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Mesons Produced by the Cyclotron

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January 16, 1950

I. Introduction

The nature of the forces that hold the protons and neutrons of an atomic nucleus together has interested physicists for many years. Clearly these forces are not the same as the electrostatic forces which are ordinarily demonstrated with pith balls. Electrostatic theory would say that since protons are positively charged they should all repel one another and the nucleus should fly apart. Actually, of course, the protons and neutrons are so tightly bound together in the nucleus that it takes millions of electron volts of energy to knock one out. The exact nature of the nuclear force is not at all well understood; however, an attack on the problem has been made on the basis of the meson theory of nuclear forces as proposed by Yukawa[1] in 1935. According to this theory, each proton and neutron is accompanied by a "meson cloud". The mesons are thought of as being something like the quanta of an electromagnetic field, except that mesons may carry a charge and they have a finite rest mass. Nuclear forces are not explained in terms of "action at a distance" but rather by the interaction of protons and neutrons with the meson cloud.

[1] H. Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935)

Under some conditions it is possible to dislodge a meson from a nucleus and study it as an independent particle. Mesons as components of cosmic rays are produced when high energy particles strike atomic nuclei in the atmosphere. In the process of creating a meson, the incident particle loses a quantity of energy

* Office of Naval Research, San Francisco

in the kinetic form; this quantity then reappears in the form of the rest mass energy of the meson. Mesons are produced in the same manner in the cyclotron -- by bombarding a target with protons, alpha-particles, or neutrons. The mesons from the synchrotron are produced when high energy x-rays strike a target. The main processes of production and decay of mesons were discovered in cosmic ray experiments,[2] but contributions are now beginning to come from experiments on

[2] For references to original papers see "Guide to Literature of Elementary Particle Physics" by J. Tiomno and John A. Wheeler, American Scientist 37, 202, 417 (1949). For review of both cosmic-ray and artificially produced mesons, see "Mesons Old and New" by Joseph M. Keller, American Journal of Physics 17, 356 (1949)

mesons produced by cyclotrons and synchrotrons. In this paper we shall describe some of the methods used for detecting mesons, and some results obtained with high energy protons from the 184-inch Berkeley cyclotron.[3]

[3] For recent experiments with mesons produced by the synchrotron, see E. M. McMillan, J. Peterson, and R.S. White, Science, 110, 579 (1949)

Two kinds of mesons, π and μ, have been positively identified and studied extensively. Both are unstable particles with masses intermediate between the electron mass and the proton mass. They are ordinarily studied with the same apparatus, and they frequently occur together in the same experiment. But in spite of these similarities, they are really very different types of particles. The most striking difference is that π mesons have a strong interaction with nuclei whereas μ mesons have a weak interaction. According to present ideas, the π's are primary particles which are produced in nuclear collisions, either in cosmic rays or in accelerators. Probably all of the μ's observed in cyclotron experiments are secondary in origin, arising from the decay of the π's. Thus it is probable that it is the π mesons which are responsible for nuclear forces. There are both positively and negatively charged π mesons. Possibly there are also neutral π mesons,[4] although we shall not discuss them in this

[4] W. E. Crandall, B. J. Moyer, and H. F. York, Phys. Rev. to be published; M. F. Kaplon, B. Peters, and H. L. Bradt, Phys. Rev. 76, 1735 (1949); R. E. Marshak, Phys. Rev. 76, 1736 (1949)

paper.

When π^+ and π^- mesons decay in free space they give rise to μ^+ and μ^- mesons, respectively. This process, known as π-μ decay, will be discussed in a later section. When a μ^+ or μ^- decays in free space, it gives off a positron or an electron. The positron and electron energies indicate that in each μ disintegration two neutrinos are also given off.[5] If π^- mesons come to rest in

[5] R. B. Leighton, C. D. Anderson, and A. J. Seriff, Phys. Rev. 75, 1432 (1949)

matter, they enter nuclei and disappear, their rest energy being transformed into nuclear excitation energy. This phenomenon is observed in photographic emulsion "stars" which occur at the ends of π^- meson tracks. The prongs of the stars are attributed to charged particles ejected from excited nuclei. μ^- mesons seldom, if ever, make these stars.[6] Low velocity π^+ and μ^+ mesons are

[6] W. Y. Chang, Rev. Mod. Phys. 21, 166 (1949)

prevented by electrostatic forces from entering nuclei. Thus when these positively charged mesons come to rest in matter, they decay in the same way in which they decay in free space.

