First photo-micrographs of tracks of α-particles in a photographic emulsion

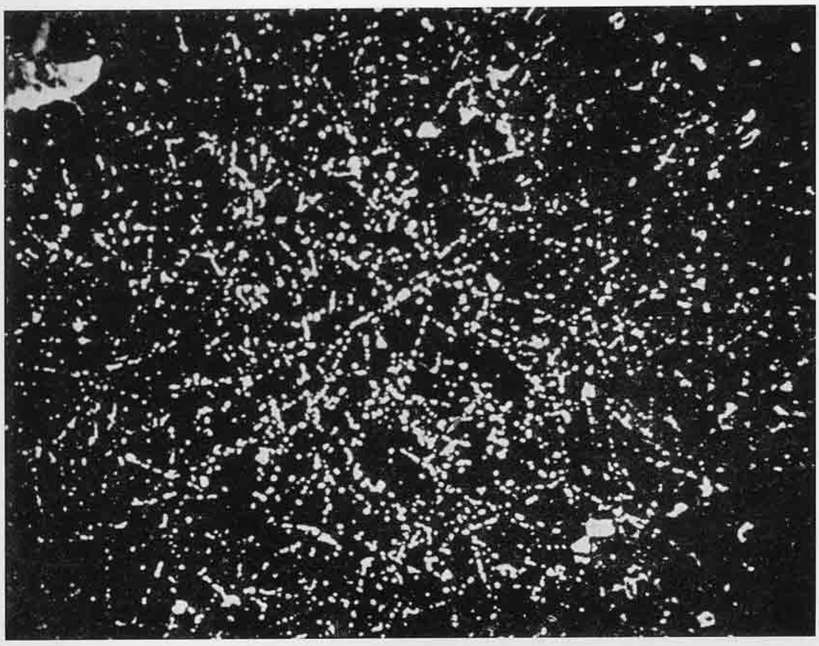

PLATE 1–3

Ilford 'Process' Plate. WALMSLEY and MAKOWER (1914).

Tracks produced by α-particles from a metal plate exposed for a few seconds to a small quantity of radon. The α-particles are directed at random, but lines of grains due to individual particles can be clearly distinguished.

Tracks of individual α-particles

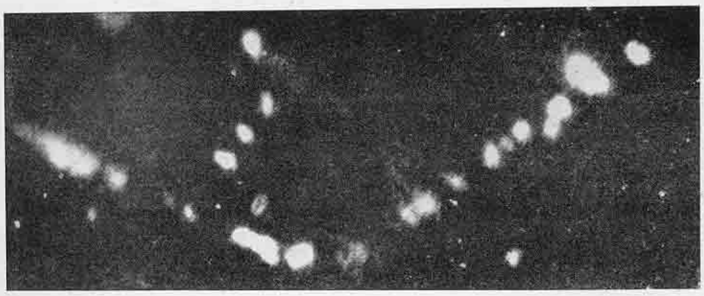

PLATE 1–4

Ilford 'Process' Plate. WALMSLEY and MAKOWER (1914).

Branched track originally attributed to the scattering of an α-particle, but now believed to have been produced by two separate particles diverging from the same, or nearly the same, point.

Radioactive contamination of an emulsion

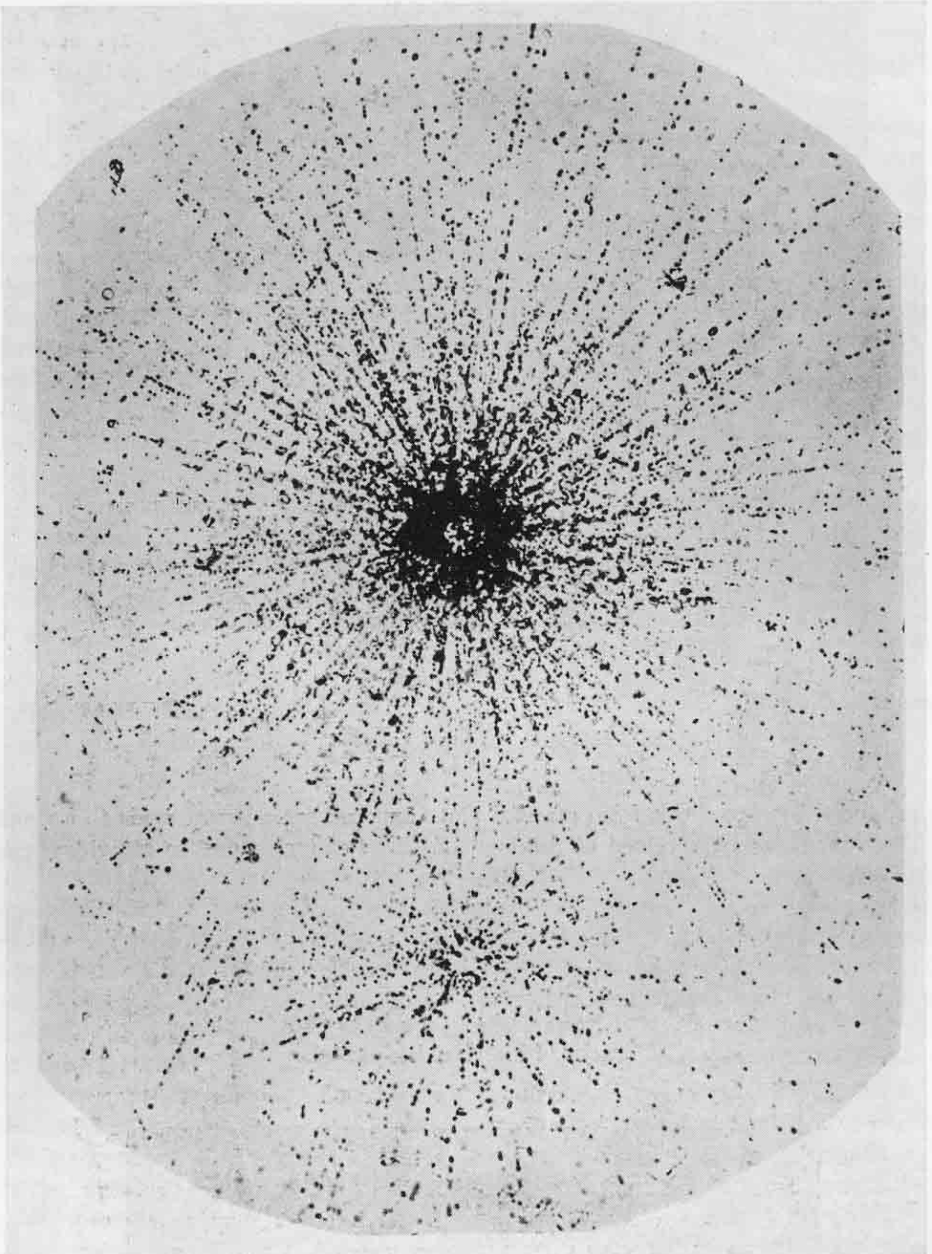

PLATE 1–5

Wratten 'Ordinary' Plate. KINOSHITA and IKEUTI (1915).

The α-particle tracks were produced by means of a sewing needle of which the point had been rubbed on a metal plate exposed to radon. The hole left by the needle point can be seen as a light patch at the centre of each pattern. Most of the tracks are due to RaC′ of range in the emulsion 54μ, the mean number of grains per track being 16. Many of the α-particles enter the emulsion from points on the needle above the level of the surface so that there is no clearly marked halo. Note the absence of large-angle scattering of the particles.

Halos due to radioactive infection of an emulsion

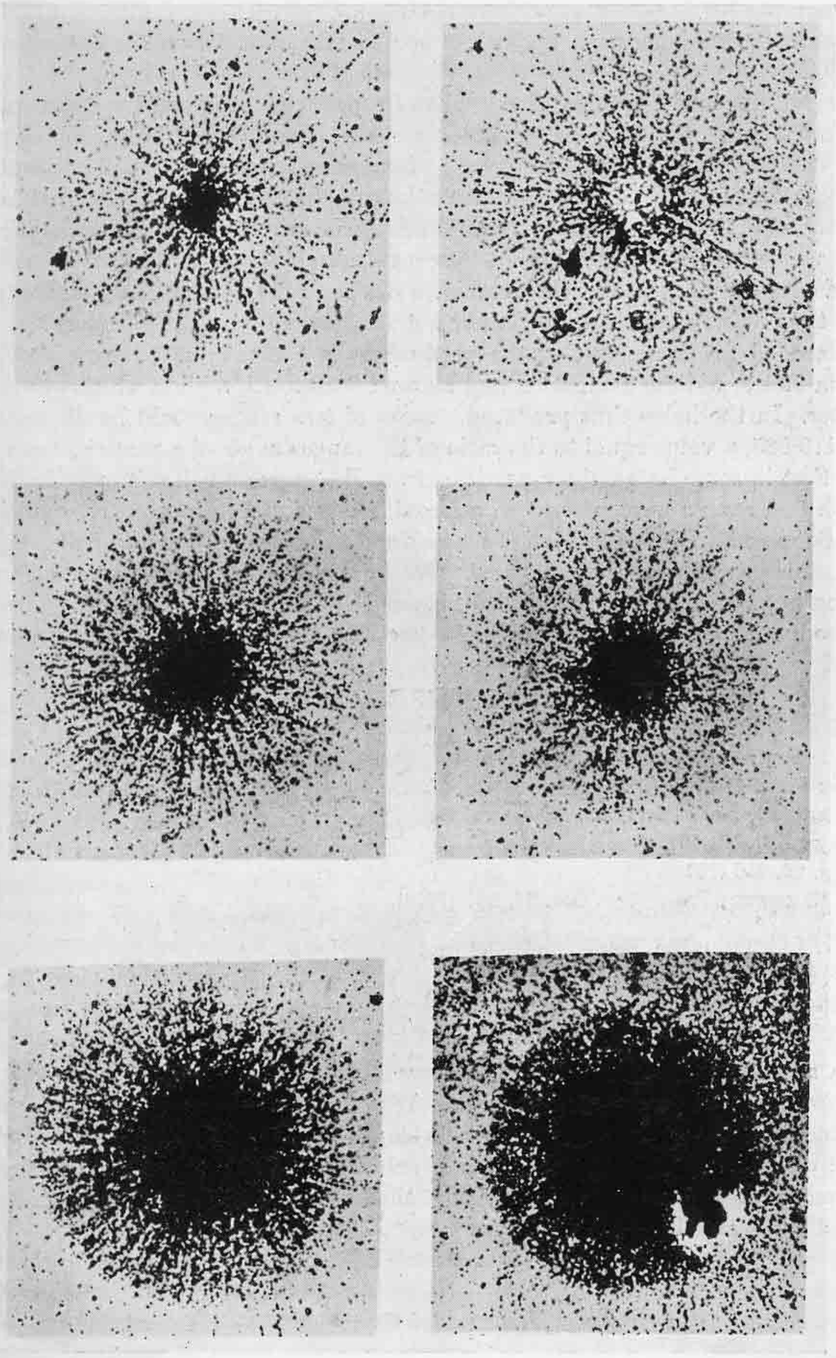

PLATE 1–6

Wratten 'Ordinary' Plate. KINOSHITA and IKEUTI (1915).

A series of exposures, of gradually increasing intensity, designed to show the development of 'halos' similar to those observed in minerals. The diameter of the solid central core depends upon the length of exposure and the number of α-particles emitted. The outer ring is due to the constancy in range of the α-particles (from RaC′) the mean diameter being $\sim 108\,\mu$. The radioactive material was introduced by touching the plate with a needle point contaminated by exposure to radon.

(Continued from page 12)

of the tracks of the type shown in Plate 1–4, to the large-angle scattering of α-particles, but this explanation is now believed to be incorrect; see below.

Later photographs by KINOSHITA and IKEUTI (1915), SAHNI (1915), and IKEUTI (1916) also showed individual α-particles diverging from a speck of radioactive material on the surface of an emulsion; see Plate 1–5.

SAHNI, like MIEHL, mentions that the tracks of α-particles observed by REINGANUM were often curved 'due to the particular way the emulsion contracts on drying'; he made experiments to test the recording characteristics of different types of commercially available plates and, among those studied found that WRATTEN and WAINWRIGHT's 'lantern' plates were the most satisfactory, followed by Ilford 'Process' and 'Imperial Sovereign' Plates. He also stressed the difficulties produced by 'chemical fog' which makes it more difficult to recognise tracks and to determine their precise length. SAHNI exposed plates to β-rays and was unable to distinguish any individual tracks, remarking that if they can be thus recorded, they are certainly not straight.

IKEUTI succeeded in demonstrating the production of 'halos' due both to RaA and RaC. He exposed an iron ball to radium emanation and allowed it to touch a plate which was developed about 30 minutes later. In the halos thus produced, tracks of two ranges could be distinguished of which the ratio was 1:0·685, a value equal to the ratio of the ranges in air of α-particles from RaA and RaC. IKEUTI found that in some halos, the α-particles from RaA were much the more frequent; in others, particles of the two ranges were present in approximately equal numbers. He explained this result as due, on the one hand, to the deposition of RaA on specks of dust on the iron ball during the exposure to emanation; this gave the radium A halos. On the other hand, the ball picked up some 'active deposit' by contact with the mercury which retained the emanation in the glass vessel containing it, and this produced halos in which the RaC α-particles were approximately as numerous as those from RaA.

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KINOSHITA and IKEUTI; Phil. Mag. **29**, 420 (1915).
MAYER; Ann. der Phys. **41**, 931 (1913).
MIEHL; Wien. Ber. **121**, 2*a*, 1431 (1912).
REINGANUM; Phys. Zeit. **11**, 1076 (1911).
SAHNI; Phil. Mag. **29**, 836 (1915).
WALMSLEY and MAKOWER; Proc. Phys. Soc. **26**, 261 (1914).

5. ATTEMPTS TO EXTEND THE METHOD

KINOSHITA and IKEUTI (1915), whose later work was contemporaneous with that of SAHNI, also studied the photographic action of β-particles. Whereas KINOSHITA (1910) had found that every grain penetrated by an α-particle is made to develop, the new experiments showed the β-rays to be less effective by a factor of six or eight. The conclusion was correctly drawn that in the available emulsions, it was probably not possible to detect them because of the 'wider separation of grains in the tracks, and the scattering of the particles'.

KINOSHITA and IKEUTI also placed an α-particle source near an emulsion in a magnetic field of about 10,000 gauss, and found no indication of a resulting curvature of the tracks. They recognised that this result follows from the high momenta of the α-particles. The expected radius of curvature of a track was about 40 cm., a curvature quite beyond the limits of detection with tracks $\sim 50\ \mu$ long. They also observed that among the tracks of α-particles, diverging from a speck of radioactive material on a plate, there were very few which showed evidence of large-angle scattering, whereas, from an extended source such as is provided by a metal plate exposed to radon, many examples appear. They noticed that apparent angles of scattering, $\sim 90°$, were as frequent as much smaller deviations, and suggested that 'further investigations will be necessary to decide whether the apparent scattering is due to two particles passing through the same point in different directions'.

Most of the apparent examples of large angles of scattering, first observed by WALMSLEY and MAKOWER, must have been due either to pairs of α-particles, or to the successive decay of individual radioactive nuclei, a process similar to that responsible for the 'thorium stars' often seen in emulsions

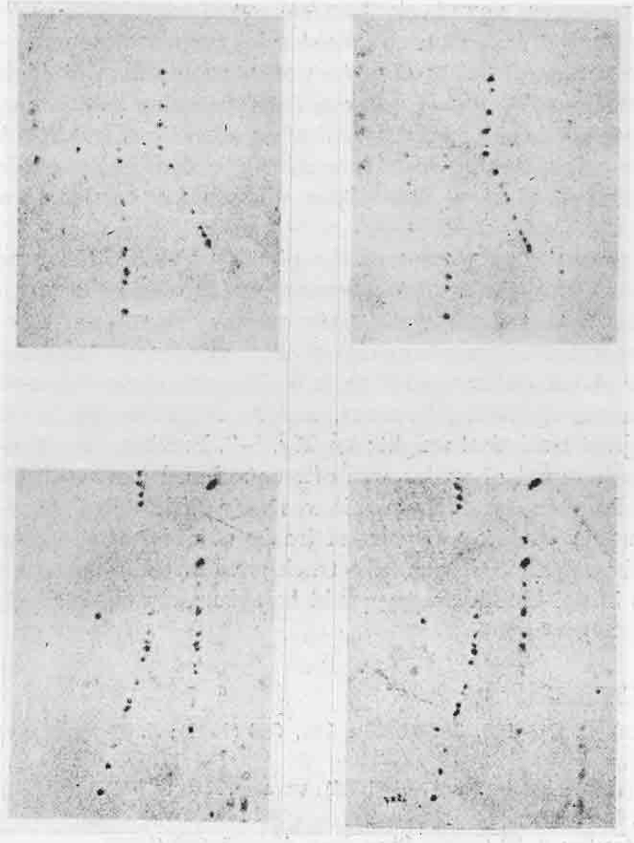


PLATE 1–7

Special emulsion. MYSSOWSKY and TSCHISHOW (1927).

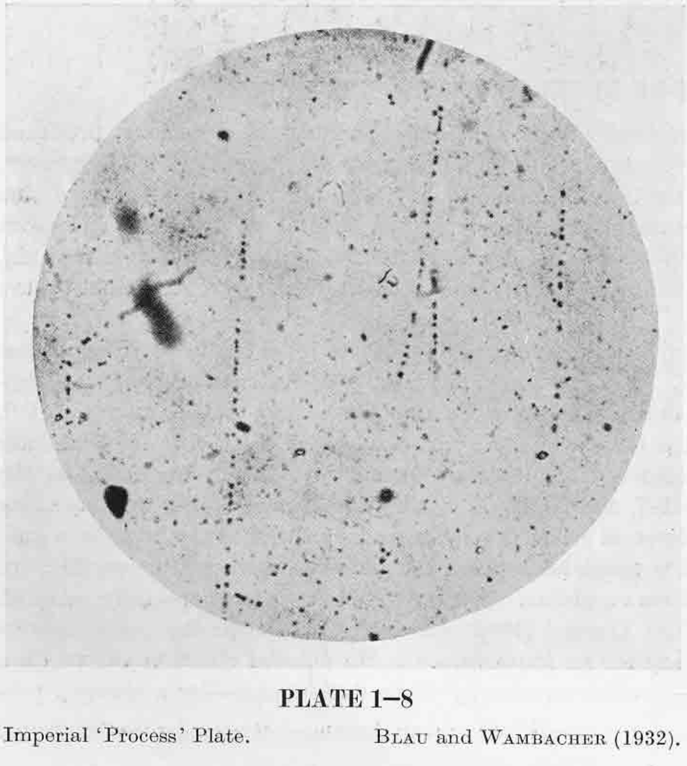


PLATE 1–8

Imperial 'Process' Plate. BLAU and WAMBACHER (1932).

◄ PLATE 1–7

Stereographic pairs of photo-micrographs of α-particle tracks

Stereographic pairs of photographs of α-particle tracks in an emulsion of 'lantern plate' type. The tracks show convincing examples of scattering through angles of about 20°.

PLATE 1–9 ►

Tracks of artificially accelerated protons

Tracks of protons recorded in a plate sensitised with pinakryptol yellow. The tracks have been photographed with 'dark-ground' illumination.

◄ PLATE 1–8

Tracks of protons

Tracks of protons in a plate treated by bathing in a solution of pinakryptol yellow. In these experiments, several tracks were observed with a length $\sim 600\,\mu$. The grain-density in the tracks is much greater than in the absence of the dye; see also Plate 1–9.

K is a constant, $\bar{d}$ is the mean grain-diameter, and M the mass of silver halide per cc. of the emulsion. To improve the precision of the method, Δ must be made small. He therefore prepared a series of emulsions, with a given concentration of silver halide but different values of the mean grain-size, by varying the temperature of the solution from which the halide was precipitated. With these emulsions, it was shown that the number of developed grains in the tracks of α-particles can be increased by reducing the grain-size.

The improvement which could be made by the above approach was limited by the change with size of the sensitivity of the grains. Like BLAU and WAMBACHER (1932), ZHDANOV found no tracks in LIPPMAN Plates in which the grain-size is very small (see Plate 1). In his own emulsions, as the grain-size increased, tracks of α-particles appeared when the mean 'grain-diameter' was of the order of 0·2–0·4 μ, but protons were only recorded by larger grains, $\sim$0·8 μ. He also found that the mean

Tracks of artificially accelerated protons

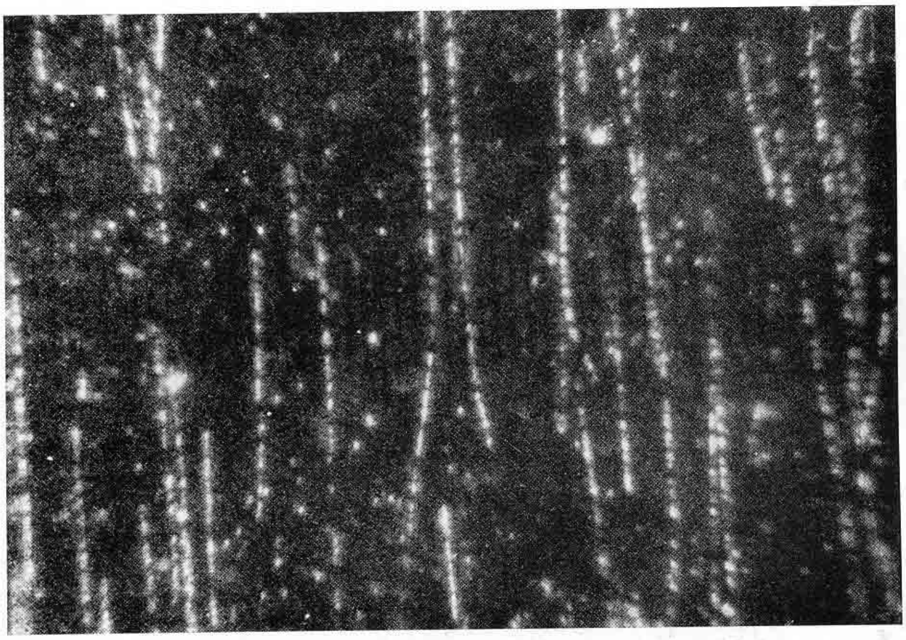


PLATE 1–9

Ilford 'R 2' emulsion. WILKINS (1940).

gap-length in the tracks of protons increased with the range of the particles, and he related this effect to the variation of the specific ionisation with velocity. It may be remarked that the essential point—that a certain average amount of energy must be absorbed by a grain of a given size and type, if it is to be made to develop—and that the probability of its doing so depends on the specific ionisation of the particle—appears not to have been appreciated by all workers at this time; see, for example, WILKINS (1936, 1940).

An alternative approach to the problem of improving an emulsion is to increase the concentration of silver halide in it. This was impracticable in 1935, but it became technically possible ten years later, and was largely responsible for the important improvements in emulsions then brought about; see, for example, Plates 1–12 and 1–13.

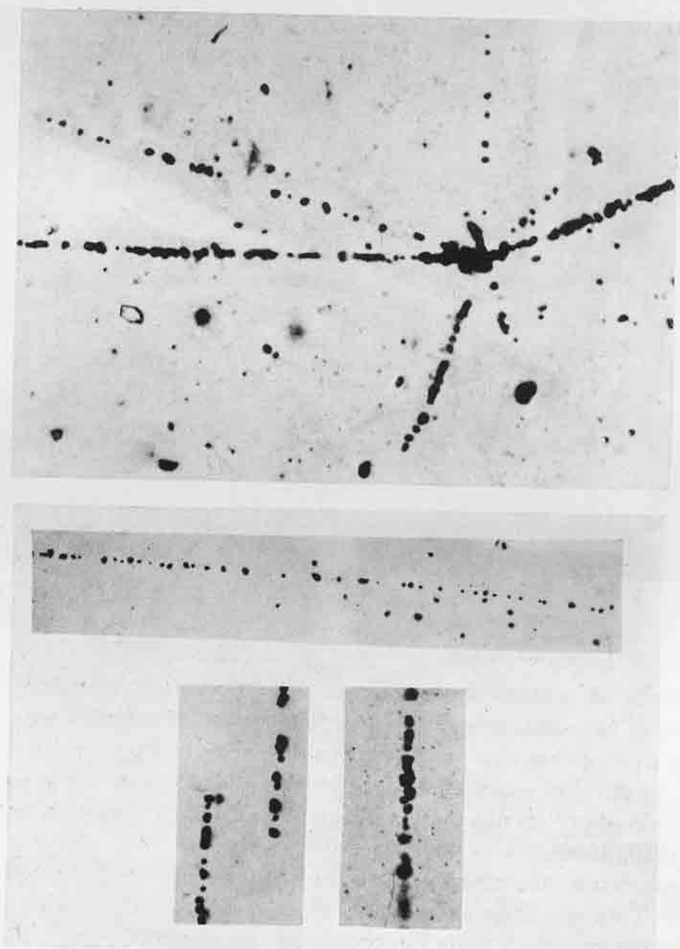
In addition to his work on new emulsions, ZHDANOV also stressed the similarity in principle of the photographic method and the WILSON chamber, the importance of employing thicker emulsions ($\sim$50 μ), and the need to determine the spatial orientation of tracks within it. He also directed attention to the importance of the binocular microscope in contributing to the ease with which tracks can be inspected.

An independent attempt to improve emulsions was made by BLOCH and SMITH of Ilford Limited (1935) who produced two types designated R 1, and R 2, and who also succeeded in reducing the number of background grains. In the Ilford R 1 plates the grain-size was $\sim$0·2 μ; the background was almost entirely eliminated, but at the expense of a certain loss of sensitivity so that protons were not recorded. The R 2 plates, with similar grain-size, were more sensitive than R 1, but the background grains were more numerous. Some of the best photo-micrographs of proton tracks, in the period before the development of more sensitive emulsion in 1945, were obtained by BLAU (1937) and by WILKINS (1940) using Ilford R 2 plates treated with pinakryptol yellow; see Plate 1–9. The emulsion was sensitised by bathing in an aqueous solution of pinakryptol yellow (1 in 200) for 2 min., and the tracks were then found to 'correspond to the full-range of the particles'. The grain-density in a track was substantially less in an untreated emulsion. The photograph was taken with 'dark-ground' illumination, and the image of an eye-piece graticule can just be distinguished crossing the field. Proton-tracks with an even greater grain-density were obtained by BLAU and WAMBACHER (1937) also using pinakryptol yellow.

In 1935, using the new Ilford R 1 and R 2 emulsions, TAYLOR published an account of a very careful examination of the precision which could be obtained with the method. He pointed out that in

(*Continued on page 23*)

Tracks of protons and α-particles in an Agfa K-plate



(a)

(b)

PLATE 1–10

Agfa K-plate. SCHOPPER and SCHOPPER (1939).

The upper photograph shows a nuclear disintegration produced by cosmic radiation, and displays a marked degree of discrimination between tracks of large and small specific ionisation. There is a satisfactory absence of background grains. The photograph is a mosaic of two pieces of which the outlines can just be distinguished.

The lower photographs also illustrate the 'discriminating power' of the emulsion and the absence of background, and show the tracks of a proton (horizontal) and three α-particles (vertical).

Radioactive contamination of an emulsion by a speck of radium

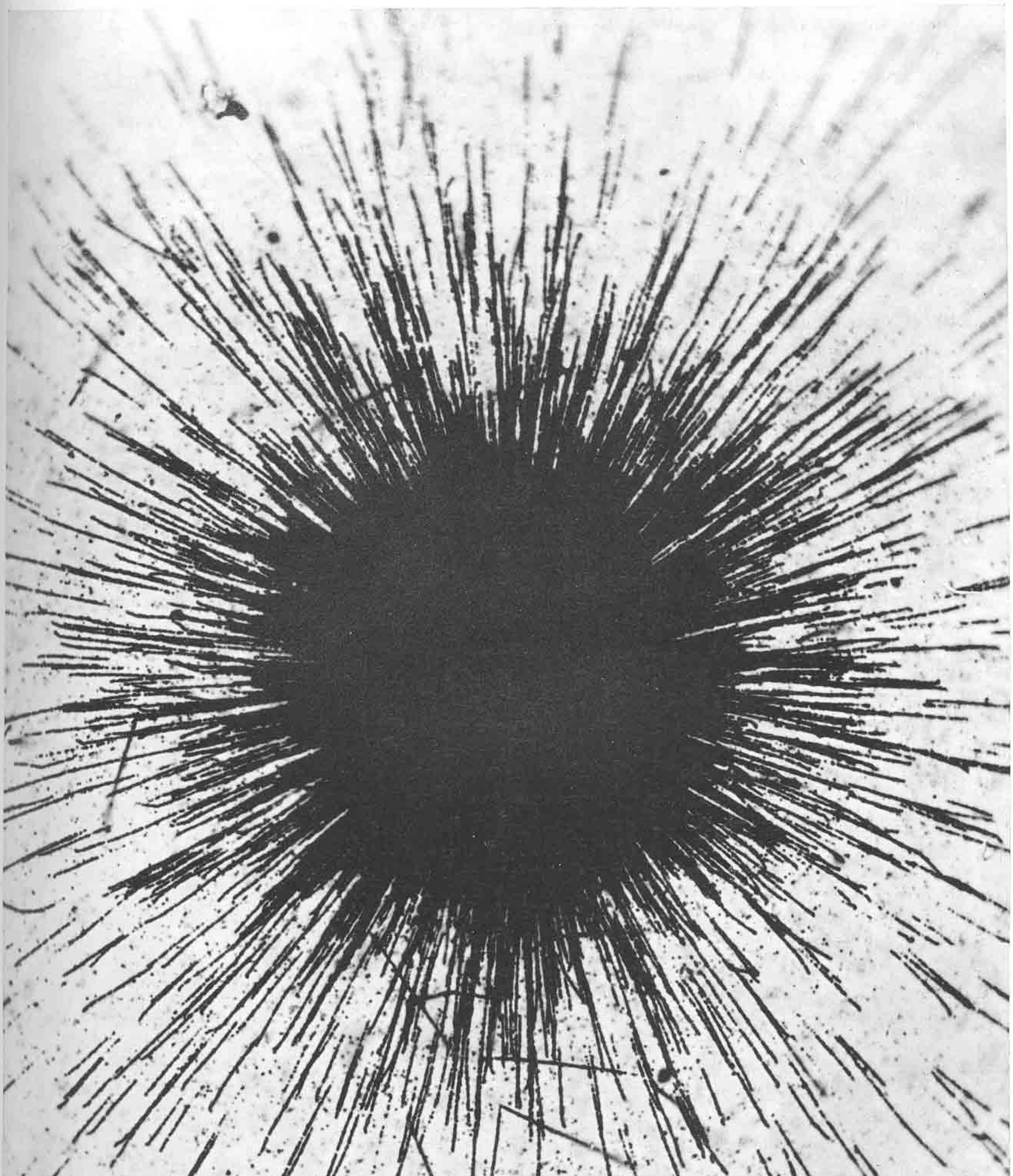
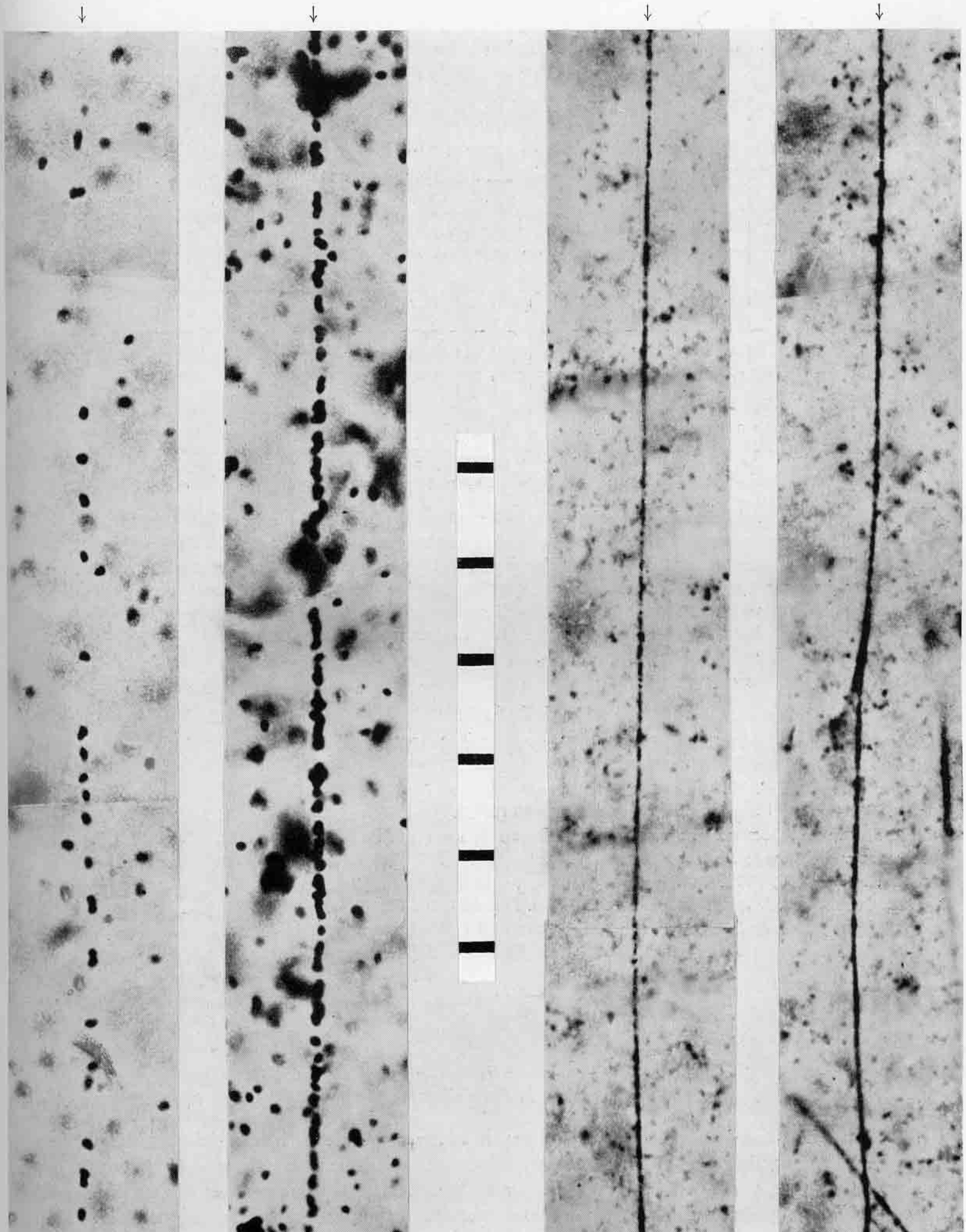


PLATE 1–11

50μ

Ilford B emulsion. Occhialini and Powell (1947).

The α-particles emerged from a speck of a radium salt which was allowed to fall on the surface of the plate. The more heavily ionising α-particles give continuous tracks in this emulsion.

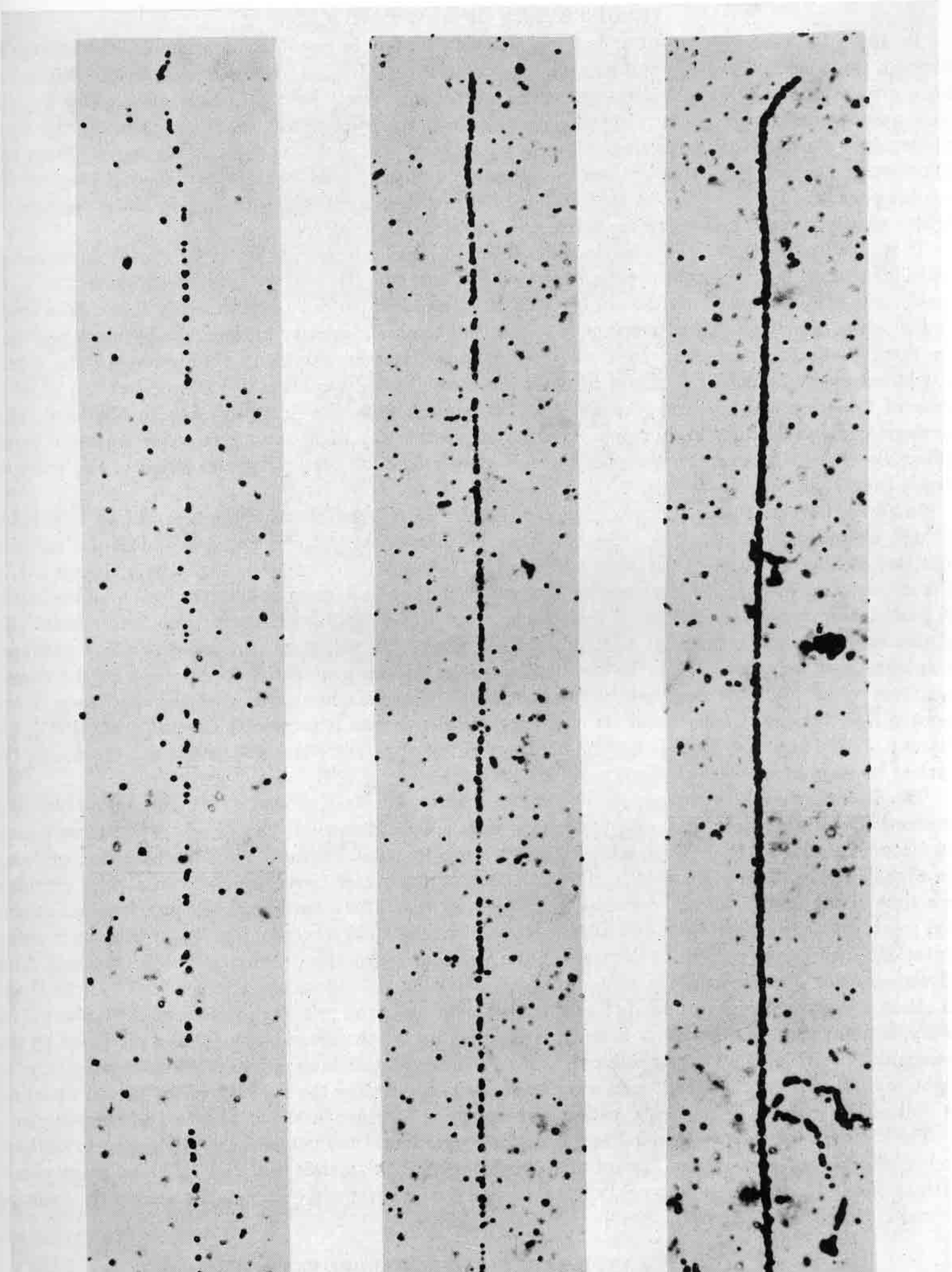


(a) (b) (c)

PLATE 1—12

Various emulsions. DEMERS.

Tracks in different emulsions of protons approaching the end of their range



(a) (b) (c)

PLATE 1–13

Bristol (unpublished).

Tracks of electrons at the end of their range in Kodak NT2a emulsion

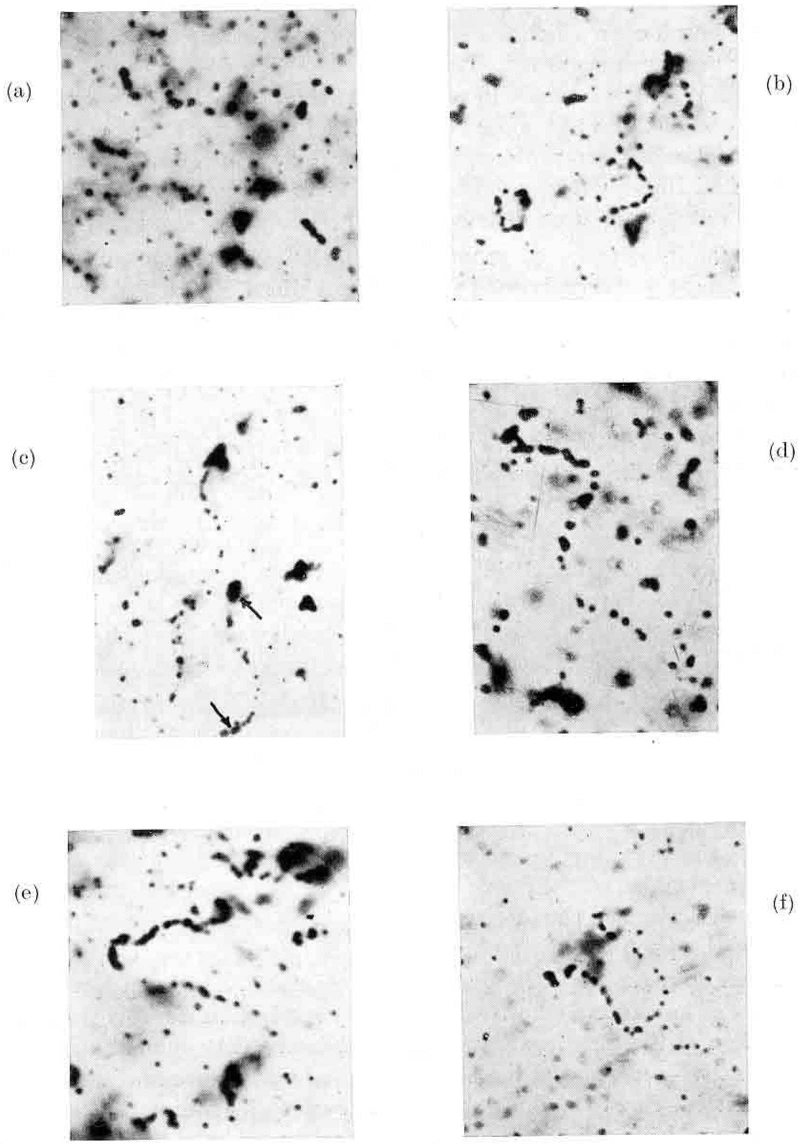


PLATE 1–14

Kodak NT2a. (After HERZ 1948.)

The tracks were produced by X-rays excited by electrons of different energy incident on a platinum anti-cathode. Before reaching the emulsion, the X-rays were passed through absorbers of different thicknesses; details are as follows:

(a) 35 kV; no filter. (b) 65 kV; 0·2 mm of copper.

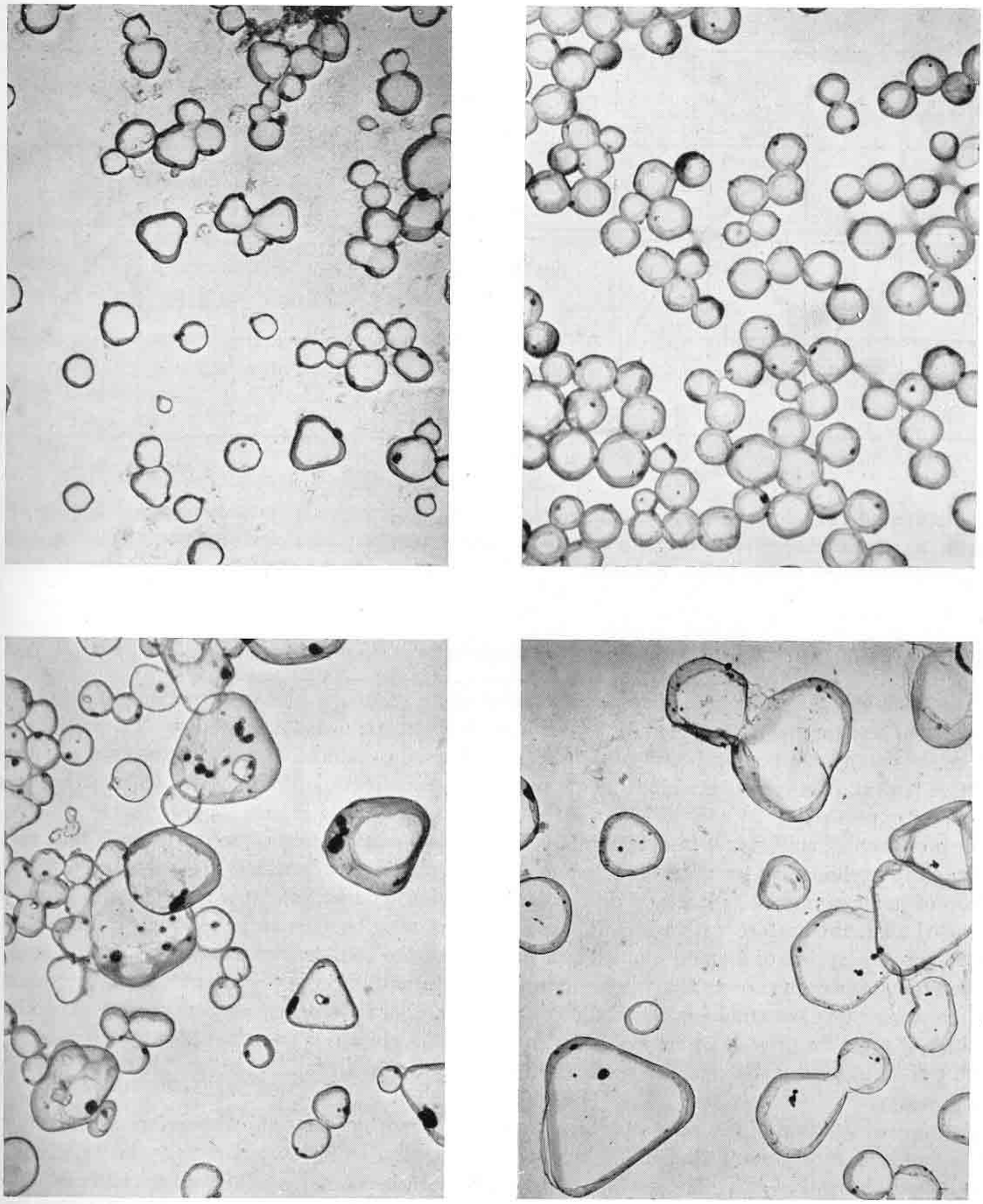
(c), (d), and (f), 200 kV; 10 mm of copper. (e) 130 kV; 1·8 mm of copper.

