and 230-electron masses. All of the 16 heavy mesons gave observable secondaries. It is assumed that the 14 which entered the emulsion from the glass were light mesons which came from decay of heavy mesons in the glass above or below the emulsion.

Since the magnetic field of the cyclotron separates the positive mesons from the negative ones, we can be reasonably sure that disintegrations of the type shown in Figs. 4-6 are due to positive mesons. No disintegrations of this type have been found in a study⁴ of negative mesons produced by the cyclotron. This study has included about two thousand heavy negative meson tracks. Light meson tracks have been found, but

FIG. 5. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Ilford C 2 plate. The heavy tracks on the left-hand side of the photomicrograph are due to protons from the target. They are often the most troublesome part of the background.



⁴ Frank Adelman and Stanley Jones, private communication.

TABLE I. Ranges of secondary mesons which stopped in the emulsion (Ilford plates).

Track No.	Range in microns
1	625
2	630
3	612
4	604
5	560

none of them started at the point at which a heavy negative meson track ended. This substantiates the assumption of Lattes, Occhialini, and Powell³ that positive mesons are responsible for the events in which a heavy meson comes to rest in the emulsion and then disintegrates to give a secondary meson.

IV. RELATIVE NUMBERS OF POSITIVE AND NEGATIVE MESONS

By means of symmetrically placed plates, as shown in Fig. 2, we plan to measure the relative numbers of positive and negative mesons produced in targets of various materials. So far only carbon has been studied, and the study has included only a limited range of meson energies. The target was the usual $\frac{1}{16}$ -inch carbon. The

energy range studied is not very well defined, but is of the order of 2-3 Mev in the laboratory system. In this energy range 40 positive mesons have been counted as compared with 136 negative ones in an equivalent area. Of the 40 positive mesons, 26 are known to be heavy since they form observable secondaries. Some of the secondaries may have been missed, so that the number of heavy mesons may be larger than 26. It is estimated that more than 90 percent of the 136 negative mesons are heavy.

Operation with the arrangement illustrated in Fig. 3 has shown that there are some heavy positive mesons which leave the target in a direction opposite to beam direction. In order to illustrate the relative numbers of positive mesons in the backward beam direction and negative mesons in the forward direction, the numbers will be given for one run made with a $\frac{1}{16}$ -inch carbon target. For this run, mesons were counted along the full 3-inch edge of the plate, so that the energy range is of the order of 2-5 Mev in the laboratory system. 144 negative mesons were counted along one edge of the plate and 16 positives along the opposite edge. The numbers given include both light and heavy mesons.

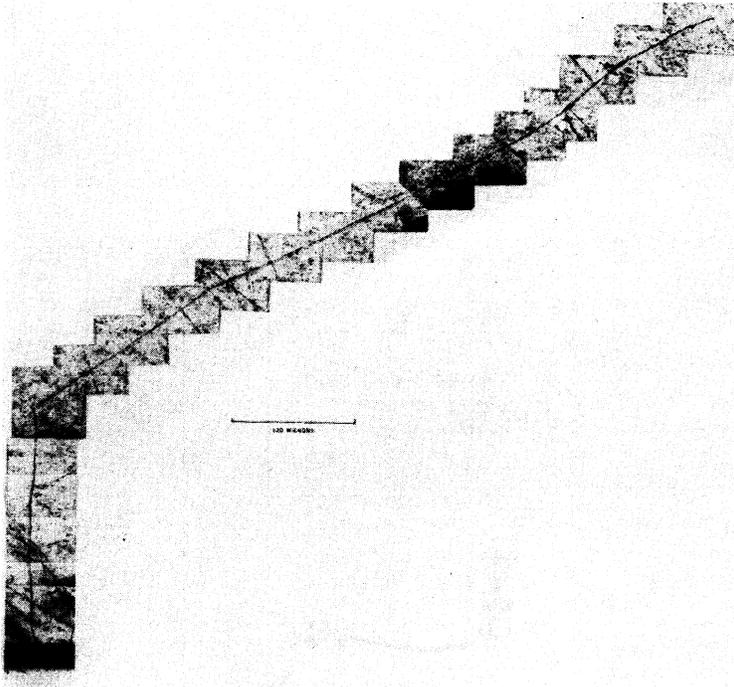


FIG. 6. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Ilford C 3 plate.