II. Methods Used for Detecting Mesons Produced by the Cyclotron

The problem of detecting mesons produced by the cyclotron is one of finding a few mesons produced along with a great many more protons and other heavy particles. When mesons are produced by bombarding a target with 345 Mev protons, these "background" particles are a thousand times as numerous as the mesons. Two types of detectors which are well-suited to this kind of problem are cloud chambers and photographic plates. With both of these devices, charged particles are studied by means of their tracks. If the background of unwanted tracks is high, one may have to look at large numbers of extraneous tracks before finding a track of the particle of interest; however, once the track is found, measurements made on it are not affected much by the presence of the other tracks. Mesons produced by the cyclotron have been detected by means of photographic plates[7] and also with the cloud chamber.[8] Up to the present time, most of the

[7] E. Gardner and C. M. G. Lattes, Science 107, 270 (1948)

[8] W. Hartsough, E. Hayward, and W. M. Powell, Phys. Rev. 75, 905 (1949)

work with mesons produced by the cyclotron has been done with photographic plates. This is due in part at least to the fact that the early work was done inside the cyclotron, where operation of the cloud chamber is extremely difficult. Recently, L. W. Alvarez and his associates[9] have devised a method of

[9] L. W. Alvarez, A. Longacre, V. C. Ogren, and R. E. Thomas, Bull. Am. Phys. Soc. 24, No. 7, 20 (1949). See also J. Steinberger and A. S. Bishop, Bull. Am. Phys. Soc., New York Meeting, February, 1950.

detecting positive mesons from the cyclotron by means of scintillation counters. This offers a great saving in time and effort, and it is probable that counters will replace photographic plates for many meson studies.

Although the use of photographic plates as charged particle detectors has a long history,[10] the special plates now used so extensively have been produced

[10] For early use of photographic plates in cosmic-ray studies, see Blau and Wambacher, Nature 140, 585 (1937). For review of use of photographic plates, see C. F. Powell and G. P. S. Occhialini, Nuclear Physics in Photographs (Clarendon Press, Oxford, 1947); H. Yagoda, Radioactive Measurements with Nuclear Emulsions (John Wiley and Sons, New York, 1949); M. M. Shapiro, Rev. Mod. Phys. 13, 58 (1941)

only during the past three or four years. Some of these plates are made by the workers who use them;[11] however, most laboratories buy their plates from manu-

[11] Pierre Demers, Science 110, 380 (1949). This paper gives references to earlier work.

facturers. The Ilford Nuclear Research Plates were announced[12] in 1946, and

[12] C. F. Powell, G. P. S. Occhialini, D. L. Livesey, and L. V. Chilton, Jour. Sci. Instr. 23, 102 (1946)

since that time new types of plates have appeared at frequent intervals. Similar plates, called Nuclear Track Plates, are produced by the Eastman Kodak Company, and by Kodak Limited. These special plates used for detecting charged particles have a higher concentration of silver bromide than ordinary photographic plates, and the emulsion is thicker. If a charged particle passes through the emulsion it leaves a trail of developable grains of silver bromide. When the plate is developed and viewed under the microscope, one sees a track of silver grains which shows the path of the charged particle. The silver grains have a diameter of 0.2-0.4 microns, and the track is viewed under the microscope with a magnification of from 100x to 2000x, depending on the problem at hand.

One of the advantages of the photographic plate method of detecting charged particles is that plates are available with almost any sensitivity one wishes. Thus, for the study of heavily ionizing particles like low energy α-particles or fission fragments, there are plates which are so insensitive that they will register only heavily ionizing particles, and the observer does not have to look at tracks of electrons or other lightly ionizing particles. On the other end of the sensitivity scale, there are plates which will register tracks of even the most lightly ionizing particles. For a quick identification of meson tracks, one uses plates like Ilford C.2 plates, which have a sensitivity such that a meson track shows a change in grain density in the last few hundred microns of the meson's range. This gives the meson track a characteristic appearance, and one can pick out the tracks by inspection. Meson tracks are further identified by a wandering, associated with small-angle scattering. This grain density change and wandering are illustrated by the meson track shown in Fig. 1. A proton track is shown for comparison. The proton track shows some scattering, but not as much as the meson track; also, the proton track has only a small rate of change of grain density. The π^- meson whose track is shown in the figure was moving from left to right. After it slowed down and stopped in the emulsion it entered a nucleus and gave up its rest energy to nuclear excitation energy. The excited nucleus then ejected four ionizing particles, which made the four tracks shown. Events of this type are called "stars."

The search for these meson tracks is rather time consuming, and every effort is made to expose the plates in such a way that the ratio of meson tracks to background tracks will be as high as possible. Two of the arrangements which have been used for exposing photographic plates to mesons are shown in Figs. 2 and 3. The photographic plates shown in these figures are placed in position in black paper wrapping, or left unwrapped with the cyclotron enclosure darkened. As indicated in these figures, the mesons are formed when the circulating beam of 345 Mev protons strikes a target inside the cyclotron. Fig. 2 shows one arrangement for detecting π^- mesons. Those π^- mesons which leave the target in the forward beam direction are deflected by the magnetic field away from the region occupied by the circulating beam of high energy protons. Protons and heavier nuclear fragments produced at the target in the forward direction are deflected toward the center of the cyclotron because of their opposite charge, and they do not strike the photographic plate. Neutrons from the target and from other parts of the cyclotron collide with nuclei in the emulsion and produce a background of protons, alpha-particles, and other nuclear fragments on the plate. The best exposures made so far have given a ratio of meson tracks to background tracks of about 1 to 50. The plates are tilted so that mesons from the target enter through the top surface of the emulsion, their trajectories making an angle of about 5° with the plane of the emulsion. A 10-second exposure gives about 1000 π^{-} meson tracks on one photographic plate of dimensions 1 inch by 3 inches.