It may be seen that the ranges of the electrons increase with increasing quantum energy of the radiation in going from 65 to 130 kV; thereafter there is little apparent change.

In the NT2a emulsion, the tracks of electrons of smaller specific ionisation than those recorded could not be readily distinguished.

Electron-micrography of the grains in different types of photographic emulsions

(a) (b)



(c) (d)

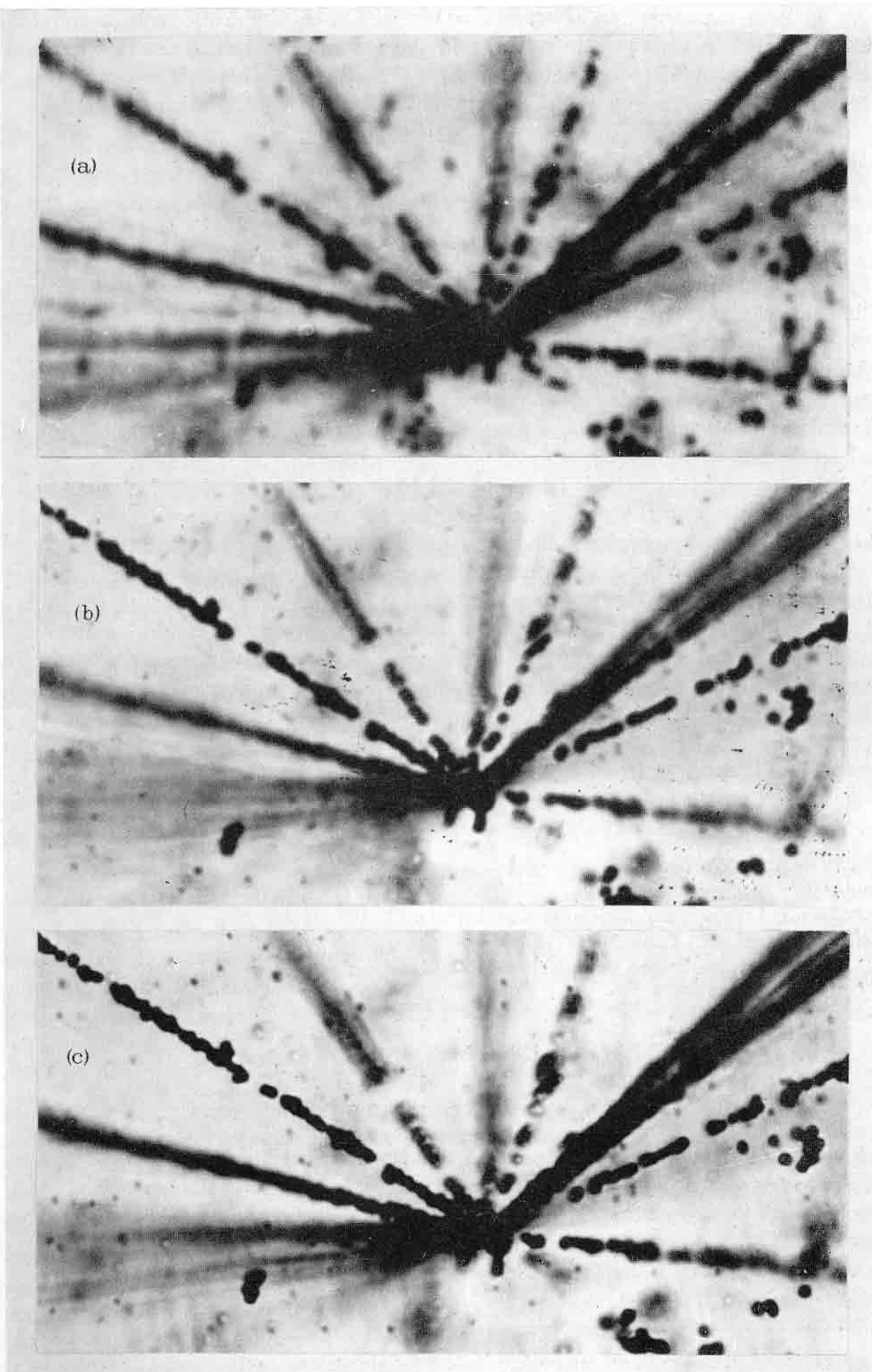
PLATE 2–1

Magnification × 20,000. HAINE (unpublished) (1954).

(a) Ilford half-tone. (b) Ilford G 5 nuclear research emulsion. (c) Special lantern plate. (d) 'Selochrome' emulsion.

The uniformity of size, and nearly spherical form, of the grains in the G5 emulsion are well displayed. Note also (i), the much greater variation in size in the other emulsions designed to record 'half-tone' effects; (ii), the presence of plate-like grains of roughly triangular form; and (iii), the very much larger grains present in the more sensitive emulsions. The magnification in (d) is less than that of the other photographs. The micrographs were obtained by the 'carbon-replica' method.

Photomicrography with objectives of different resolving power



Ilford G 5 emulsion. **PLATE 2–2** Bristol (unpublished).

The same subject has been photographed with objectives of numerical aperture (a) 0·45, (b) 095, and (c) 1·3, the final overall magnification being brought to the same value. The increase in the resolving power with numerical aperture is apparent together with associated decrease in depth of focus. In (b), and (c), the planes of sharp focus are not exactly the same in the two photographs.

Tracks due to α-particles in an emulsion impregnated with a salt of thorium

PLATE 2–3

Ilford A1 Emulsion. OCCHIALINI and POWELL (1947).

7. SANDWICH EMULSIONS

a) Layers of gelatine

Methods of distinguishing between disintegrations produced in light and heavy elements, based on diluting emulsions with gelatine or water, suffer from the disadvantage that the nature of the element involved in any particular disintegration is generally unknown. It follows that conclusions can be drawn only from a statistical study of the different effects produced in diluted and normal emulsions similarly exposed.

This difficulty can be avoided by employing thin layers of gelatine between layers of normal emulsions; see PERKINS (1949), HARDING (1949). Any interaction occurring in the insensitive gelatine layer will not be recorded. If the tracks in the immediate neighbourhood of a centre of disintegration are absent, the interaction must have involved the nucleus of one of the light elements. This method has been employed by MENON, MUIRHEAD and ROCHAT (1950) to distinguish the characteristics of the disintegrations of the light elements, carbon, nitrogen, and oxygen following the nuclear capture of negative π-mesons; see Plates 8–11 and 8–12. The gelatine layers were 5 μ thick sandwiched between layers, 30 μ thick of Ilford C2 emulsions loaded with boron.

(Continued at top of page 61)

Tracks due to the fission of uranium

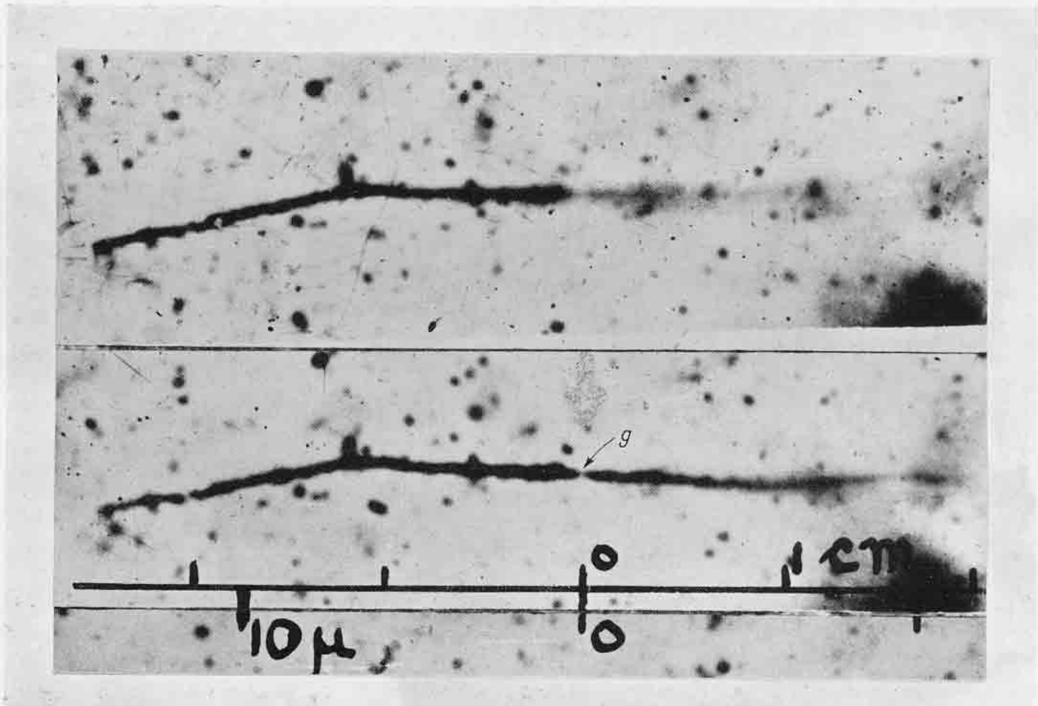


PLATE 2–4

Demers' Emulsion II. DEMERS (1946).

Tracks due to the fission of uranium. A thin layer of a uranium salt was 'sandwiched' between two layers of emulsion so that the origin of the two fission fragments can be determined by the gap in the track (g), and the two ranges thus separately determined. The fragment on the left has collided with a nucleus in the emulsion to produce a forked track. The refinement of detail given by the very fine-grain emulsions produced by DEMERS is immediately apparent. The upper scale is divided to correspond approximately to the equivalent range in centimetres of air at N.T.P.

Origin of a K-meson and its decay in the τ-mode

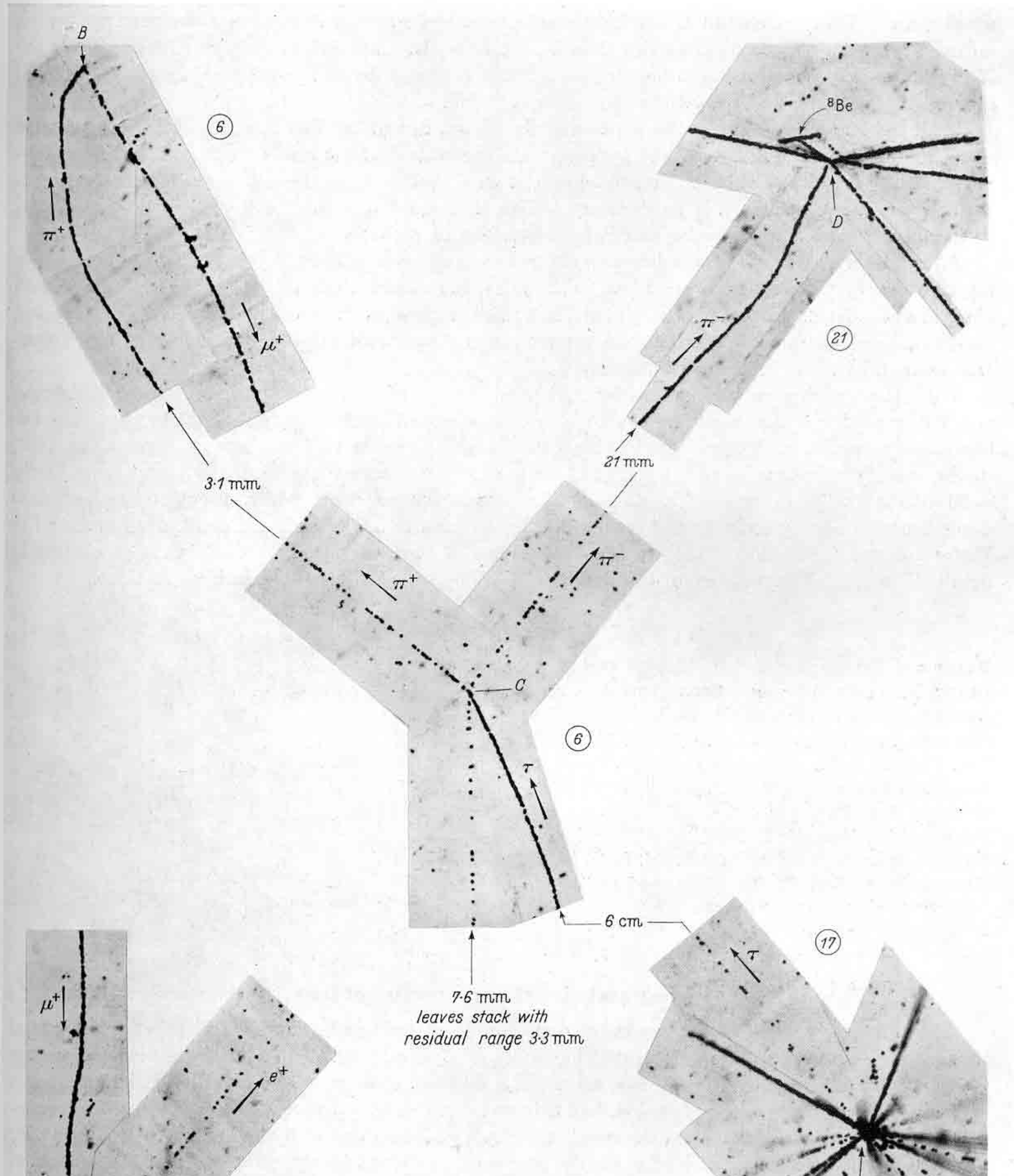


PLATE 2–5

Ilford G5 emulsion. Exposure over S. England (1952).

Successive fragmentation of a heavy nucleus of the primary cosmic radiation

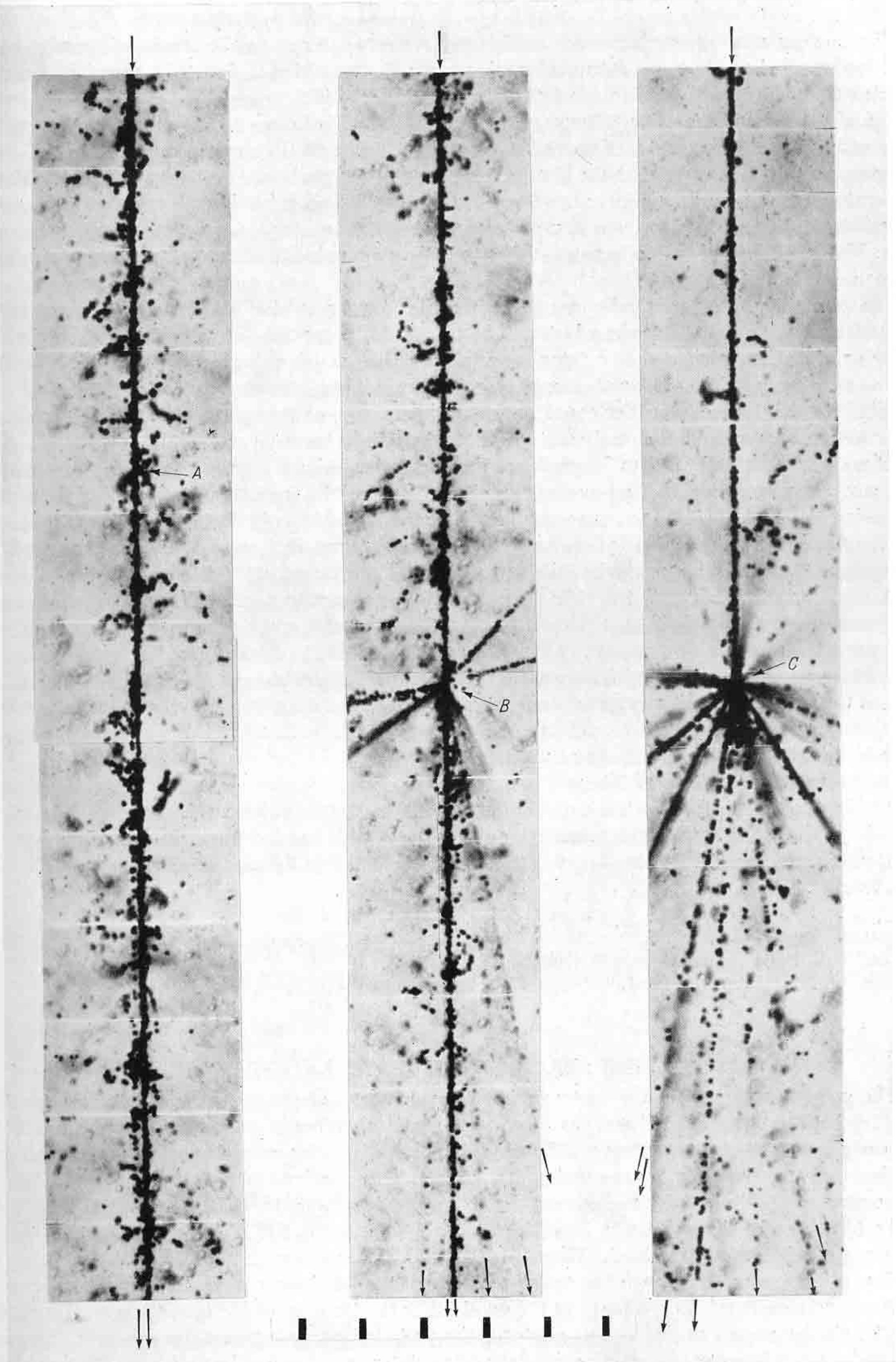


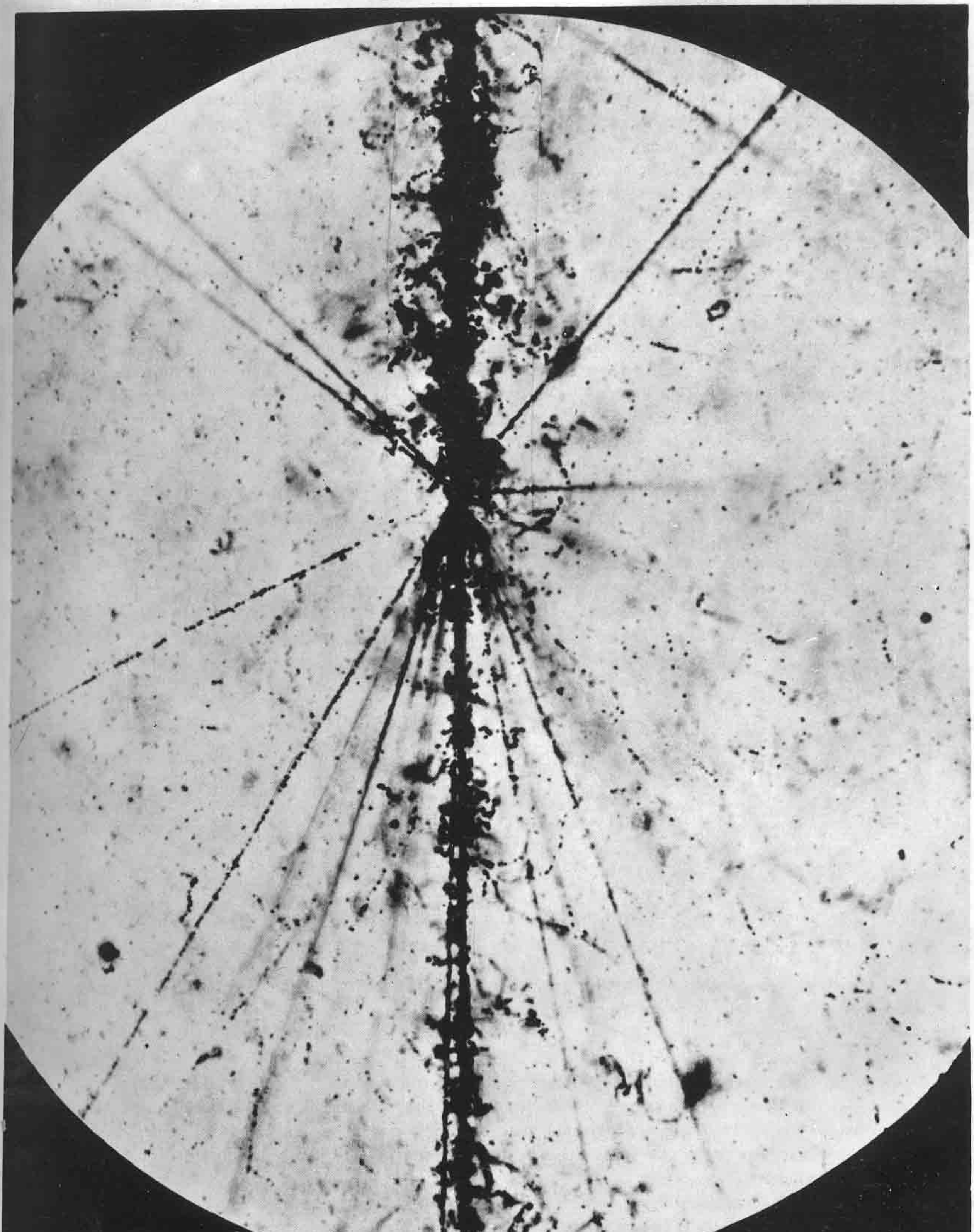
PLATE 2–6

Ilford G 5 emulsion.

Sardinian Expedition 1953 (unpublished).

Collision of a nucleus of iron

↓



Ilford G 5 Emulsion

PLATE 3–1

Dainton and Fowler (unpublished)

(Continued from page 94)
log E. This increased rate of loss is not all reflected in a corresponding increase in the grain-density, for much of it is dissipated at points outside the core of the track. Some of the additional energy loss leads, however, to the formation of relatively slow δ-rays, which do contribute to the observed limited increase in the grain-density. For a discussion of other aspects of this problem, see p. 49.

The magnitude of the rise above the minimum also depends on the polarisation of the medium; it is much greater in air, for example,—about 50%—than in emulsion. In practice, the ratio of the minimum to the plateau grain-density, varies in different emulsions of the same nominal type. Values as high as $\sim$14% have been observed (SHAPIRO *et al.* 1952) and as low as $\sim$6% (unpublished); see also ALEXANDER and JOHNSTON (1957).

a) Isotropic recording properties of nuclear emulsions

It has already been mentioned that the equi-axed form of the grains has a very important bearing on the recording properties of an emulsion. Thus, tabular grains—see Plate 2–1 (d)—show a marked tendency to settle down parallel to the substrate, as the emulsion dries, even if they are orientated at random when it is wet. This is an inevitable consequence of the fact that, in drying, the emulsion collapses in a direction normal to the substrate. Such an emulsion would have markedly anisotropic recording properties, since the thickness of the tabular grains is commonly much less than their width. The average length of track of a particle in a single grain, and hence its loss of energy, would then be much smaller if its direction of motion were normal to the surface of the emulsion than if parallel to it. It would thus be possible for a particle with a given specific ionisation to produce a track by traversing the emulsion in one direction, but not in another; in general, the sensitivity would show a marked anisotropy. The observed forms of the grains actually found strongly suggest that any such effect is very small. In practice, however, for experiments of high precision, grain-counts are confined to long tracks nearly parallel to the plane of the emulsion, and it is possible that there are small residual errors due to such an anisotropy, which have hitherto escaped recognition. In the case of tracks of low specific ionisation, the grain-density for dipping tracks can be determined directly from the angle of dip and the number of grains in a measured length of the projection of a track. For higher grain-densities, other methods must be employed; see p. 101.

(Continued on page 100)

PLATE 3–2. Tracks due to particles of different specific ionisation ▸

The event was produced by the nuclear collision of a π-meson of energy 750 MeV. The heavily ionising secondary particles have large angles of dip. That on the right has associated spurs due to δ-rays of low energy.

PLATES 3–3 and 3–4 (following pp. 98 and 99). Grain density in the track of a π-meson

Grain-counting becomes difficult in the G5 emulsion for particles with velocities less than $\beta = 0{\cdot}5$, because the individual grains are frequently unresolved. The tracks shown in Plates 3–3 and 3–4 were produced by π-mesons, but the variation of the ionisation with velocity is, to a very close approximation, independent of the mass of the particle. The grain-density, but not the scattering, in the tracks of all particles with the electronic charge shows a similar variation with velocity. The actual values of the grain-density vary with the degree of development of the emulsion. The 'plateau' grain-density, g_p, in the plates from which the photographs were obtained was 22 grains per 100 μ; see p. 94.

The tracks of some of the individual δ-rays of energy $\sim$15 keV can be distinguished. They are more frequent in the regions of the track corresponding to the smaller velocities, $\beta \sim 0{\cdot}3$. If a plate has been left at ground-level for some weeks before an exposure at high altitude, a general 'background' of slow electrons is produced in the plate. Because of the large scattering of the electrons, it is difficult to define their point of origin precisely. It may then be difficult to determine the frequency of occurrence of δ-rays along the track of a particle of low charge, $Z = 1$ or 2, because of the 'background' due to electrons unrelated to the track.

Tracks due to particles of different specific ionisation

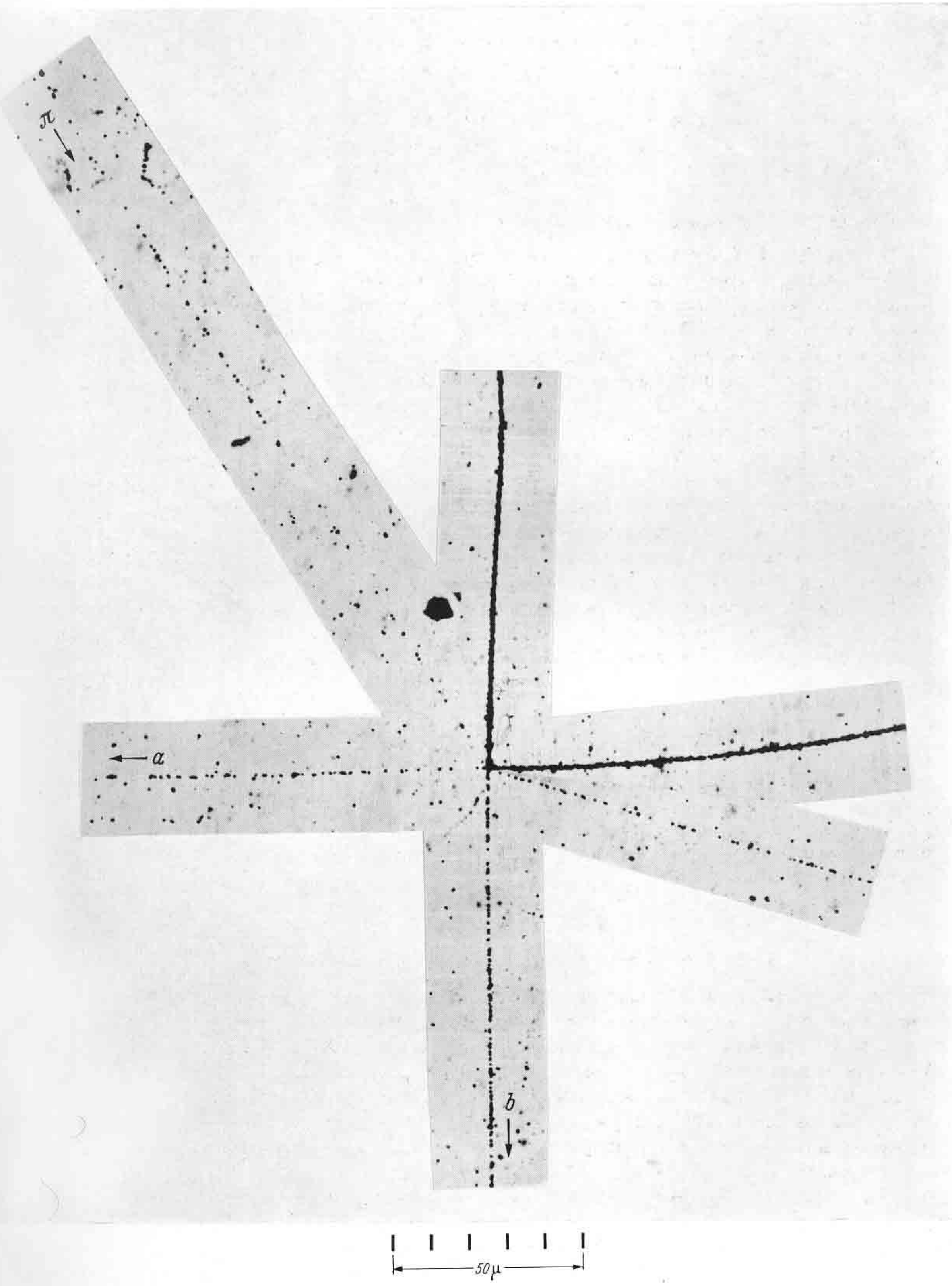
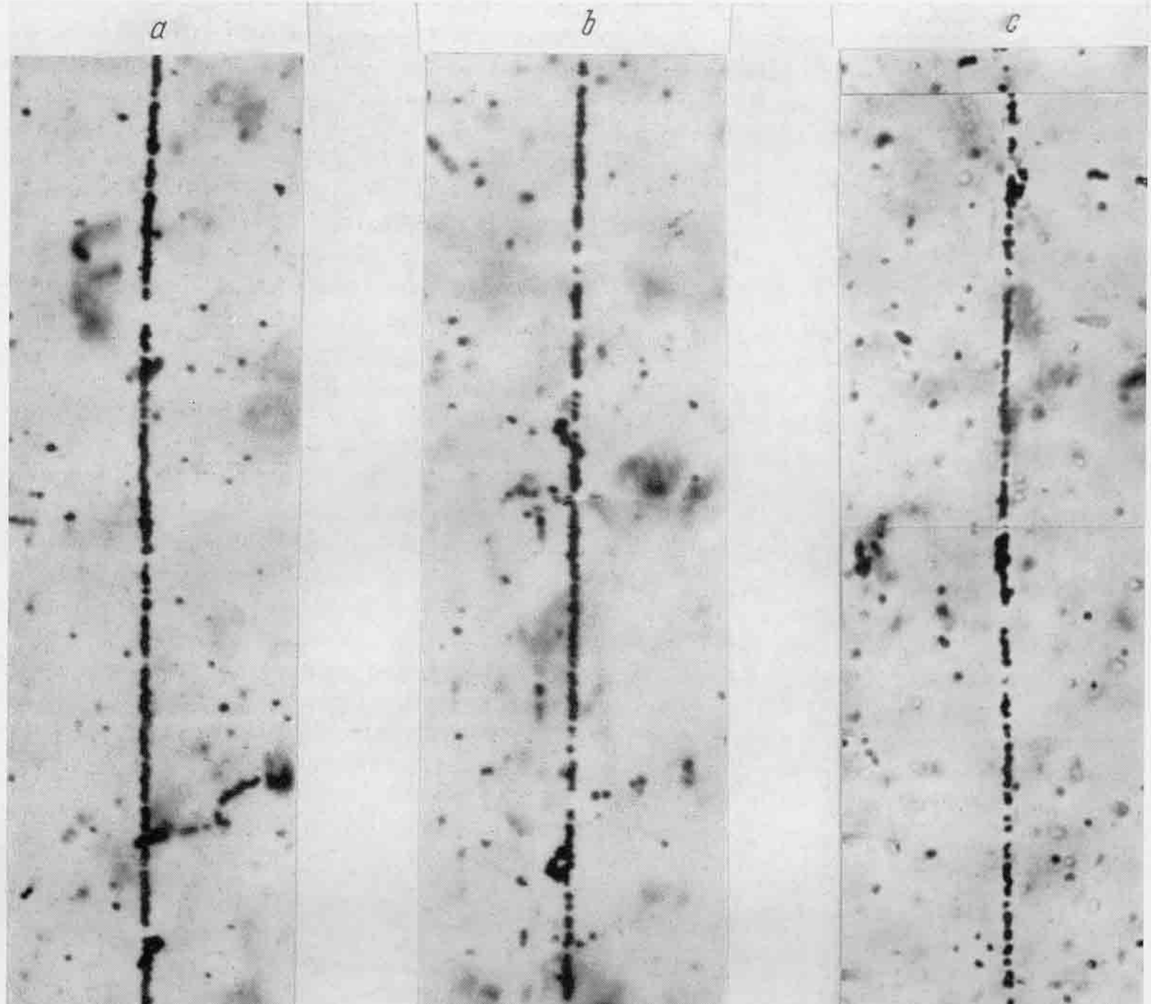


PLATE 3–2

Ilford G5 emulsion. Bristol (unpublished).

Grain-density in the track of a π-meson for different values of its velocity

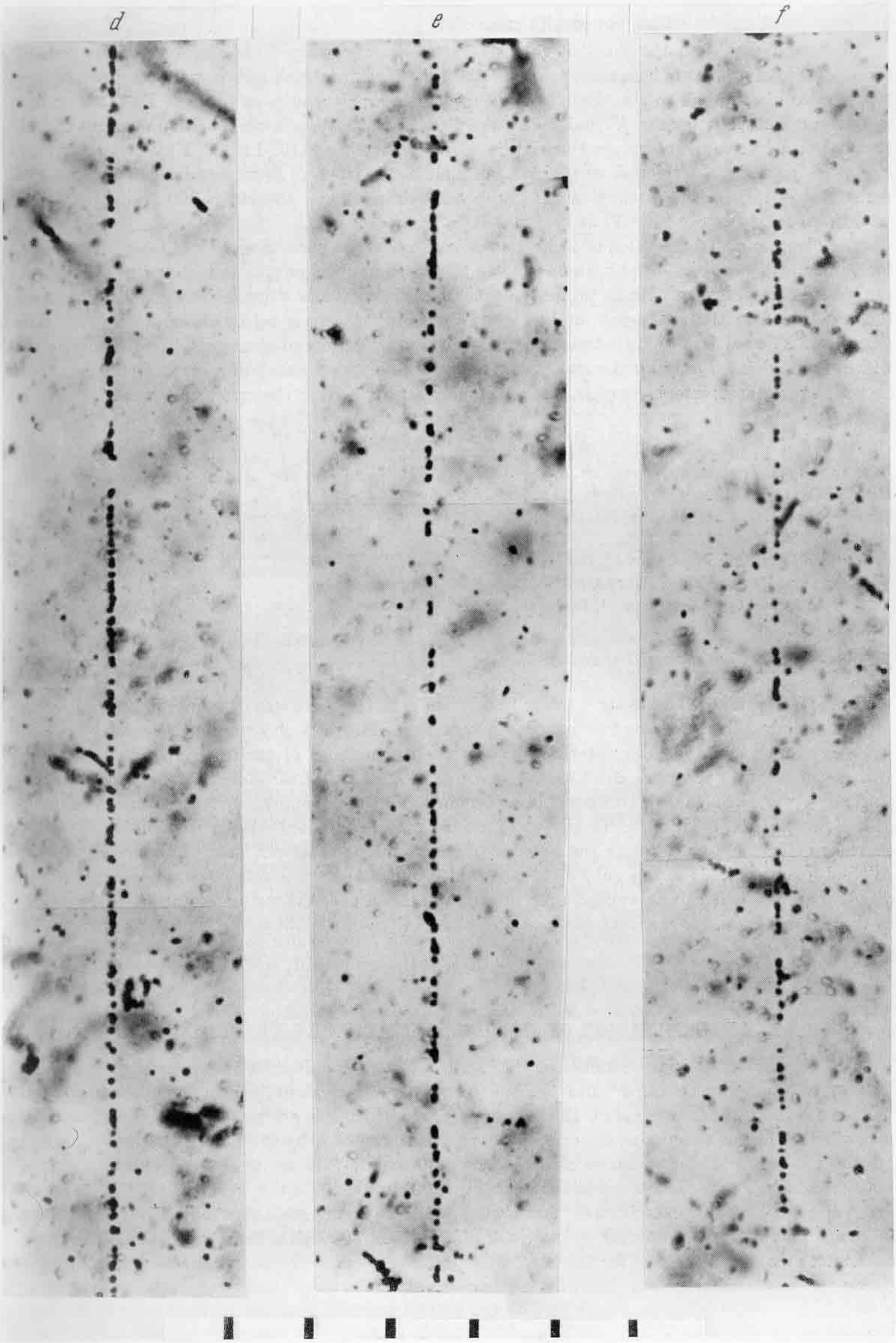


$\beta = 0{\cdot}28;\ dE/dR = 3{\cdot}8\ \mathrm{keV}/\mu$

$\beta = 0{\cdot}34;\ dE/dR = 2{\cdot}1\ \mathrm{keV}/\mu$

$\beta = 0{\cdot}46;\ dE/dR \parallel 1{\cdot}7\ \mathrm{keV}/\mu$

Grain-density in the track of a π-meson for different values of its velocity



$\beta = 0{\cdot}51$; $dE/dR = 1{\cdot}45$ keV/μ

$\beta = 0{\cdot}56$; $dE/dR = 1{\cdot}2$ keV/μ

$\beta = 0{\cdot}59$; $dE/dR = 1{\cdot}1$ keV/μ

Ilford G5 emulsion.

PLATES 3–3 and 3–4

Menon (unpublished).

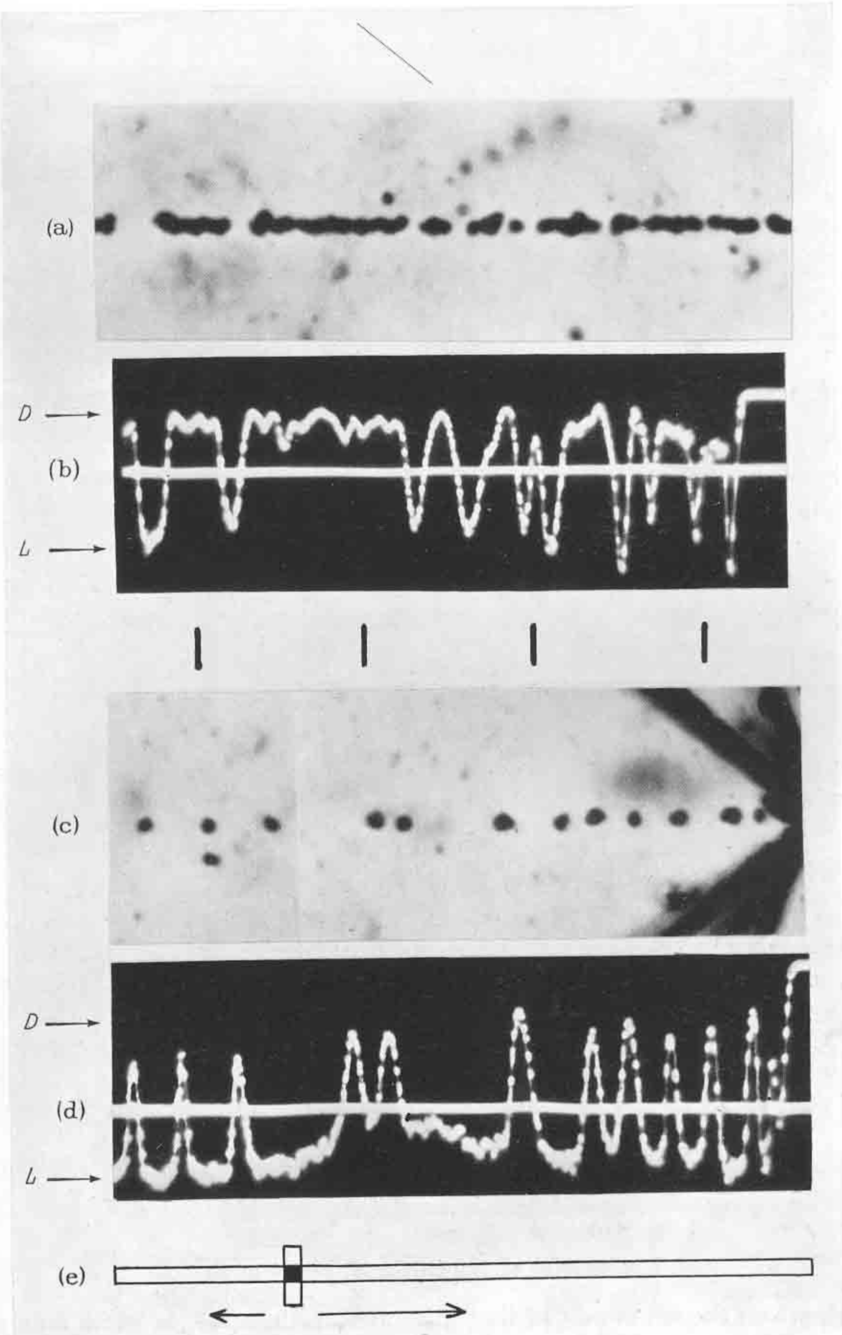


PLATE 3–5

(a) and (c) show photo-micrographs of two tracks, of widely different grain-density, and (b) and (d) the corresponding photometer tracings on the cathode-ray oscillograph. In the latter, D and L correspond to the levels of darkness and full illumination, respectively. The lateral displacements of the oscillograph are not linear, but the correlations between the main features of the track and the photometer trace are clearly displayed. The upper record is equivalent to gap-counting, and the lower to grain-counting. The illumination is confined to a strip parallel to the track, which, in effect, is scanned by another slit at right angles to it; see (e). (After van Rossum 1954.)

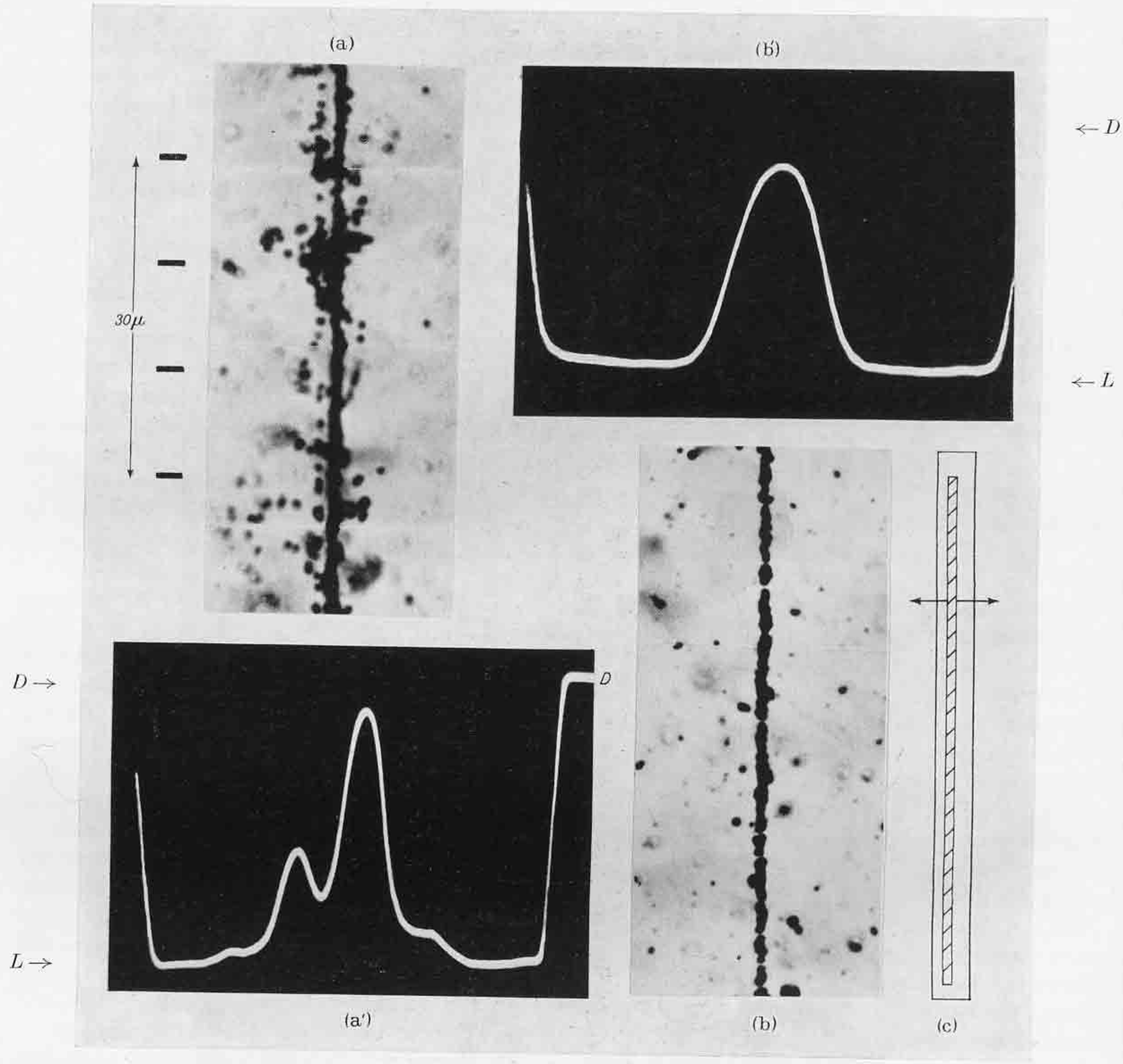


PLATE 3–6

Photometry of the tracks of heavy nuclei

The event shown on the left is part of that illustrated in Plate 2–6, in which an α-particle and a nucleus with $Z \sim 10$ emerge from the nuclear impact of a heavy primary particle of the cosmic rays. The photometer curves show the obscuration across tracks as measured by long, narrow slit. The level of the photometer readings for full illumination and complete darkness are indicated L and D, respectively. The lateral scale of the photometer traces, a' and b' are greatly magnified compared with that in the photo-micrographs of the tracks, a and b. In a', the effects of the δ-rays,—which give 'wings' to the main peak,—and of the parallel α-particle track, can be clearly distinguished. The effective width in the object plane of the slit employed was $\sim 0{\cdot}3\,\mu$. The illumination is provided by an aperture parallel to the track, which, in effect, is scanned by a narrow parallel slit; see c. Note that the lateral scale of the photometer curves is about four times greater than that of the tracks in the photomicrograph. (After van Rossum 1954.)