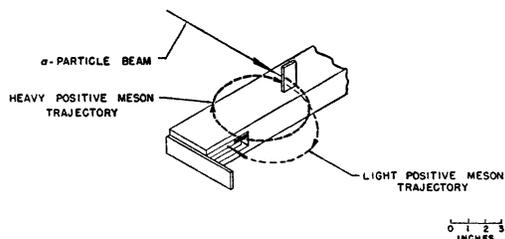


FIG. 7. Diagram showing a possible method of production of light mesons in the target. Heavy meson goes through 360° trajectory and returns to the target, where it disintegrates to give a light meson.

V. CONCLUSIONS

Positive mesons of mass about 300-electron masses are produced when a beam of 380-Mev alpha-particles strikes a carbon target. At points in the emulsion at which these heavy positive mesons come to rest, tracks of secondary mesons of mass about 200-electron masses are ordinarily observed. The fraction of the heavy positive meson tracks for which secondaries are observed depends on the sensitivity and thickness of the emulsion; however, it is thought that all, or almost all, of the heavy positive mesons decay to give secondaries. All of the secondaries have a range which corresponds to a kinetic energy of about 4 Mev. Light meson tracks are observed which do not start at the ends of heavy meson tracks; these are attributed to light mesons which come from the decay of heavy positive mesons at positions other than in the emulsion. It is thought that all of the light positive mesons observed come from the decay of heavy positive mesons.

Preliminary results indicate that for a $\frac{1}{16}$ -inch carbon target there are about one-fourth as many heavy positive mesons as heavy negative ones for meson energies of 2-3 Mev in the laboratory sys-

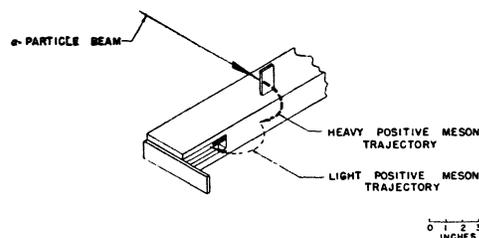


FIG. 8. Diagram showing how a light meson trajectory could start at a point not at the target. Heavy meson from the target comes to rest in the copper of the plate holder in a position such that the secondary meson can reach the photographic plate.

tem. This is not inconsistent with the ratio expected on the bases of Coulomb interaction. A calculation by Serber⁵ gives the ratio of heavy positive to heavy negative mesons in this energy range as about 1 to 3.5.

VI. ACKNOWLEDGMENTS

The authors wish to express their appreciation to Professor Ernest O. Lawrence, whose interest and encouragement have made this work possible. The program has been greatly aided by discussion with Professors R. L. Thornton, E. M. McMillan, R. Serber, L. W. Alvarez, and E. Segrè. We are indebted to Dr. Walter H. Barkas of the Office of Naval Research in San Francisco for microscope observations and suggestions. We wish to thank Mr. A. J. Oliver for the preparation of Figs. 4-6, and Mr. James Vale and the cyclotron crew for making the bombardments. This paper is based on work performed under Contract No. W-7405-eng-48 with the Atomic Energy Commission, in connection with the Radiation Laboratory, University of California, Berkeley, California.

⁵ R. Serber, private communication.

FIG. 4. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Eastman NTB plate.