One method used for detecting π^{+} mesons is shown in Fig. 3. The arrangement is similar to that used for π^{-} mesons except that π^{+} mesons which leave the target in a direction opposite to beam direction are recorded. It is true that protons and other positively charged particles from the target can follow the same trajectories as the π^{+} mesons; however, the heavy particles which follow these trajectories have such a low energy and correspondingly short range that they do not interfere much with the study of the mesons.

III. Meson Mass Measurements

A program is now in progress in this laboratory to measure the masses of π and μ mesons. The system which we are using is similar to that developed by Brode[13] and others in connection with mass measurements of cosmic-ray mesons.

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13 R. B. Brode, Rev. Mod. Phys. 21, 37 (1949)

By using the apparatus shown in Figs. 2 and 3 we are able to measure the momentum and range of a meson, and the determination of these two quantities is sufficient to define the mass of the meson. If the magnetic field were uniform, the trajectory would be a part of a circle, and the momentum could be found from the magnetic field intensity and the radius of curvature of the meson trajectory. The radius of curvature of the trajectory could be found from the position of the target, the position at which the meson strikes the photographic plate, and the angle which the track makes with the edge of the plate. Actually the magnetic field of the 184-inch cyclotron decreases slightly with increasing radius, so that the meson trajectory is not exactly a circle. For this case, the momentum must be found by a calculation which takes account of the field variation.[14]

[14] W. H. Barkas, Bull. Am. Phys. Soc. 24, No. 8, 13 (1949)

The range of the meson in emulsion is found by measuring the track length under the microscope.

The equation which makes use of the momentum measurement is an exact relationship for a charged particle moving in a magnetic field.

$$E\left(1+\frac{E}{2mc^2}\right)=\frac{e^2}{2mc^2}(B\rho)^2 \qquad (1)$$

where

E = kinetic energy of meson (ergs)

m = rest mass of meson (grams)

e = charge of meson, assumed to be equal to the charge of the electron (e.s.u.)

c = velocity of light (cm sec.$^{-1}$)

B = magnetic induction (gauss)

ρ = radius of curvature of trajectory (cm)

The equation which uses the range measurement is an empirical relationship which has been found[15] to give a good representation of range-energy values in the energy region in which we are working.

[15] H. Bradner, F. M. Smith, Walter H. Barkas, A. S. Bishop, Phys. Rev., to be published.

$$E = k\,m^{1-n}\,R^n \qquad (2)$$

where

E = kinetic energy of meson (Mev)

m = rest mass of meson (in units of the proton mass)

k,n = constants determined empirically,
numerical values[15]: k = 0.250; n = 0.581

By combining Equations (1) and (2) it is possible to eliminate E and solve for m, the mass of the meson.

In this method of measuring meson masses, we make use of the fact that the meson trajectories start at the target. Thus the method is applicable to the measurement of masses of π^+ and π^- mesons, since these mesons are formed at the target. π^+ mesons which come to rest in the target decay to give μ^+ mesons; thus the target is a source of μ^+ mesons which can be used for measuring the μ^+ mass. When π^- mesons come to rest in the target they are captured by nuclei; thus the target is not a source of μ^- mesons and our method is not applicable to the measurement of the μ^- mass.

We find no difference between the masses of π^+ and π^- mesons, to the accuracy with which we have made the measurements. Preliminary mass values are[16]

[16] F. M. Smith, W. H. Barkas, A. S. Bishop, H. Bradner, and E. Gardner, Bull. Am. Phys. Soc. 24, No. 8, 9 (1949)

$$m_\pi = (276 \pm 6)\ m_e$$

$$m_{\mu+} = (210 \pm 4)\ m_e$$

where m_e is the mass of the electron. These values were found by applying Equations (1) and (2) as described above. A new measurement is now in progress in which meson masses are found by comparison with the proton mass. It is thought that this method will give more accurate values; however, no results from this new measurement are yet available.

IV. π-μ Decay

One of the most interesting facts connected with the meson decay process is that all μ^+ mesons coming from the decay of π^+ mesons at rest seem to have the same energy, about 4 Mev. This was first found in experiments with cosmic rays,[17] and was later verified in cyclotron experiments.[18] When π^+ meson

[17] C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature 160, 453, 486 (1947)

[18] J. Burfening, E. Gardner, and C. M. G. Lattes, Phys. Rev. 75, 382 (1949)

tracks are observed to end in Ilford C.2 plates, or plates of greater sensitivity, it is found that a μ^+ meson begins at the point at which the π^+ track ends. If the μ^+ meson remains in the emulsion for its entire range, the track always has a length of about 600 microns, except for some variation attributed to straggling, i.e., variation due to the statistical nature of the energy loss process. It is seen from Equation (2) that this range corresponds to an energy of about 4 Mev. An example of a π-μ decay as recorded in Ilford C.2 emulsion is shown in Fig. 4.