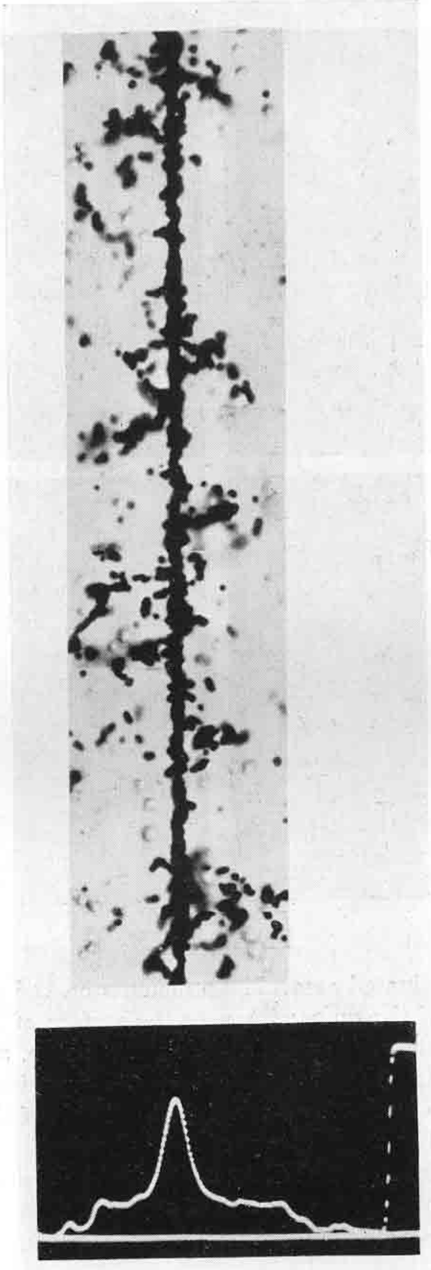


PLATE 3–7

Photometry of the track of a heavy nucleus using long, narrow slit as shown in Plate 3–6. The 'wings' due to δ-rays are very prominent. (After VAN ROSSUM 1954.)

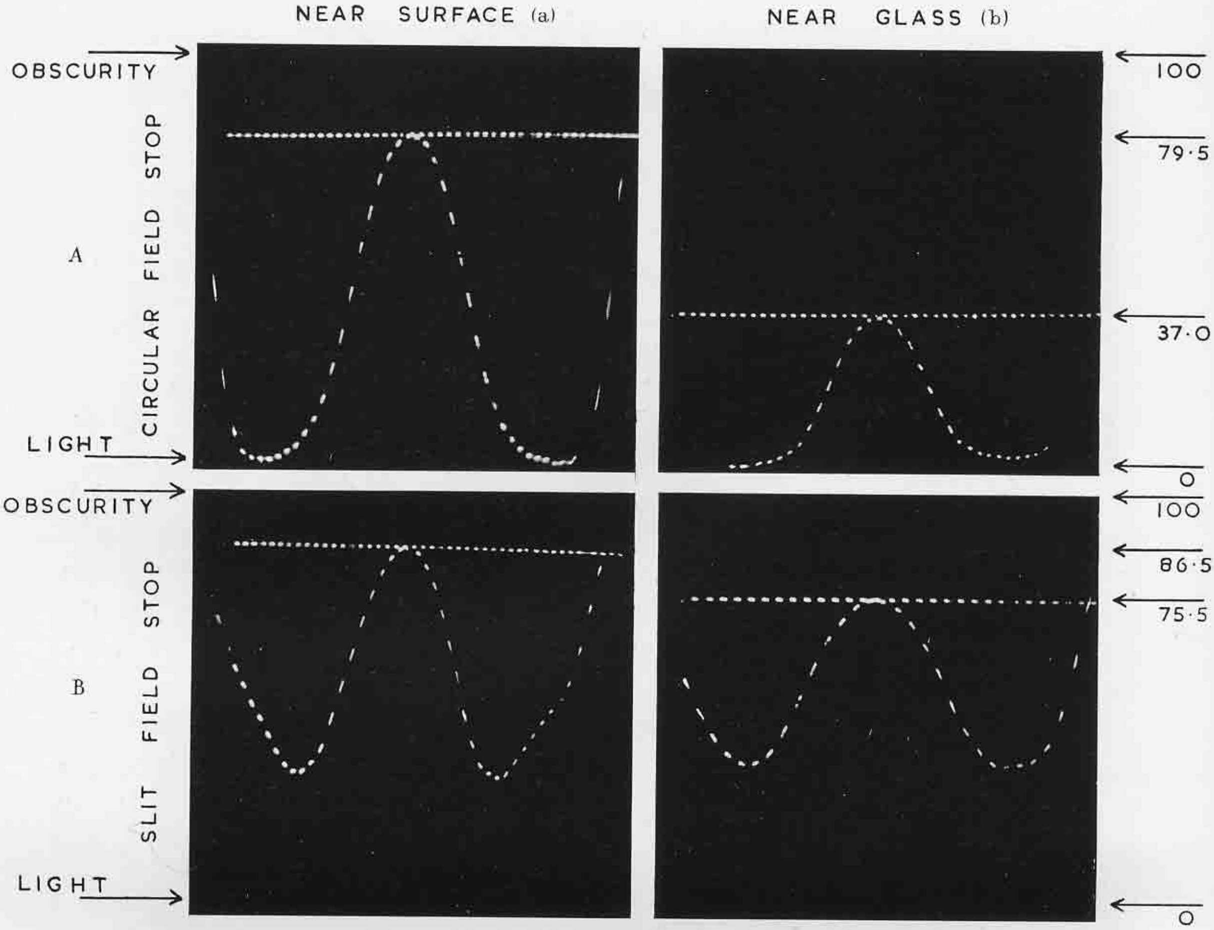


PLATE 3–8

Effect of restricting the illuminated area. Measurements on the tracks of two protons of equal grain density, towards the end of the range; (a), near the surface of the emulsion; and (b) near the glass. The measurements were made, (A) with a circular field-stop, and (B) with a 'slit' field-stop. The great loss of contrast, due to scattering of light by the emulsion, when a circular field-stop is employed, is well displayed. The numerals on the right-hand side of the figure show the obscuration produced by the track expressed as a percentage of total obscuration.

With ordinary illumination, the measured obscuration for the track at the bottom of the emulsion must be corrected by 114% to take account of loss of contrast. With slit illumination (width $\sim 1\ \mu$) the corresponding correction is $\sim 15\%$. (After van Rossum 1954.)

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Rossum, van; C. R. Acad. Sci., Paris **236**, 2234 (1953); Nuovo Cim. Suppl. **11**, 212 (1954).

Observations on the scattering of a π-meson

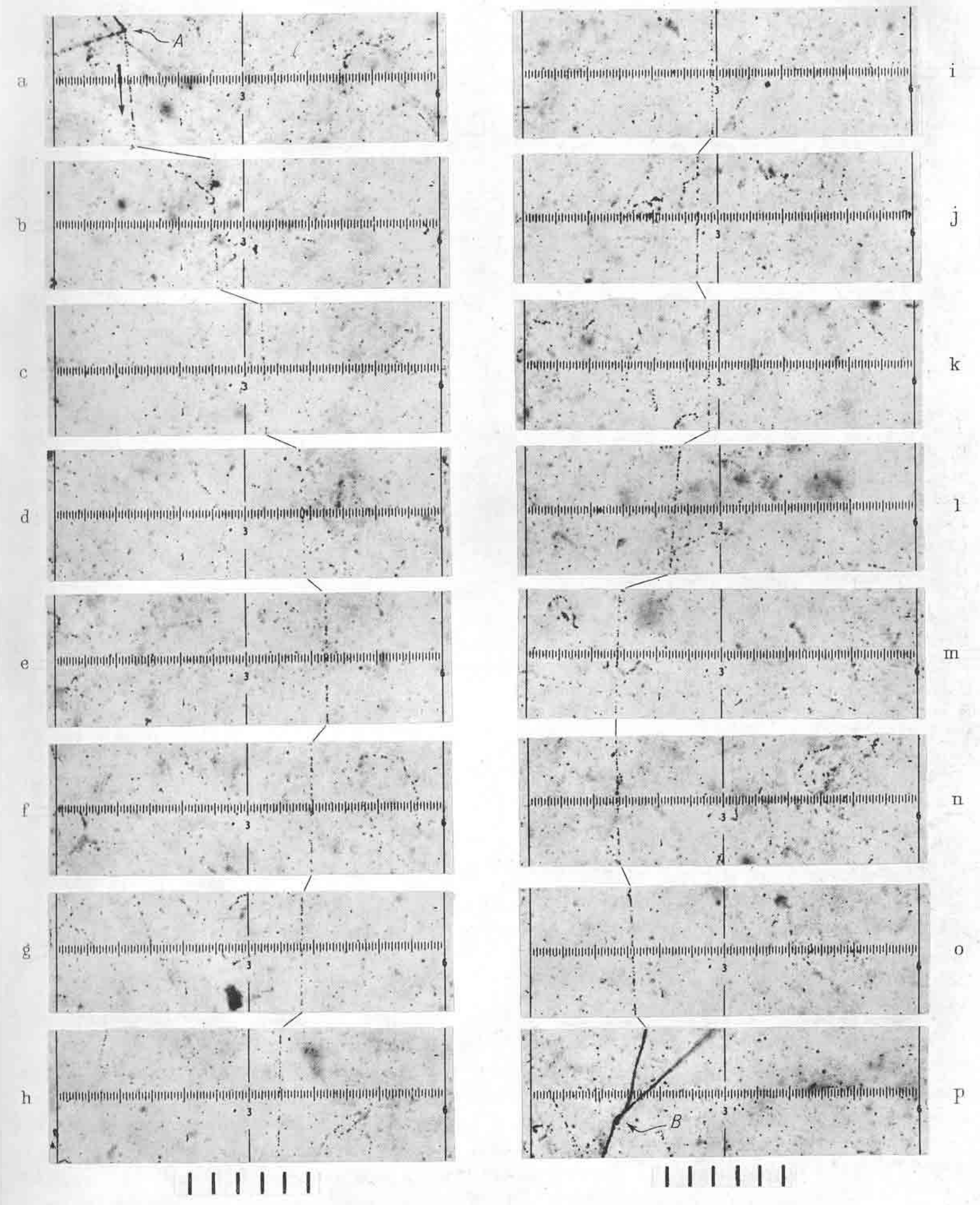


PLATE 4–1

Ilford G 5 emulsion.

(Unpublished.)

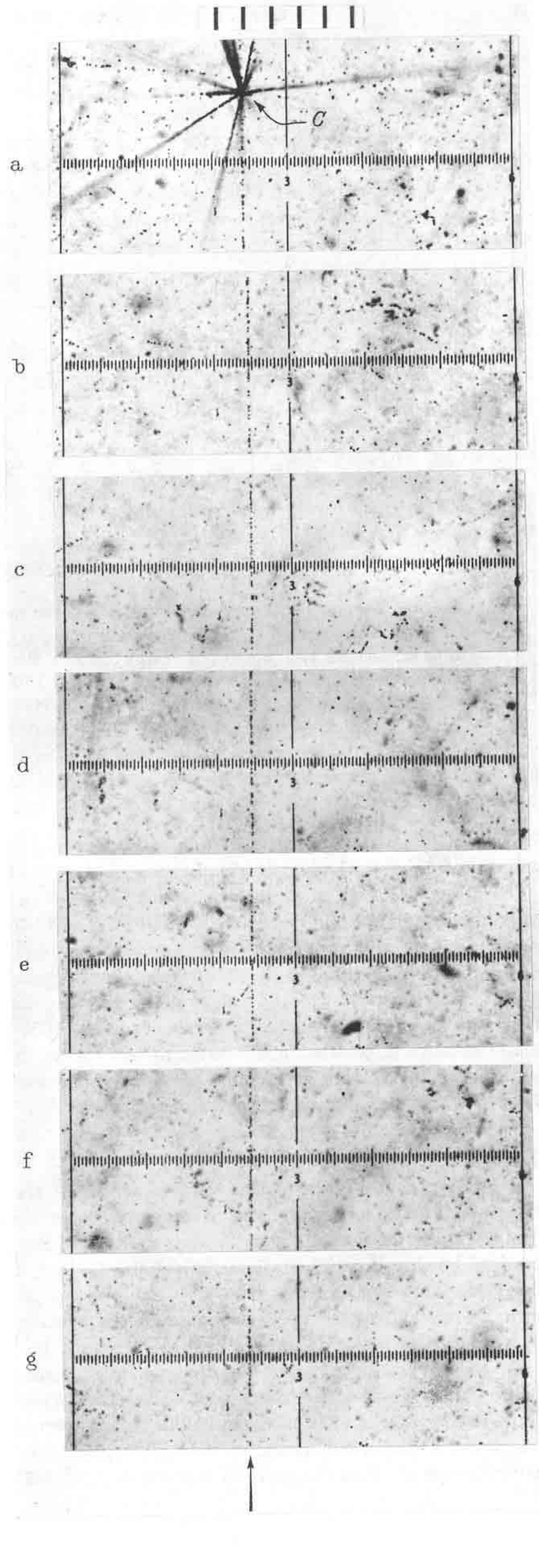
PLATE 4–2. Observations on the scattering of a fast α-particle

Table 4–2.
Observations on the scattering of an α-particle

	Intercept	1st Difference	2nd Difference
a	24·2	− 0·4	
b	24·6	− 0·1	− 0·3
c	24·7	+ 0·2	− 0·3
d	24·5	+ 0·2	0
e	24·3	+ 0·4	− 0·2
f	23·9	+ 0·5	− 0·1
g	23·4		
		Total	0·9 sc. divs.
		Mean $\bar{D}$ =	0·18 „ „

$$\bar{\alpha} = \frac{0{\cdot}18 \times 2{\cdot}75 \times 57{\cdot}4}{1000\sqrt{10}} = 0{\cdot}009^\circ \text{ per } 100\,\mu.$$

With $K = 26$, this corresponds to a value for $p\beta$, and an energy $\sim$7 BeV. More extensive measurements, on a greater length of track, gave a value $\sim$10 BeV.



Ilford G 5 emulsion

Fragmentation by collision of a heavy nucleus

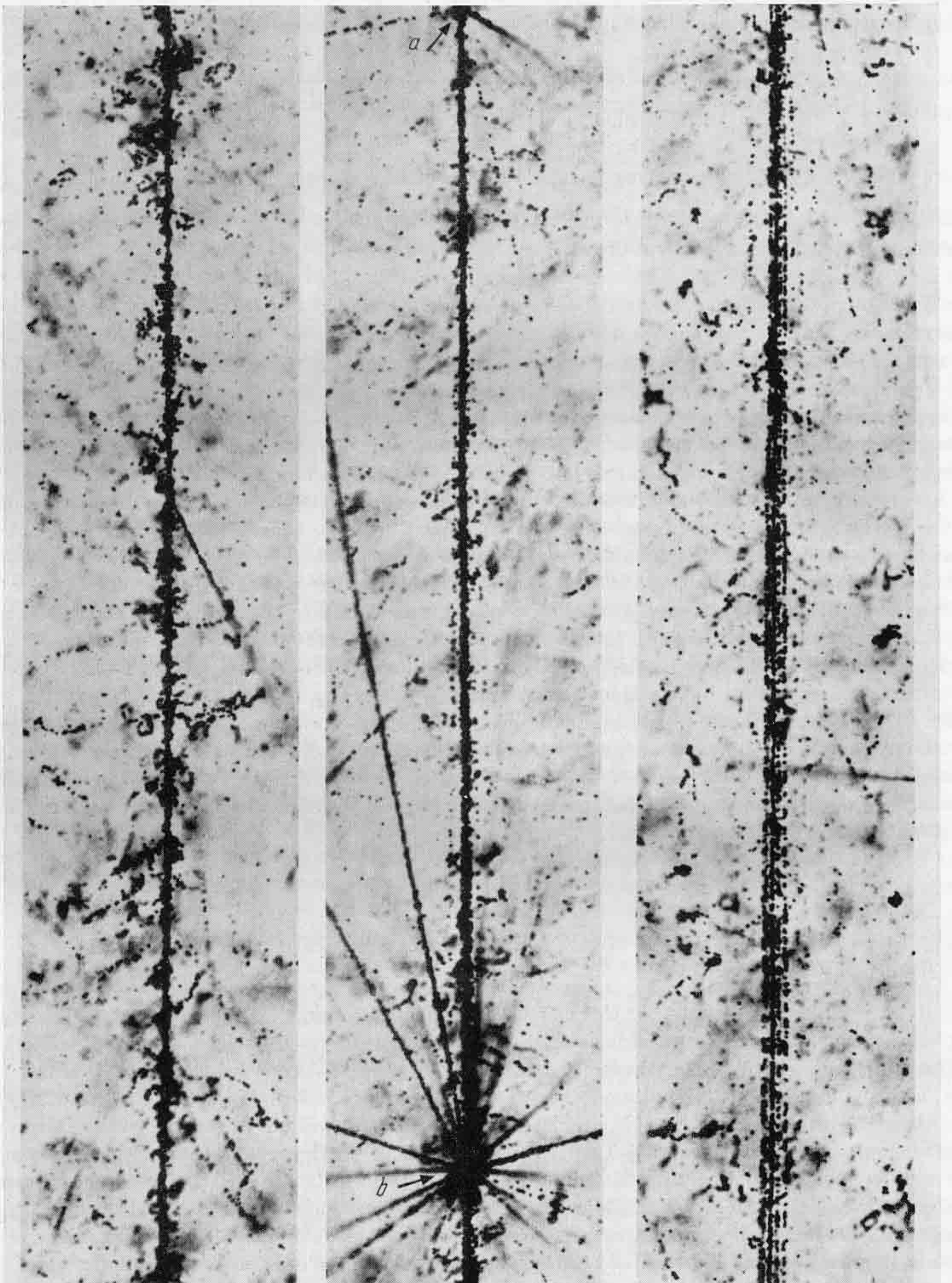
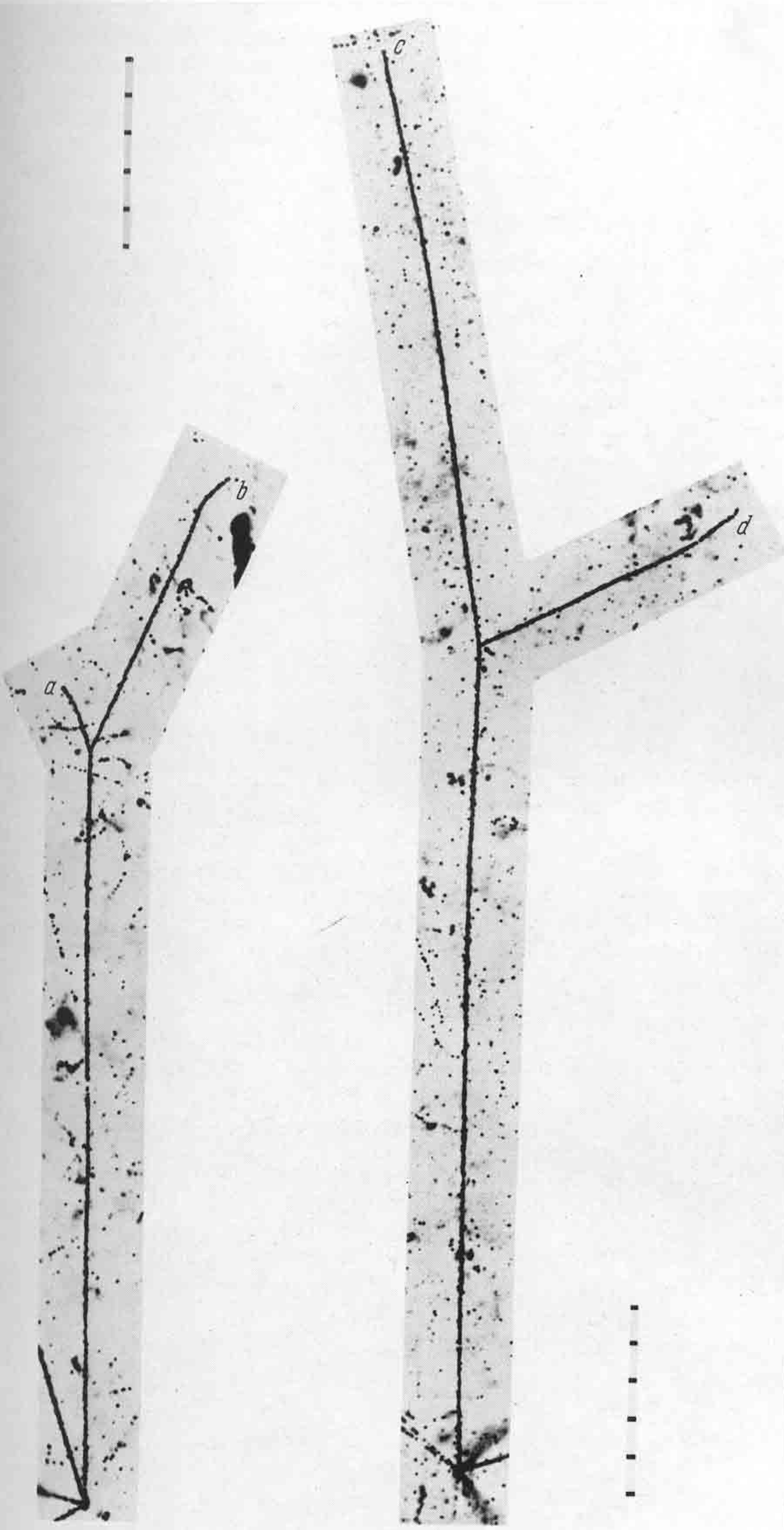


PLATE 4–3

Ilford G 5 emulsion. DAINTON and FOWLER (unpublished).



◄ PLATE 5–1

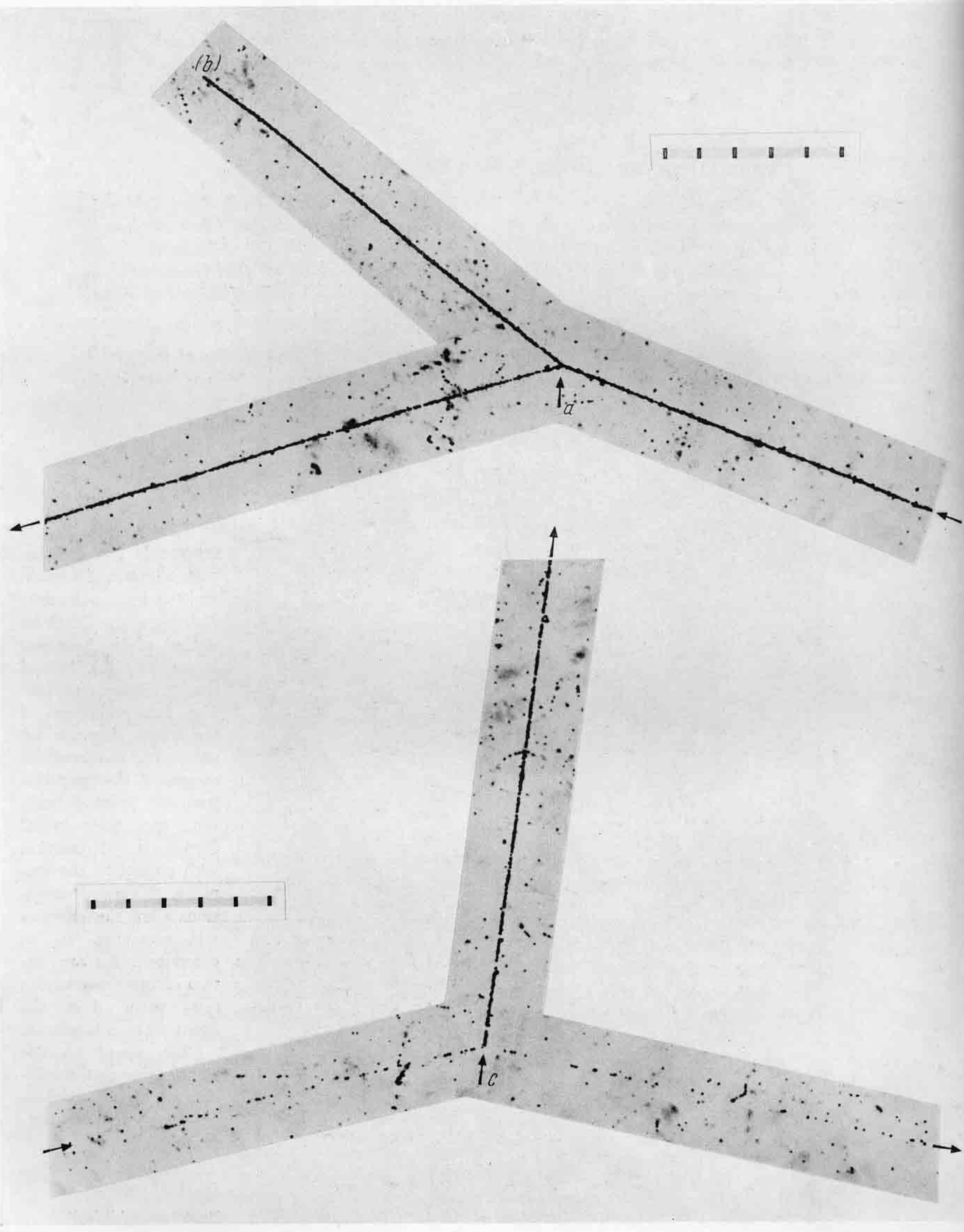
The event on the left represents the collision with a proton of a triton emitted from a nuclear disintegration. Track (a) is that of the recoiling triton, and (b) that of the projected proton. The interpretation of the event depends on measuring the residual ranges of the particles from the point of collision, and their initial directions of motion with respect to the primary. These observations allow the energies and momenta to be computed. An application of the conservation laws then allows the event to be interpreted.

The event on the right is due to the collision of an α-particle—track (c)—with a proton-track (d).

Ilford G 5 emulsion.

Bristol (unpublished).

Elastic collisions with protons



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MINGUZZI, PUPPI and RANZI; Nuovo Cim. **10**, 1753 (1953).

2. THE OBSERVATION OF BREMSSTRAHLUNG

It is well known that the identification of charged particles presents considerable difficulties when they are moving at relativistic velocities where the specific ionisation changes very slowly with the momentum (see p. 162). A case of particular importance occurs for particles of momentum between ~100 and 600 MeV/c, and of specific ionisation near the minimum value; the corresponding tracks may be produced by electrons, μ-mesons or π-mesons. If tracks of length ~5 cm are available, however, it is generally possible to distinguish any electrons as a result of the occurrence of *bremsstrahlung* (see p. 180). If it can be shown that the rate of loss of energy of the particle is much greater than that which can be attributed to ionisation alone, it is almost certain that the particle is not a μ-meson or a π-meson. This method was important in the first experiments which established the beta-decay of heavy mesons (see p. 321).

3. NUCLEAR INTERACTION IN FLIGHT

A second method of identifying charged particles, with momentum less than 500 MeV/c moving at relativistic velocities, depends on observing their interaction with a nucleus and its resultant disintegration. Such an observation makes it almost certain that the particle was a π-meson, and not a μ-meson or an electron. This method made an important contribution to the proof of the presence of fast π-mesons among the secondary particles produced in the decay of heavy mesons; *i.e.* in the χ-mode (see p. 316).

In the case of individual tracks, no conclusions can, in general, be drawn from the absence of a nuclear collision. For an assembly of tracks, such as the 'shower particles' from nuclear disintegrations, it may be possible to determine the mean 'interaction-length' between nuclear collisions. This method was employed to demonstrate that the 'shower particles' emerging directly from nuclear disintegrations in emulsion have an interaction-length near the 'geometrical value' and therefore that few or none of them are μ-mesons; see, for example CAMERINI *et al.* (1950).

REFERENCE

CAMERINI, FOWLER, LOCK and MUIRHEAD; Phil. Mag. **41**, 413 (1950).

4. OBSERVATION OF CHARACTERISTIC MODES OF DECAY OR OF INTERACTION WITH NUCLEI

The identity of several types of mesons can be established by the characteristic secondary processes occurring at the end of their range. The most important examples are as follows:

(i) *μ-mesons.* When a positive μ-meson reaches the end of its range, it decays into an electron, and in well-developed electron-sensitive emulsions, the track of the secondary particle can be distinguished with a probability of about 95%. The direct β-decay of the π-meson is extremely rare; see p. 248.

◄ **PLATE 5–2. Elastic collisons with protons**

The upper photograph shows the collision of a deuteron with a proton at the point (a), the recoiling proton producing the track (b).

The lower event is due to the collision of a fast π-meson with a proton.

Bristol (unpublished).

Ilford G 5 emulsion.

The observation of the track of a fast secondary particle with grain-density near minimum therefore makes the identification of the parent particle as a μ-meson probable, but not certain, because K-mesons and charged hyperons can produce superficially similar effects; see Plate 10–4. The secondary particles from the decay of some types of K-particles and hyperons often have velocities approaching c, and the grain-density in their tracks is then near g^*_{min}; see p. 311. Because of the large differences between the masses of the K-particles and hyperons on the one hand, and μ-mesons on the other, however, the inspection of short lengths, $\sim 200\,\mu$, of the tracks at the end of their range, commonly allows the light and heavy particles to be distinguished by experienced observers. When lengths of the order of 3 mm or more are available, decisive evidence can be obtained by mass measurements. An important example of the application of this method of identifying μ-mesons is shown in Plate 10–3. See also, Plates 7–5 and 7–6, p. 234–236.

The observation of the decay-electron does not establish the sign of the charge of the meson, because about 40% of the negative μ-mesons are brought to rest in the gelatine, and are captured into orbits round the nuclei of one of the light elements, carbon, nitrogen, or oxygen; they then almost invariably decay with the emission of a negative electron before interacting with a nucleus.

(ii) *Negative π- and μ-mesons.* The π^--particles produce characteristic nuclear disintegrations at the end of their range; see Plates 8–11 and 8–12. If two or more secondary charged particles, which produce recognisable tracks, are emitted, it is highly probable, in plates exposed to cosmic rays, that the incident meson was a negative π-particle, but the following alternative possibilities must be considered:

(a) There is the rare possibility that the interaction was due to a K^--particle, or a negative hyperon. The actual values of the energy and the nature of the secondary charged particles may then be important in reaching a decision. Thus, one of the secondary particles arising from the nuclear interaction of a negative heavy meson, is often an energetic π-meson; see p. 343. In other cases, it may be possible to show that the total visible energy of the disintegration, made manifest in the tracks of

(Continued at top of page 150)

PLATE 5–3. Tracks of electrons in 'electron-sensitive' emulsions ▸

Kodak NT4 emulsion — HOOPER and KING (1950) unpublished.

The particles are much scattered owing to their small mass. They become heavily ionising, and thus produce tracks with large grain-density, only over a short path at the end of their range. These effects are clearly shown in the photographs; see also Plate 5–4.

Before the production of 'electron-sensitive' emulsions, there had been a tendency to expect that there would be serious difficulties in employing them for experiments with cosmic radiation. It was anticipated that, owing to their continuous sensitivity, even moderate exposures at mountain altitudes would result in a heavy background of electron tracks; and that this would make it difficult to inspect the plates and to interpret the observations. In practice, this difficulty was found not to be serious; plates can be exposed for a month at an altitude of 10,000 ft without producing a serious background. Because of the action of local radioactivity and of the cosmic rays, however, it is an advantage, even when plates are stored at sea-level, to reduce to a minimum the time between manufacture and development, and thus to eliminate, as far as possible, tracks other than those produced in the desired exposure.

If delays in development and exposure cannot be avoided, it is an advantage to store plates deep underground. In doing so, however, a site must be chosen where the local radioactivity is weak, for otherwise, it can produce a background of slow electrons which give more difficulty than an equal exposure to cosmic radiation at sea-level. The use of a stack of emulsions has the advantage that it can be 'shuffled' immediately before an exposure, exposed to X-rays in order to produce registration marks—see p. 64—and 're-shuffled' after the main exposure. In the subsequent examination of the processed plates, it will then be possible to follow, from one plate to the next, only those tracks produced during the main exposure.

Tracks of electrons of low energy in 'electron-sensitive' emulsions

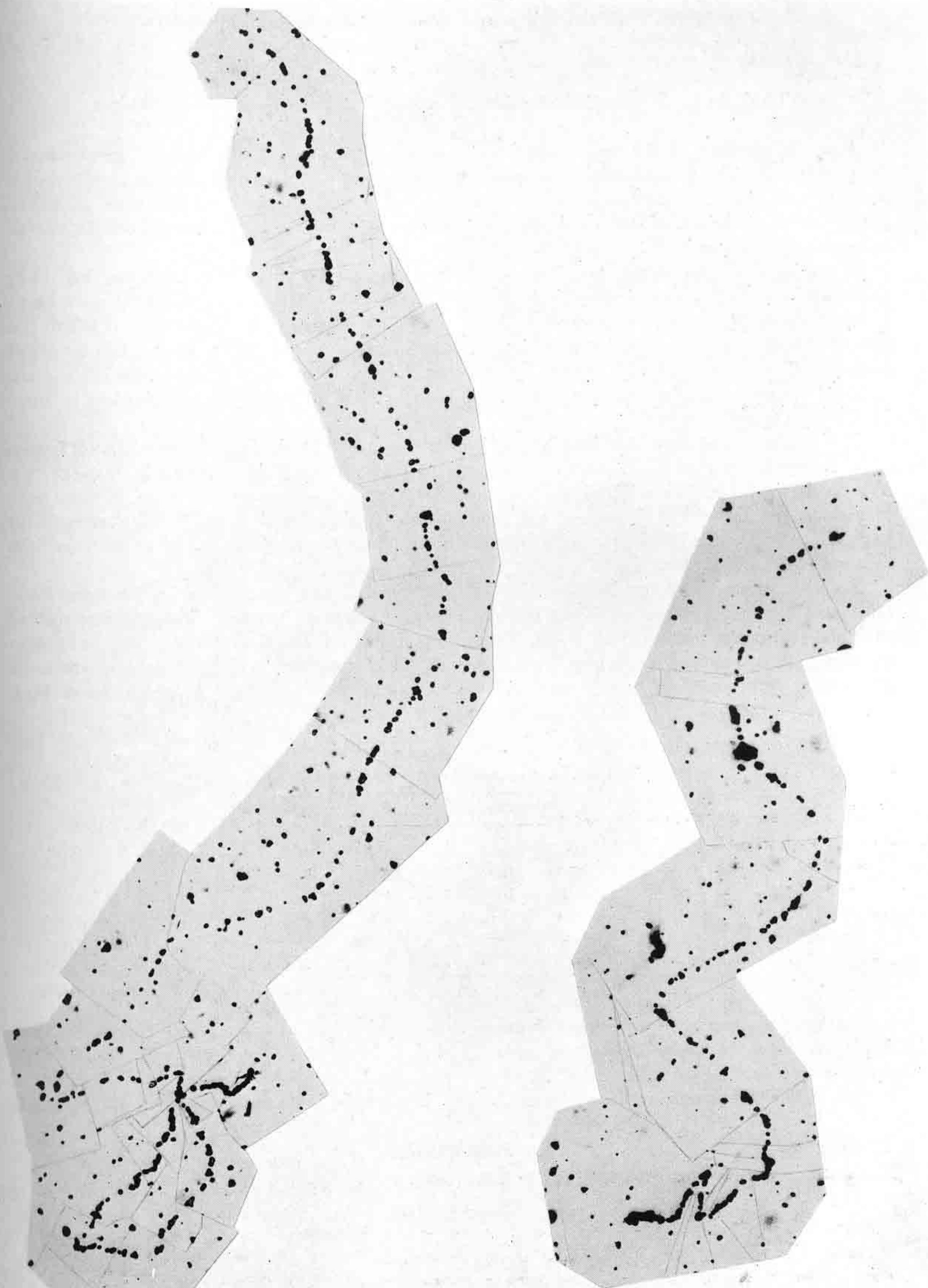


PLATE 5–4. Tracks of electrons of low energy in 'electron-sensitive' emulsions ▶

A pair of electrons of low energy appears to originate at a point in the lower left-hand corner of the photograph. The rapid variation of the scattering and grain-density along the tracks is in marked contrast with that of μ-mesons of mass $\sim 207\ m_e$. No particles of intermediate mass are known. If the pair was indeed produced by the materialisation of a photon in the Coulomb field of a nucleus, its quantum energy must have been about 1·5 MeV.

In passing through a material medium, an electron loses energy not only by ionisation, but also by producing quanta in interactions with charged particles along its line of motion, by '*bremsstrahlung*'. The probability of such a process varies with the square of the charge of the particle. It follows that *bremsstrahlung* commonly results from interactions with nuclei and rarely from interactions with electrons. The rates of loss of energy by *bremsstrahlung* and ionisation become equal at a certain 'critical' energy which in photographic emulsions is ~ 20 MeV. At higher energies loss by *bremsstrahlung* predominates.

The production of *bremsstrahlung* by an electron may result in the loss of a considerable fraction of its energy in a single interaction. Large losses may also occur in collisions with other electrons. As a result, the ranges in a solid substance of the individual electrons composing a homogeneous group of high-energy are widely dispersed; the fluctuations associated with straggling are exceptionally large. In contrast with heavier particles therefore, the range of an energetic electron gives an unreliable measure of its initial energy.

For electrons with energy less than 250 keV, however, it has been shown by Ross and Zajac (1948, 1949) that significant and useful measurements of range can be made. These authors confined their observations to 'unbranched' tracks; i.e. to those in which the electron had not projected another electron with an energy greater than 20 keV. Mean values are given in Table 5–1 below and are in satisfactory agreement with those deduced from the equation $E = k\, M^{1-n}\, R^n$ which, for electrons, reduces to: $E\ (\text{keV}) = 10{\cdot}8\ R_\mu^{0{\cdot}581}$.

Table 5–1. Mean range of electrons of different energy.

E (keV)	Range (μ)
30	7·0
50	15·8
100	46·7
147	95·4
200	141
250	201

Tracks of electrons are sometimes observed which appear to terminate in the emulsion without displaying the characteristic increase in ionisation of particles at the end of their range. Some of these events may be attributed to the annihilation of a positron, but a positive interpretation in individual cases is difficult because a similar effect can be produced by the large-angle scattering of the particle.

REFERENCE

Ross and Zajac; Nature **162**, 923 (1948); *ibid.* **164**, 311 (1949).

Tracks of emulsions of low energy in 'electron-sensitive' emulsion

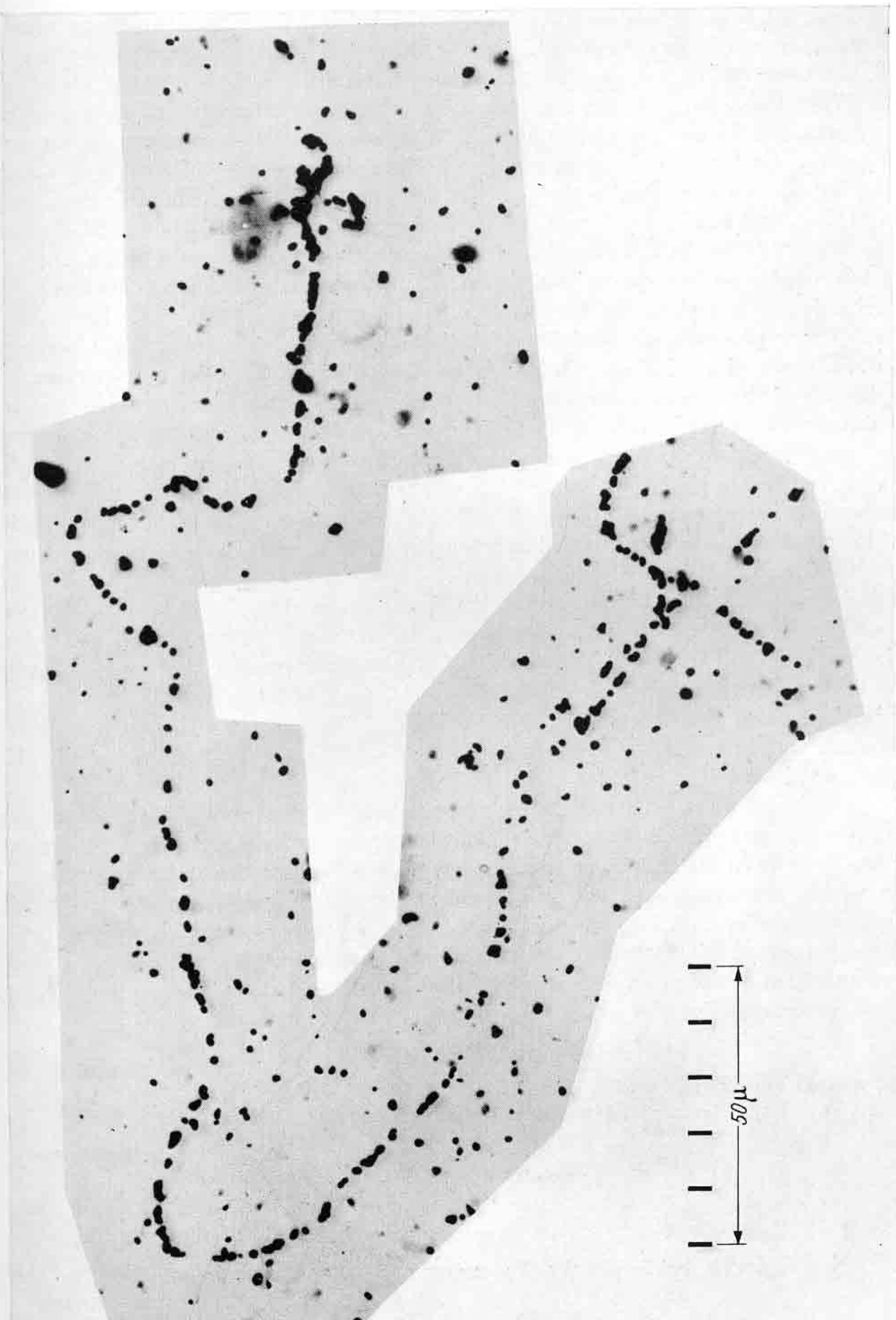


PLATE 5–4

Kodak NT4 emulsion. D. T. King (1950) unpublished.

(Continued from page 146)
the *charged* particles, is greater than the value corresponding to the rest-mass of the π-meson; viz. >140 MeV. Alternatively, if the visible track of the primary particle is sufficiently long, mass measurements may allow a decision.

(b) It is believed that μ^--mesons sometimes, but very rarely, produce 'two-prong' stars following nuclear capture; see p. 232. In such events, however, the energy of the two charged particles is generally very small, and their ranges less than that commonly observed in the 'two-prong' stars produced by π^--mesons. When a negative π-meson is captured by a nucleus, it interacts with two or more nucleons, and a large fraction of the energy corresponding to the rest-mass of the meson can appear in the resulting disintegration. On the other hand, a negative μ-meson is believed to interact with a single proton of the capturing nucleus according to the equation: $P+\mu^- \rightarrow N+\nu^0$. The neutron receives an energy of only ~ 10 MeV, and any charged particles appearing in the resulting disintegration are attributed to its interactions with nucleons in escaping from the nucleus. Only about a tenth of the disintegrations therefore appear as 'one-prong' stars, and a much smaller fraction as 'two-prong' stars, the secondary charged particles being of very short range (George *et al.* 1950, 1951; Morinaga and Fry 1952, 1953). The appearance of a disintegration from which two or more charged particles emerge, following the capture of an L-meson, is therefore very strong evidence for a π^--particle.

If the capture of the meson produces no charged secondary particles, or only one, the ambiguities are more difficult to resolve. Thus, about 28% of π^--particles produce disintegrations at the end of their range with which no tracks of secondary charged particles are associated, and 25% produce only one such track. On the other hand, 7·5% of the μ-particles arrested in *silver bromide* crystals produce one-prong stars, and the others no visible disintegration. The resulting ambiguity can be resolved if the track of the meson is sufficiently long to allow its mass to be determined with sufficient precision to distinguish between π- and μ-mesons.

(iii) *Positive π-mesons.* The observation of the characteristic decay of the π-meson into a μ-meson of range $\sim 600\,\mu$ is decisive. Very rarely, a K-particle may decay into a μ-meson of low energy, an example being shown in Plate 10–2. The chance of a μ-meson from this rare process having a range within the narrow limits commonly resulting from the $\pi \rightarrow \mu$ decay is extremely small.

(iv) *The K-particles.* The observation of the characteristic decay into three π-particles emitted in directions which are co-planar, is almost invariably decisive. The methods of making a final identification are discussed in detail in p. 290 *et seq.*

The K-particles frequently produce secondary effects at the end of their range superficially similar to those of positive μ-mesons. Their identification presents an important technical problem discussed in detail on p. 310. Briefly stated, they can be distinguished by determining the mass and energy of the secondary particles, or by mass measurements on the primary.

(v) *Charged hyperons.* Whilst these particles frequently decay 'in flight', they sometimes reach the end of their range where they decay or interact with nuclei. In this case, also, mass measurements of sufficient precision are of great importance if the particles are to be distinguished from μ-mesons or K-particles; see Sect. 11.

REFERENCES

George and Evans; Proc. Phys. Soc. **63**, 1248 (1950); *ibid.* **64**, 193 (1951).
Morinaga and Fry; Phys. Rev. A **87**, 182 (1952); Nuovo Cim. **10**, 308 (1953).