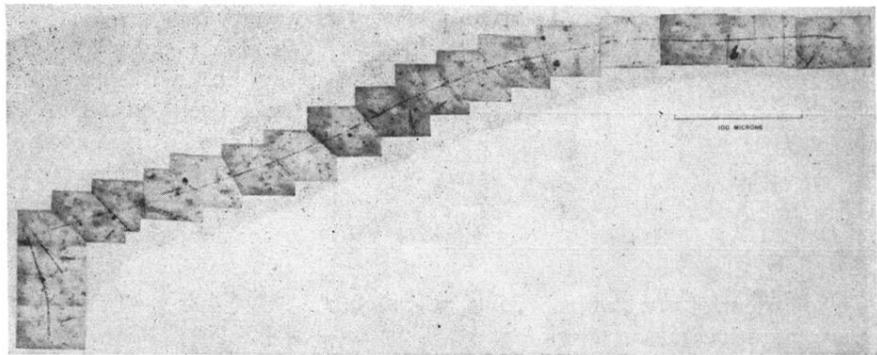
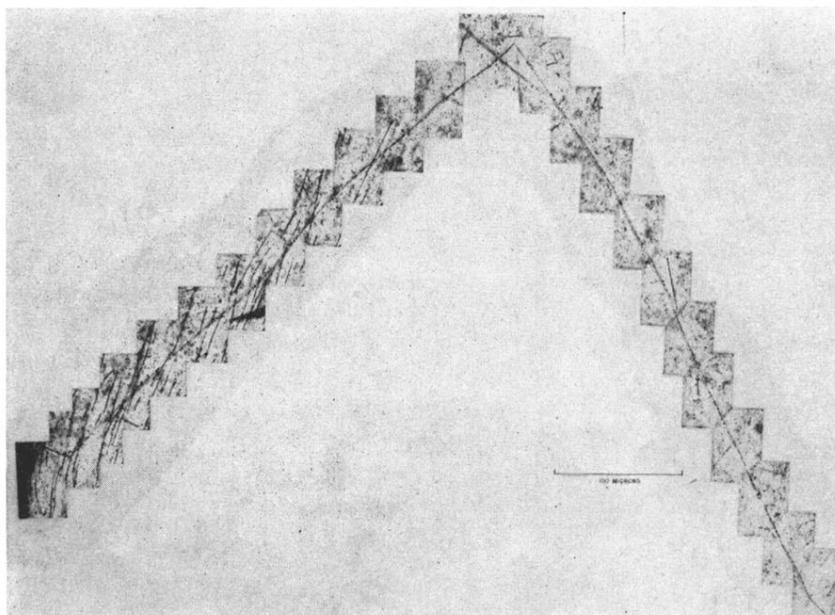


FIG. 5. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Ilford C 2 plate. The heavy tracks on the left-hand side of the photomicrograph are due to protons from the target. They are often the most troublesome part of the background.



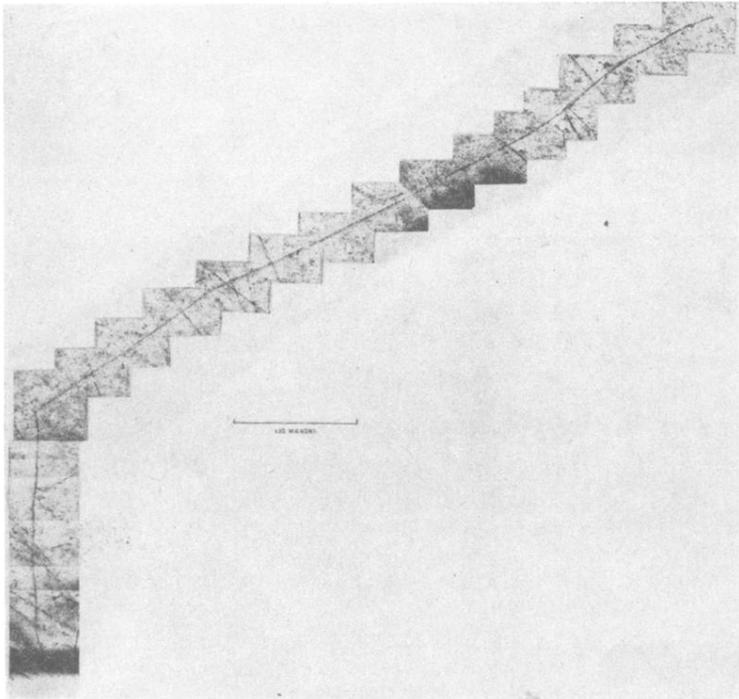


FIG. 6. Disintegration of a heavy positive meson to give a secondary. Photomicrograph made from Ilford C 3 plate.