The fact that μ mesons from π-μ decay always have the same kinetic energy is a very strong indication that one and only one other particle is given off in the disintegration. This other particle does not leave an observable track even in the most sensitive emulsion, so that it is thought to be an electrically neutral particle. From the mass values given in the preceding section, it is seen that the μ meson is about 66 electron masses lighter than the π meson. This mass difference is equivalent to about 34 Mev of energy, of which 4 Mev is accounted for as kinetic energy of the μ meson. It is assumed that the neutral particle carries off the remaining 30 Mev of energy, and enough momentum to balance that received by the μ meson. Calculations show that these conditions are satisfied if the neutral particle has zero rest mass.

V. The Lifetime of the π Meson

The lifetime of the π meson is so short that some of the mesons undergo π-μ decay before they reach the position of the plates shown in Figs. 2 and 3.

If the mesons were not intercepted by the plates but were allowed to continue in approximately circular orbits, they would make, on the average, only about two revolutions before they decayed. Richardson[19] and Martinelli and Panofsky[20]

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[19] J. R. Richardson, Phys, Rev. 74, 1720 (1948)

[20] E. Martinelli and W. Panofsky, Phys. Rev., to be published

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have made measurements of the π meson lifetime by observing how many mesons disappear from a group of mesons in the time required for the group to travel through one revolution. A schematic diagram of the arrangement is shown in Fig. 5. One group of mesons, A, spirals upward and strikes the top photographic plate after traveling one half revolution. A second group, B, spirals downward and travels for one and one half revolutions before striking the bottom plate. Suitable shielding (not shown) prevents mesons from reaching the plates by any paths other than the ones shown. Numbers of mesons striking the two plates are found by counting meson tracks after the plates are developed. After appropriate geometrical corrections are made, the lifetime of the mesons is found from the number lost from group B in the time required to travel the extra revolution.

Richardson[19] worked with π^- mesons and obtained a value of $\left(1.11 {+.31 \atop -.22}\right) \times 10^{-8}$ sec. for the mean life. Martinelli and Panofsky,[20] working with π^+ mesons, found a mean life of $\left(1.97 {+.14 \atop -.17}\right) \times 10^{-8}$ sec. The values given are not in agreement within the errors quoted; however, this discrepancy is not interpreted as proving that the mean life of the π^- meson is really different from that of the π^+ meson.

The mean life of the μ meson, as found in cosmic-ray experiments, is larger than that of the π meson by a factor of about a hundred. The value of the mean life of the μ^+ meson is given by Nereson and Rossi[21] as $(2.15 \pm 0.07) \times 10^{-6}$ sec.

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[21] N. Nereson and B. Rossi, Phys. Rev. 64, 199 (1943)

VI. Stars Initiated by π^- Mesons

The photographic emulsion stars initiated by π^- mesons exhibit a wide variation. They differ in the number of prongs per star, in the orientation of the prongs, and in the types and energies of the particles making the prongs. The prong number distribution has attracted interest as an aid in the study of the mechanism by which the π^- meson gives up its rest energy to a nucleus,[22-24]

[22] D. H. Perkins, Phil. Mag. Ser 7, Vol. XI, p. 601 (1949)

[23] R. E. Marshak, Echo Lake Cosmic Ray Conference, June 22-28, 1949.

[24] Fujimoto, Hayakawa, and Yamaguchi, Prog. Theo. Physics (in press)

and as a method of finding out how many π^- meson tracks are present in a mixture of tracks which includes some μ meson tracks. As shown in the prong distribution table which follows shortly, some of the π^- meson tracks are not accompanied by stars, and there is no simple way to distinguish these tracks from tracks of μ mesons. If the prong number distribution is known, however, the number of star-forming mesons can be counted, and the appropriate number added for those which do not make stars. This method has been used by McMillan, Peterson, and White[3] to find the ratio of π^- to π^+ mesons produced by x-rays from the 335 Mev Berkeley synchrotron.

In order to find the prong number distribution of stars initiated by π^- mesons, it is important to have a group of π^- mesons which is free from contamination of other types of mesons. With the apparatus arranged as shown in Fig. 2, only mesons with a negative charge can reach the photographic plate. In addition to the π^- mesons, however, there will be some μ^- mesons which come from the decay-in-flight of the π^- mesons. By applying the method described in Sec. III, one can make a mass measurement for each individual meson. The measured masses of the π^- mesons will form a group whose average value is approximately 276 electron masses, but the μ^- mesons will not, in general, have ranges and momenta such that they could be confused with this group. Prong number distribution studies can be done with the same mesons used for mass measurements.

The prong number distribution as found from 512 stars initiated by π^- mesons is given by Adelman and Jones[25] as follows:

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25 Frank L. Adelman and Stanley B. Jones, to be published

Number of prongs (includes recoils)	0	1	2	3	4	5	6 or more
Percent of stars having this number of prongs	26.8%	21.5%	27.0%	15.2%	7.8%	1.8%	none found in this study

VII. Yield of π Mesons as a Function of Bombarding Energy

The number of mesons produced by bombarding a target with protons increases rapidly as the proton energy is increased. A convenient method for studying this effect is to move the target and plate shown in Figs. 2 and 3 to different radii in the cyclotron. In this way one can observe the yield of mesons as a function of proton energy from energies as small as desired up to 345 Mev, the maximum proton energy available from the cyclotron. If a carbon target is used, the integrated beam current can be obtained by observing the positron activity of the C^{11} formed in the $C^{12}(p,pn)C^{11}$ reaction. The relative meson yields at the various energies are found by counting meson tracks on the photographic plates. Appropriate corrections are made for integrated beam currents and relative volumes of emulsion scanned.