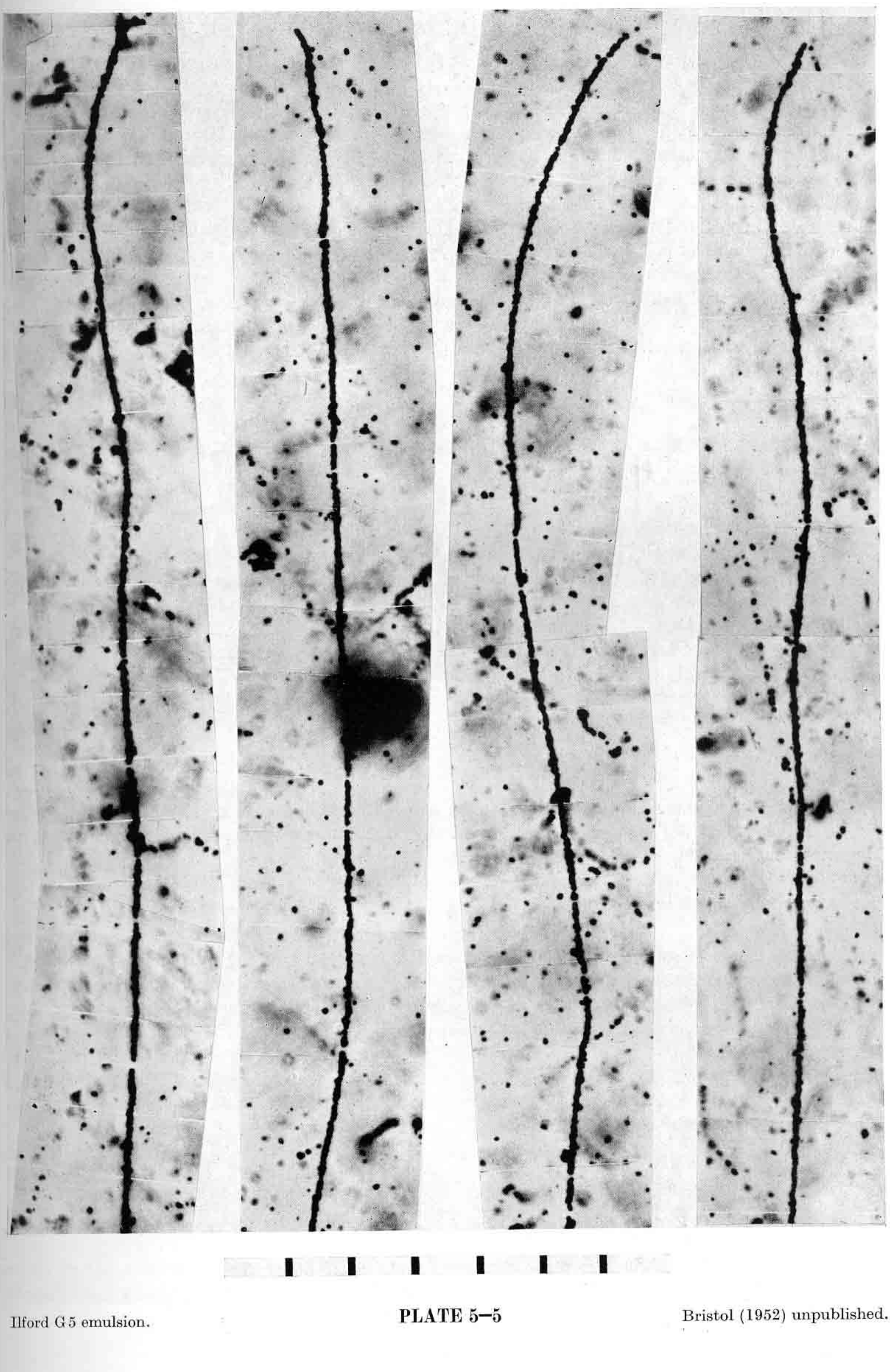
(Continued at top of page 152)

PLATE 5–5. Tracks of μ-mesons at the end of their range ►

The μ-mesons were identified by mass measurements; see p. 154, and by the presence of the tracks of associated fast electrons starting from the end of the range; tracks (b), and (d); see also Plate 7–2.

The pronounced scattering of the particles, as compared with protons, allows the tracks to be distinguished by inspection, with high efficiency. The rate of loss of energy varies from about 7 keV/micron, where a track enters the field of view, to 25 keV/micron, 10 μ from the end of the range, without producing any clearly marked change in the density of grains in the tracks. Large deviations due to scattering are, however, clearly more frequent towards the end of the range.

Tracks of μ-mesons at the end of their range



Ilford G 5 emulsion.

PLATE 5–5

Bristol (1952) unpublished.

(*Continued from page 150*)

5. SLOW SECONDARY ELECTRONS AT THE END OF THE RANGE

Slow secondary electrons may be produced at the end of the range of a charged particle, due either to Auger processes associated with the atomic capture of the particle (see p. 219), or to the β-decay of the product nucleus following nuclear interaction. In either case, the presence of an associated electron indicates that the parent particle was negatively charged. Especially in plates in which the tracks of slow electrons are numerous, however, the possibility of the chance association of an electron with a particular event may have an important bearing on the weight of the evidence.

Electrons from Auger and nuclear processes occur so infrequently—with probability of $< 10\%$ in the case of π^-- and K^--mesons—that no conclusions can be drawn from the absence of secondary electrons in individual events. Useful information can be obtained, however, by working with sufficiently large samples. Thus, among the first three hundred K-mesons observed to decay in photographic emulsions with the emission of a single secondary charged particle, no example of an associated slow electron was reported. Such electrons were observed, however, associated with K^--mesons which interact with nuclei. It was therefore certain that all, or almost all, the K-mesons observed to decay are positively charged.

6. SUDDEN TERMINATION OF TRACKS IN THE EMULSION

Tracks of particles are sometimes observed to terminate suddenly in the emulsion at a point where the velocity of the parent particle, as shown by the grain-density in the track, was still very great. Such an effect may be due to one or other of the following causes:

(a) To the annihilation of a positive electron by collision with a negative.

(b) To the scattering of an electron through a large angle, the subsequent track being too heavily scattered to be easily distinguished.

(c) To charge exchange of a $\pi^{\pm}$-meson, a proton, or a deuteron, as a result of a nuclear interaction; see p. 483. Such processes may occur also in the interaction of $K^{\pm}$-particles with nuclei.

It may be remarked that such effects do not occur for $\mu^{\pm}$-mesons. Their observation therefore allows the presence of a μ-meson to be excluded.

7. MASS MEASUREMENTS

It frequently happens that a particle cannot be positively identified by any of the methods discussed in the preceding paragraphs; when possible, direct mass measurements may then provide important information.

a) Grain-density and range (g^*, R)

The determination of the mass of charged particles recorded in photographic emulsions presents problems similar to those met in the early classical experiments on the electron and the positive-rays. Assuming the charge to be known, the determination of a single parameter, such as the range, provides information from which the mass and velocity cannot be individually deduced, and a second quantity must be determined such as the velocity or the momentum. The following are the most important methods employed hitherto. In comparing them, it is useful to be able to state the 'resolving power' achieved in any particular application: If a homogeneous group of particles of mass M yields a peak in the observed mass distribution of which the width, at half-maximum, is ΔM, the resolving power may be defined as $M/\Delta M$.

PLATE 5–6. Tracks of π-mesons at the end of their range ▶

Short lengths of the tracks of π- and μ-mesons cannot be distinguished by inspection, but the effects at the end of the range are commonly decisive. Sometimes, however, no secondary tracks appear from the ends of the range of π^-- and μ^--mesons; see p. 150.

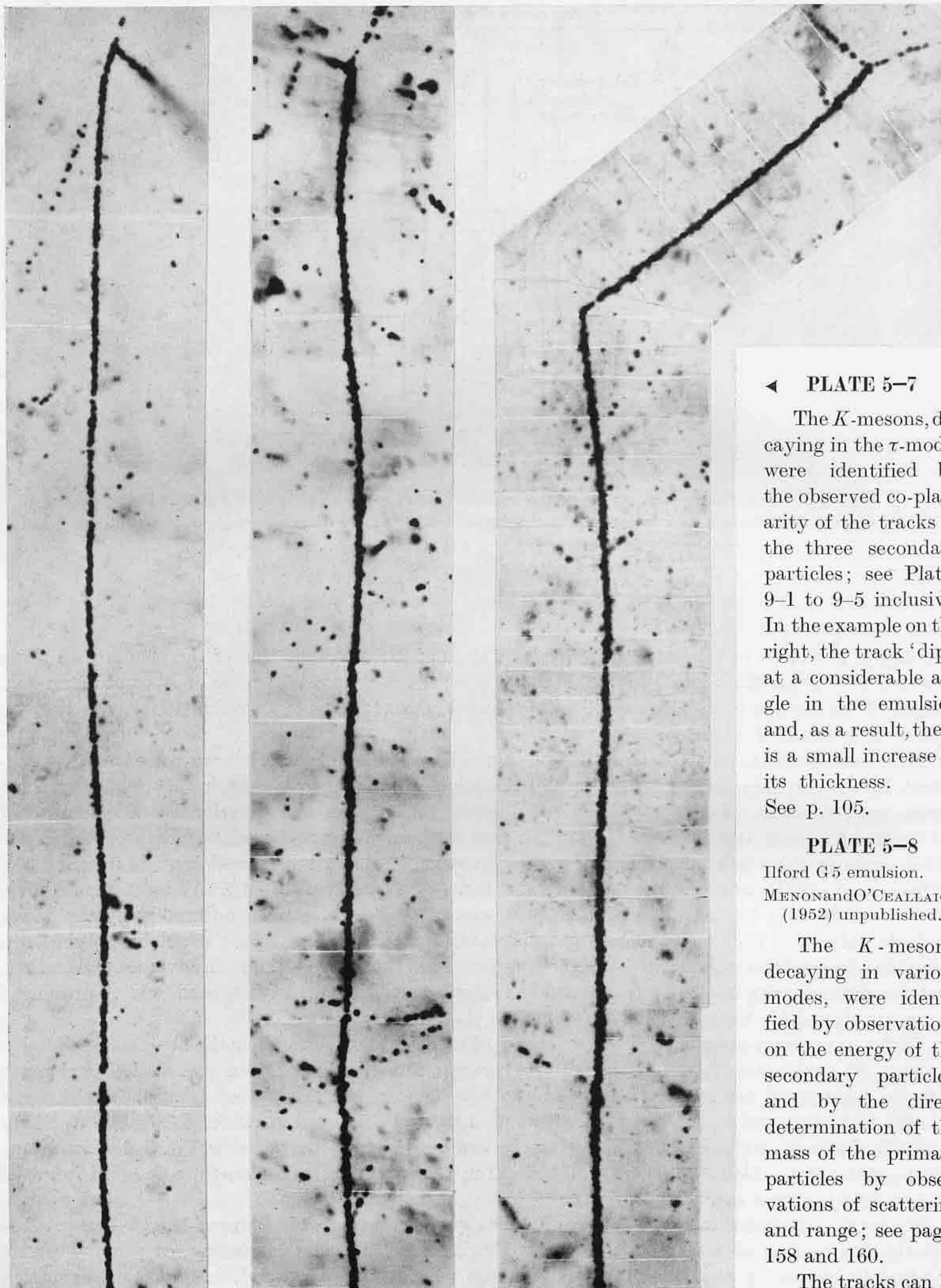
Tracks of π-mesons at the end of their range

Ilford G5 emulsion.

PLATE 5–6

Bristol (1952) unpublished

Tracks of *K*-mesons at the end of their range



Ilford G 5 and Kodak NT 4 emulsions. Bristol (1952) unpublished.

◄ **PLATE 5–7**

The *K*-mesons, decaying in the τ-mode, were identified by the observed co-planarity of the tracks of the three secondary particles; see Plates 9–1 to 9–5 inclusive. In the example on the right, the track 'dips' at a considerable angle in the emulsion and, as a result, there is a small increase in its thickness.
See p. 105.

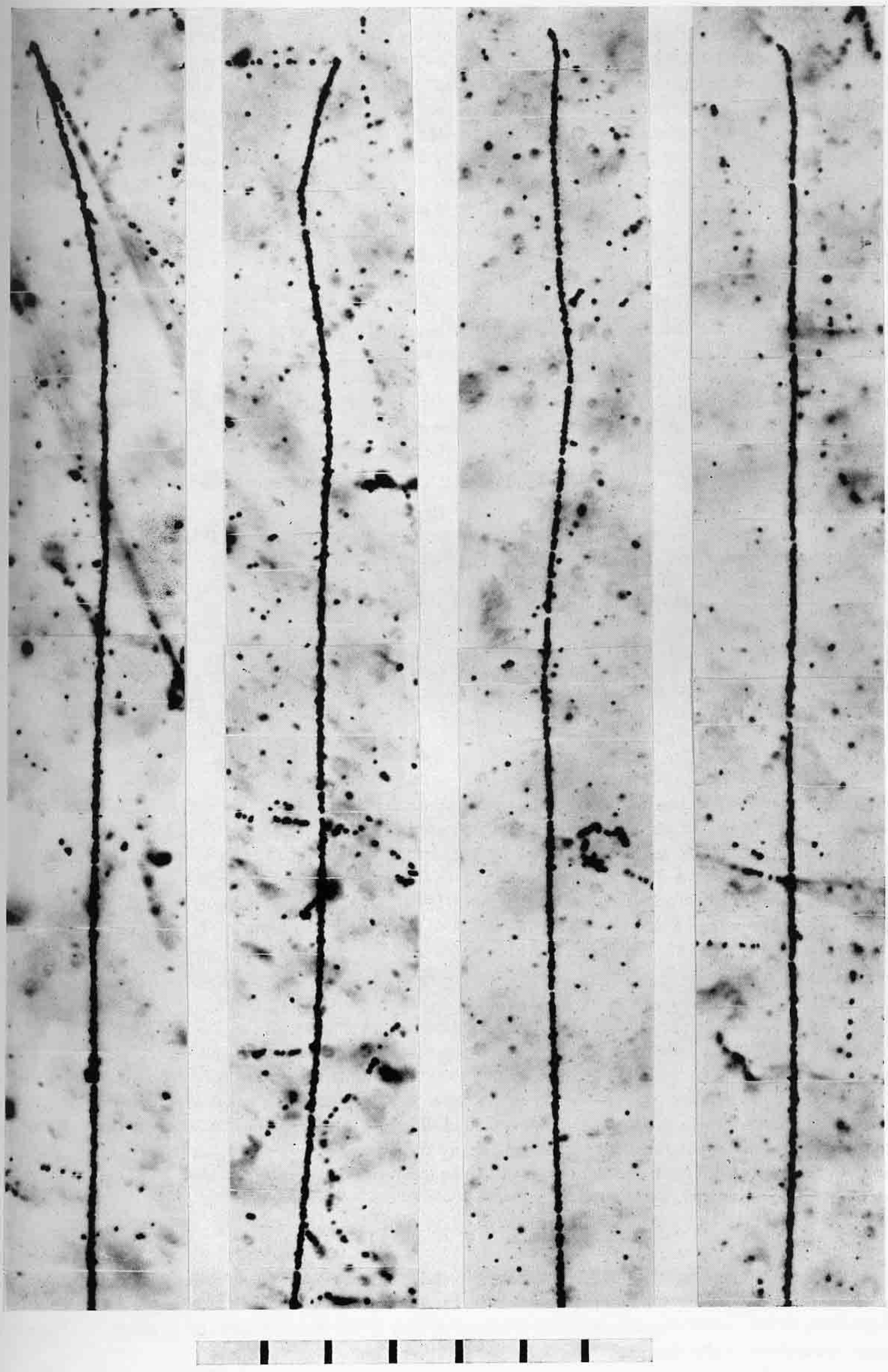
PLATE 5–8 ►

Ilford G 5 emulsion.
Menon and O'Ceallaigh (1952) unpublished.

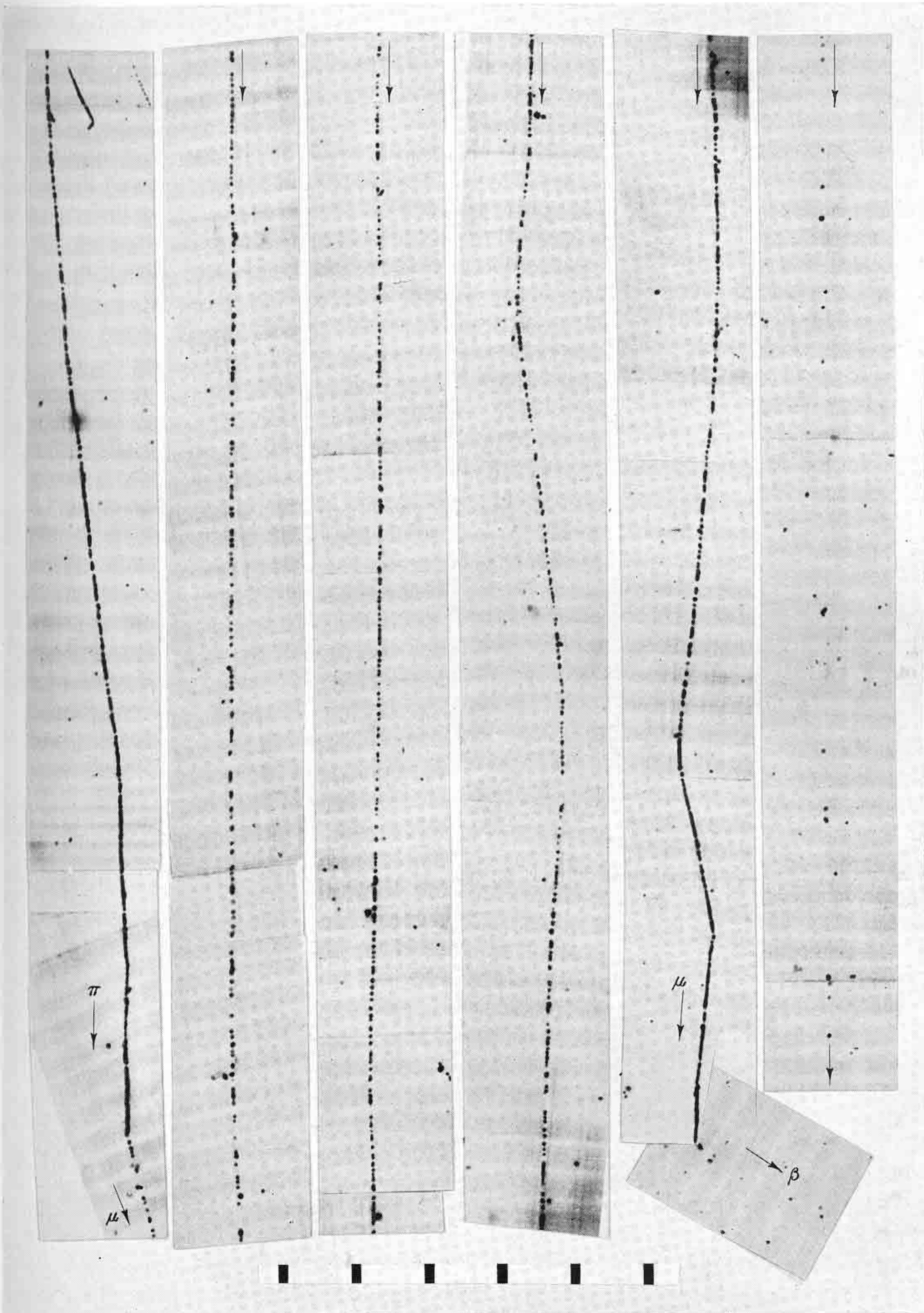
The *K*-mesons, decaying in various modes, were identified by observations on the energy of the secondary particles, and by the direct determination of the mass of the primary particles by observations of scattering and range; see pages 158 and 160.

The tracks can be distinguished from those of μ-mesons with high efficiency by an experienced observer.

Tracks of *K*-mesons at the end of their range



$\pi \to \mu \to \beta$ decay in an emulsion of fine grain-size



Fine-grain emulsion of DEMERS. **PLATE 5–9** DEMERS.

The decay of a π-meson occurs at the bottom of the left-hand photograph, and the track of the μ-meson is shown in the succession of four strips. The decay of the μ-meson, and the resultant electron track, are shown in the two right-hand strips. The grain-density in the electron-track is about 12 per 100 μ.

(Continued from page 158)

In single emulsions, the tracks are usually too short to allow the measurements to be confined to segments of the trajectory over which the velocity was sensibly constant, and the following procedure may be adopted: A track which ends in the emulsion is divided into two halves, and a mean value of $\bar{\alpha}$ is determined for that portion of the track over which the particle moved with the greater velocity. The remaining portion is then again divided into two, and the value of $\bar{\alpha}$ again determined using a smaller cell-length, made appropriate by the increased scattering of the particle at the reduced speed. The measurements of $\bar{\alpha}$ for the different segments are taken to correspond to the residual range at the middle point of each. Similar observations on the tracks of identified protons allow the mass to be determined; MENON and ROCHAT (1951).

An alternative approach to this problem has been made by HOLTEBEKK *et al.* (1953); BISWAS *et al.* (1953); and by DILWORTH *et al.* (1953), who adopt the procedure referred to as the 'constant sagitta' method of which the essential features have already been described; see p. 124. In determining the mass of a particle by this method, it is not important that the set of values of 's' employed should correspond to its mass. The determination is based on a comparison of the observed value of $\bar{\alpha}_s$ for the particle with the corresponding value for particles of known mass. It is only necessary that the set of values of s should ensure that the true signal is sufficiently greater than that due to 'noise'. $\bar{\alpha}_s$ is the value of the scattering parameter as determined with the varying cell-size employed in the constant sagitta method.

The above methods suffer from the fact that the value of $\bar{\alpha}$ changes only slowly with the mass; $\delta M/M = 2{\cdot}39 \, . \, \delta(\bar{\alpha}_s)/\bar{\alpha}_s$. It has the advantage that it is independent of variations in the degree of development of the emulsion. Its field of application is greatly increased in work with stripped emulsions which allow observations on tracks of great length with a corresponding gain in the statistical weight of the observations. DILWORTH *et al.* (1954) give a valuable appraisal of the precision which can be obtained in measurements by these methods. The precision which can be achieved by this and other methods with tracks of different lengths is illustrated in Table 9–3, p. 292, and Table 10–2, p. 316, which give the results of measurements of various types of K-particles.

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PLATE 5–10. Tracks of protons at the end of their range ▶

A comparison of the tracks shown in Plates 5–9, 5–10 and 5–11 illustrates the slow variation of the scattering with the mass. Work on tracks 200 μ long does not allow the track of a K-meson to be distinguished from that of a deuteron with certainty. Application of the constant-sagitta method of measuring the scattering increases the possibility of distinguishing tracks of particles of different mass. Such measurements became of great importance with the discovery of charged hyperons; and the need to distinguish them from K-mesons which often gave superficially similar effects at the end of the range. It is also evident from the photographs that the tracks are so 'clogged' that no change of grain-density along any single track can be detected. Similar remarks apply to tracks of tritons and α-particles; see Plates 5–12 and 5–13.

Tracks of protons at the end of their range

Ilford G 5 emulsion.

PLATE 5–10

Bristol (1952) unpublished.

of mass $\sim 1450\, m_e$, but there was little evidence for their existence from other experiments, and later work showed that the effects were due to a combination of unsuspected spurious scattering and statistical fluctuations.

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d) Observations of range and magnetic deflection (p, R)

The most accurate determinations of the masses of mesons have been made by determining their trajectories in a magnetic field of known intensity, H, and their residual range, R. For low velocities, if ϱ is the radius of curvature of the trajectory of a particle of unit charge,

$$H e v = \frac{m v^2}{\varrho}; \qquad E = \frac{(m v)^2}{2m} = \frac{(H e \varrho)^2}{2m}.$$

For a particle of mass $M \,.\, m_p$, this may be written:

$$E = \frac{(H e \varrho)^2}{2 M \,.\, m_p} = \varkappa \,.\, M^{1-n} \,.\, R^n.$$

It follows that

$$M = \left\{\frac{(H e)^2}{2 \varkappa m_p}\right\}^{\frac{1}{2-n}} . \, \varrho^{\frac{2}{2-n}} . \, R^{-\frac{n}{2-n}} \qquad \text{Eq. (5–iii)}$$

which reduces to $M = C\, \varrho^{1.41}/R^{0.41}$, where C is a constant. More generally, for a particle of charge Ze, it is easily shown that $M/Z^2 = C\varrho^{1.41}/R^{0.41}$. ϱ can generally be determined with great precision and M/Z^2 follows. There is commonly little difficulty in determining Z from other considerations.

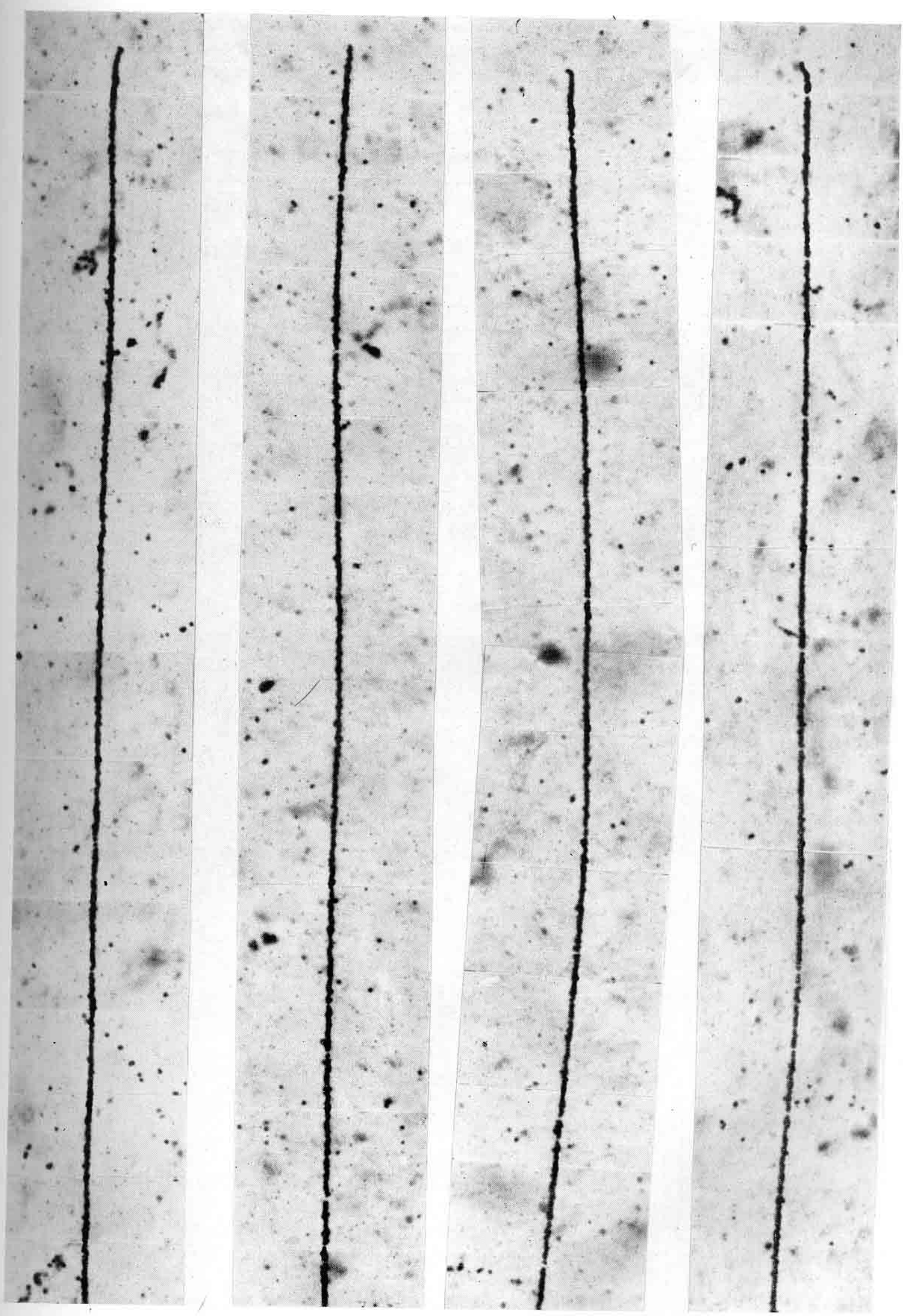
The method has been successfully applied to the artificially produced π-mesons produced in the synchro-cyclotron; see Fig. 5–8. In the magnetic field of the machine, the particles move in semicircular orbits from their point of production to the recording photographic plates where their range is determined; see BARKAS *et al.* (1949, 1951); BIRNBAUM *et al.* (1951); SMITH *et al.* (1953).

Methods similar in principle have been employed by FRANZINETTI (1950), BARBOUR (1949) and GOLDSCHMIDT-CLERMONT and MERLIN (1950) to determine the masses of particles of the cosmic radiation see Fig. 5–7. These authors measured the deflection of the charged particles in passing across the air-gap between two parallel plates with emulsions face to face. In FRANZINETTI's experiments, a magnetic field of $\sim$30,000 gauss, in a direction normal to the plates, was produced by an electro-magnet. By careful mapping, the track of the same particle in the two emulsions could be recognised. The deflection due to the field, and thence the corresponding value of $H\varrho$, could thus be determined. The precision of measurements thus obtained is illustrated by the mass spectrum deduced from FRANZINETTI's observation; see Fig. 5–9. A very important feature of magnetic deflection experiments is that they allow the sign of the charge as well as the mass of a particle to be determined.

PLATE 5–11. Tracks of deuterons at the end of their range ▶

The deuterons were identified by mass measurements on very long tracks. Because of the reduced scattering of protons and deuterons, discrimination between them by inspection is impossible.

Tracks of deuterons at the end of their range



Ilford G5 emulsion.

PLATE 5–11

Bristol (1952) unpublished.

An unsatisfactory feature of the above methods is that they depend on a knowledge of the precise form of the range-energy relation, sometimes in regions where no accurate measurements have hitherto been made. To eliminate this difficulty, BISHOP *et al.* (1949) have made experiments in which, with

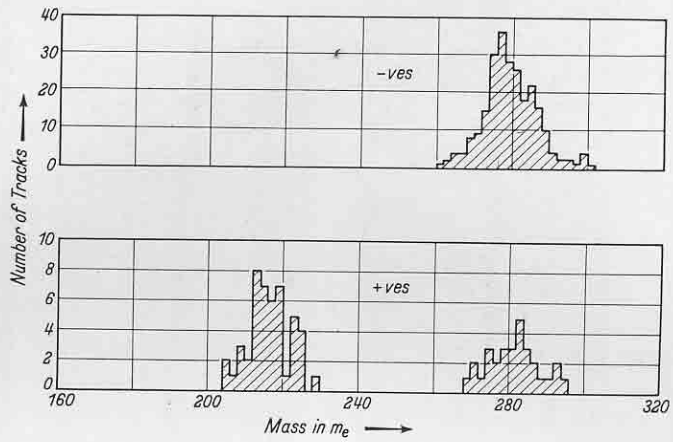
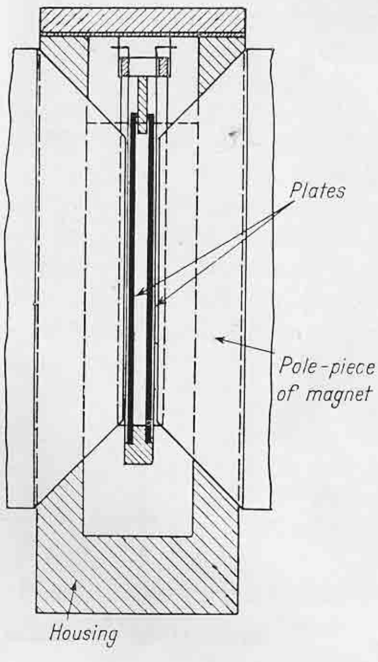


Fig. 5–6. Masses of artificially produced mesons as deduced from measurements of momentum and range (p, R) method. Resolving power about 18. (After BARKAS *et al.* 1949.)

a suitable experimental disposition, they can determine the ratio of the ranges of protons and π-mesons recorded in a single plate, and the corresponding values of $H\varrho$ for the two types. By determining the particular value of $(H\varrho)_p/(H\varrho)_\pi$ which is equal to R_p/R_π, they obtain a measure of the ratio of the masses m_p/m_π independent of a precise knowledge of the range-energy relation and of the absolute magnitude of the magnetic field; see Fig. 8–6, p. 266.

(Continued on page 168)



◄ Fig. 5–7. Apparatus employed by FRANZINETTI for determining the masses and charges of particles produced by cosmic radiation. The two plates face one another, and measurements are made on particles which pass through one emulsion, across the air-gap, and are brought to rest in the second emulsion. (After FRANZINETTI 1950.)

PLATE 5–12. Tracks of tritons at the end of their range ►

Here also it is apparent that no distinction can be made in grain-density or scattering, between the tracks of tritons and α-particles in the last 200 μ of their range. The tracks are, however, commonly manifestly less scattered than those of K-particles and protons.

Tracks of tritons at the end of their range

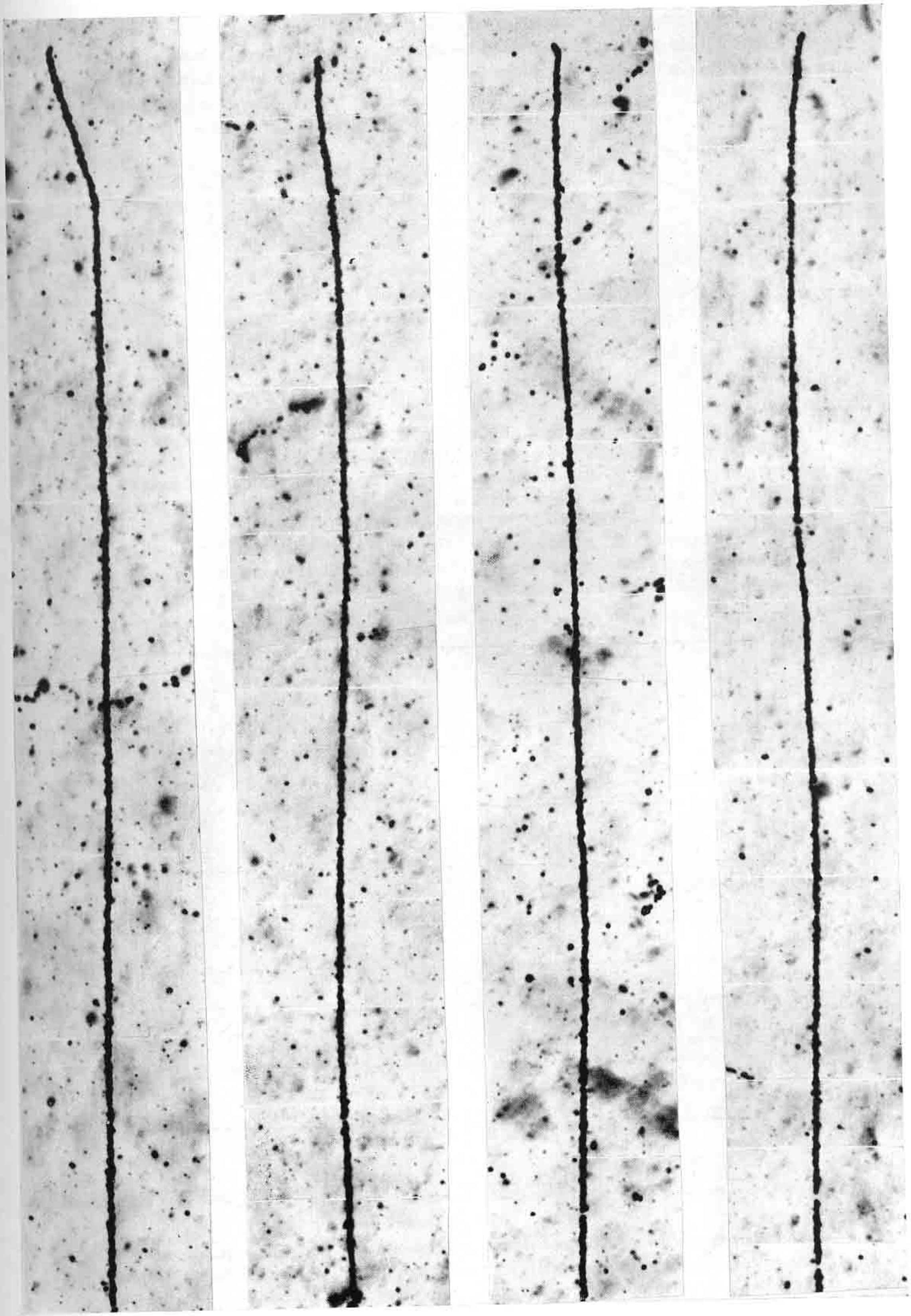


PLATE 5–12

Ilford G 5 emulsion.

Bristol (1952) unpublished.

a charged particle, such as a K-meson or a proton, moves too slowly to produce such δ-rays; their presence in the track of a particle under examination therefore provides strong evidence that it was not near the end of its range.

The average number of δ-rays per $100\,\mu$ in the tracks of particles of charge e, and of different mass, are shown in Fig. 5–10. The marked differences between the expected values for particles of different mass in the last millimetre of their trajectories is well displayed. Whilst the method has the advantage that it is relatively insensitive to differences of development, it is severely limited by the small statistical weight of the observations. To overcome this difficulty, δ-rays containing only three grains may sometimes be included in the analysis. A discussion of the problems encountered in δ-ray counting have been given by TIDMAN *et al.* (1953).

A particularly important application of the method occurs in connection with the problem of distinguishing between particles of charge e and $2e$. Thus, all the methods of determining mass described in the previous sections depend upon the assumption that the charge of the particles is known. In determining the mass of an individual particle, it is therefore necessary to establish the charge, and this is not always easy by grain-density and scattering measurements alone. The variation with range of the values of g^* and $\bar{\alpha}$ along the track of a triton, for example, are similar to those for an α-particle. On the other hand, the numbers of δ-rays associated with the two tracks are widely different:

Since the value of Z^2/M is very nearly equal for the proton and the α-particle, so also is the variation of velocity with residual range; it follows, since N_δ varies as Z^2, that the form of the distribution of N_δ v R for α-particles is similar to that for protons, but the δ-rays are four times more frequent. This fact permits the two particles to be distinguished with high efficiency by δ-ray counts on the last millimetre of track; in this range, the contrast between the track of a triton and an α-particle is even more marked.

Such observations at points near the end of the range have the advantage that there are no δ-rays of high energy owing to the limited velocity of the heavy particle, so that the association of the δ-ray with the track can be made with little ambiguity, and difficulties due to background are commonly not serious. Further, the number of δ-rays is of a convenient order of magnitude to allow a decision about the charge if the available length of track is ~ 2 mm or even less.

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TIDMAN, GEORGE and HERZ; Proc. Phys. Soc. A **66**, 1019 (1953).
VOYVODIC; Canad. J. Research **28**, 315 (1950).

PLATE 5–13. Tracks of α-particles at the end of their range ▸

The α-particles were identified by observations on the scattering and δ-ray-density along the tracks of particles of great range which, by chance, stopped in the emulsion. The rate of loss of energy of the particles, dE/dR, varies from about 70 keV per micron where the residual range is $\sim 200\,\mu$, to 200 keV per micron at a point $\sim 10\,\mu$ from the end of the range. It is more difficult to distinguish the tracks of hydrogen nuclei and α-particles in 'electron-sensitive' emulsions than in the Ilford C2 emulsion.

Tracks of α-particles at the end of their range

Ilford G5 emulsion. **PLATE 5–13** Bristol (1952) unpublished.

Tracks of carbon and nitrogen nuclei approaching the end of their range

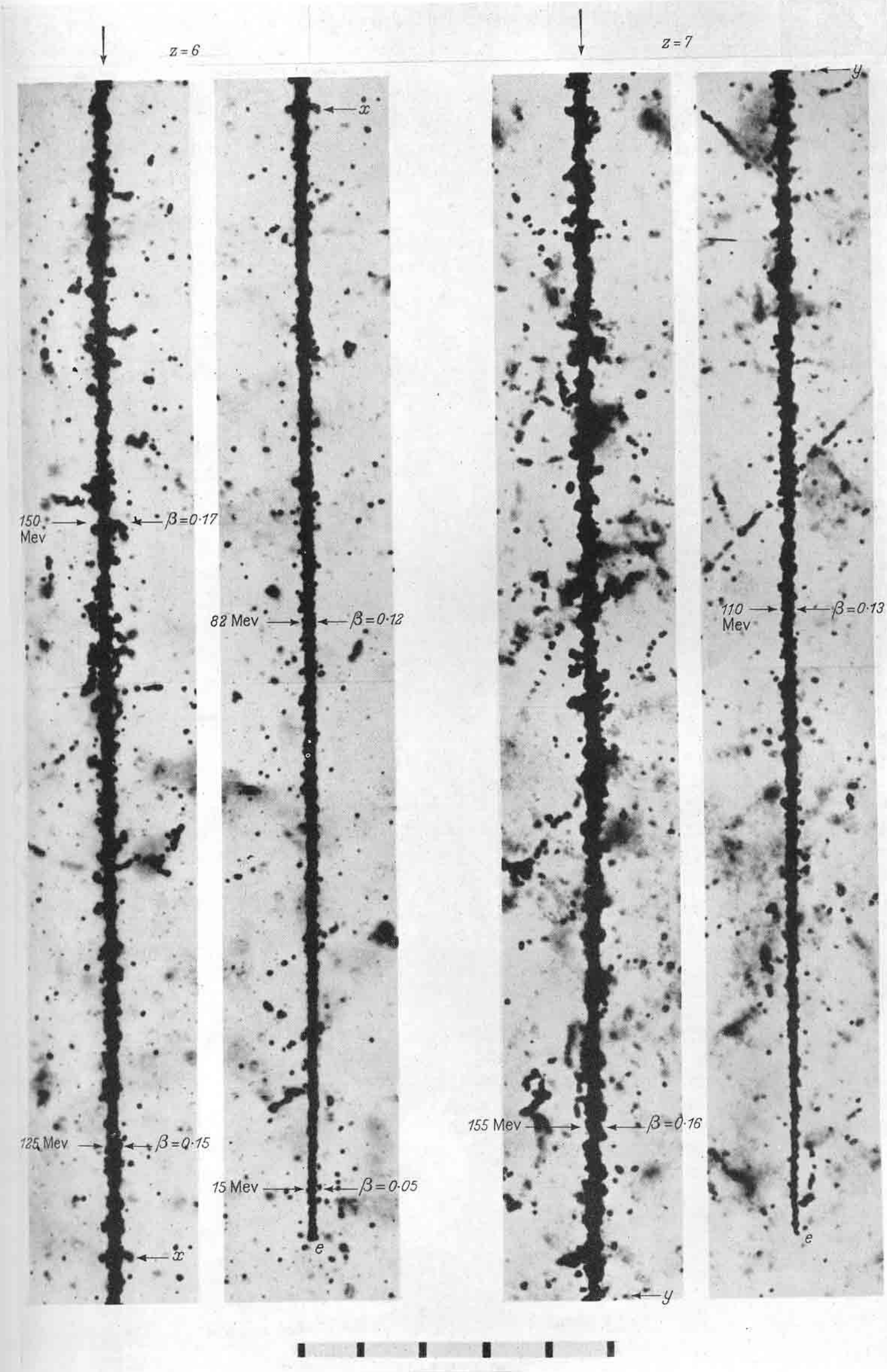


PLATE 5–14

Tracks of nuclei with $Z = 10$ and $Z = 11$ or 12 approaching the end of their range

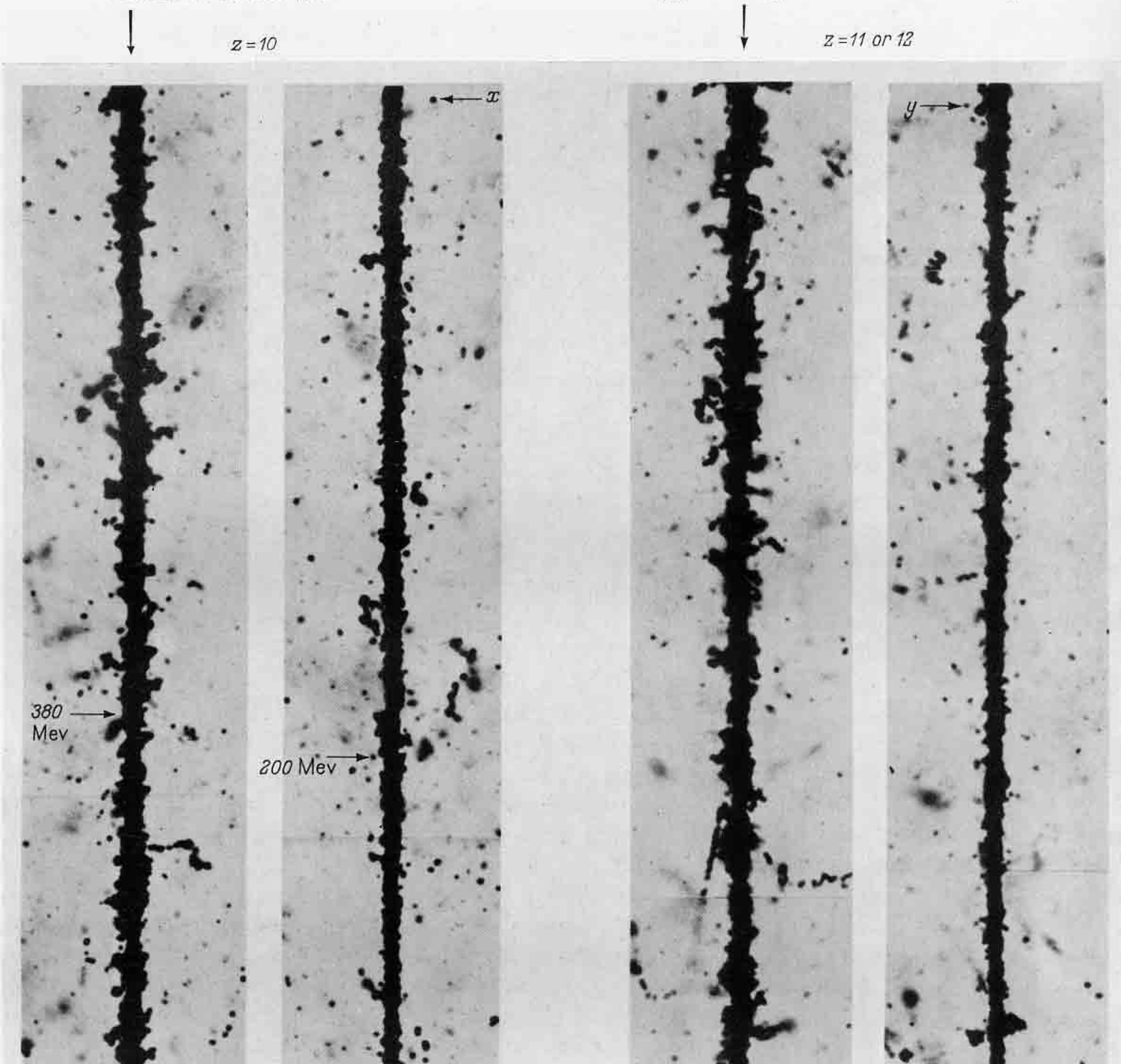


PLATE 5–15

PLATE 5–14. Tracks of carbon and nitrogen nuclei approaching the end of their range — page 173

Ilford G5 emulsion. DAINTON and FOWLER (unpublished).

The tracks are each given in two parts which overlap at the points marked x or y. The particles producing the tracks shown in Plates 5–14 to 5–18, inclusive, were identified by the methods described in Section 16, the observations being confined to very long tracks which, by chance, reached the end of their range in the emulsions of a stack. The carbon and nitrogen nuclei are completely 'stripped' for values of the residual range greater than 10 μ. The track of the carbon nucleus appears to terminate before it has become as thin as that of the nitrogen nucleus at the extreme end of the range. This is probably due to a nuclear collision. in which the particle was scattered.

PLATE 5–15. Tracks of nuclei with $Z=10$ and $Z=11$ or 12 approaching the end of their range — page 174

Ilford G5 emulsion. DAINTON and FOWLER (unpublished).

A comparison of Plates 5–14 and 5–15 suggests that great care should be taken in attempting to identify heavy nuclear particles by observations on tracks with residual range less than 200 μ.

The nuclei begin to capture electrons when their residual range is less than 10 μ.

PLATE 5–16 and 5–17. The last 2 mm in the track of a nucleus of charge $\sim 18e$ approaching the end of its range — pages 176 and 177

Ilford G5 emulsion. POWELL (1950).

The track is shown in ten overlapping sections starting top left. Corresponding points in the successive photographs may be readily distinguished. The increase in the thickness of the core and the decrease in the maximum range of the δ-rays, corresponding to the falling velocity of the particle, can be seen in the first seven photographs, followed by the 'thin-down' as the particle approaches the end of its range at e. Between sections 7 and 8, the particle traversed a narrow air-gap between facing emulsions. As the particle grazes the surface of the two emulsions, only a fraction of the δ-rays are recorded and the tracks are visibly thinner in these regions. The tracks of similar particles moving at relativistic velocities are shown in Plates 16–3 and 16–7.

PLATE 5–18. Tracks of nuclei with charge numbers $Z=14\pm 1$ and $Z=24\pm 2$ approaching the end of their range — page 178

Ilford G5 emulsion. DAINTON and FOWLER (unpublished).

In the case of the heavy nucleus $Z = 22$, capture of electrons into the K-orbit becomes possible when the residual range is 80 μ; and into the L-orbits, when the range is 15 μ. 'Capture and loss' and the resultant decrease in the effective charge of such a nucleus increases its range by about 40 μ.

REFERENCE

POWELL; Repts. Prog. Phys. XIII, p. 350 (1950).

The last 2 mm in the track of a nucleus of charge $\sim 18\,e$ approaching the end of its range

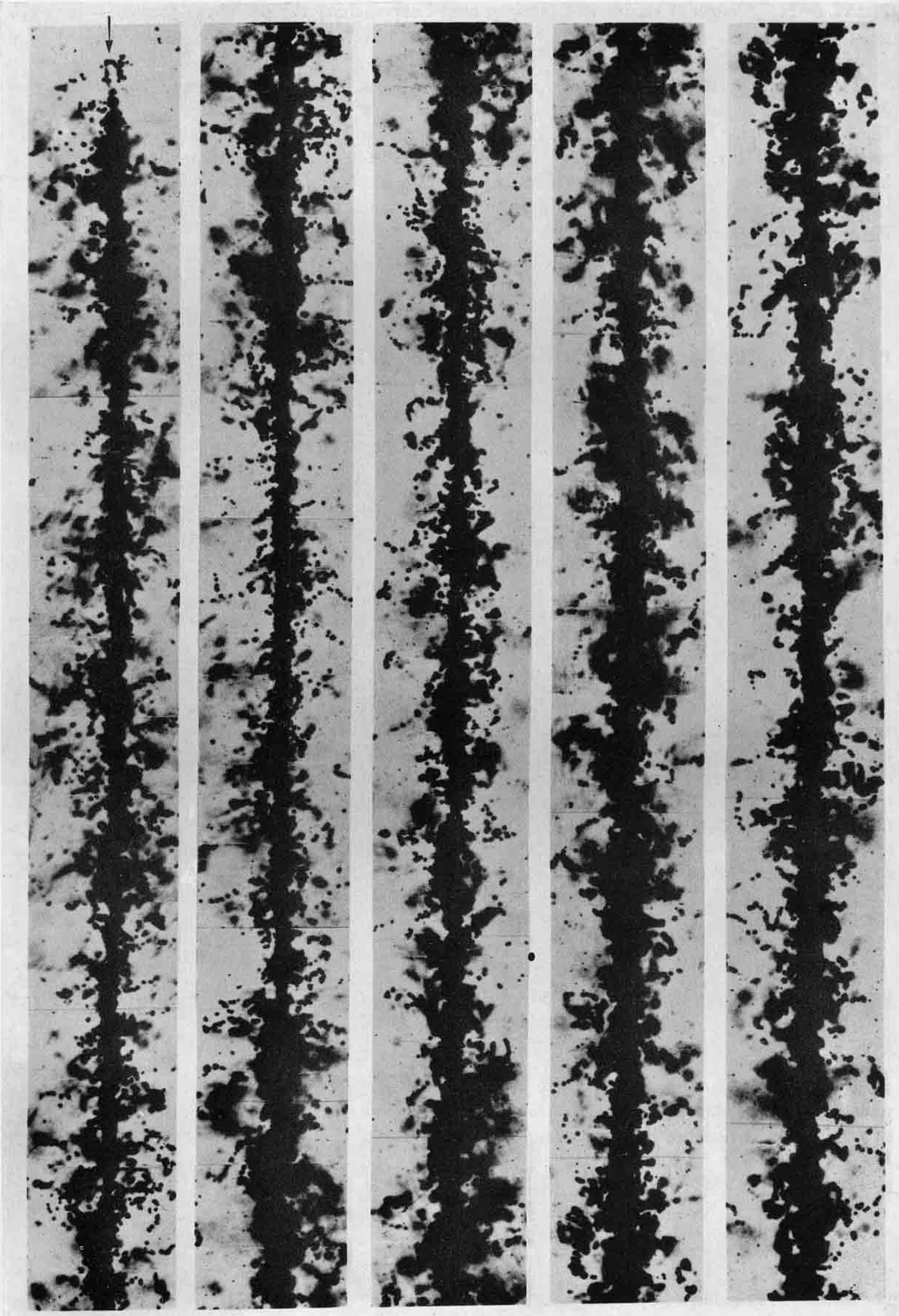


PLATE 5–16

The last 2 mm in the track of a nucleus of charge $\sim 18e$ approaching the end of its range

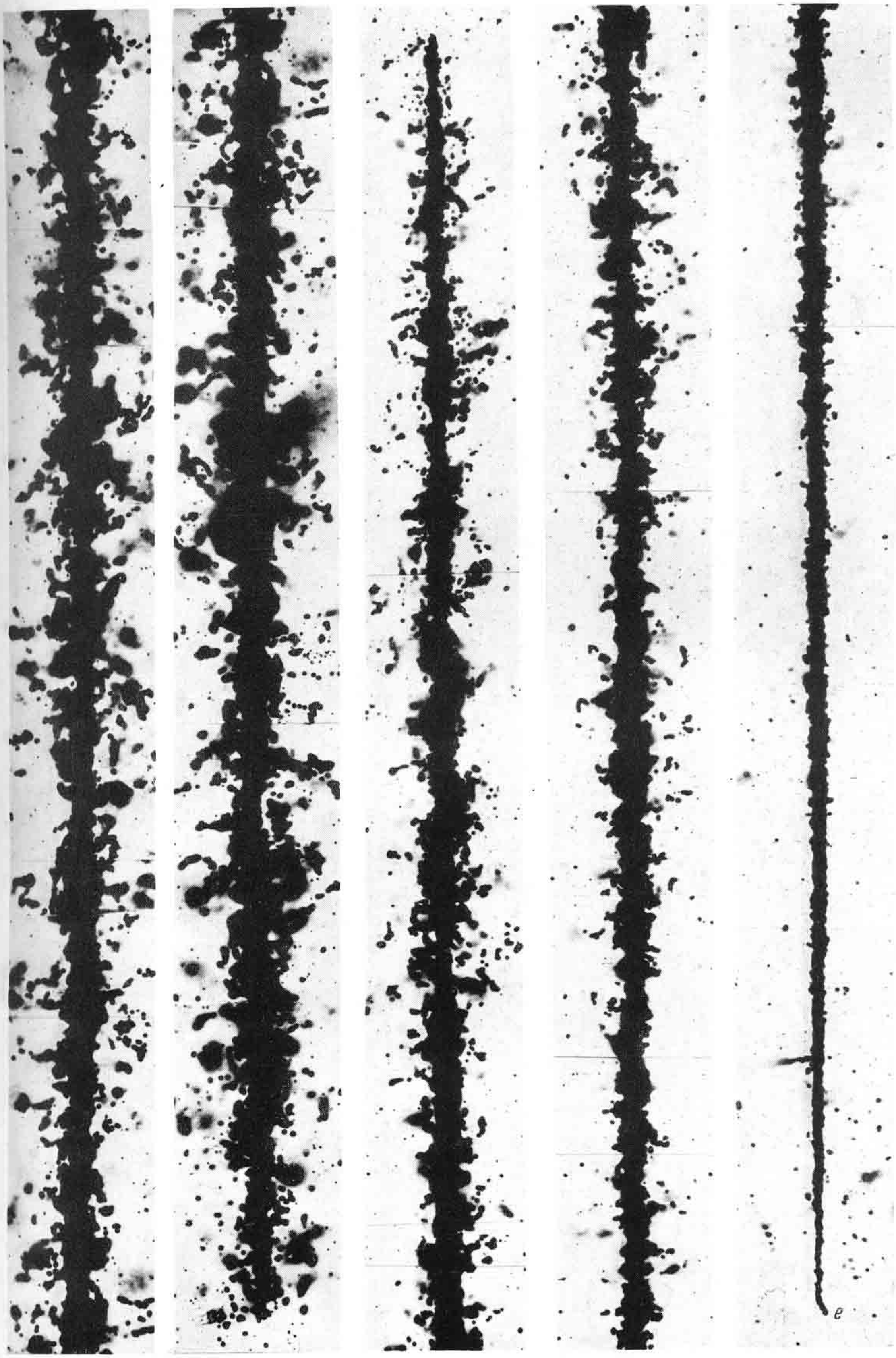


PLATE 5–17

Tracks of nuclei with charge numbers $Z = 14 \pm 1$ and 24 ± 2 approaching the end of their range

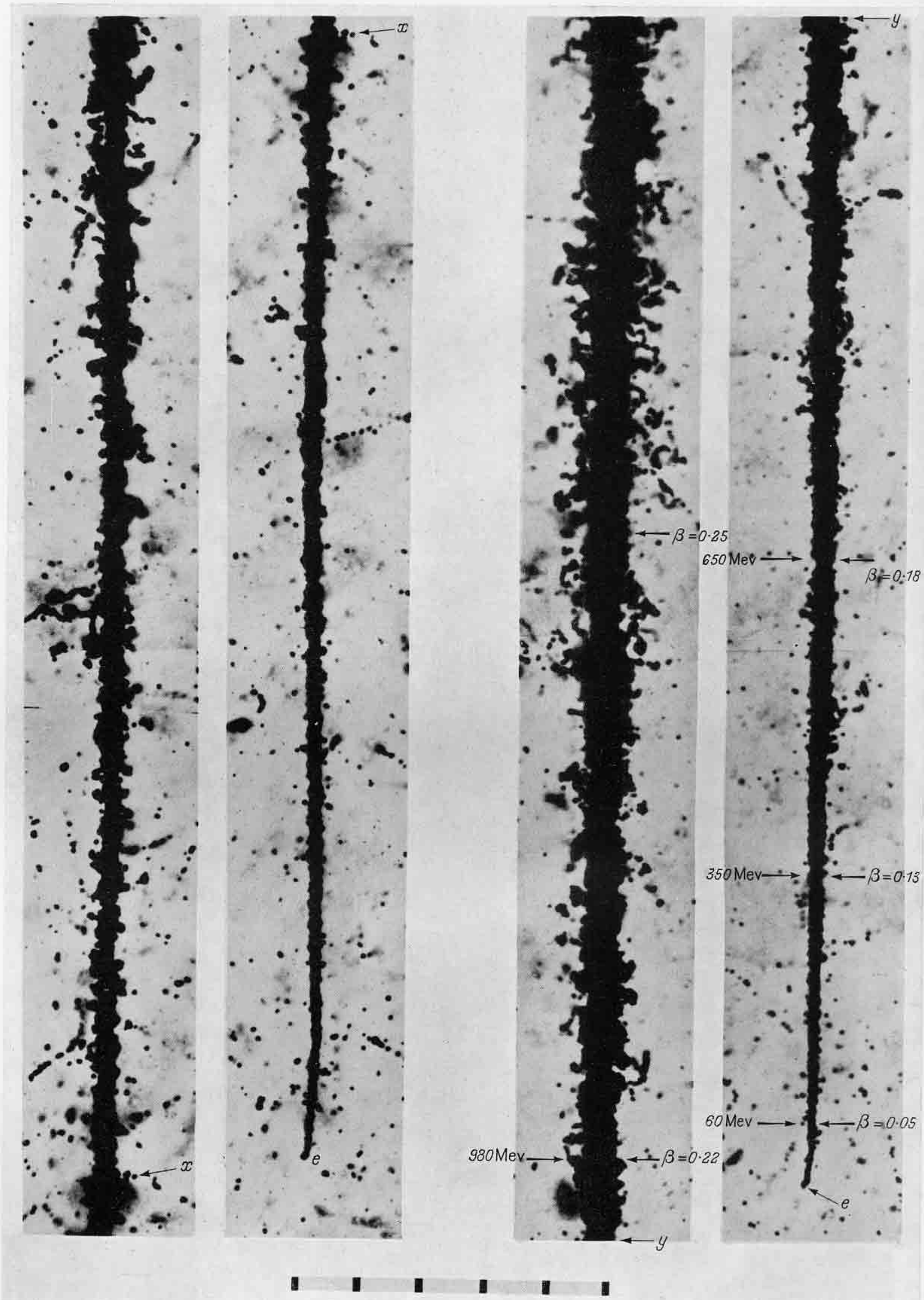


PLATE 5–18

Electron pairs produced by γ-rays

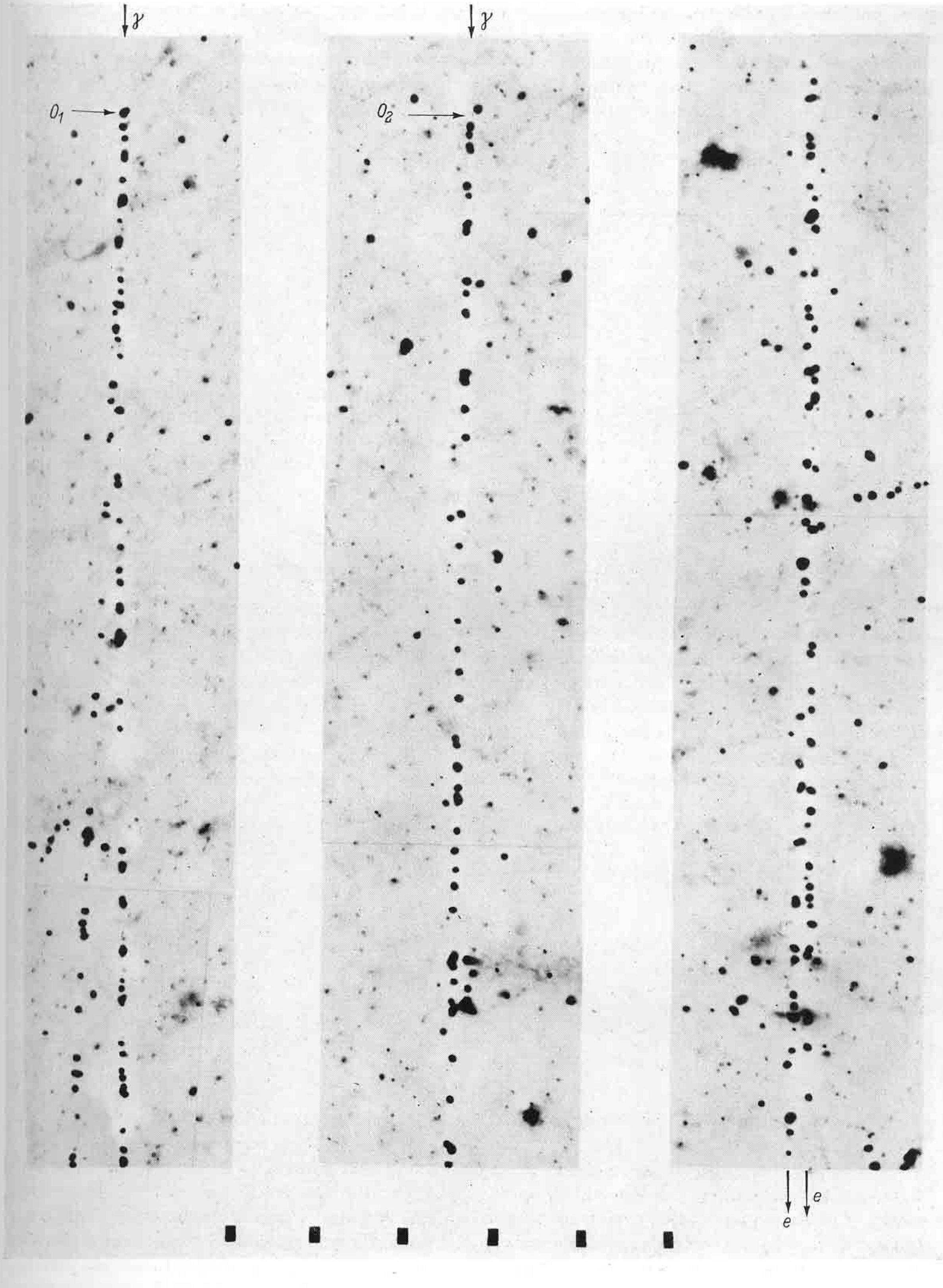


PLATE 6–1

Ilford G 5 emulsion.

Hooper and King.

(Continued from middle of page 182)

pairs produced by the materialisation of a homogeneous group of γ-rays of high energy, should be distributed in the manner shown in Fig. 6–3. The curves are computed for material of $Z=50$, but the dependence on atomic number is small, and they are valid for photographic emulsion; it has also been assumed that there is an equipartition of energy between the two electrons; if not, the angles are all increased by the factor $4a(1-a)$, where $a=E/E_0$. Values of the function $F(a)$ are shown in Fig. 6–4.

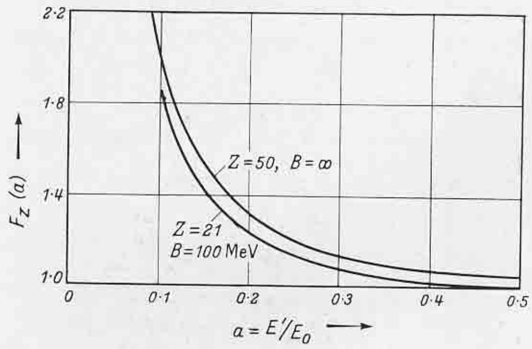


Fig. 6–4. $F_z(a)$ depends on the atomic number Z of the medium; and on the disparity, $a=E'/E_0$, between the energies of the two electrons. The figure shows the variation of $F_z(a)$ with a, for $Z=50$, $B=\infty$; and for $Z=21$, $B=100$ MeV.

The principal difference between the predictions of the two theories arises from the logarithmic term in STEARNS' formula which has the effect that $2\sqrt{\overline{\theta^2}}/\bar{\delta}=\log\frac{E_0}{mc^2}\Big/2$. A comparison of the validity of these equations has been examined by HINTERMANN (1954), who measured the opening angles of pairs of electrons due to the materialisation of γ-rays of energy ~ 100 MeV in plates exposed at mountain altitudes. The energies of the two electrons were determined by scattering measurements, and the results are shown in Fig. 6–5. The figure suggests that, at the energies involved, the general trend of the observations is better expressed by BORSELLINO's formula.

In the case of radiative collisions, STEARNS gives the following relation for the angular divergence of the secondary photon of energy E' from the line of motion of the parent electron, energy E_0:

$$\sqrt{\overline{\Phi^2}}=f\left(\frac{E'}{E_0}\right)\cdot\frac{mc^2}{E_0}\cdot\log\frac{E_0}{mc^2}, \qquad \text{Eq. (6–iii)}$$

where $f\left(\frac{E'}{E_0}\right)$ does not depart widely from the value 0·6.

PLATE 6–2. Electron pair produced by the materialisation of a γ-ray ▸

The tracks of the two electrons of which the first recognised grain is at O, are given in three continuous photographs. Only in the third, on the right, can the two tracks be resolved. Unresolved tracks of electron pairs of this type were first recognised by the fact that the apparently single track has a grain density nearly twice the minimum value, whereas the scattering is so small that the particles are certainly moving with a velocity close to that of light. If the track is attributed to a single particle, the difficulty has to be met that the minimum ionisation of a particle with charge $Z=2$ is four times the corresponding value for a singly charged particle. This would indicate that the assumed single particle has a non-integral charge. The difficulty is immediately resolved by the assumption of a pair.

Electron pair produced by the materialisation of a γ-ray

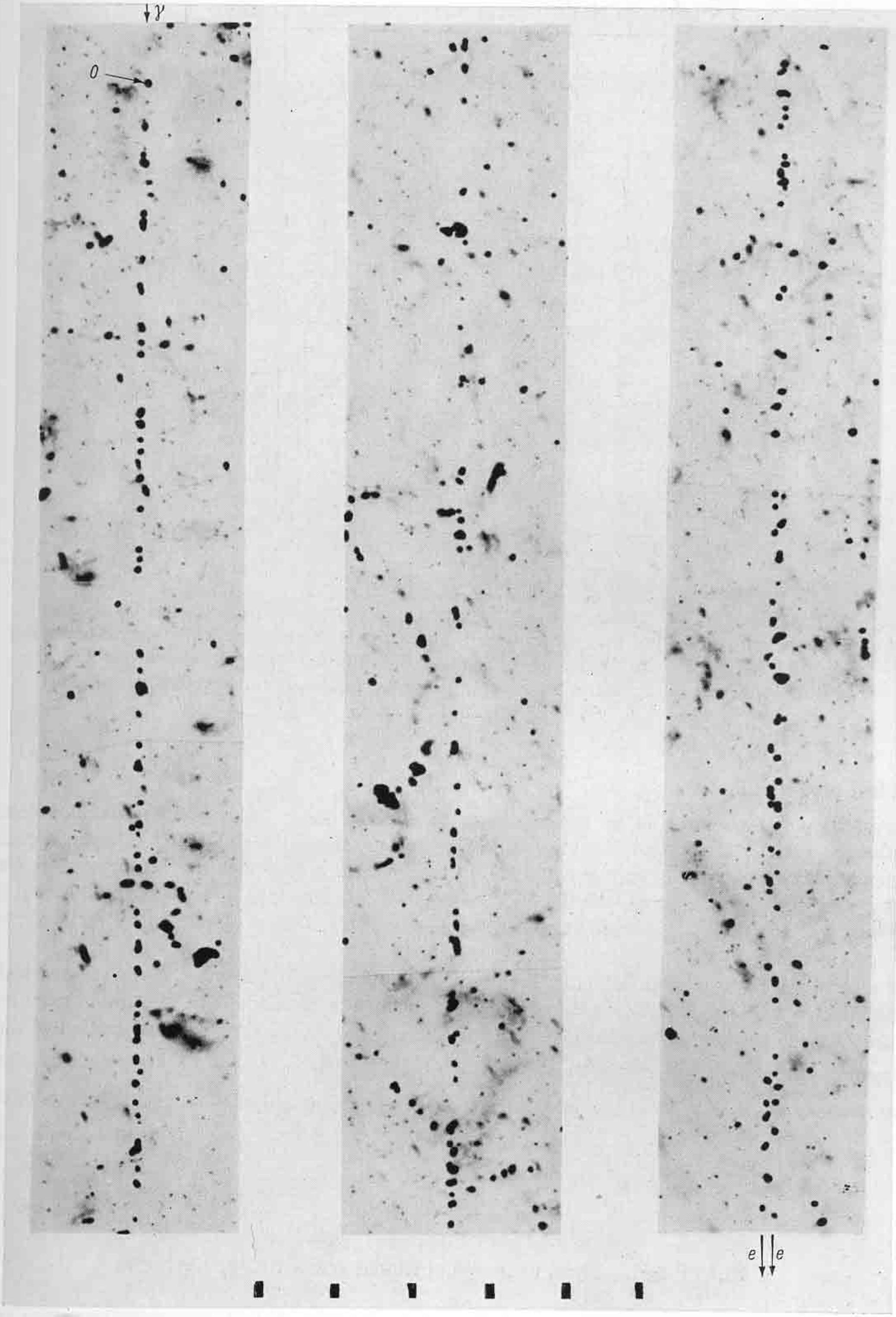


PLATE 6–2

Ilford G5 emulsion.

HOOPER (unpublished, 1952).

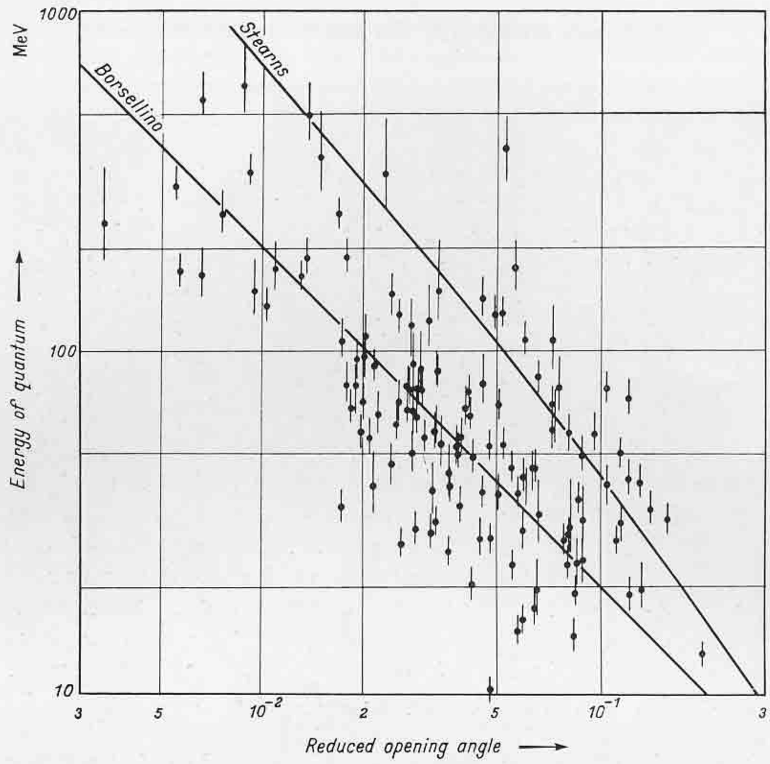


Fig. 6–5. Observations by HINTERMANN (1954) on the opening angles of pairs of which the energies of the individual electrons were determined by scattering measurements. The observed angles have been reduced to take account of the observed disparity in energy of the electrons of each pair. The observations appear to be in better agreement with the formula of BORSELLINO than with that of STEARNS.

c) Trident production

In addition to losing energy by *bremsstrahlung*, fast electrons can also produce pairs of electrons, by interaction with the electro-magnetic field of a nucleus, so that a single fast electron approaches a nucleus, and three emerge (see Plate 6–3). The existence of such a process was anticipated by OPPENHEIMER, and it was studied theoretically by FURRY and CARLSON (1933), BHABHA (1935), and many other workers. It was first observed in photographic emulsions, and is referred to as 'trident' production; see OCCHIALINI (1949), BRADT *et al.* (1950).

In making observations on 'tridents', they must be distinguished from other processes which can sometimes give apparently similar effects. Thus, we have seen that when an electron of great energy produces a photon by *bremsstrahlung*, the angular divergence in the directions of motion of the two products may be very small, of the order $\frac{mc^2}{E}$ radians, where E is the initial energy of the electron. If, by chance, the secondary γ-ray materialises after traversing only a short path in the emulsion,

(Continued on page 188)

PLATE 6–3. Three examples of trident production by electrons ▶

The tracks of the incoming electrons, and the points of origin of the pairs are indicated by arrows. The events are of relatively low energy so that there is a wide angular divergence of the tracks. In these circumstances, it is improbable that a pair produced by *bremsstrahlung* will originate precisely on the line of motion of the parent electron.

Three examples of trident production by electrons

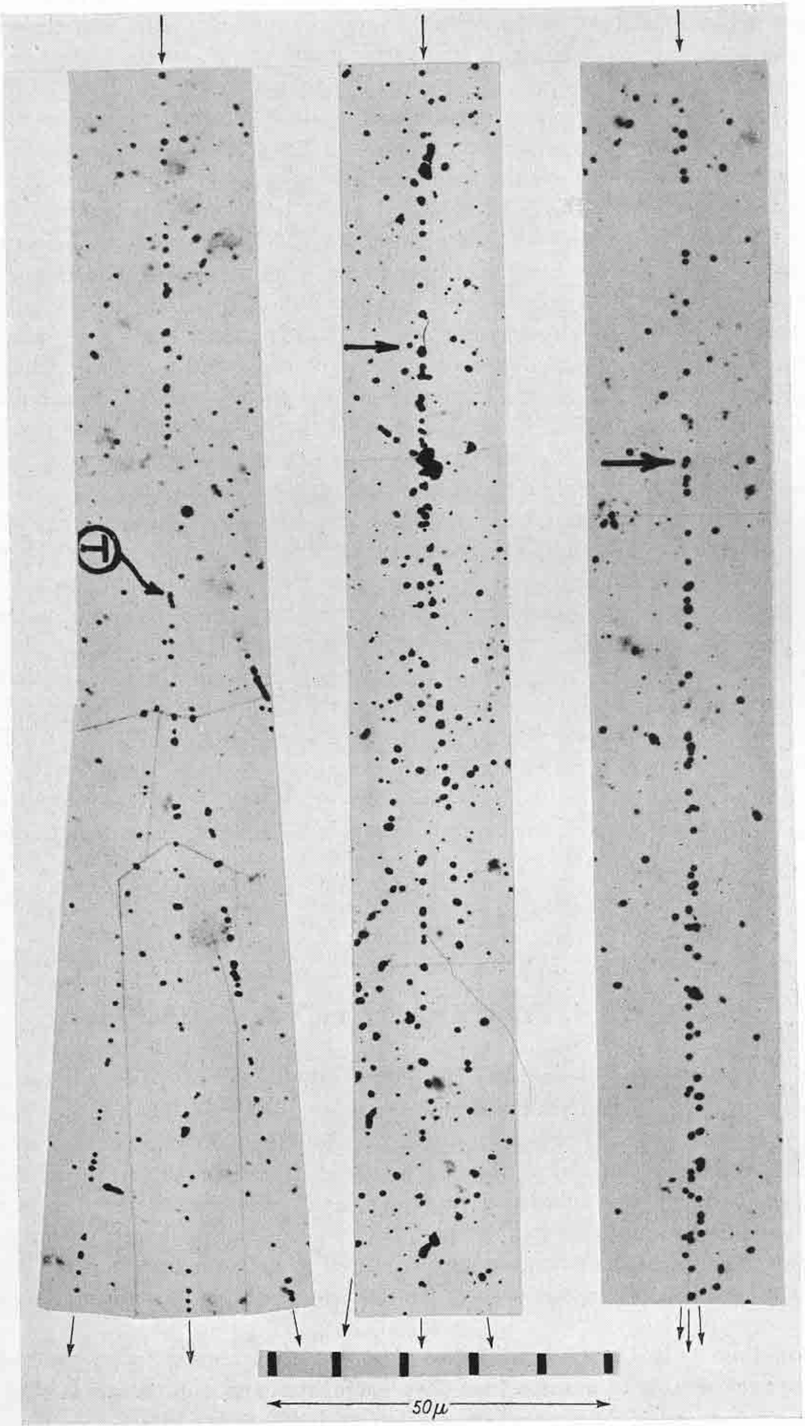


PLATE 6–3

Ilford G5 emulsion.

Bristol (1952).

(Continued from page 186)

the pair may originate at a point which is apparently coincident with the track of the primary electron. Similar processes, in which a small separation is found between the origin of a pair and the track of a neighbouring electron, are frequently observed. The separation between the point of origin of the pair due to the conversion of *bremsstrahlung* and the track of the parent electron depends on the scattering of the latter particle, as well as on the initial divergence. Nevertheless, at very high energies, it is to be expected that an appreciable proportion of the pairs due to *bremsstrahlung* will originate at points separated from the parent electron track by distances less than can be resolved under the microscope, and will thus give rise to 'pseudo-tridents'.

In order to show that fast electrons can indeed produce electron pairs directly, HOOPER *et al.* (1951) made measurements on the separation of the points of origin of electron pairs from the line of motion of an associated electron, — the association being proved by the almost parallel directions of motion of the three particles. The observations include both 'tridents' and separated pairs. The resulting distribution showed a clearly defined group for which there was no measurable separation, too great in number for them to be accounted for in terms of the materialisation of *bremsstrahlung* alone. The expected distribution for the latter process could be estimated from cascade theory. At the low energies of the events on which measurements were made, less than 1 BeV, the cross-section for the trident process was in satisfactory agreement with the anticipations of the theory.

According to electro-magnetic theory, the cross-section for the production of tridents should be approximately 1% of that for *bremsstrahlung*, but some of the early experimental results with electrons of higher energy suggested that it is considerably greater than the expected value. Such a result, if confirmed, would throw serious doubt on the validity of the theory which, as we shall see, is in excellent agreement with the general features of the cascades; in particular, measurements of the 'conversion length' are in satisfactory agreement with the theoretical predictions; PINKAU (1956).

In order to examine this difficulty more precisely, BLOCK and KING (1954) also made measurements on the separation of the points of origin of close pairs due to *bremsstrahlung* from the line of motion of an accompanying electron, similar to those of HOOPER *et al.* (1951), but for electrons of greater energy, between 1 and 10 BeV. Good agreement was found between the distribution of the observed values of the separation and those calculated, a result which gives strong support for the estimates of the proportion of similar pairs which would have been unresolved.

BLOCK and KING estimate that for electrons of energy between 1 and 10 BeV, about 6% of the pairs due to *bremsstrahlung* will appear as 'tridents', whilst for higher energies the proportion will be much greater; at 100 BeV, about 70%. The most recent results indicate that, at least up to energies $\sim$10 BeV,

PLATE 6–4. Associated pairs and related phenomena ▶

(a) At first sight, this event appears to correspond to the creation of four electrons in a single act. Closer inspection, however, shows that there are two separate points, indicated by arrows, from each of which two electrons diverge. There is a single parallel track due to an associated fast electron.

(b) Creation of six singly charged particles. Measurements of the scattering of the particles show that they are of high energy; the relatively large angular divergence, in comparison with the energy, indicates that the tracks are not due to electrons, and this is confirmed by their failure to 'multiply' as they passed through the stack. The event is attributed to the collision of an energetic neutron with a nucleus, and the creation of mesons or heavier particles without any visible evidence for nuclear disintegration.

(c) Pair production by a γ-ray in which two slow electrons appear to be emitted from the same centre. It appears reasonable to assume that they come from the same atom as that involved in the conversion of the γ-ray, possibly through ionisation and the Auger effect.

(d) A pair of electrons is created at a point, shown by the arrow, indistinguishable from the track of an incoming electron. The directions of motion are so nearly parallel that the tracks do not separate for several hundred microns. In individual events of this type, the origin of a pair, whether due to conversion o a γ-ray from *bremsstrahlung* or to trident production, cannot be stated with confidence.

Associated pairs and related phenomena

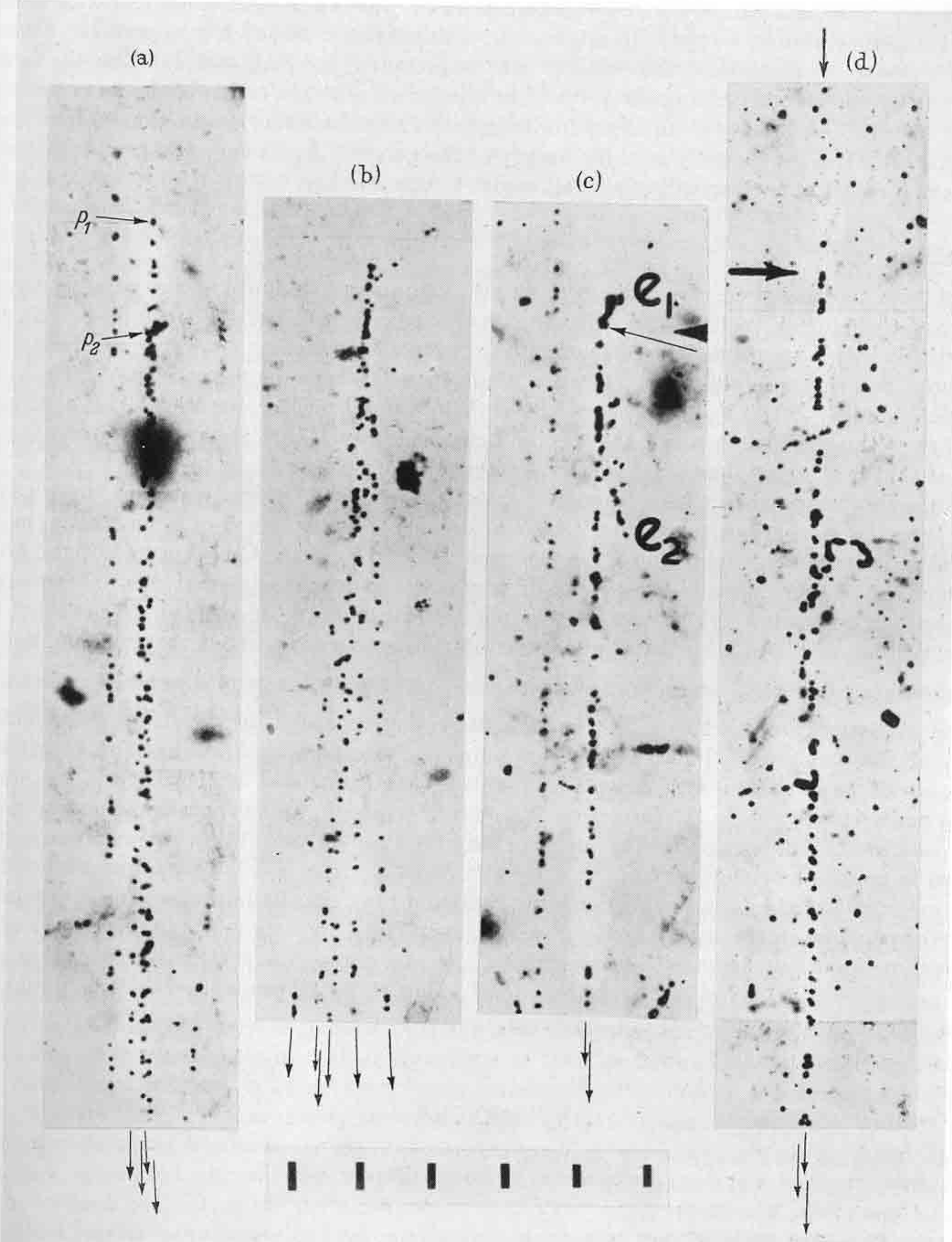
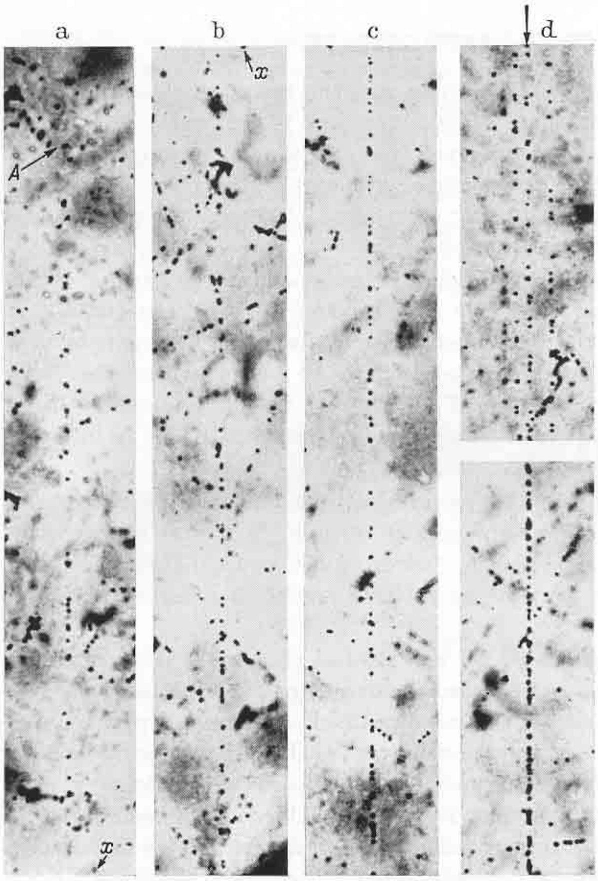


PLATE 6–4

Ilford G 5 emulsion.

Bristol (1952).

a b c d



e

PLATE 6–5

A γ-ray of energy $\sim 10^3$ BeV, which has entered the stack and its container apparently unaccompanied, materialises into a pair of electrons after passing 5 mm through the emulsion; the first grain in the resulting tracks is that at (A). The angle of divergence of the pair is so narrow, and the multiple scattering of the components is so small, that they appear not to separate for a path-length of more than 30 mm (see e).

The tracks in Plate 6–5, (a) and (b) are contiguous, corresponding grains being shown at (x); it may be seen by inspection that there is a marked increase in the grain-density of the track of the pair in passing from near the origin to the region illustrated in (c), a distance of 0·5 mm. Thus, in the strip (a), the number of grains is ~ 30, in (b) ~ 54 and in (c) ~ 68, the latter value corresponding to $2g_p$, where g_p is the plateau ionisation.

The above effect is due to the fact that the separation between the two electrons forming the pair, at points within a few hundred microns of their origin, is so small ($< 10^{-7}$ cm) that they form a close doublet, an electric dipole, and their specific ionisation is thereby considerably reduced.

In (d), 15 mm from the origin, a number of new pairs due to *bremsstrahlung* have appeared, but they are of much lower energy than the original pair which is indicated by an arrow. In (e), ~ 30 mm from the origin, the early *bremsstrahlung* pairs have diverged so that they are no longer in the field of view, and the original pair is now accompanied by a second pair of great energy, collinear with the first; it was formed either by the conversion of an energetic γ-ray due to *bremsstrahlung*, or by 'trident' production. The apparently single track now has a grain-density $\sim 4g_p$.

f
g
h

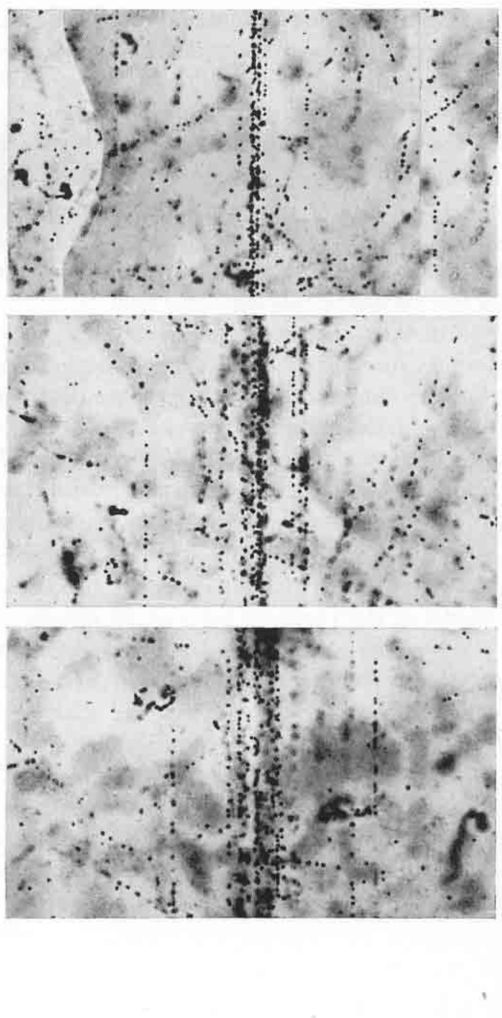


PLATE 6–6

At (f), 40 mm from the origin, further multiplication has taken place and several pairs are now apparent within the central core of the cascade. At (g), 64 mm from the origin, the central core is still well marked but the number of companions of lower energy has greatly increased. At (h), at 78 mm, the total number of energetic electrons in the cascade, with $E > 200$ MeV, is ~ 50.