So far meson yields have been measured only for mesons of energy 2-10 Mev. In a study by Jones and White[26] the relative yields were measured for π^- mesons

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26 Stanley B. Jones and R. S. White, to be published

produced by bombarding a 1/32 inch carbon target with protons. Their results are as follows:

Proton Energy (Mev):	345	305	270	235	200	165
Relative Yield:	100%	47%	22%	8%	1%	0%

These results are of interest to workers who are planning the construction of accelerators which might be used for meson studies.

The work described in this paper was done under the auspices of the Atomic Energy Commission.

(This is the first of two papers on the subject of mesons produced by the cyclotron. The second paper, by Chaim Richman and Howard Wilcox, will describe experiments with mesons produced outside the cyclotron by the deflected proton beam.)

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Figure Captions

Fig. 1. Upper: Photomicrograph showing track of π^- meson. This meson came to rest in the emulsion and initiated a four-prong star.

Lower: Track of proton for comparison.

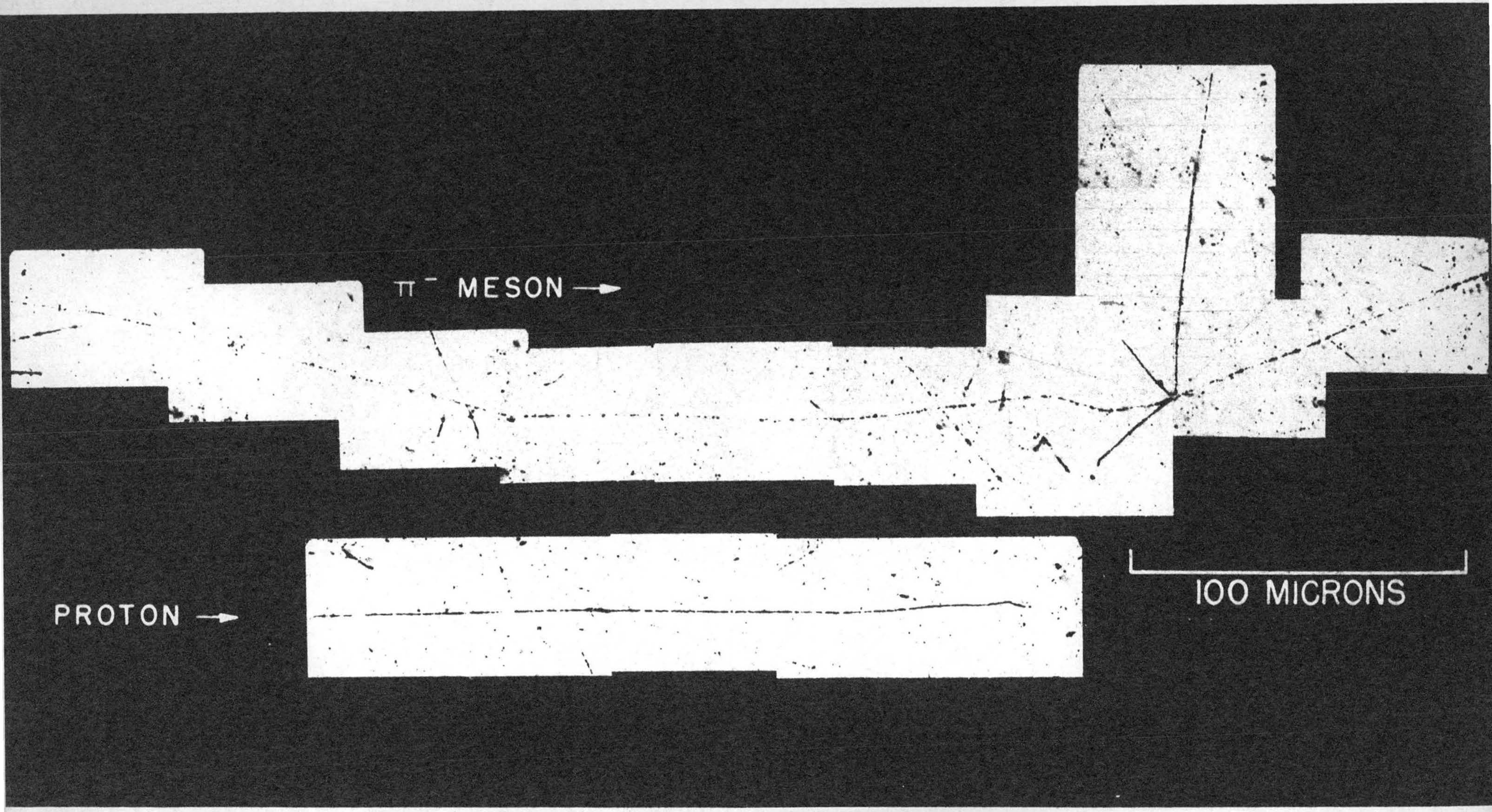
Ilford C.2 emulsion.
(Photomicrograph by A. J. Oliver)

Fig. 2. Sketch of cyclotron showing arrangement for detecting π^- mesons. (not to scale)

Fig. 3. Sketch of cyclotron showing arrangement for detecting π^+ mesons. (not to scale)

Fig. 4. Photomicrograph showing track of π^+ meson which slowed down and stopped in the emulsion and then decayed to give μ^+ meson. The μ^+ meson subsequently slows down and stops in emulsion. The μ^+ meson track has the characteristic length of about 600 microns. Ilford C.2 emulsion. (Photomicrograph by A. J. Oliver)

Fig. 5. Sketch of target and plates showing one group of mesons, A, which travels through one half revolution and another group, B, which travels through one and one half revolutions. (not to scale)



OZ 80

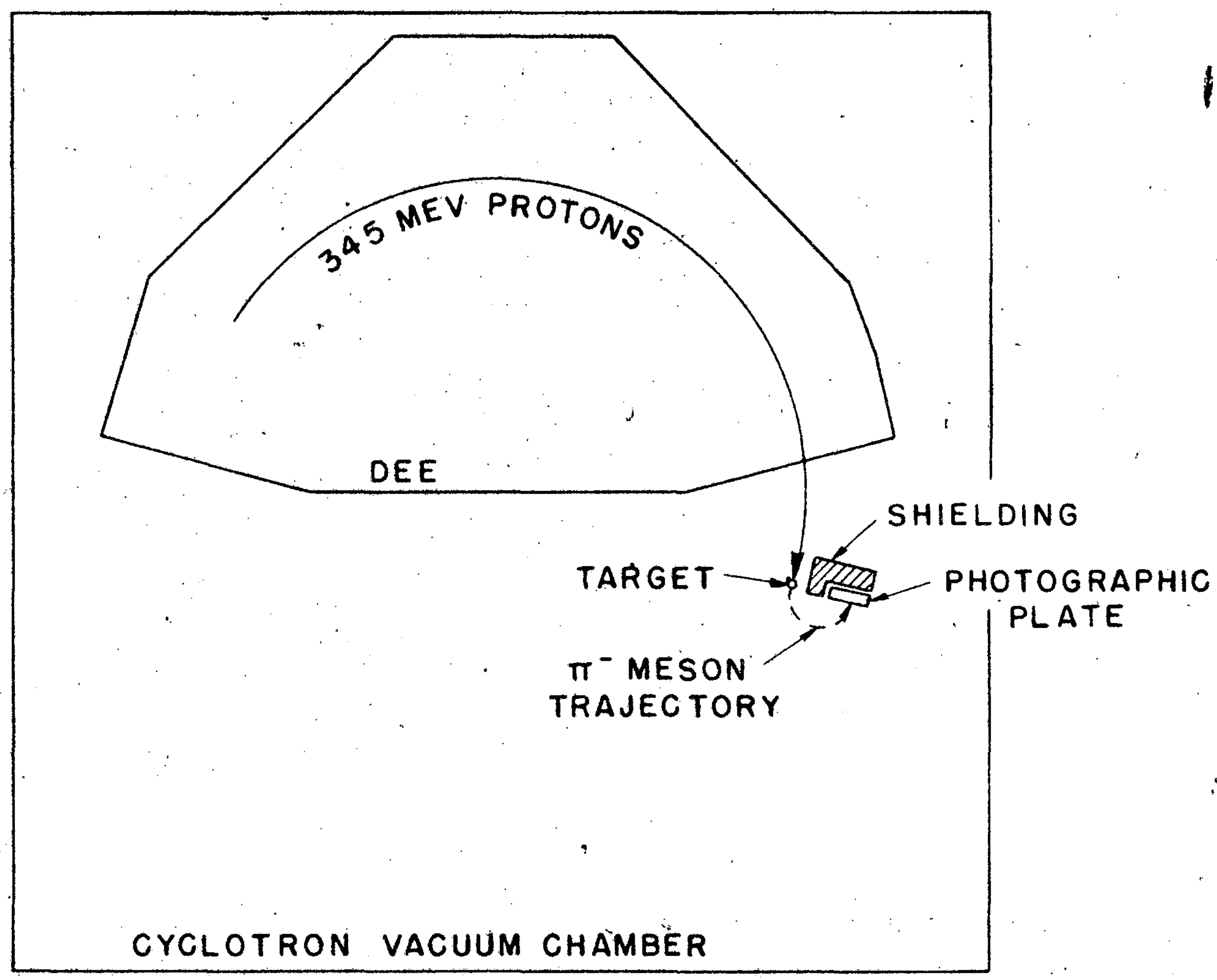

345 MEV PROTONS
DEE
SHIELDING
TARGET
PHOTOGRAPHIC PLATE
π⁻ MESON TRAJECTORY
CYCLOTRON VACUUM CHAMBER

Fig 2

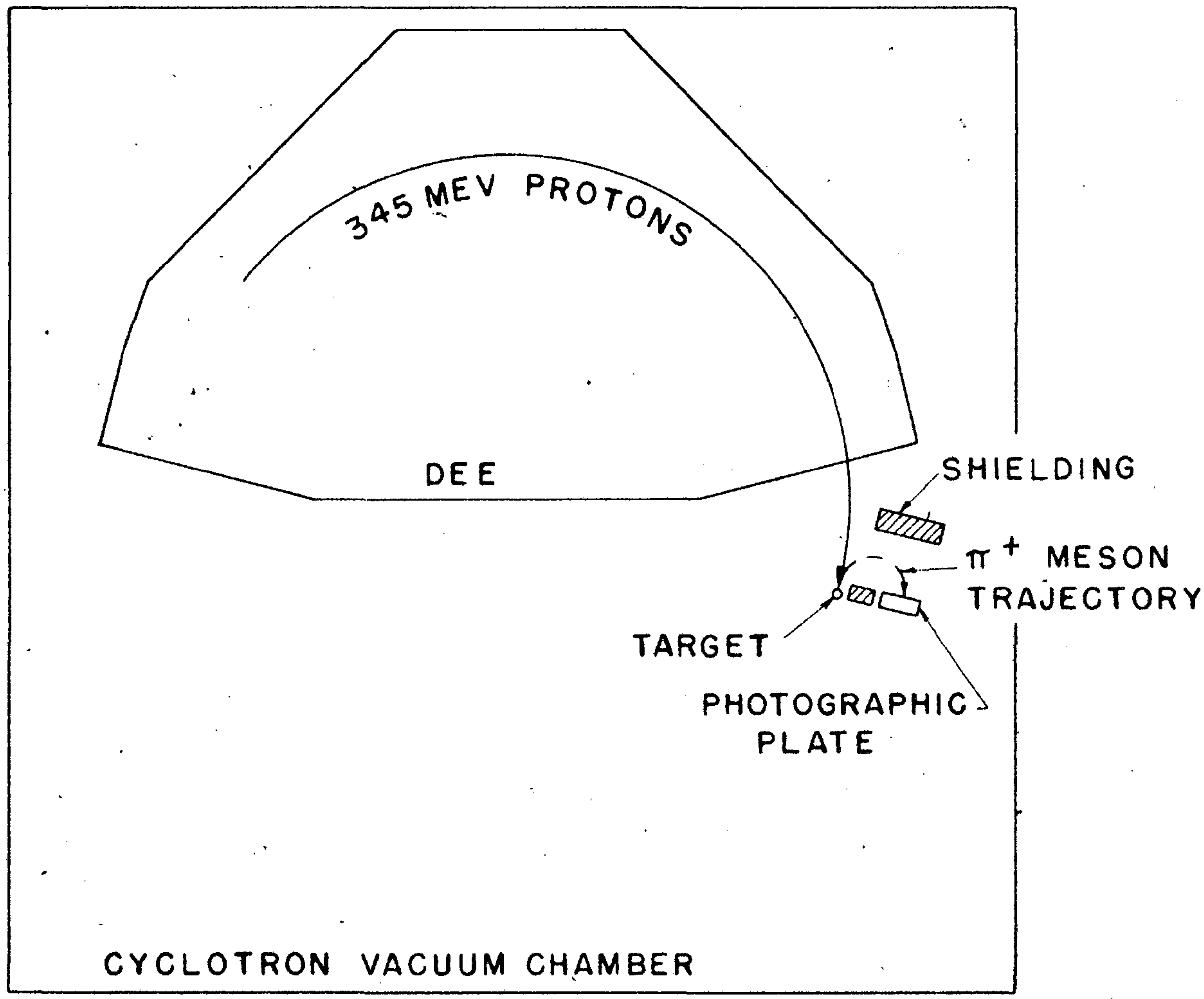
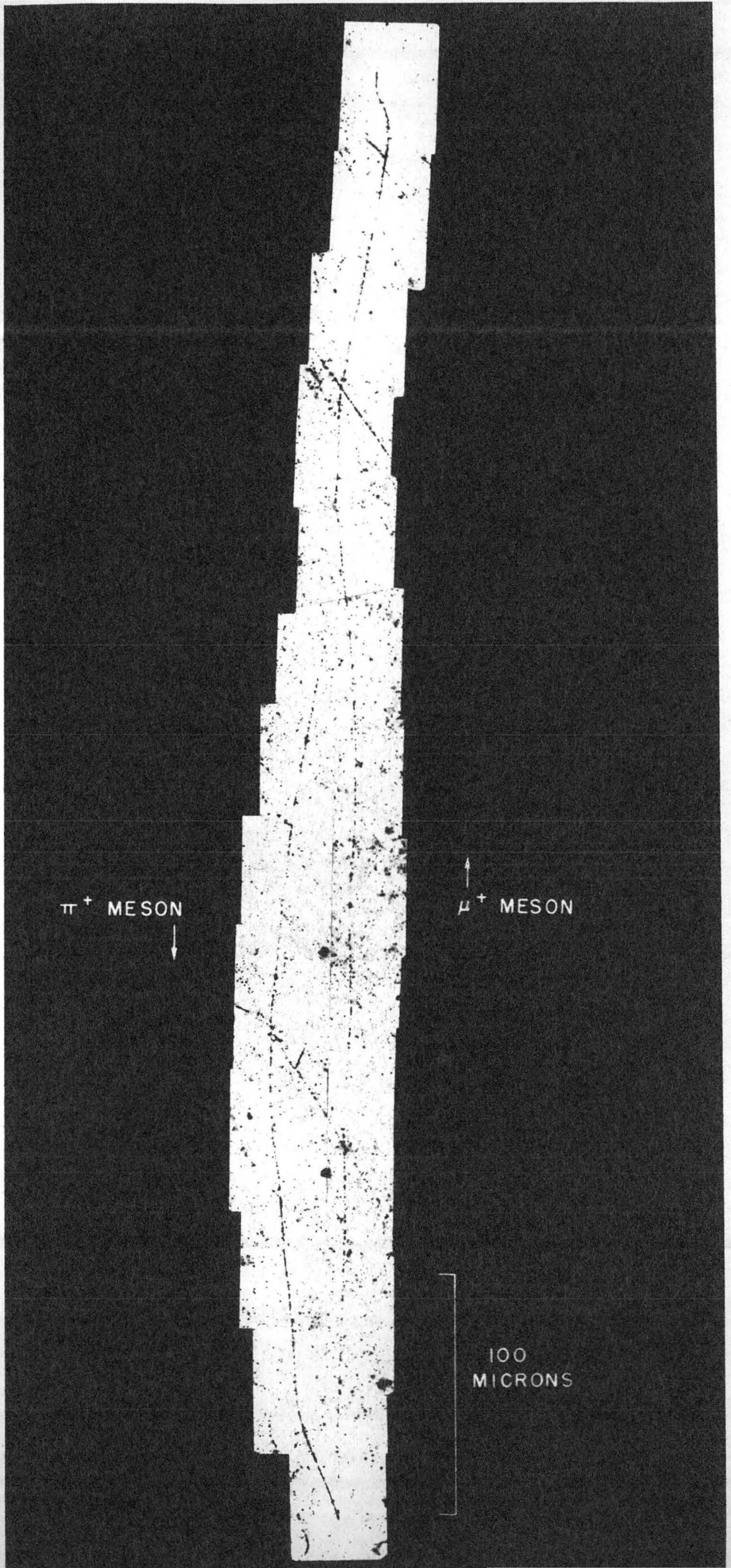