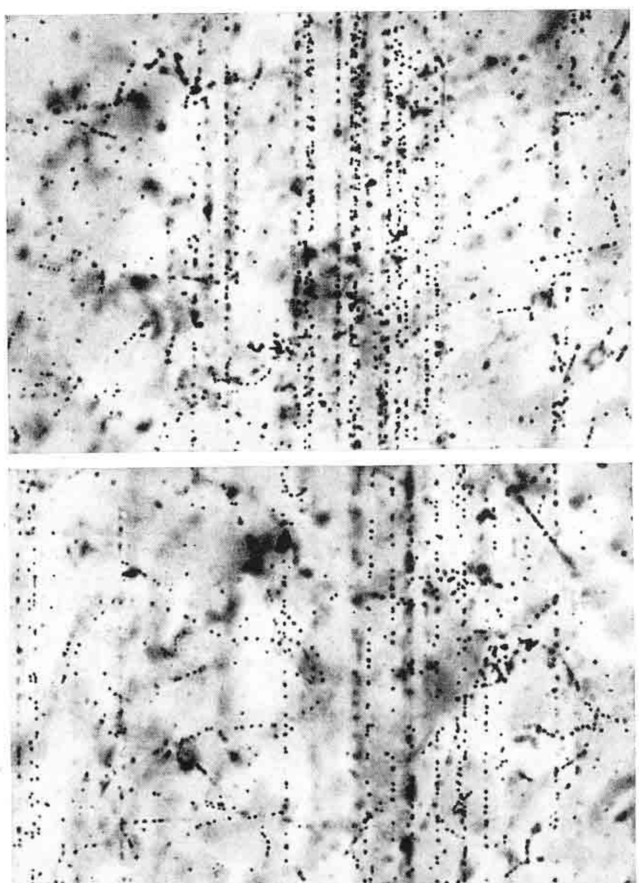
PLATE 6–7

At (i) and (j), 93 and 123 mm from the origin, respectively, considerable dispersion has taken place. At (i) the number of tracks has reached its maximum, and there are approximately 100 electrons with energy >200 MeV.

This cascade may profitably be compared with that shown in Plates 15–14, 15–16. At first sight, the early development of the present cascade suggests that the parent γ-ray was of comparable energy with that shown in Plate 15–14. Thus, it shows a continuous unresolved core for 30 mm, an effect comparable with those seen in the Plate 15–14. The later development of the cascade, however, clearly demonstrates that it is of lower energy, for the total number of tracks is much smaller at the maximum of development, which occurs after only about 10 cm (3 to 4 radiation lengths).

i

j



In general, it may be said that the persistence, for some centimetres, of an unresolved core does indicate that the relative scattering of the two component particles is very small; and, therefore, that their energy is at least of the order 300 BeV. On the other hand, separation of the two tracks may occur, as a result of large losses of energy, by either electron, in producing *bremsstrahlung*, at points near the origin, even although the energy of the initial pair is much greater than 10^3 BeV.

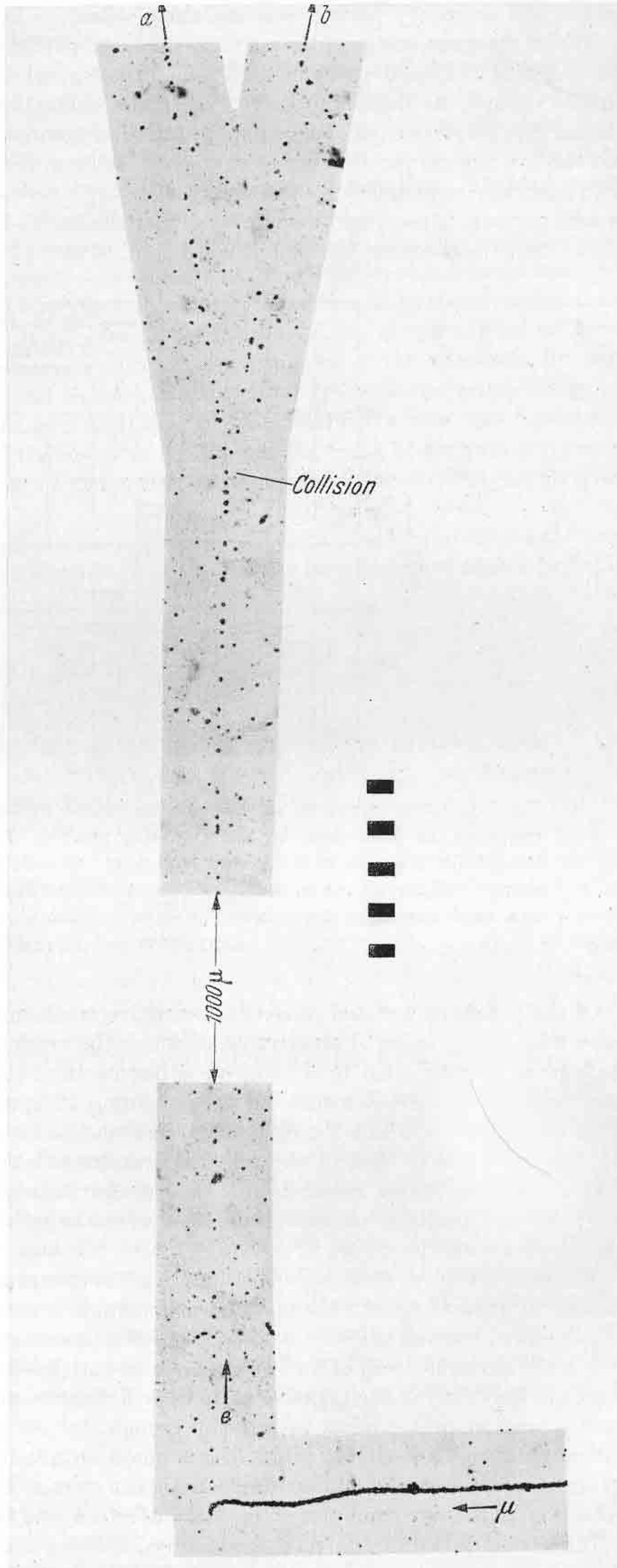
Cascades initiated by a single γ-ray, or a single electron, entering the emulsion would not be expected to show multi-core structure such as is displayed in Plate 15–17. A single core is indeed observed in the present event, although transient accompanying cores appear from time to time in the development of the cascade; but being of lower energy they quickly disperse. An example is shown at (f), Plate 6–6, where the right-hand member is due to a pair produced in the emulsion between the fields of view shown in (e) and (f).

PLATE 7–1

Collision with an electron of the charged particle formed by the β-decay of a μ-meson

The charged particle emitted in the β-decay of a μ-meson makes a collision with an electron in the emulsion. The tracks before and after the collision are long enough to allow the momenta of the particles to be determined. An analysis of the dynamics of the collision can therefore be made, assuming it to be elastic so that no appreciable energy is emitted in the form of photons. It may thus be shown that if track (a) is due to the recoiling electron, the mass of the particle producing the track (b) is $3 \pm 2\ m_e$; and if track (b) is due to an electron, the mass of the other particle is $1{\cdot}5 \pm 1{\cdot}0\ m_e$. This observation therefore proves that the particle produced in the decay of the μ-meson is of small rest-mass and gives very strong support for the view, commonly held, that it is an electron.

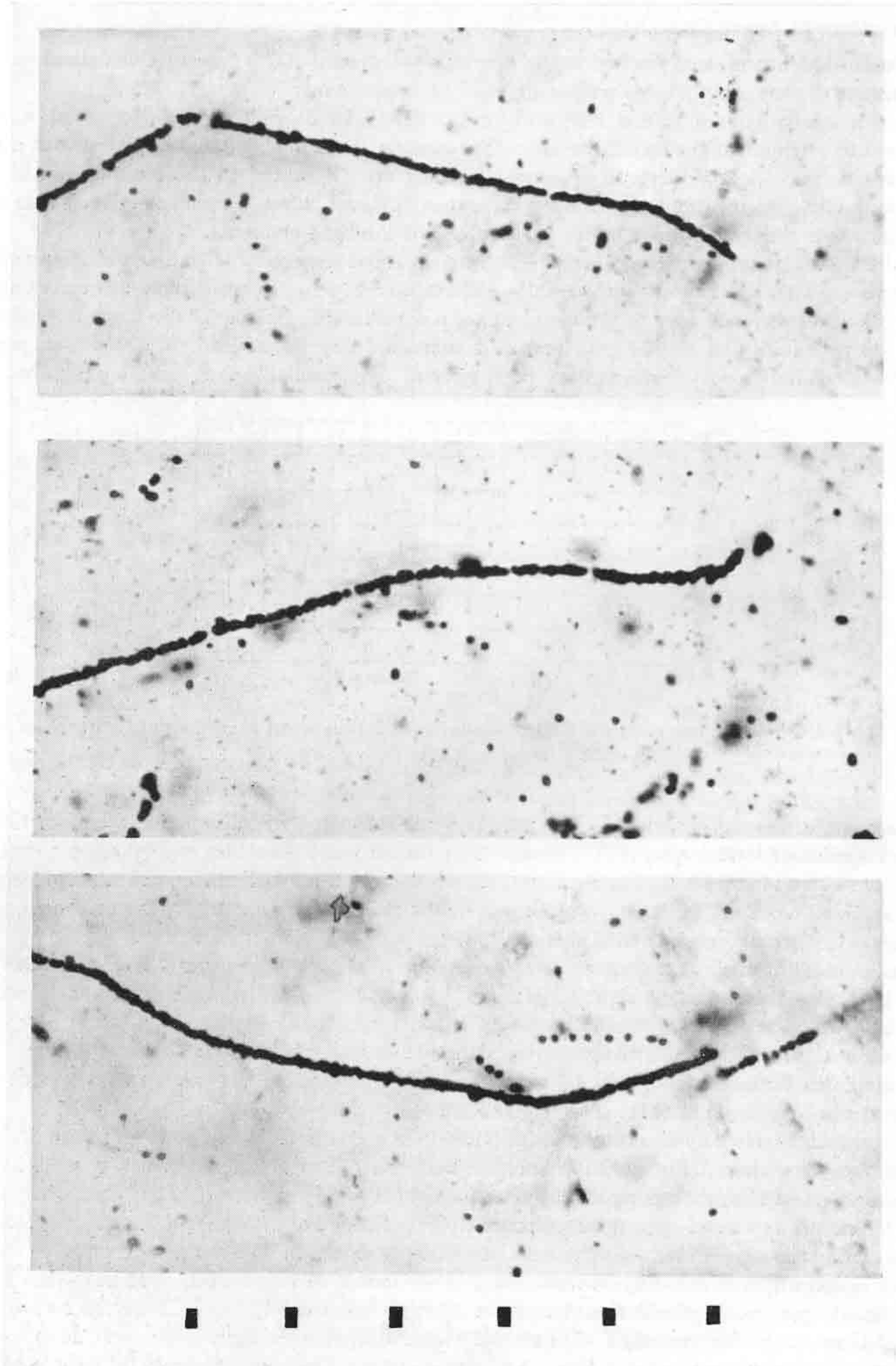
Although the collision is almost certainly due to two particles of equal mass, of which one was originally 'at rest', the subsequent directions of motion of the two particles are not at right angles, since the velocities are in the relativistic region.



Ilford G 5 emulsion.

CAMERINI and FOWLER.

Auger electrons produced by the capture of μ^--mesons by silver and bromine nuclei



(a)

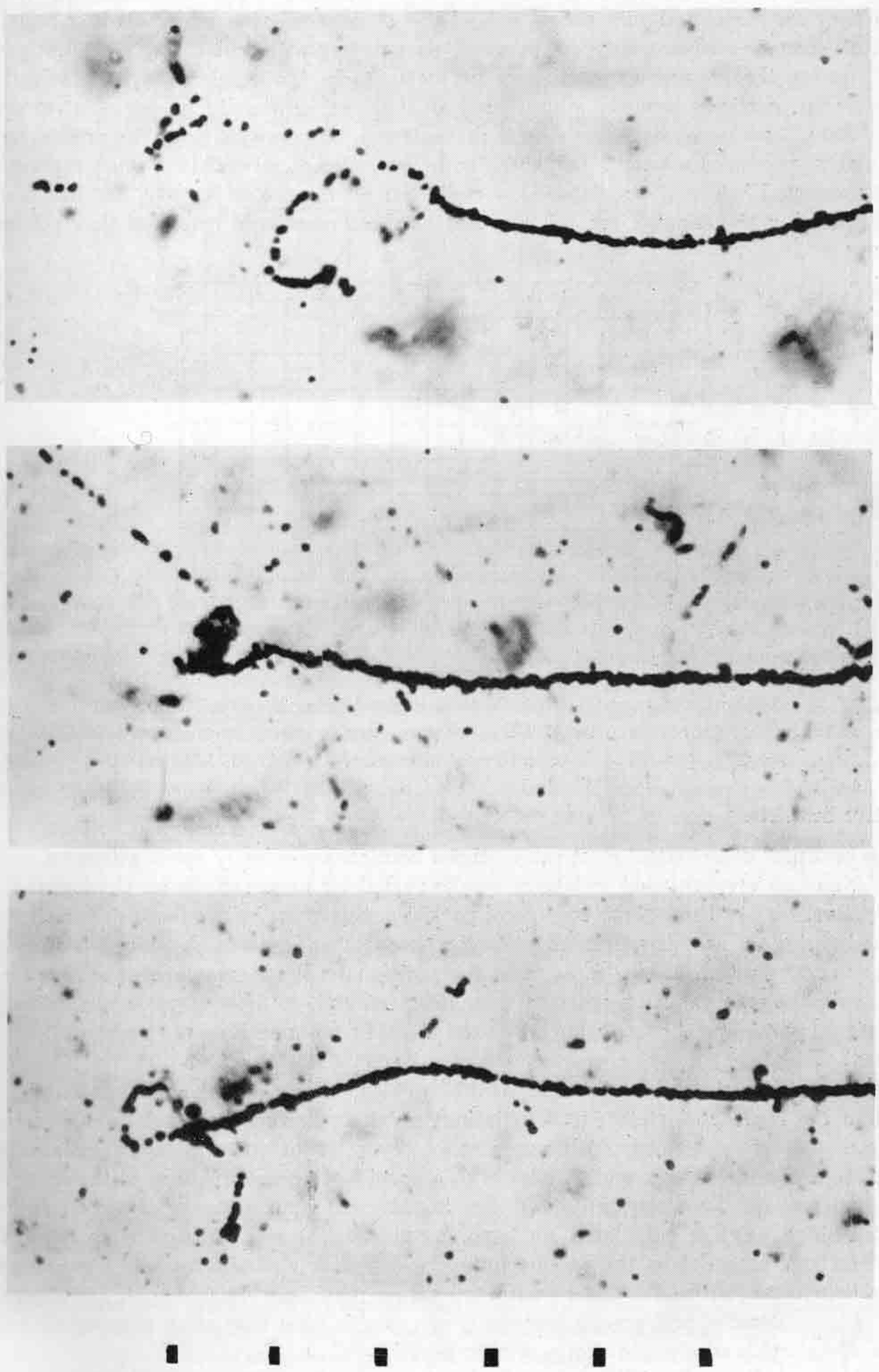
(b)

(c)

Ilford G 5 emulsion. **PLATE 7–2** Unpublished.

In Plates 7–2 and 7–3, (a) shows a characteristic example of the decay of a μ-meson, of unknown charge, in which no Auger electrons can be distinguished. In (b) the cluster of two or three grains near the end of the range of the μ-meson is probably due to an Auger electron. In (c), (d), (e) and (f), the tracks of associated slow electrons can be clearly distinguished. For an example of Auger electrons associated with the arrest in emulsion of other negative particles, see Plate 8–8.

Auger electrons produced by the capture of μ^--mesons by silver and bromine nuclei



(d)

(e)

(f)

PLATE 7–3

Since the mass of the meson appears in the above equation, the measurement of the quantum energy resulting from a known transition permits m_μ to be determined. Owing to the very small intensity of the emitted radiation available hitherto in such experiments, and the limited precision of the methods employing scintillation counters, the quantum energy of the radiation has been investigated by absorption measurements. Suppose, for example, that the frequency of the emitted radiation is a little greater than the value corresponding to the ordinary K-absorption edge of an element of atomic number Z_a: A thin film of this element will then produce a strong absorption; otherwise, if the frequency is less than the absorption limit, little reduction in intensity will occur. By finding the value of $Z_a + 1$ and Z_a, such that the frequency for the K-absorption edge of the first is greater, and of the second less, than that of the emitted radiation, limits to the frequency, ν, and thence to the mass of the mesons, m_μ can be deduced; see, for example, Fig. 7–7, p. 223).

In experiments of this type, observations with a particular element (Z) only determine upper and lower limits to the mass m_μ. The interval between the limits can be made very narrow, however, by experiments with a number of elements. By varying Z and Z_a and employing different quantum transitions, and after making a small correction for vacuum-polarisation, Koslov *et al.* (1954) have shown that m_μ lies between 208·9 and 206·9, in good agreement with the most accurate values determined by other methods, viz. $206{\cdot}9 \pm 0{\cdot}2\, m_e$.

c) End-point of the β-ray spectrum of μ^+-mesons

It has been remarked that the observed maximum energy of the electrons formed by the decay of μ^+-mesons, taken in conjunction with the mass m_μ and the conservation laws, proves that the two neutral particles accompanying the electron are of very small rest-mass. Alternatively if it is accepted that the two neutral particles are neutrinos of zero rest-mass, the observed end-point of the spectrum can be employed to deduce the mass of the positive μ-meson. The electron receives its maximum energy when the two neutrinos recoil together against it. The observed maximum energy, and thence the momentum of the electron, defines the momentum of the two neutrinos, and the total release of energy can be determined. The corresponding value of the mass of the positive μ-meson is $207 \pm 0{\cdot}8\, m_e$; Sagane *et al.* (1954).

The measurements by the different methods are in good accord, and show that the masses of the positive and negative μ-mesons are both equal, within narrow limits, to 207 m_e.

REFERENCES

Crowe; Nuovo Cim. **5**, 541 (1957).
Koslov, Fitch, and Rainwater; Phys. Rev. **95**, 291 (1954).
Lederman, Tinlot, and Booth; Phys. Rev. **81**, 281 (1951).
Sagane, Dudziak, and Vedder; Phys. Rev. **95**, 863 (1954).
Smith, Birnbaum, and Barkas; Phys. Rev. **91**, 765 (1953).

PLATE 7–4

▶

These events, due to capture of a negative μ-meson, were recorded in photographic plates manufactured underground at a depth of about 40 metres of water equivalent. They were left at this depth for several months, and then processed without being brought to the surface. In such plates, the number of μ-mesons arrested in the emulsion is very much greater than the number of π-mesons. Thus only five positive π-particles were observed, and identified by the characteristic π-μ decay, in comparison with 1014 μ-mesons. In addition, 30 examples were found of negative mesons which produced disintegrations. Assuming that the slow positive and negative π-mesons occur in approximately equal numbers, about 25 of the 30 negative mesons producing disintegrations must be attributed to negative μ-particles.

The above conclusion was confirmed by a comparison of the distribution of the number of heavily ionising particles emitted in these disintegrations with the quite different distribution produced by the nuclear interactions of artificially produced π^--mesons. The two examples represent typical disintegrations with one secondary charged particle, most of which are certainly due to the nuclear capture of μ-particles by the heavier elements in the emulsion.

Disintegrations following the nuclear capture of negative μ-mesons

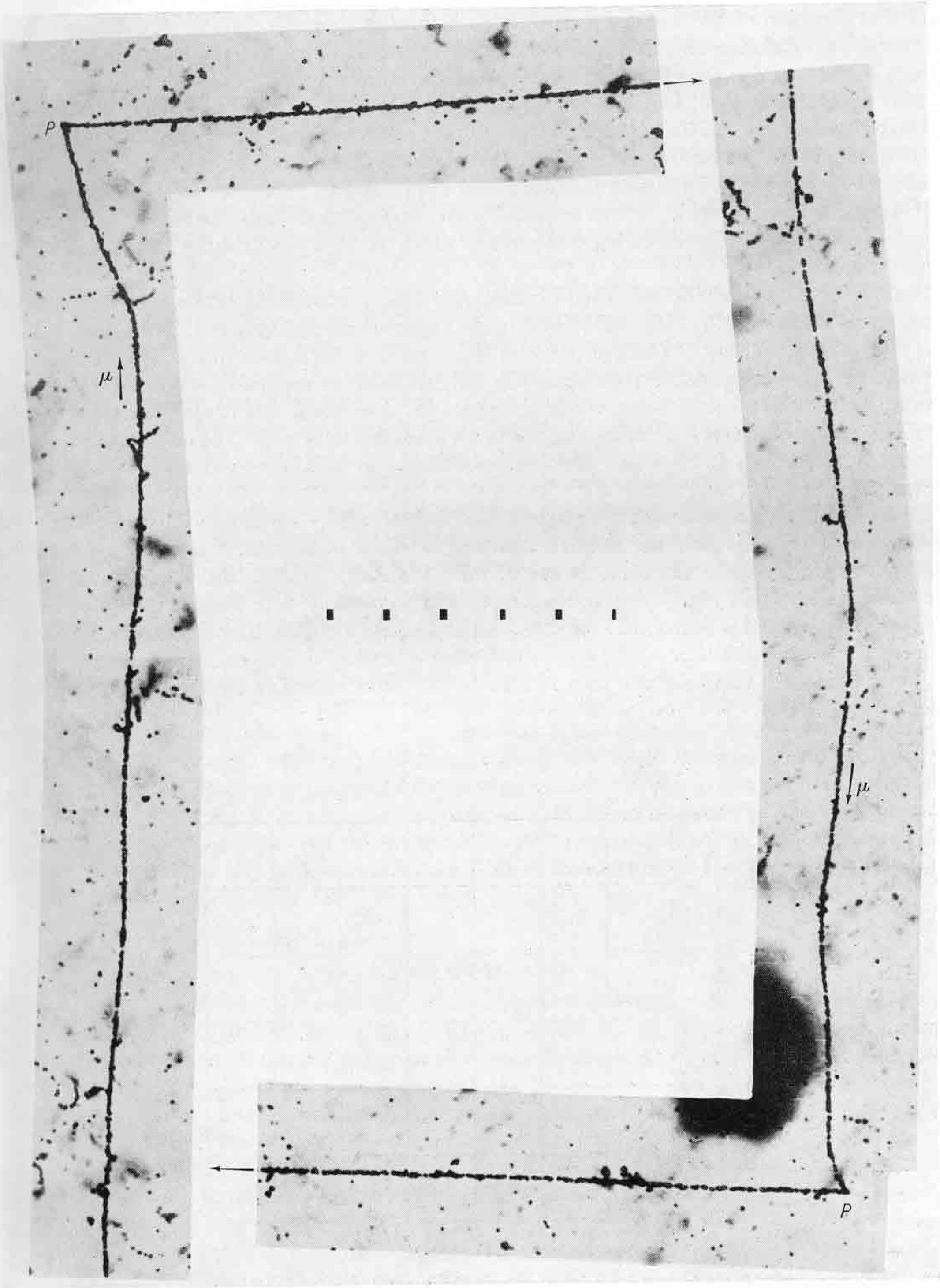


PLATE 7–4

Ilford G 5 emulsion. George and Evans (1951).

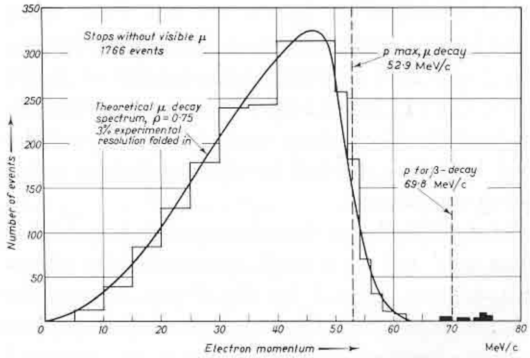


Fig. 7–14. Observations by IMPEDUGLIA *et al.* (1958) of the energy distribution of electrons produced by the decay of L-mesons arrested in a hydrogen bubble-chamber operated in a magnetic field. Artificial positive π-mesons were arrested in the chamber, and the energy distribution was determined for those mesons in which the track of the secondary μ-mesons could *not* be distinguished. The distribution includes many examples of ordinary $\pi \to \mu \to e$ decay, but in addition six examples, among about 65,000 tracks, where the decay electron has an energy equal to $\sim$70 MeV; these are shown 'blocked-in' in the histogram.

REFERENCES

CAMERINI, MUIRHEAD, POWELL and RITSON; Nature **162**, 433 (1948).
FAZZINI, FIDECARO, MERRISON, PAUL and TOLLESTRUP; Phys. Rev. Letters **1**, 247 (1958).
GEORGE and EVANS; Proc. Phys. Soc. A **63**, 1248 (1950); **64**, 193 (1951); **68**, 829 (1955).
IMPEDUGLIA, PLANO, PRODELL, SAMIOS, SCHWARTZ and STEINBERGER; Phys. Rev. Letters **1**, 249 (1958).
MORINAGA and FRY; Nuovo Cim. **10**, 308 (1953).
SHERMAN, HECKMAN, and BARKAS; Phys. Rev. **85**, 771 (1952).

PLATE 7–5. Direct production of an L-meson which undergoes β-decay ▸

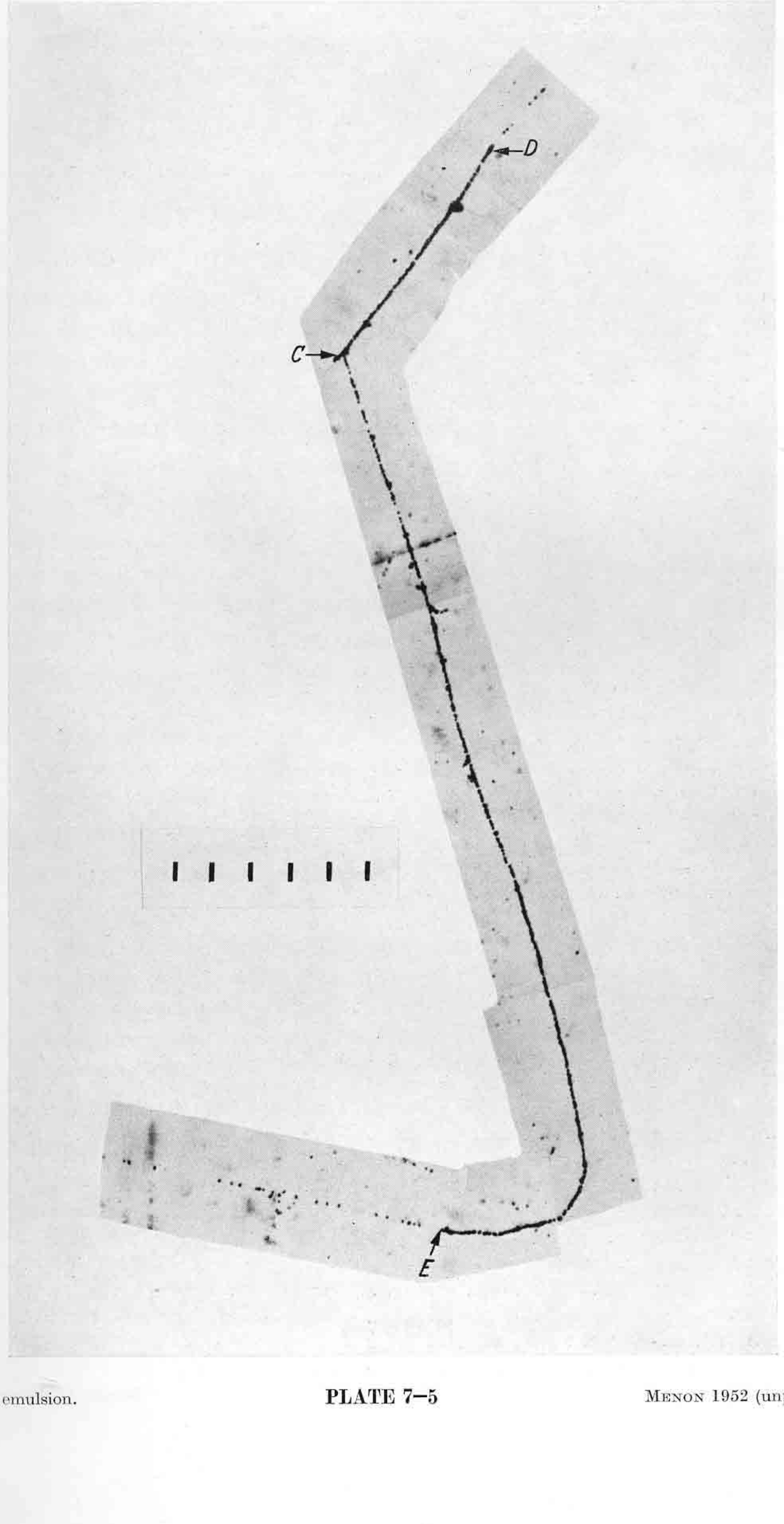
In this event, an L-meson of range $\sim 270\,\mu$ appears to emerge from an interaction occurring at the point C, and to decay into an electron at the point E. The track CD ends in the glass of the plates at D, and the thin track near D is due to an unrelated particle. The track CD is inclined at a considerable angle to the surface of the emulsion, and its ionisation is somewhat less than that indicated by the apparent grain-density. Although the direction of motion of the track CD cannot be established with confidence, the spur track C, and the observed range of the μ-meson CE, make it very difficult to attribute the event to the decay of a π-meson at the point C. The spur at C also makes it difficult to assume that the event corresponds to the nuclear collision of a μ-meson at that point. The simplest explanation is that the L-meson was ejected from a nuclear interaction.

PLATE 7–6. Evidence for the β-decay of the π-meson (see p. 236)

This event appears to represent the direct production of an L-meson in a nuclear disintegration. Starting at a point indistinguishable from the centre of disintegration at A, the meson reaches the end of its range at B, and appears to decay into an electron. The track is reproduced in two parts which overlap at x. The particle is certainly an L-meson, and its range is about 550 μ; it might therefore be attributed to a μ-meson formed by the decay of a π-meson the latter being ejected from the disintegration at A with very small range, $\sim 1\ \mu$. The disintegration was, however, due to silver or bromine, and from such nuclei, positive π-mesons are very rarely emitted with a range less than several hundred microns, because of electrostatic repulsion. Presumably a π-meson could appear with very low energy by penetrating the Coulomb barrier, but such a process appears to be very improbable.

Since there is no track of a π-meson approaching the centre of the disintegration, the event cannot be attributed to the chance juxtaposition of two events; viz. the disintegration at A, and an associated π-μ decay. It is therefore reasonable to assume, either, that very rarely μ-mesons can be directly produced in high energy nuclear collisions, or that the event is an early example of the β-decay of a π-meson which went unrecognised.

Direct production of an *L*-meson which undergoes β-decay



Ilford G 5 emulsion.

PLATE 7–5

MENON 1952 (unpublished).

Evidence for the β-decay of the π-meson

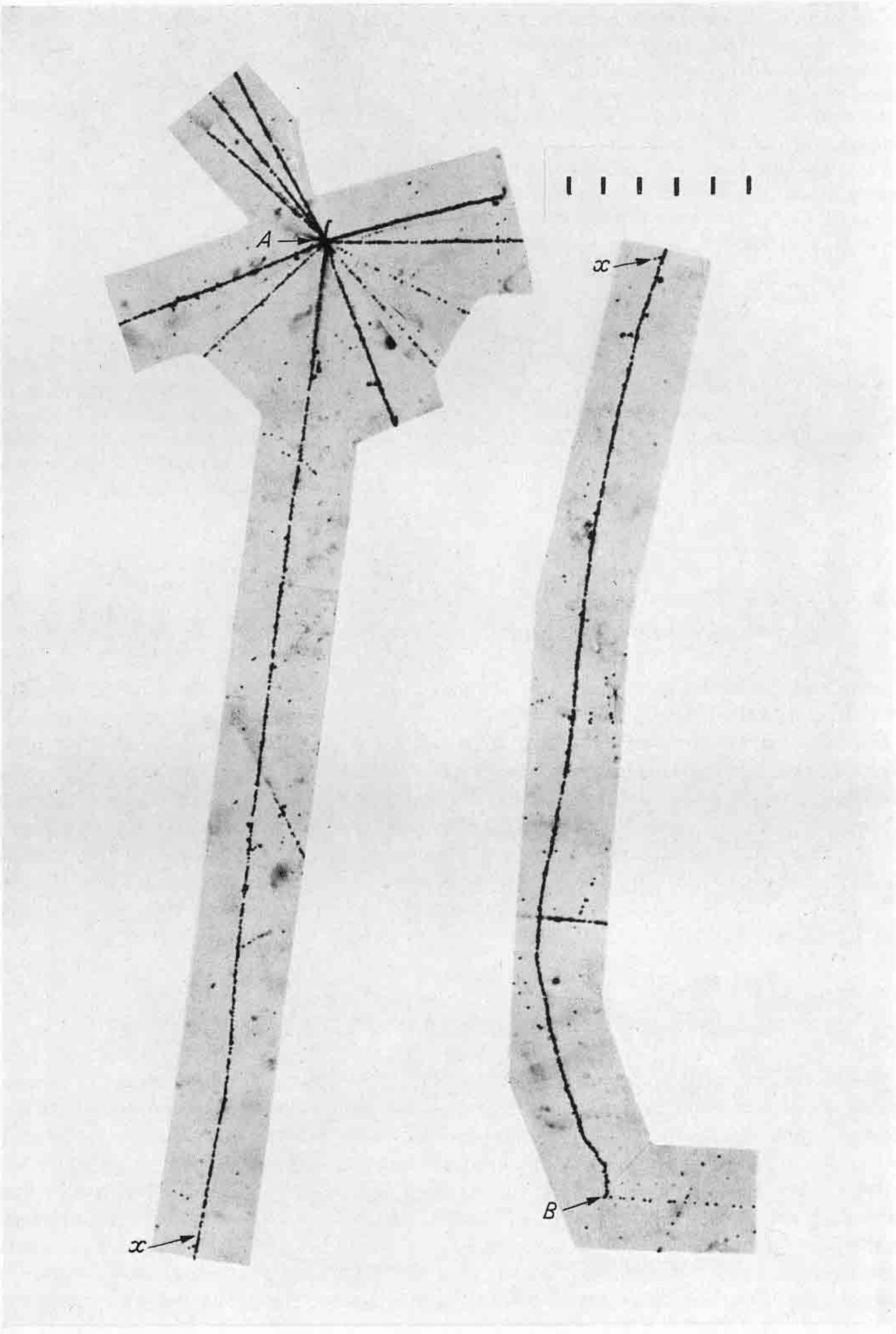


PLATE 7–6

Ilford G 5 emulsion.

MENON 1952 (unpublished).

First observation of a disintegration by a negative meson

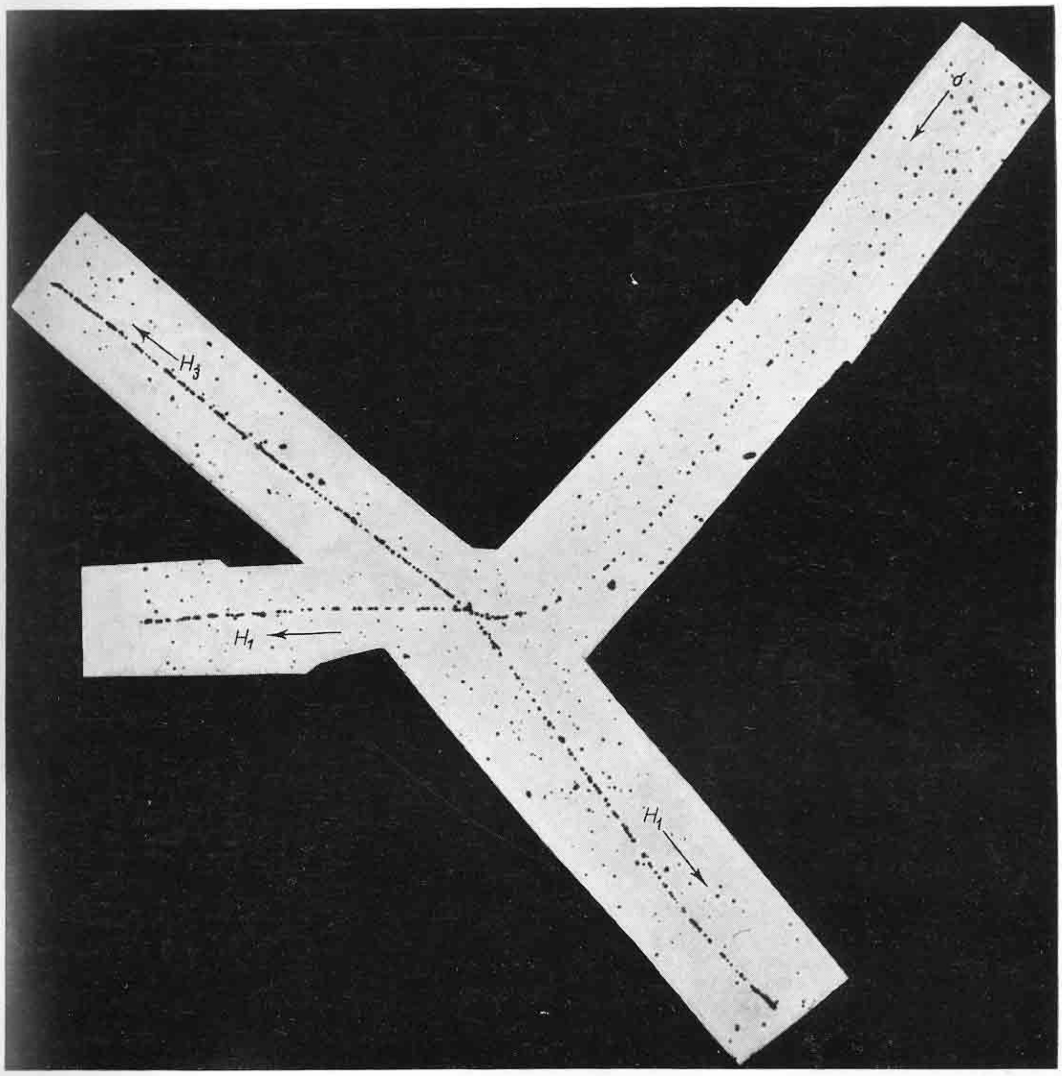


PLATE 8–1

Ilford B1 emulsion. PERKINS (1947).

The change in grain-density as the meson approaches the end of its range, and the increased scattering, are clearly displayed. These features provided the decisive evidence that the particle had indeed approached the centre of disintegration and had not receded from it; and that the particle, which must have produced the disintegration, was moving very slowly when it interacted with the nucleus. It followed that the energy of disintegration was provided by the disappearance of rest-mass of the incident particle, a process which had not previously been observed.

The good discrimination of this early emulsion is well displayed, the differences in the rate of change of grain-density along the tracks of the meson and of the secondary hydrogen nuclei being clearly apparent. The attribution of one of the tracks to a triton depends upon a comparison of the rates of change of grain-density along the tracks.

Disintegration produced by a negative π-meson

One of the first photographs of the disintegration produced by a meson; see track 'π'. Three secondary charged particles, one of short range, are emitted. The scattering and variation of grain-density along the track of the meson are well displayed, and provide decisive evidence for its direction of motion and low mass. The characteristics of the track strongly suggested that the particle produced a disintegration when moving at low or zero velocity; it was therefore attributed to a negative meson. At the time of the observation, the π-mesons had not been discovered and the event was tentatively interpreted as due to the capture of a μ-meson by a silver or bromine nucleus. Following the discovery of π-mesons, an ambiguity arose as to the nature of the mesons producing disintegrations at the ends of their range. They might have been attributed either to π^--mesons, or to negative μ-mesons captured by heavy elements in the emulsion. They were therefore referred to as σ-mesons, although it was believed that most of them were negative π-particles. This view was subsequently confirmed.

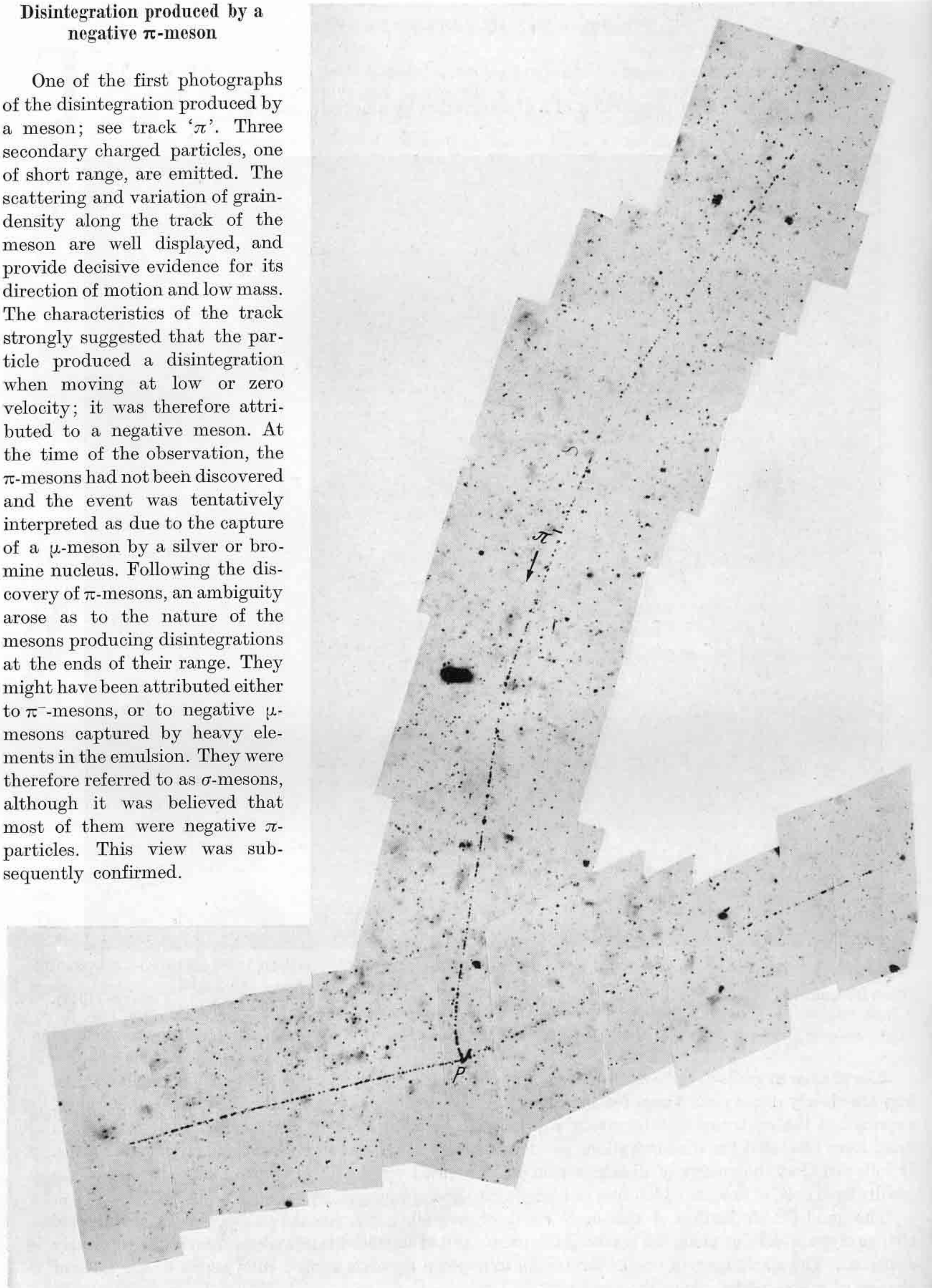


PLATE 8–2

Ilford C2 emulsion.

Occhialini and Powell; Nature **159**, 186 (19

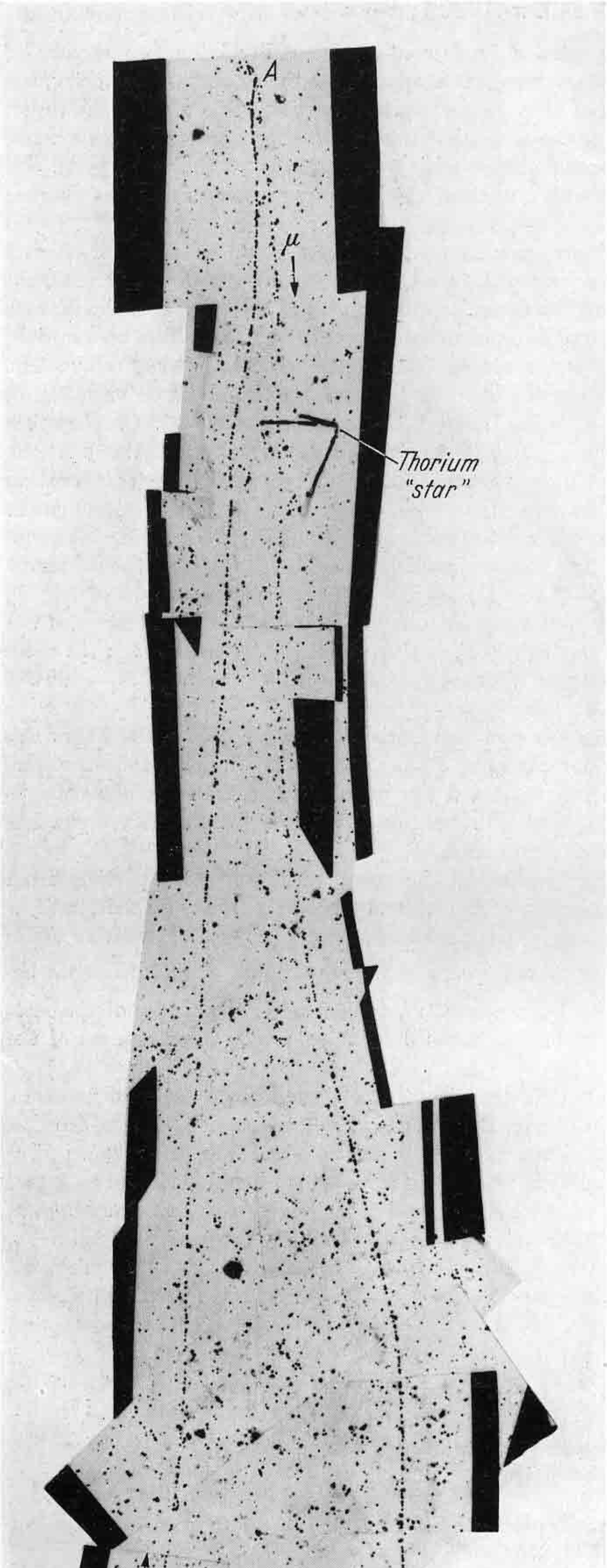


PLATE 8–3

First observations of the decay of a π-meson

The parent particle π reached the end of its range at the point A and the secondary μ-meson was ejected nearly backwards along the line of motion of the π-meson. The variation in the scattering and grain- density along the tracks made it evident that both particles were much less massive than a proton, and allowed their directions of motion to be established without ambiguity. A comparison of the grain density in the two tracks showed that, at the point where the μ-meson left the emulsion, its residual range was small. The black edges were retained to show the extent of the individual photographs of which the mosaic is constructed.

LATTES, MUIRHEAD, OCCHIALINI and POWELL; Nature **159**, 694 (1947).

Ilford C2 emulsion.

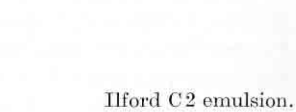
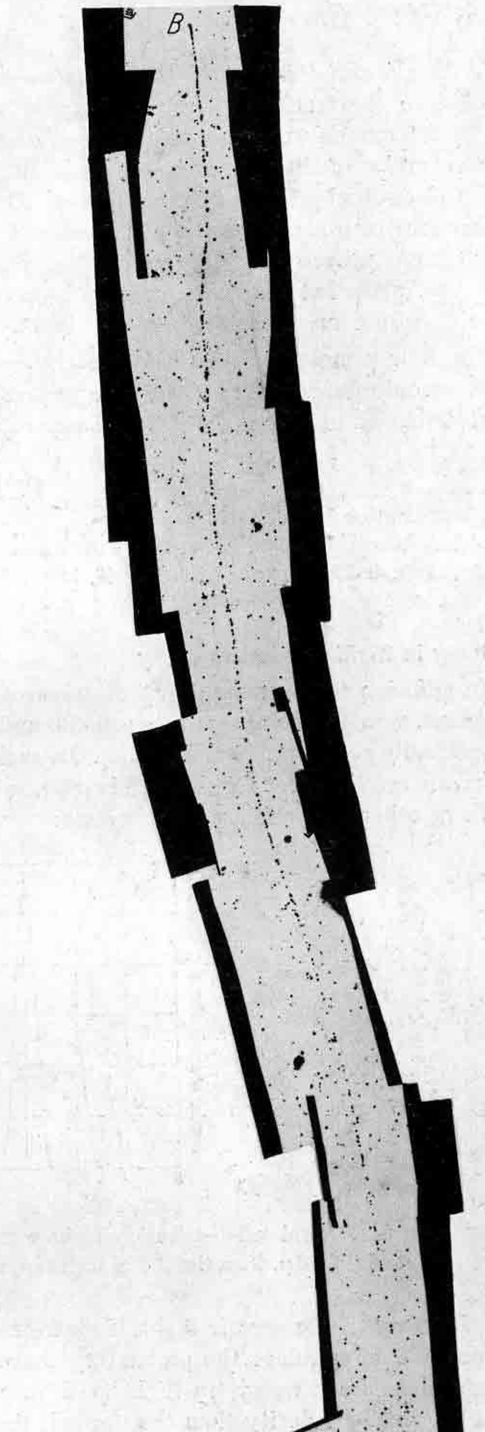


PLATE 8–4

First observations of the decay of a π-meson

This second example of the decay of a π-meson was found shortly after the first. Although the track of the parent particle is short, it gives unambiguous evidence for the direction of motion of the particle and for its low mass. The secondary μ-meson came to rest in the emulsion, its range being 610 μ.

Lattes, Muirhead, Occhialini and Powell; Nature **159**, 694 (1947).



Ilford C2 emulsion.

50μ

PLATE 8–5

Kodak NT4 emulsion. POWELL; Repts. Prog. Phys. **13**, 384 (1950).

With the development of the electron-sensitive emulsions (BERRIMAN 1948), it became possible to observe the tracks of electrons moving at relativistic velocities. Among the effects observed shortly afterwards were examples of the β-decay of the μ-meson (BROWN *et al.* 1949). Plate 8–5 shows four examples of the process $\pi \rightarrow \mu \rightarrow \beta$. In favourable cases, it was possible to measure the energy of the electrons by the scattering method (DAVIES *et al.* 1949), and the values obtained were similar to those for cosmic-ray mesons as measured in Wilson chambers operated in a magnetic field. These observations proved that the penetrating particles in the cosmic radiation are identical with the μ-mesons, and that they are commonly produced by the decay 'in flight' of fast positive and negative π-mesons. The latter result directly from nuclear collisions occurring in the atmosphere.

The four μ-mesons shown have nearly equal ranges; the variations in range due to 'straggling' are commonly much greater than is suggested by these photographs; see Fig. 3–7, p. 80, which shows the distribution in range of $\sim$600 μ-mesons formed by the decay of π-mesons at rest.

REFERENCES

BERRIMAN; Nature **162**, 992 (1948).
BROWN, CAMERINI, FOWLER, MUIRHEAD, POWELL and RITSON; Nature **163**, 47, 82 (1949).
DAVIES, LOCK and MUIRHEAD; Phil. Mag **40**, 1250 (1949).

a) Decay in flight; Radiative decay

In addition to the main group of μ-mesons, produced by the decay of π-mesons in photographic emulsions, which have ranges between 480 and 700 microns, there are a few of exceptionally long, or exceptionally short, range (FRY 1952). In such events, the departures of the individual values from the mean are too great for them to be attributed to straggling, and they are believed to be produced in one or other of the following processes:

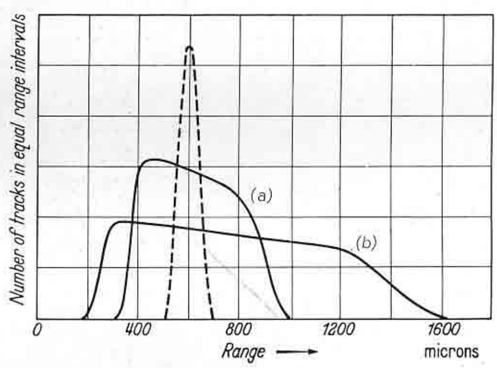
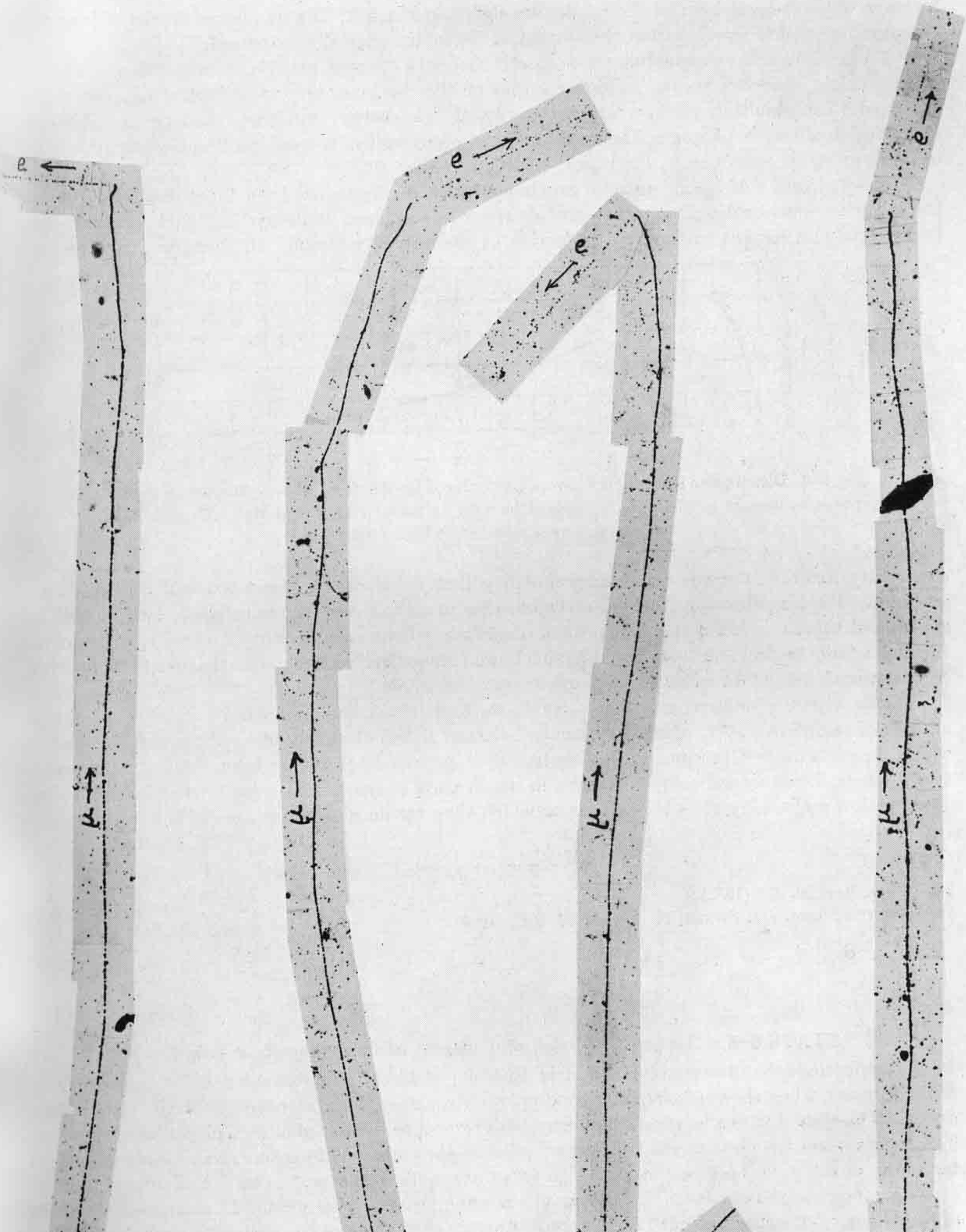


Fig. 8–1. Calculated distribution in range of μ-mesons produced by π-mesons decaying (a), 1 μ, and (b), 10 μ, from the end of their range. The dotted curve corresponds to decay at rest.

(i) Decay of the π-meson in flight. Knowing the mean lifetime of the π-meson—about $2{\cdot}5 \times 10^{-8}$ sec—it is possible to calculate the probability that a π-particle will decay before being brought to rest in the emulsion. Such decay 'in flight' will, in general, cause the resulting μ-meson to appear with a greater or smaller velocity than the normal; the actual value will depend on the direction of ejection of the μ-meson with respect to the line of motion of the parent π-particle at the instant of decay. The order of magnitude of the effect to be expected from such a process is illustrated in Fig. 8–1 which shows the calculated distribution in range of the μ-mesons, assuming that the π-mesons all decay in the emulsion when their residual range is 1 μ, curve (a), or 10 μ, curve (b). The μ-mesons have been assumed to be emitted isotropically in a co-ordinate system moving with the π-meson at the moment of transformation.

Similar estimates, for all values of the residual velocity of the parent π-mesons at the moment of decay, allow the expected range distribution of the μ-mesons to be computed from the known decay

Successive decay of the π-meson, $\pi \to \mu \to \beta$



constant of the π-particles, and the results are shown in Fig. 8–2. The number of tracks of long range actually observed is equal, within the statistical fluctuations, to that expected.

(ii) According to the classical electro-magnetic theory, a charged particle radiates when accelerated. Corresponding therefore to the sudden ejection of the μ-meson, electro-magnetic radiation will be produced. The resulting photons are commonly of low energy, and they then produce no easily recognisable effects in photographic emulsions; but occasionally they are sufficiently energetic to lead to an appreciable reduction in the energy of the μ-meson.

μ-mesons from this second process can generally be distinguished from those due to the first by the following considerations. A μ-meson of short range, produced by decay 'in flight', must be ejected backwards with respect to the line of motion of the parent π-meson. If, therefore, it is projected

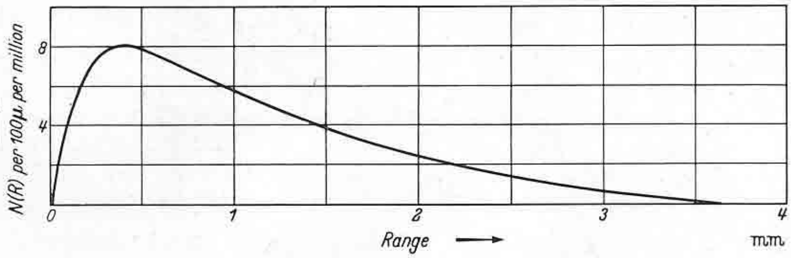


Fig. 8–2. Distribution in energy of μ-mesons produced by the decay of a homogeneous group of π-mesons moving in photographic emulsions with an initial energy of 1 MeV. The lifetime of the π-mesons is assumed to be $2{\cdot}5 \times 10^{-8}$ sec.

apparently forward, there is a strong probability that the decay is associated with the ejection of a photon. The identification is not unambiguous because the π-meson was certainly moving with low speed, and there is a finite probability that immediately before the instant of decay it was scattered through a large angle. The decay could have followed immediately after the scattering of the π-particle, so that the change of direction was not apparent in its track.

Among 11,800 π^+-mesons arrested in emulsion, Fry (1953) found six examples of decay in flight and six of radiative decay. Fry, Schneps and Swami (1955) observed an example of $\pi \rightarrow \mu$ decay in which, in addition to the μ-meson, an electron pair appeared to diverge from the point of arrest of the π-meson. Such second-order processes, in which pairs of electrons appear in the place of a γ-ray, occur with a probability of $\sim 1\%$ of that to which they are an alternative; see p. 264.

REFERENCES

Fry; Phys. Rev. **86**, 418 (1952).
Fry, Schneps, Snow and Swami; Phys. Rev. **99**, 1055 (1955).

PLATE 8–6. Apparent emission of μ-mesons of short range in π → μ decay ▶

These photographs illustrate the technical difficulty of identifying examples of the radiative decay of the π-meson when the tracks are steeply dipping. Accepting the evidence *prima facie*, the μ-mesons appear to be ejected with a forward component with respect to the line of motion of the parent π-meson. The events could then be regarded as accompanied by the emission of photons, and not attributable to the decay of the parent particle in flight. In these examples, however, the tracks attributed to π-mesons dip steeply in the emulsion, and this results in an increase in their width. In particular, the tracks of the alleged π-mesons, near 'P', are markedly thicker than those of the μ-mesons at the end of their range. Such effects can sometimes be produced by the scattering of a μ-meson through a large angle, so that, although most of its trajectory is steeply inclined, it approaches the end of its range in a direction nearly parallel to the plane of the emulsion; this is a possible explanation of the events illustrated but unambiguous examples of radiative decay do occur. The photographs emphasise the importance of making full allowance for the effect of dip on the appearance of tracks, especially in the analysis of rare events.

Apparent emission of μ-mesons of short range in $\pi \rightarrow \mu$ decay

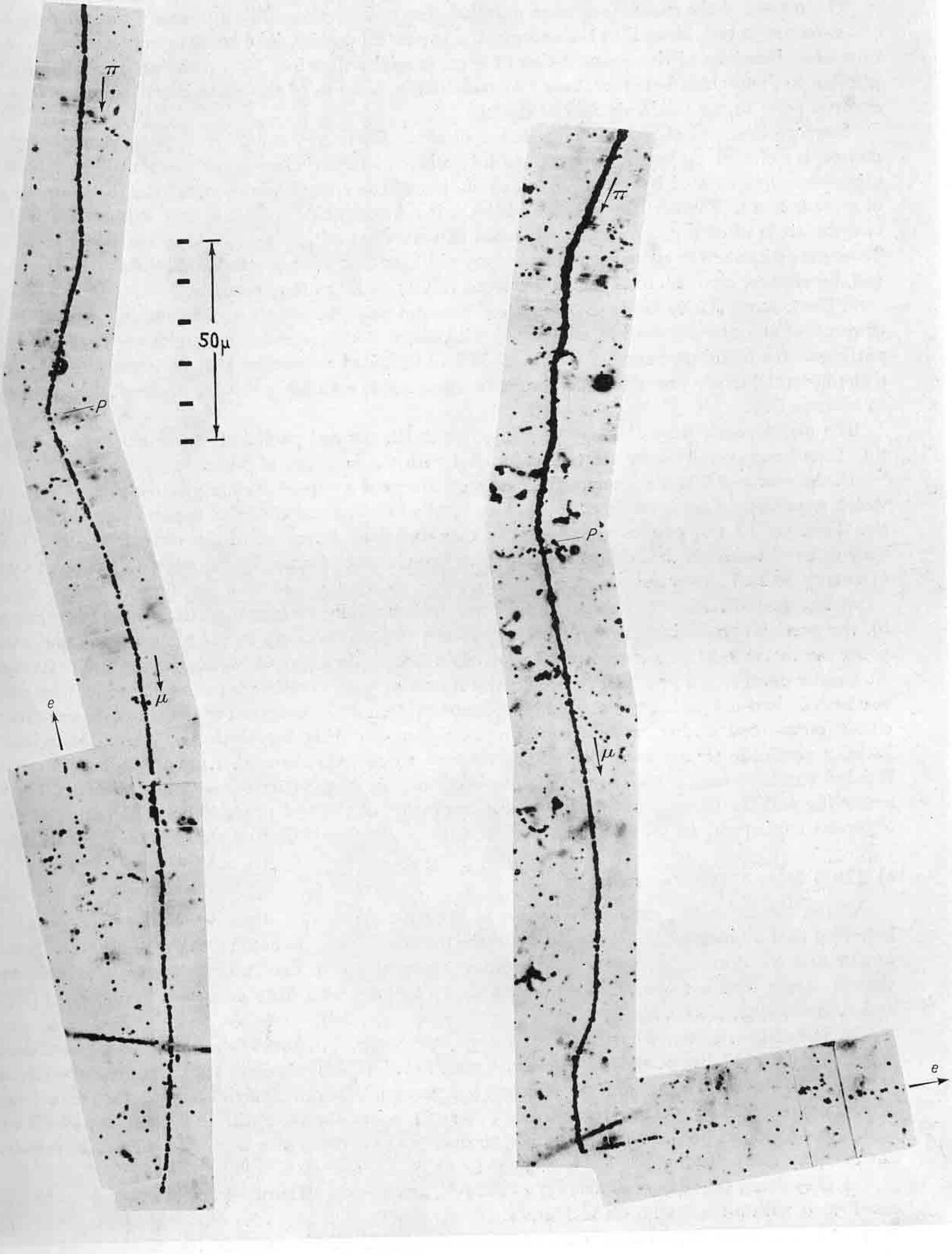


PLATE 8–6

Ilford G5 emulsion.

Pair of charged particles apparently associated with the decay of a π-meson

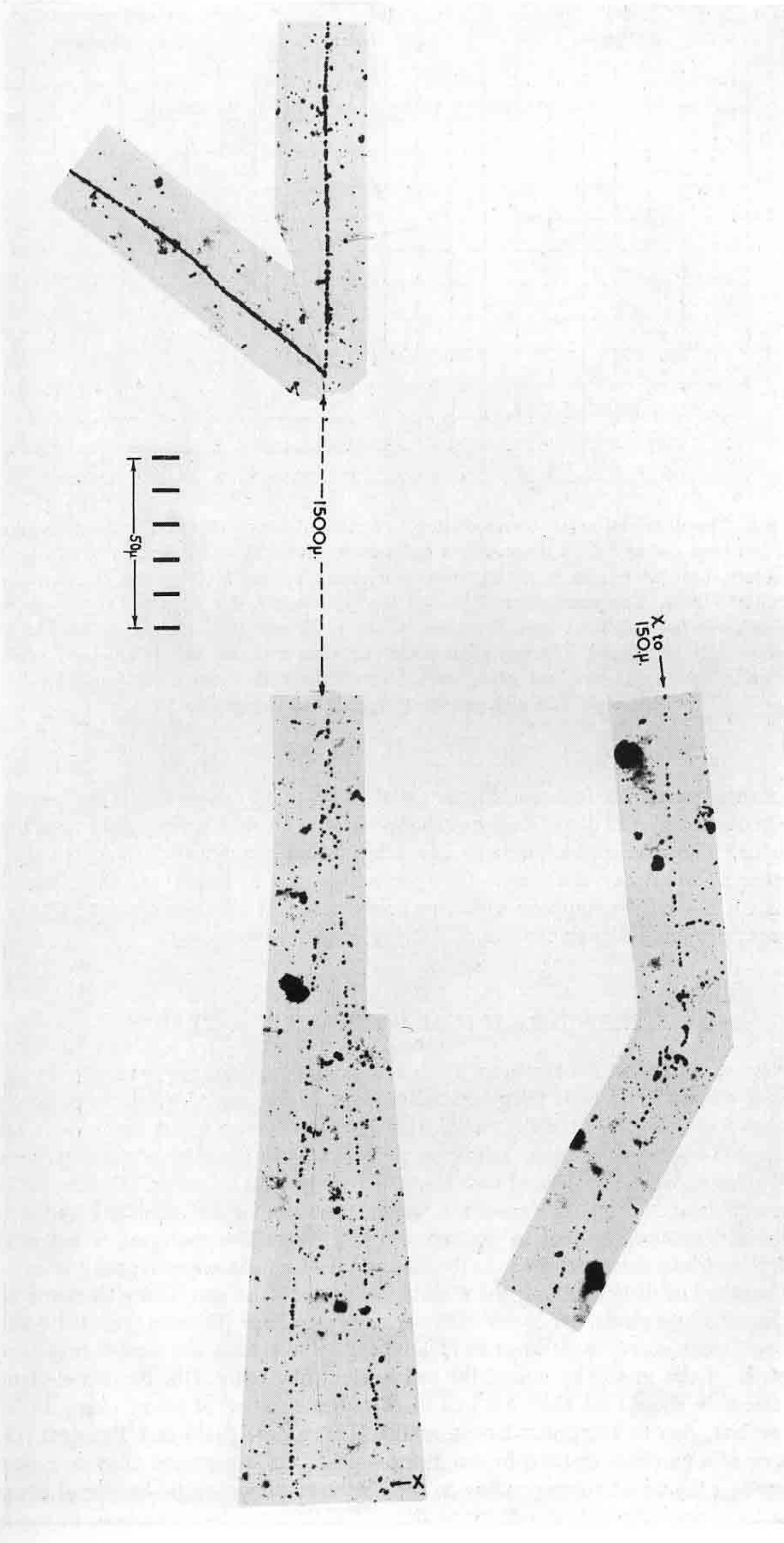


PLATE 8–7

Ilford G5 emulsion.

O'Ceallaigh; Phil. Mag. **41**, 838 (1950).

Disintegration of silver or bromine by capture of a π⁻-meson

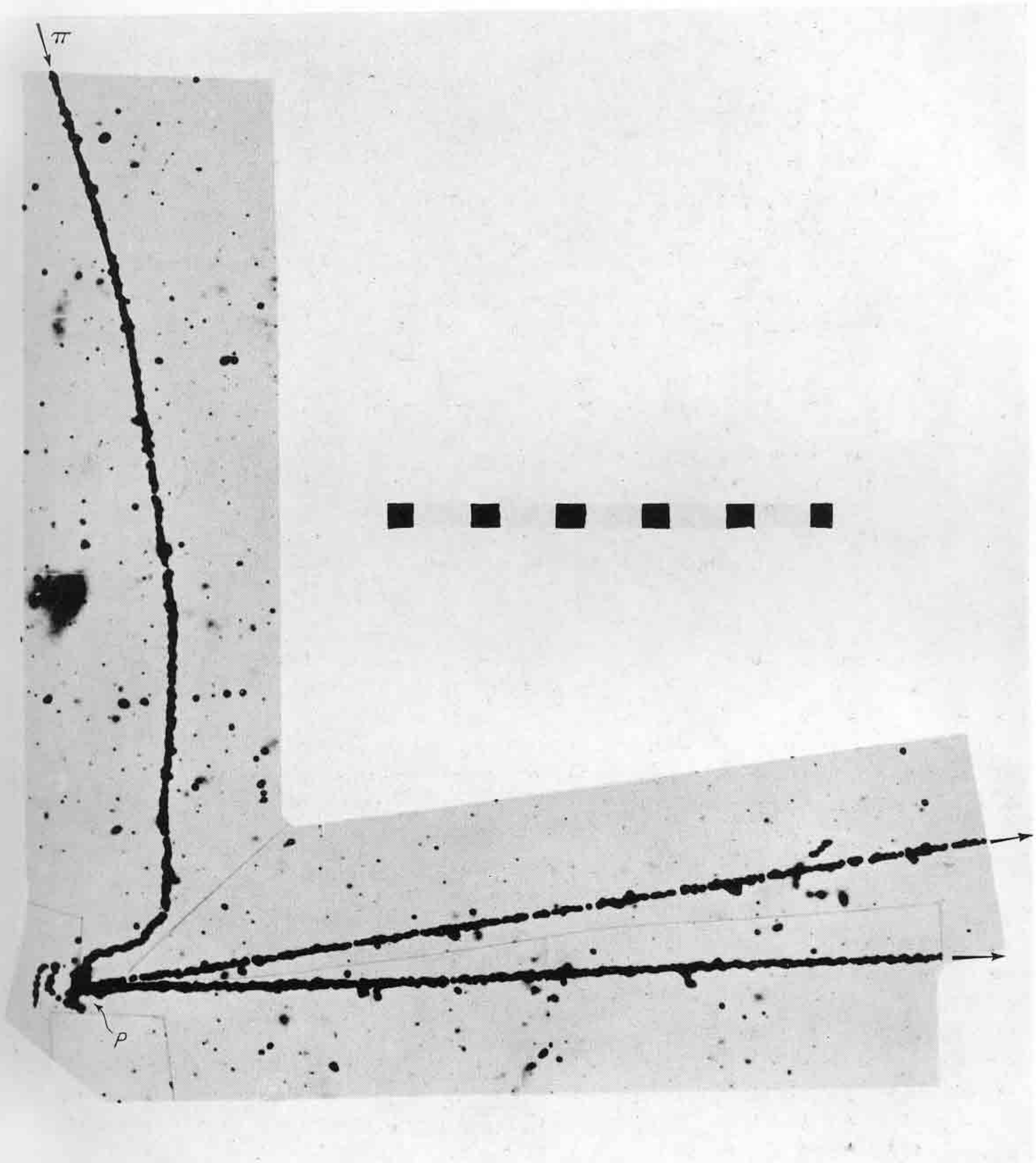


PLATE 8–8

Ilford G5 emulsion.

MENON, MUIRHEAD, and ROCHAT; Phil. Mag. **41**, 583 (1950).

The presence of the tracks of one or more Auger electrons provides very strong evidence that the meson was captured by a heavy element, probably silver or bromine.

Disintegration of light elements by the capture of negative π-mesons

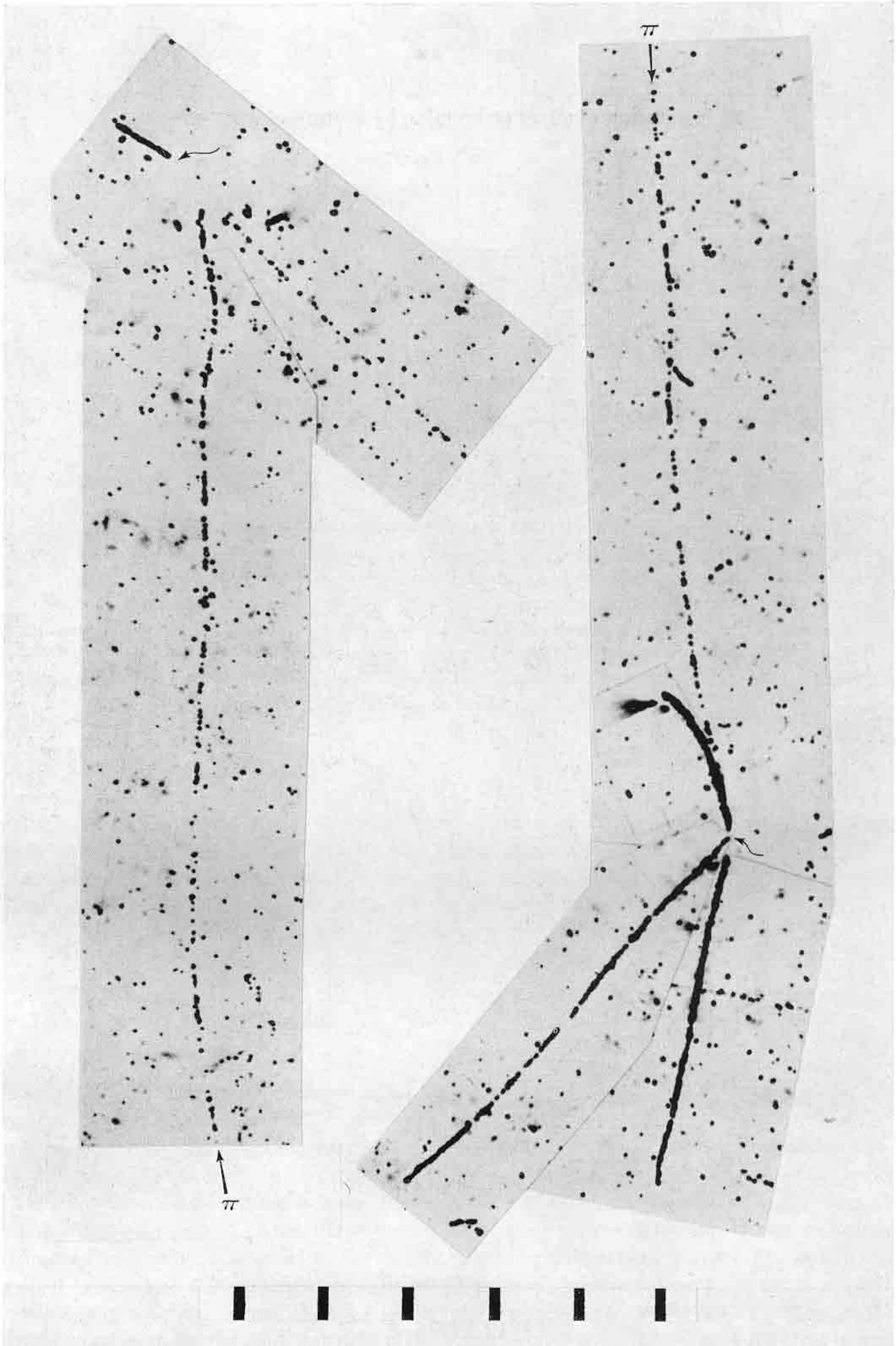


PLATE 8–9

Ilford C2 emulsion.

MENON, MUIRHEAD and ROCHAT; Phil. Mag. **41**, 583 (1950).

The π-mesons reach the end of their range in a layer of gelatine, 5 μ thick, 'sandwiched' between layers of C2 emulsion. Since they occur in the insensitive gelatine, the origins of the disintegrations are not recorded, and they must be attributed to nuclear capture by carbon, oxygen or nitrogen.

Disintegration of carbon by capture of π^--meson

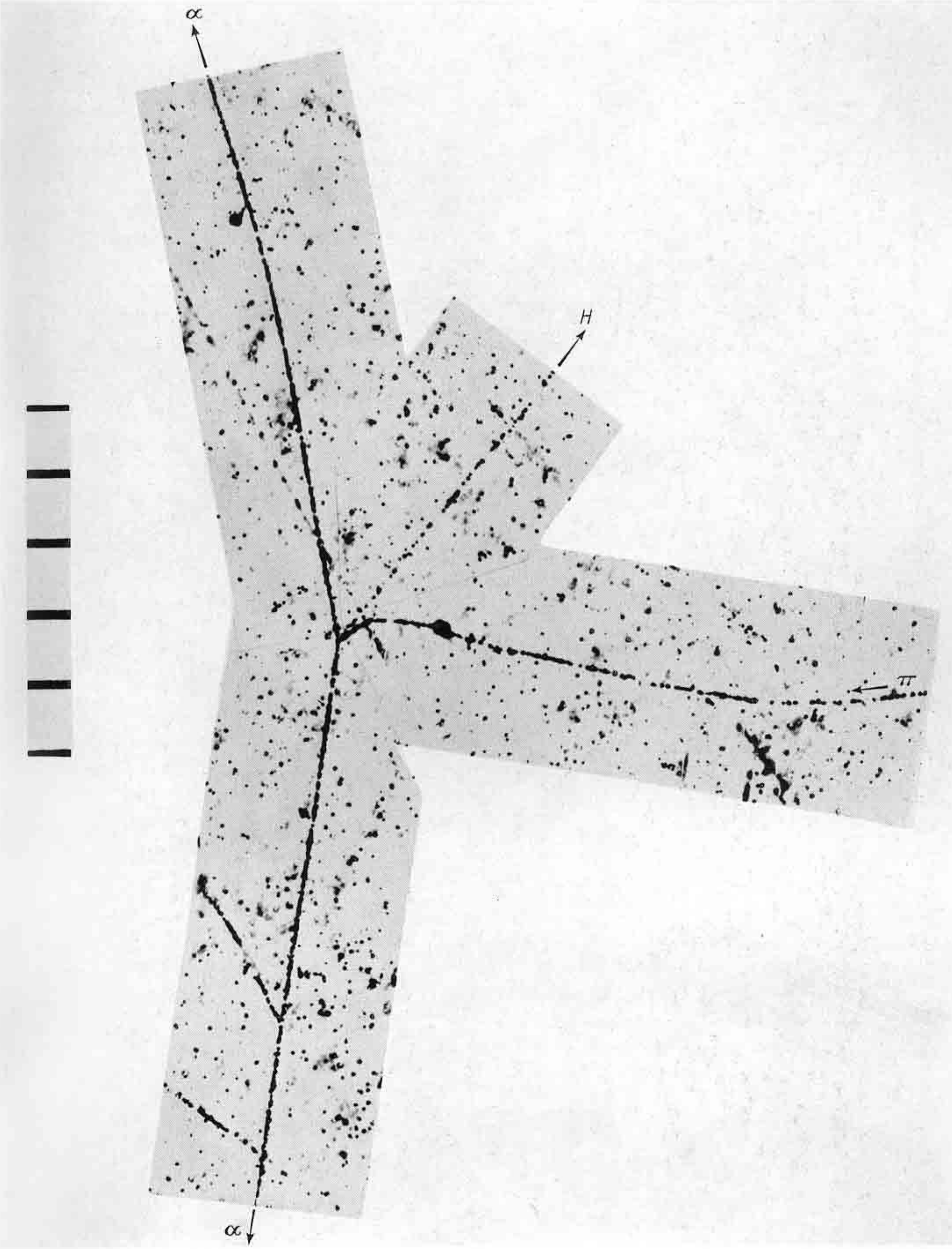


PLATE 8–10

Ilford C2 emulsion.

MENON, MUIRHEAD and ROCHAT; Phil. Mag. **41**, 583 (1950).

The identification depends upon the following considerations: The two heavily ionising particles are α-particles, each of energy about 25 MeV, which can be readily distinguished from hydrogen nuclei in C2 emulsions. The third track is due to a hydrogen nucleus. The event certainly represents the disintegration of a light nucleus, and the conservation of charge requires it to have been carbon. The evidence is insufficient to decide whether the emitted hydrogen nucleus was a proton or a deuteron; the number of ejected neutrons is correspondingly uncertain. Reactions of this type can frequently be distinguished, but this event is exceptional in that the two α-particles are of relatively great energy, and are emitted in nearly opposite directions.

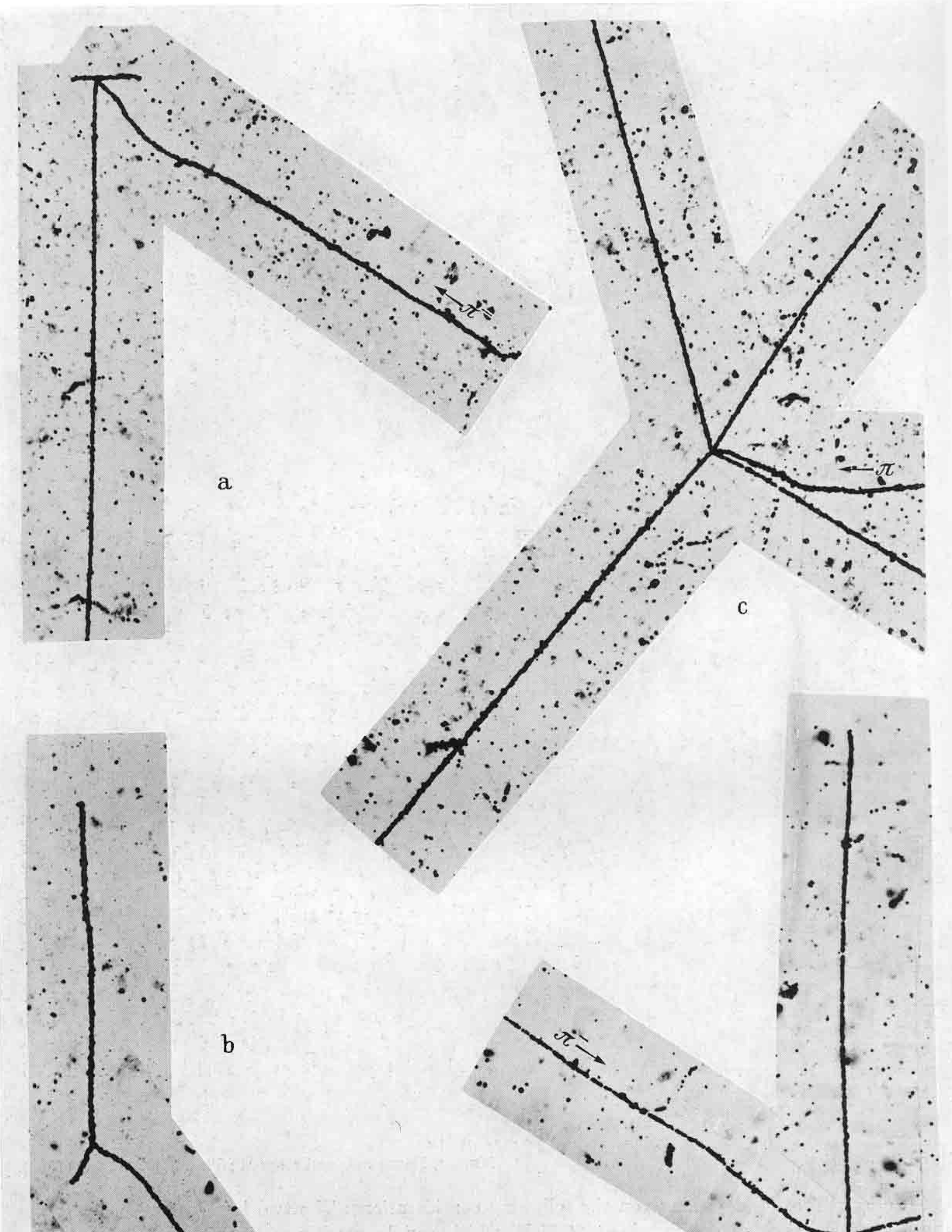


PLATE 8–11

Ilford G5 emulsion. (5 cm = 50 μ) Powell; Rep. Prog. Phys. **13**, 384 (1950).

Photographs of the disintegration of light elements carbon, nitrogen or oxygen by the nuclear capture of π^--particles.

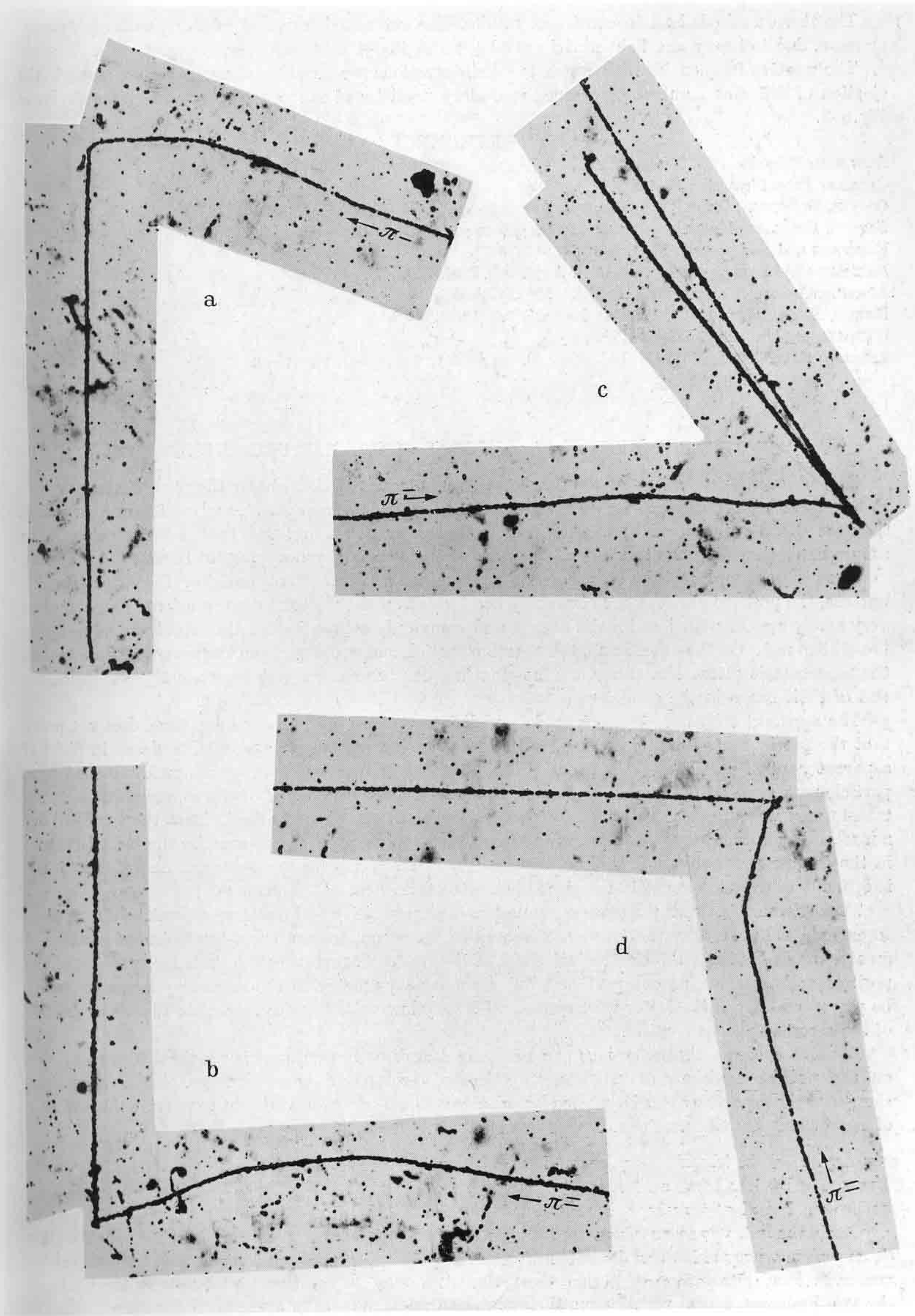


PLATE 8–12

Ilford G5 emulsion. (4 cm = 50 μ) POWELL; Rep. Prog. Phys. **13**, 384 (1950).

Photographs of the disintegration of heavy elements, silver or bromine by the nuclear capture of π^--particles.

The three methods lead to consistent results. The estimated numbers of stars, with one 'prong' or more, due to heavy and light nuclei are 52 ± 4 and $48 \pm 4\%$ respectively.

The relative frequencies with which the disintegrations produced by slow π^--mesons result in the ejection of different numbers of charged secondary particles of range greater than 5 μ are shown in Fig. 8–3.

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4. PRODUCTION OF π-MESONS IN NUCLEAR COLLISIONS

The observed production of slow π-mesons in nuclear disintegrations (LATTES, OCCHIALINI and POWELL 1947) gave support for the view that the particles interact strongly with nucleons, that they are directly produced in nuclear interactions of great energy, and that, when moving in the atmosphere, they give rise to the weakly interacting μ-mesons by decaying 'in flight'.

The early examples of the creation of π-mesons were all of negative particles. In escaping from a nucleus, the positive particles are commonly accelerated by the electrostatic repulsion. They therefore very rarely appear with low kinetic energy and commonly escape from a thin emulsion before being brought to rest. On the other hand, the negative particles must escape from the parent nucleus against the electrostatic attraction. They are therefore frequently emitted with low velocity, and reach the end of their range in the emulsion.

The apparent origin of π-mesons in nuclear disintegrations, whilst very suggestive, does not prove that the particles are directly created. They might be attributed, for example, to decay in flight of a parent neutral particle of mean lifetime less than 10^{-14} sec. The average distance travelled by a particle with such a lifetime, before decaying, is so short that the track of the π-meson into which it transformed would appear to originate from the centre of the disintegration. That the π-mesons are not secondary to such an unstable *neutral* parent, is strongly suggested however, by the great difference in the frequencies with which slow positive and negative π-mesons are observed, an effect which it is difficult to explain except in terms of the electrostatic field of the nucleus.

The difference between the observed numbers of slow positive and negative π-particles also appears to exclude the possibility that they are created as the secondaries of short-lived *charged* particles of greater mass; for if so, the electrostatic field of the nucleus could affect the relative numbers of the positive and negative parent particles, but a similar asymmetry in the secondary π-mesons would be preserved only if the latter were ejected with very low velocity with respect to the centre of mass of the assumed parent particle.

Decisive evidence that π-mesons can be singly and directly produced is provided by experiments on the nuclear collisions of artificially accelerated protons of known energy. Such experiments show that the π-particles can be created by protons with an energy insufficient to provide the rest-mass of appreciably heavier particles.

PLATE 8–13 ▸

One of the first two observations of the creation of a π-meson. The π-meson leaves the disintegration at A, and reaches the end of its range at B, where it is captured by a light element and disintegrates it. The distribution of grains along the track may be compared with that in the tracks of the two hydrogen nuclei which leave the disintegration B moving in an upward direction.