345 MEV PROTONS
DEE
SHIELDING
π + MESON
TRAJECTORY
TARGET
PHOTOGRAPHIC
PLATE
CYCLOTRON VACUUM CHAMBER

Fig 3

14338-1



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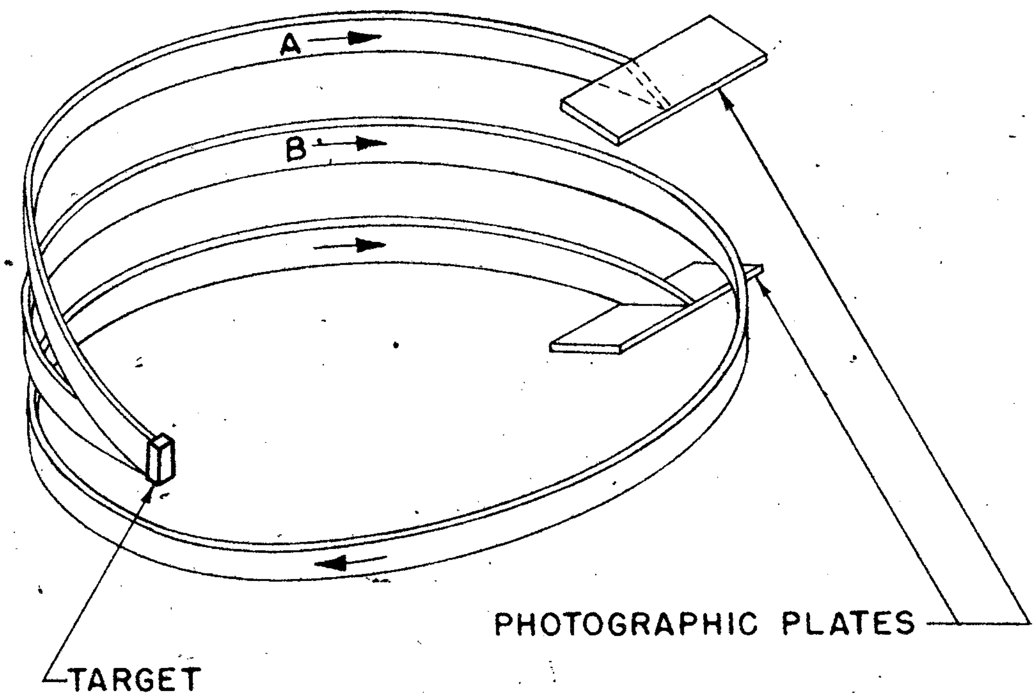

Fig 5

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