Creation of a negative π-meson in a nuclear disintegration

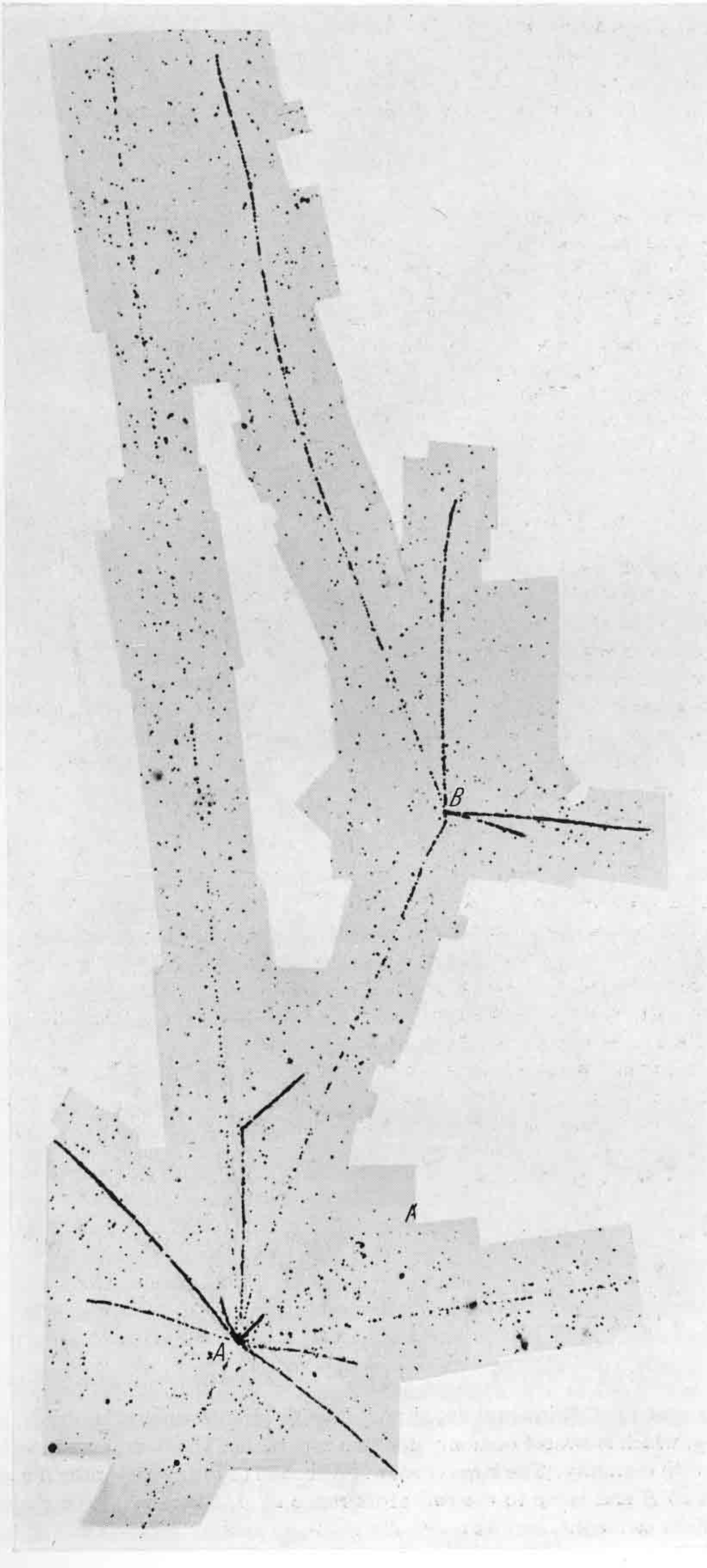

PLATE 8–13

Ilford C2 emulsion. (4 cm = 50 μ) Lattes, Occhialini and Powell; Nature **160**, 486 (1947).

Creation of a π^--particle in a nuclear disintegration

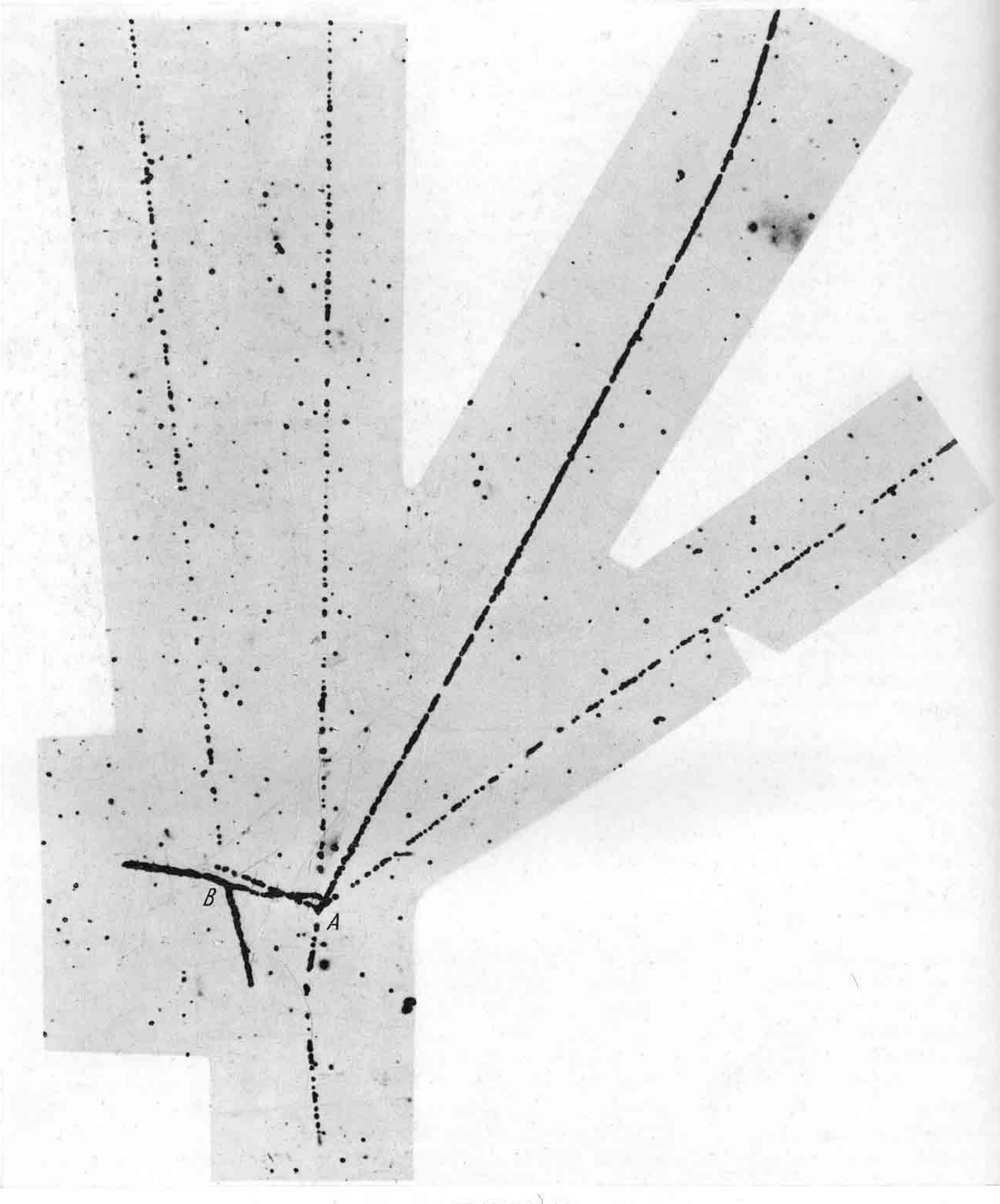

PLATE 8–14

Ilford C2 emulsion. (5 cm = 50 μ) OCCHIALINI and POWELL; Nature **162**, 168 (1948).

There are two centres of disintegration, A and B, with an interconnecting track, scattered and of high grain-density, which is almost certainly due to a π-particle. The direction of motion of the meson cannot be stated with certainty. The large change in direction of the particle near A suggests, however, that it originated at B and came to the end of its range at A, where it caused the disintegration of the nucleus of a light element.

Early observation of the production of a π-meson in electron-sensitive emulsions

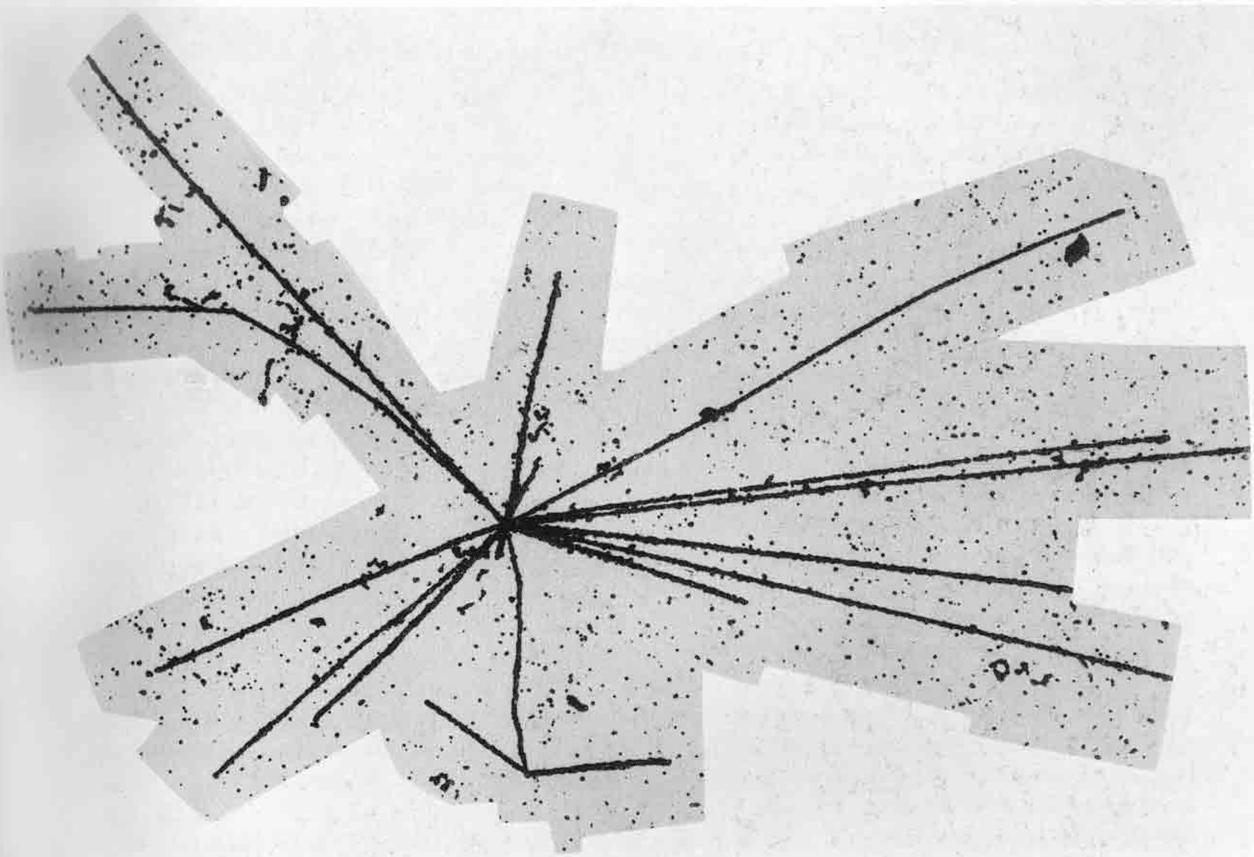

PLATE 8–15

Kodak NT4 emulsion. POWELL; 'Cosmic Radiation', p. 89 (Butterworth, London 1949).

The event is unusual in that all the associated charged particles are heavily ionising. In the case of tracks of short range, it is sometimes difficult to distinguish those due to ejected π^--mesons from those of hyperons and hyperfragments. The mesons are, however, commonly more scattered; see, for example, tracks of π-mesons, protons and other light nuclei, at the end of the range, shown in Sect. 5. More favourable conditions of observation are provided by emulsions of greater discriminating power, such as Ilford K5; see, for example, p. 389.

a) Decay of π^--mesons in flight

Since the π^--meson takes a finite time to be reduced to low velocities when arrested in emulsion, and to cascade down to orbits of low quantum number round the nucleus of the atom by which it is captured, there is a finite probability that it will decay before interacting with a nucleus. That the probability of decay is small, even in hydrogen, has been shown by SARGENT *et al.* (1953); they arrested π^--mesons in hydrogen gas at a pressure of 19 atmospheres, and showed that few of the mesons decayed. For details of the interaction of π^-mesons with hydrogen; see p. 266 and p. 270.

The decay of π^--mesons in emulsion has been reported by FRY and WHITE who found the frequency of the process to be about one in 1000 of the entering π^--mesons. The resulting μ^--mesons are not homogeneous in velocity, the distribution in range extending from 370 to 780 μ. Such a spread could result from decay of the π^--meson while in motion in an orbit round a nucleus; see FRY *et al.* (1954).

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Ejection of a positive π-meson from a nuclear disintegration

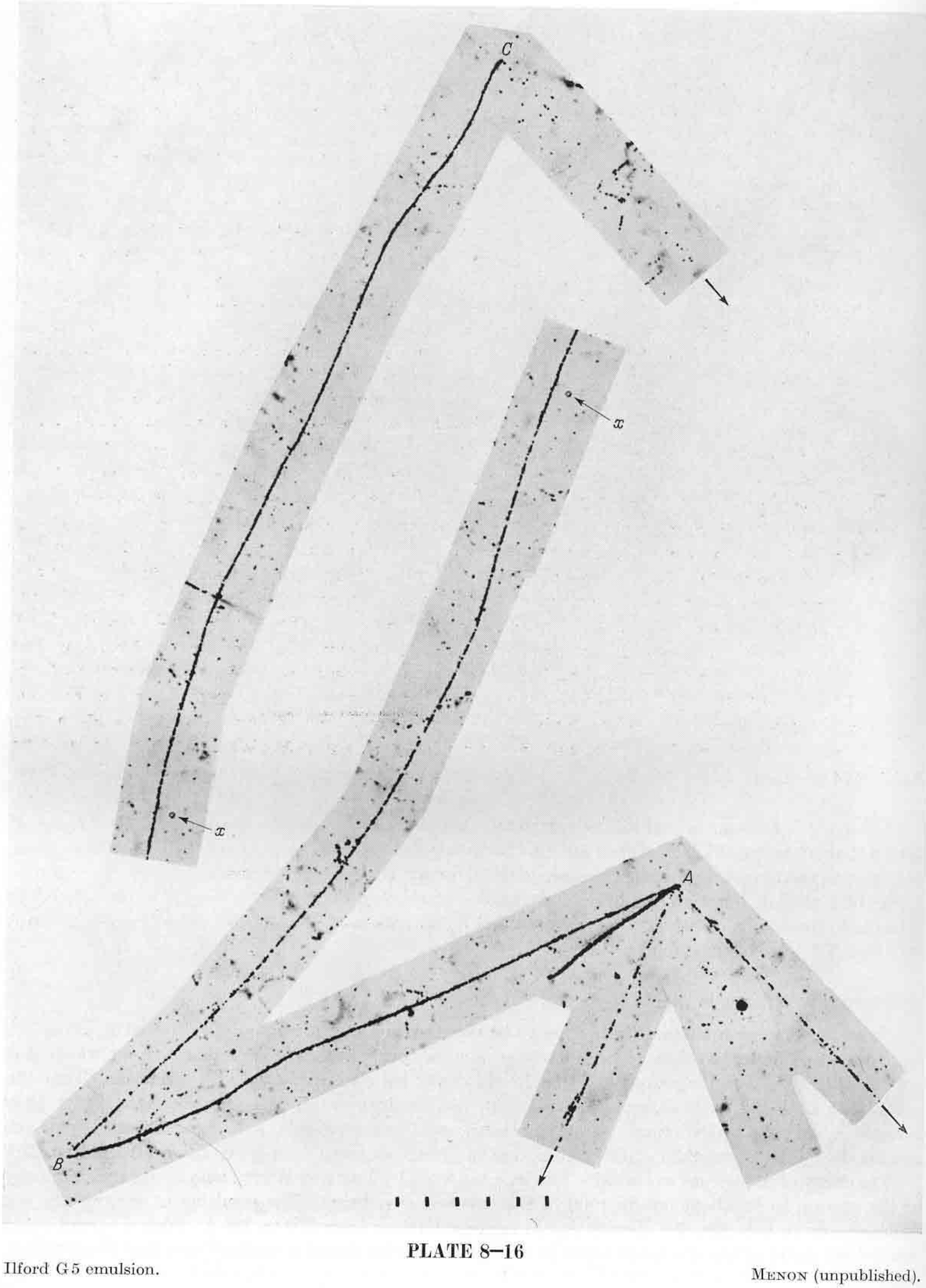

PLATE 8–16

Ilford G5 emulsion.

MENON (unpublished).

A positive π-meson is ejected from the disintegration at A and decays into a μ-meson at the point B. The track of the μ-meson is given in two parts. The track of the decay electron, starting from the end of the range of the μ-meson at C, is clearly visible.

The above result suggested that most of the γ-rays are formed by the decay of π^0-particles. With this assumption, the distribution in energy of these neutral particles can be deduced from the observed γ-ray spectrum. The distribution thus found was similar to that of the charged π-mesons created in the same disintegrations, thus giving further support for the suggested origin of the γ-rays.

The reliability of the above results has been questioned on the grounds that some low-energy γ-rays must have been recorded during the ascent of the balloon and during the fall of the equipment by parachute, the contribution being serious because of the relatively short duration of the exposure at and near the maximum altitude. Indeed, some workers consider that in the conditions of exposure employed, the true distribution of γ-rays should display no maximum in the spectrum because of the large contribution of low-energy quanta thus made. However serious such effects may be, it is certain that the method allows, at best, only an approximate estimate of the mass of the π^0-meson. The conclusions about the energy spectrum of the π^0-mesons, as deduced from the spectral distribution of the high-energy quanta, are, however, much less subject to serious errors. In particular, the similarity of the energy distribution of the charged and neutral π^0, which appeared as an important consequence of the experiments, is believed to be valid.

b) Alternative mode of decay of the π^0-meson; $\pi^0 \rightarrow \gamma + (\beta^+ + \beta^-)$.

It was first pointed out by DALITZ (1951), that general theoretical considerations strongly suggest that the neutral π^0-meson should also decay in an alternative mode in which one of the γ-rays is replaced by an electron-pair; $\pi^0 \rightarrow \gamma + (\beta^+ + \beta^-)$. DALITZ estimated that this alternative mode should occur with a frequency about 1% of that of the normal mode. Contemporaneously with these theoretical predictions, CARLSON *et al.* (1950) observed pairs of electrons to emerge, narrowly inclined to one another, from nuclear disintegrations produced by cosmic radiation. The electrons were identified by scattering measurements which showed them to have momenta much smaller than that of μ-mesons of velocity $\sim c$. In considering the origin of such electron-pairs, it had first to be excluded that they were not due to the conversion of γ-rays which had emerged from the disintegrating nucleus.

The average length of path of a γ-ray in an emulsion before it materialises into a pair of electrons, varies slowly with the quantum energy, but, for values of $h\nu$ between 10 and 1000 MeV, it is of the order of 4·5 cm. The chance that a γ-ray, originating in or very near a nuclear disintegration in the emulsion, will produce a pair at a point less than 1 μ from the parent disintegration is therefore only about 0·002%. About sixty such pairs were observed by DANIEL *et al.* (1952) and by ANAND (1953) in conditions in which, if they were due to the materialisation of γ-rays, only one or two would have been expected; see Fig. 8–5. Most of these particular pairs could not, therefore, be due to pair production by γ-rays. They are referred to as 'direct pairs' and are believed to be due to an alternative mode of decay of the π^0-meson.

Support for this view was provided by observations on the energy distribution of the direct pairs. This was found to be closely similar to that of the pairs produced by the γ-rays which arise in the normal mode of decay of the neutral π-mesons. The frequency of occurrence of the direct pairs indicates that the neutral π-particle decays in the alternative mode with a probability of about 1 in 80.

(Continued at top of page 264)

PLATE 8–17. Electron pairs due to γ-rays produced in the decay of a π^0-particle ▶

The bisector of the tracks of the electron pairs intersects the centre of disintegration and makes it almost certain that the two events are associated. The disintegration was produced by a neutral particle, probably a neutron. Such 'pairs' are referred to as 'associated pairs' to distinguish them from those, due to the alternative mode of decay, which appear to originate in the disintegration; see Plate 8–18.

Electron pairs due to γ-radiation produced in the decay of a π^0-particle

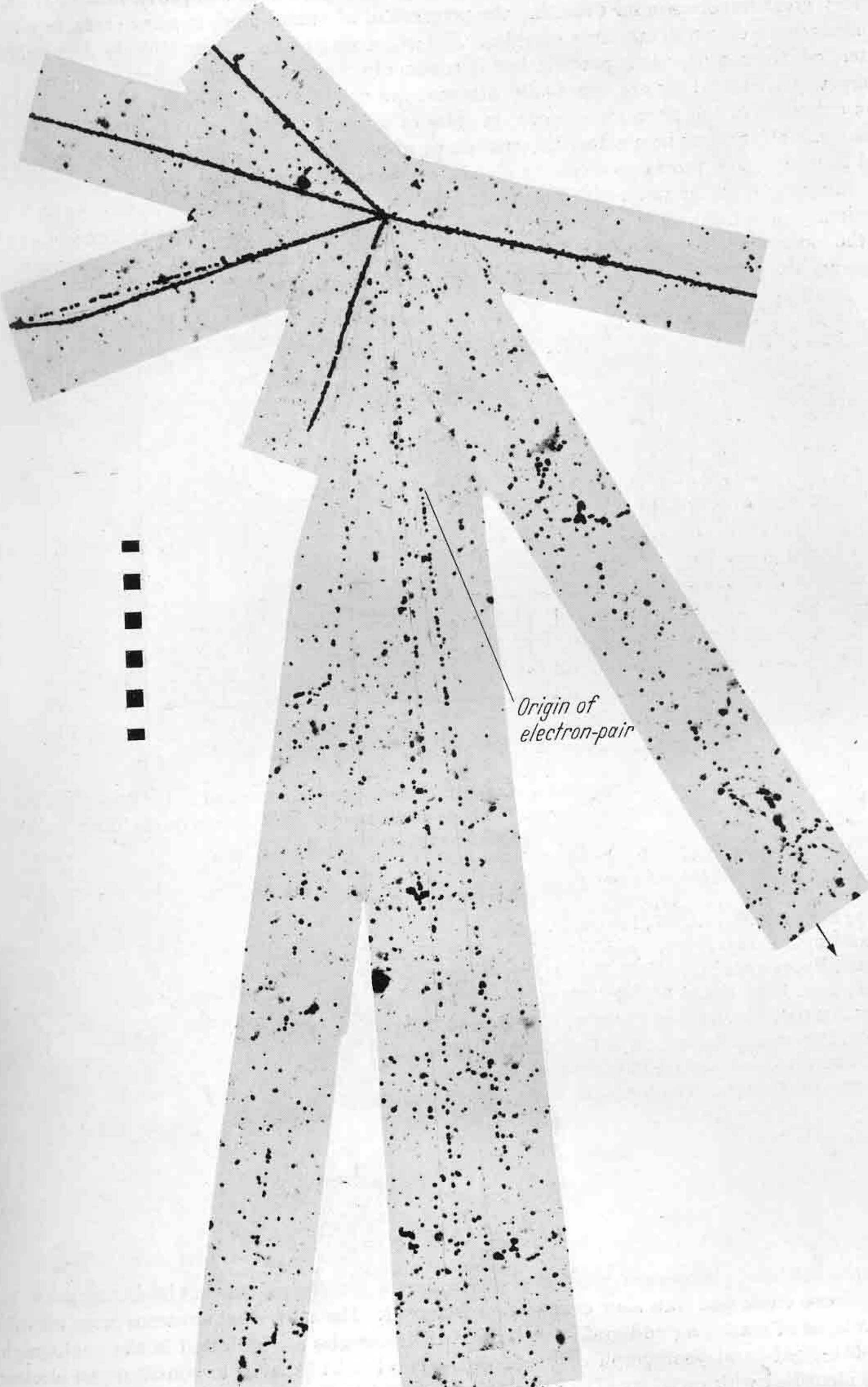

PLATE 8–17

Ilford G5 emulsion.

Carlson, Hooper and King; Phil. Mag. **41**, 701 (1950).

The existence of the alternative mode of decay of the π^0-meson has provided a technical resource of very great importance for detecting the presence of π^0-mesons and, in some cases, in allowing conclusions to be drawn about their energies. The π^0-meson provides a particularly difficult problem in detection, for not only is it neutral, but it commonly transforms into neutral radiation, so that the charged particles which are eventually detected are the tertiary products of the original radiation. The existence of the alternative mode, in spite of its rarity, greatly relieves this situation, and has given unambiguous evidence for the creation of π^0-mesons in the decay of K-mesons and hyperons, and in many other processes involving elementary particles.

The same considerations which suggested the existence of the alternative mode also indicate the possibility of a third mode of decay into two pairs of electrons with a probability of $\sim 10^{-4}$ of that of the normal mode; $\pi^0 \to (\beta^+ + \beta^-) + (\beta^+ + \beta^-)$. A single observation in a cloud-chamber appears to prove the existence of this process and will be referred to in Sect. 10, p. 318.

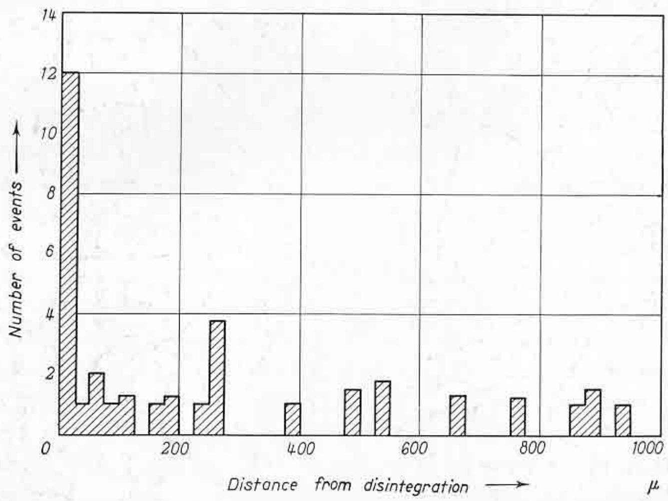

Fig. 8-5. Frequency of occurrence of related electron-pairs as a function of the distance of the point of origin from the parent star. The large number at small distances is due to 'direct pairs'. (After DANIEL *et al.* 1952.)

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PLATE 8–18

▶

In the left-hand photograph, the first grains in the track of the pair cannot be distinguished because of the dense track due to a slow evaporation fragment. The individual electrons were identified by observations of scattering and grain-density and their energies are indicated in the photograph.

In the right-hand photograph only one of the two tracks believed to constitute an electron pair can be identified with certainty. The other, of energy 430 MeV, produces a track with 'plateau' grain density g_p, whereas a π- or μ-meson with the same scattering would have a value about $0{\cdot}95\, g_p$.

Further, if the secondary particle interacted with a nucleus in traversing one of the plates, it was reasonable to conclude that the particle was a π-meson, and not a μ-meson.

A further important advance, was to employ, in addition to the 'multi-plate chamber', a second Wilson chamber placed above it and operated in a magnetic field. The upper chamber allowed the momentum of a particle to be determined; this parameter, when combined with the observed range of the particle in traversing the lower plates, gave a value for the mass, accurate within narrow limits (GREGORY *et al.* 1954). This technique, similar in principle to that used by FRETTER (1946, 1949) and BRODE (1949) in studying μ-mesons, but on a much greater scale, made it possible to study effects associated with the arrest in metal plates of heavy particles of known mass—'S-events'—in addition to the 'charged V-events' in which similar particles decay 'in flight', and it eventually led to the discovery of the mode of decay $K_{\mu 2}$. Work of high precision with a single Wilson chamber was carried out by THOMPSON on the cosmic radiation during 1952–1953, and he was thus able finally to establish the mode of decay of a neutral heavy meson into two π-mesons; $\theta_1^0 \rightarrow \pi^+ + \pi^-$, and to obtain an accurate value for the mass $m_0 = 966 \pm 10\ m_e$ (THOMPSON *et al.* 1953).

Great technical improvements were also made in work with the photographic method following the introduction of 'stripped' emulsions. In 1953, a European expedition was made to Sardinia, supported by eighteen different laboratories, to secure exposures of stacks of emulsions, with dimensions 15 cm $\times$ 10 cm $\times$ 2·5 cm, carried to high altitudes by means of free balloons; DAVIES and FRANZINETTI (1954). The flights were made at magnetic latitude $\sim$40° N, where the magnetic field of the earth ensures that no particles with energy less than $\sim$1·5 BeV can approach the atmosphere in a vertical direction. The numerous low-energy particles of the primary cosmic radiation, which produce an undesirable background of tracks at higher latitudes, were thus eliminated. As a result of this expedition, and of similar work in India, a great increase in the weight of the attack on the problems of heavy mesons was brought about, due both to the large number of laboratories engaged in it, and through the improved conditions of experiment provided by stacks of emulsions. This attack led to many important discoveries, including the observation of various new modes of decay of K-mesons, and the nuclear interaction of the negative particles.

As a further advance, the experiments with beams of protons generated in the synchrotrons in Brookhaven and Berkeley, with energies of 3 and 6 BeV respectively, led to the observation of the artificial production of the heavy mesons and, as in the case of π-mesons, this made it possible to study the properties of the particles in much greater detail. In particular, this work led to the discovery of the associated production of K-mesons and hyperons.

PLATE 9–1. First observation of decay in the τ-mode ▸

By a remarkable chance, this event, τ_1, was observed shortly after the production of the 'electron-sensitive' emulsions (BERRIMAN 1949). The track of the parent particle in the emulsion is longer than 3 mm, and its mass can be determined by measuring the grain-density and scattering along the track—see Table 9–3. Attention was directed to the event by the slow particle (a) which emerges from the end of the range of the parent τ-meson, at A, and comes to rest at B where it produces a nuclear disintegration characteristic of a π-particle.

The interpretation of the event depends on, (i), the identification of particle (a) as a π-meson; (ii), the identification of the particle producing track (b), by observations of grain-density and scattering, as a meson of mass $285 \pm 30\ m_e$; (iii), the unambiguous evidence for the direction of motion of the τ-particle, and its mass; and, (iv), the existence of a momentum balance among the assumed secondary particles.

The most plausible alternative explanation was that the assumed parent particle was in reality a proton which, by a very rare chance, reached the end of its range at the point A, and which was unrelated to the other tracks. Apart from the evidence provided by the mass of the particle, this explanation had to account for the features of the remaining tracks; viz. a centre with which were associated two π-mesons, an unidentified particle with unit charge $|e|$, and apparently no other charged particles. No other such event had been observed and, if it occurs, it is certainly extremely rare. The explanation was therefore rejected on the grounds of its extreme improbability and of the difficulties to which it gives rise.

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First observation of decay in the τ-mode

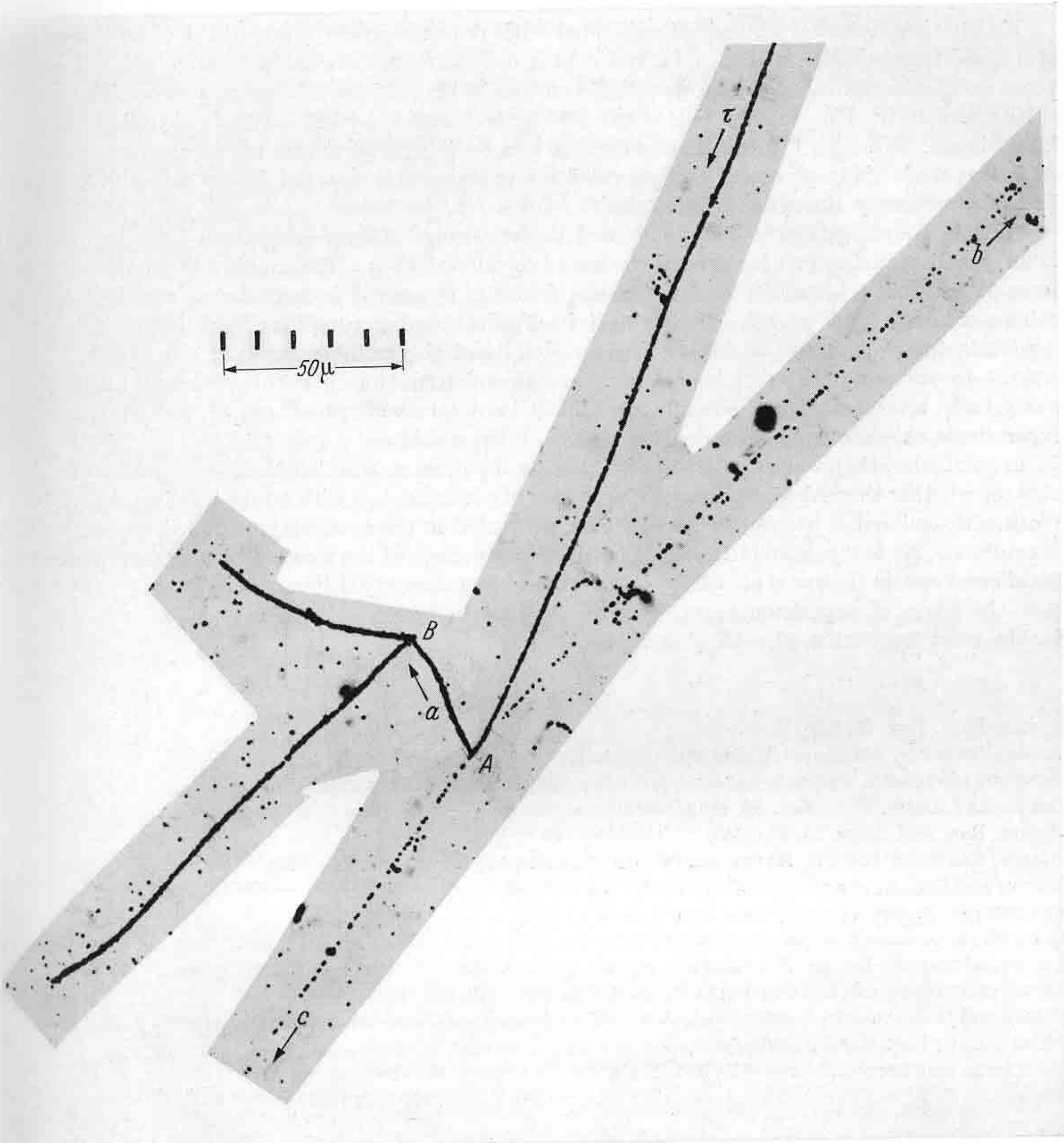


PLATE 9–1

Kodak NT4 emulsion. BROWN, CAMERINI, FOWLER, MUIRHEAD, POWELL and RITSON; Nature **163**, 82 (1949).

The results of detailed measurements on the track are shown below:

Track	Direction in common plane (degrees)	Momenta (MeV/c)	Energy (MeV)
b	$0 \pm 0{\cdot}2$	101 ± 5	33 ± 3
c	$170{\cdot}2 \pm 0{\cdot}2$	98 ± 5	31 ± 3
a	$257 \pm 2{\cdot}0$	$17{\cdot}1 \pm 0{\cdot}2$	$1{\cdot}04 \pm 0{\cdot}3$
		Total release of energy	65 ± 6

The most accurate values for the momenta of particles producing tracks *b* and *c* have been deduced by an application of LAMI's theorem.

e) If the length of the track of the parent particle is greater than 2 mm, its mass may be determined by observations of grain-density and scattering as a function of residual range; see pp. 154, 158. If the direction of motion of the assumed parent particle is unambiguous, and its mass certainly greater than 500 m_e, the evidence for a τ-meson is very strong, even when the co-planarity of the three secondary particles alone can be established.

The details of the first twelve examples of τ-mesons identified in photographic emulsions are given in Table 9–2.

b) Early determinations of mass

A summary of the first direct measurements of the mass of the τ-mesons is shown in Table 9–3.

The weighted mean of the values based on the direct measurements on the tracks of the τ-mesons is $970 \pm 57\ m_e$; and of the values deduced from an application of the conservation laws, $969 \pm 6\ m_e$ assuming all the secondary particles to be π-mesons of mass $273 \pm 0{\cdot}5\ m_e$.

Table 9–3. Determinations of the mass of τ-mesons

Event	Length of track mm	Mass			Q-Value MeV
		(g^*, R)	$(\bar{\alpha}, R)$	Conservation laws	
1	3·0	1080 ± 160	990 ± 270	946 ± 16	65 ± 8
2				967 ± 30	76 ± 15
3				954 ± 16	69 ± 8
4	2·1	1015 ± 280	910 ± 220	966 ± 8	75 ± 4
5				963 ± 14	73·5 ± 7
6	8·0	946 ± 140	995 ± 150	989 ± 15	86·5 ± 7·5
8	1·5			966 ± 9	75 ± 4
9	7·3	970 ± 130	935 ± 160	872 ± 12	78 ± 5
10	1·7		960 ± 500	972 ± 10	78 ± 5
11	4·0		890 ± 180	966 ± 17	75 ± 7
Weighted Means		994 ± 79	946 ± 81	969 ± 6	76 ± 2

Weighted mean of direct measurements = $970 \pm 57\ m_e$
Weighted mean from conservation laws = $969 \pm 6\ m_e$

The mass deduced from the conservation laws is based on the value $273 \pm 0{\cdot}5\ m_e$ for the mass of the negative and positive π-mesons. The errors in the means have been calculated on the assumption that errors in the individual measurements quoted by different authors are all due to statistical fluctuations and correspond to standard deviations.

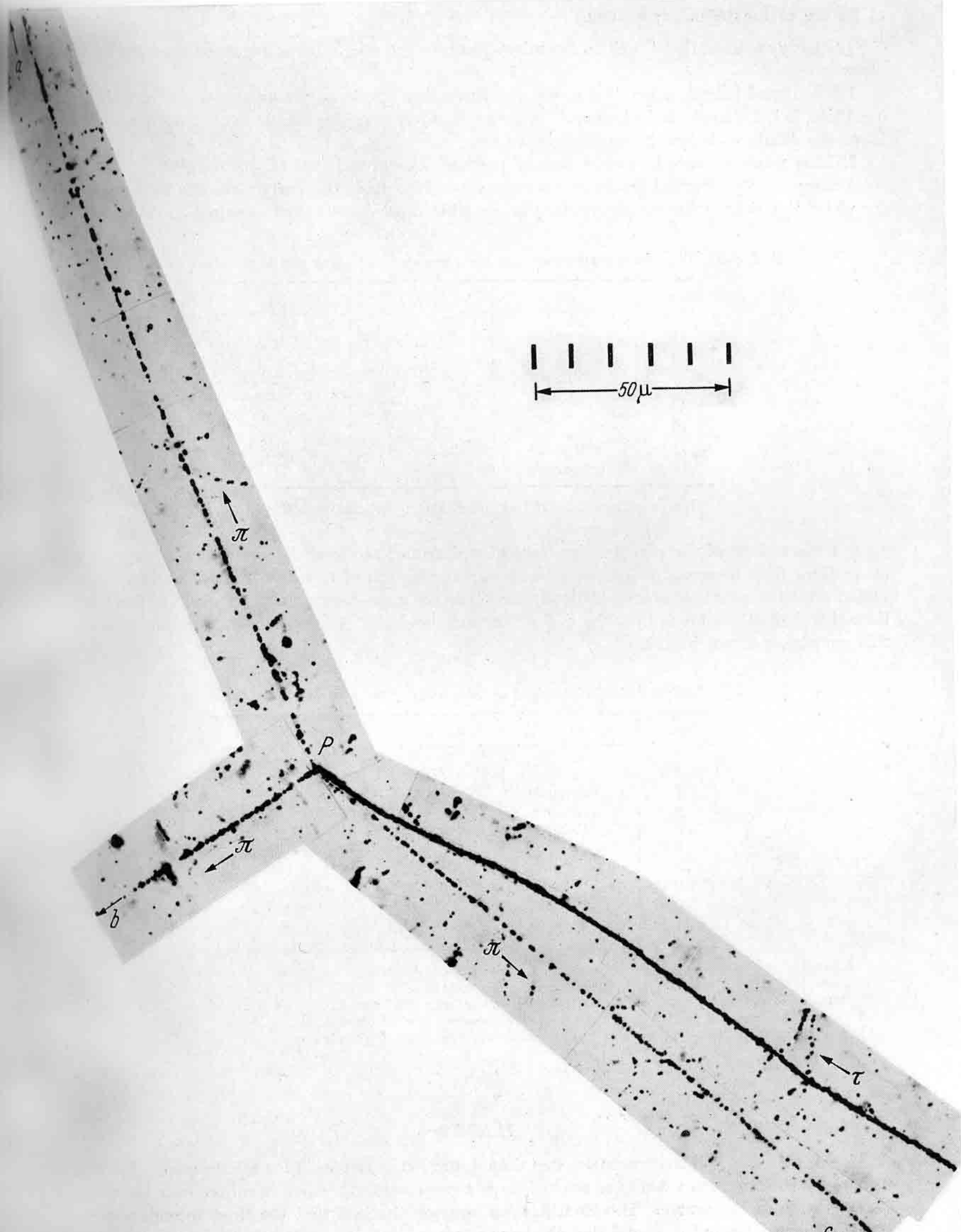
PLATE 9–2 ▸

Ilford G5 emulsion. FOWLER, MENON, POWELL and ROCHAT; Phil. Mag. **42**, 1040 (1951).

In this event, τ_4, the length of the track of the parent particle in the emulsion is 2·1 mm and determinations of its mass gave a mean value of $960 \pm 190\ m_e$. The three secondary tracks are co-planar to within $2 \pm 2°$ and one of them has a length in the emulsion of 6·4 mm. The measurements of the mass of this particle gave the value $285 \pm 20\ m_e$. The particle was moving slowly when it left the emulsion, its residual range at this point being estimated as 0·4 mm. The range-energy relation then allowed its energy and momentum to be determined with an accuracy limited only by the errors due to "straggling".

The accurate value for the momentum of the particle (a) and the relative directions of motion of the three particles in the common plane, provide very favourable conditions for determining the total release of energy Q in the transformation and the value obtained was 75 ± 4 MeV.

Early example of τ-decay



c) Nature of the secondary particles

The early evidence that the three secondary particles are all π-mesons depended upon the following observations:

1. The direct identification of π-mesons by secondary effects occurring at the end of their range; e.g. Plate 9–1. In single emulsions such evidence is rarely available because the π-mesons commonly leave the emulsion before being brought to rest.

2. Mass measurements on the secondary particles by observations of g^* and $\bar{\alpha}$.

Among the 33 observed tracks of secondary particles from the early τ-mesons there were eight for which significant mass measurements were possible. The results are summarised in Table 9–4.

Table 9–4. The direct measurement of the masses of secondary particles; values in m_e

Event	(a)	(b)	(c)
1	π-particle	280 ± 30	—
4	285 ± 20	—	—
5	260 ± 110	330 ± 140	260 ± 110
8			π^+-particle
9			
10		305 ± 25	
11	270 ± 43	284 ± 63	π^+-particle
12	π^+-particle		

Weighted mean, apart from identified π-particles, $= 286 \pm 13\ m_e$

3. Observations of the relative directions of emission of the secondary particles in their common plane allow their momenta to be compared by an application of LAMI's theorem. Further, the individual velocities could sometimes be determined from the grain-density in the tracks. The two observations therefore allowed a comparison of the masses to be made. A summary of the results obtained by this method is shown in Table 9–5.

Table 9–5. Relative values of the masses of the secondary particles

Event	Particle (a)	Particle (b)	Particle (c)
1	—[1]	(1·00)[2]	$1{\cdot}02 \pm 0{\cdot}10$
2	$1{\cdot}05 \pm 0{\cdot}20$	(1·00)	$0{\cdot}96 \pm 0{\cdot}25$
4	(1·00)[3]	$0{\cdot}88 \pm 0{\cdot}10$	$1{\cdot}03 \pm 0{\cdot}05$
5	(1·00)	$0{\cdot}93 \pm 0{\cdot}12$	$1{\cdot}09 \pm 0{\cdot}17$
6	(1·00)	$0{\cdot}98 \pm 0{\cdot}10$	$0{\cdot}89 \pm 0{\cdot}10$
8			(1)
9	(1·00)	$1{\cdot}03 \pm 0{\cdot}20$	$0{\cdot}83 \pm 0{\cdot}05$
10	$0{\cdot}97 \pm 0{\cdot}10$	(1·00)[4]	$0{\cdot}90 \pm 0{\cdot}10$
11	$1{\cdot}03 \pm 0{\cdot}08$	(1·00)[5]	(1)

[1] Identified as π-meson by disintegration at the end of the range, or by $\pi \rightarrow \mu$ decay.
[2] Particle of mass 280 ± 30 as determined by observations of g^* and $\bar{\alpha}$.
[3] Particle of mass 285 ± 20 as determined by observations of g^* and $\bar{\alpha}$.
[4] Particle of mass $305 \pm 25\ m_e$ as determined by observations of g^* and $\bar{\alpha}$.
[5] Particle of mass $284 \pm 63\ m_e$ as determined by observations of g^* and $\bar{\alpha}$.

PLATE 9–3

▶

In this event, τ_5, all the tracks are less than 1 mm long. Evidence for the direction of motion of the parent particle is not decisive, but the large-angle scattering which it suffers near the centre of disintegration is suggestive. The identification rests on the fact that the three secondary particles are co-planar to within $2 \pm 2°$ and that the total release of energy as calculated from the grain-density in the tracks of the secondary particles, assuming them to be π-mesons, is 75 ± 14 MeV.

Decay of a τ-meson

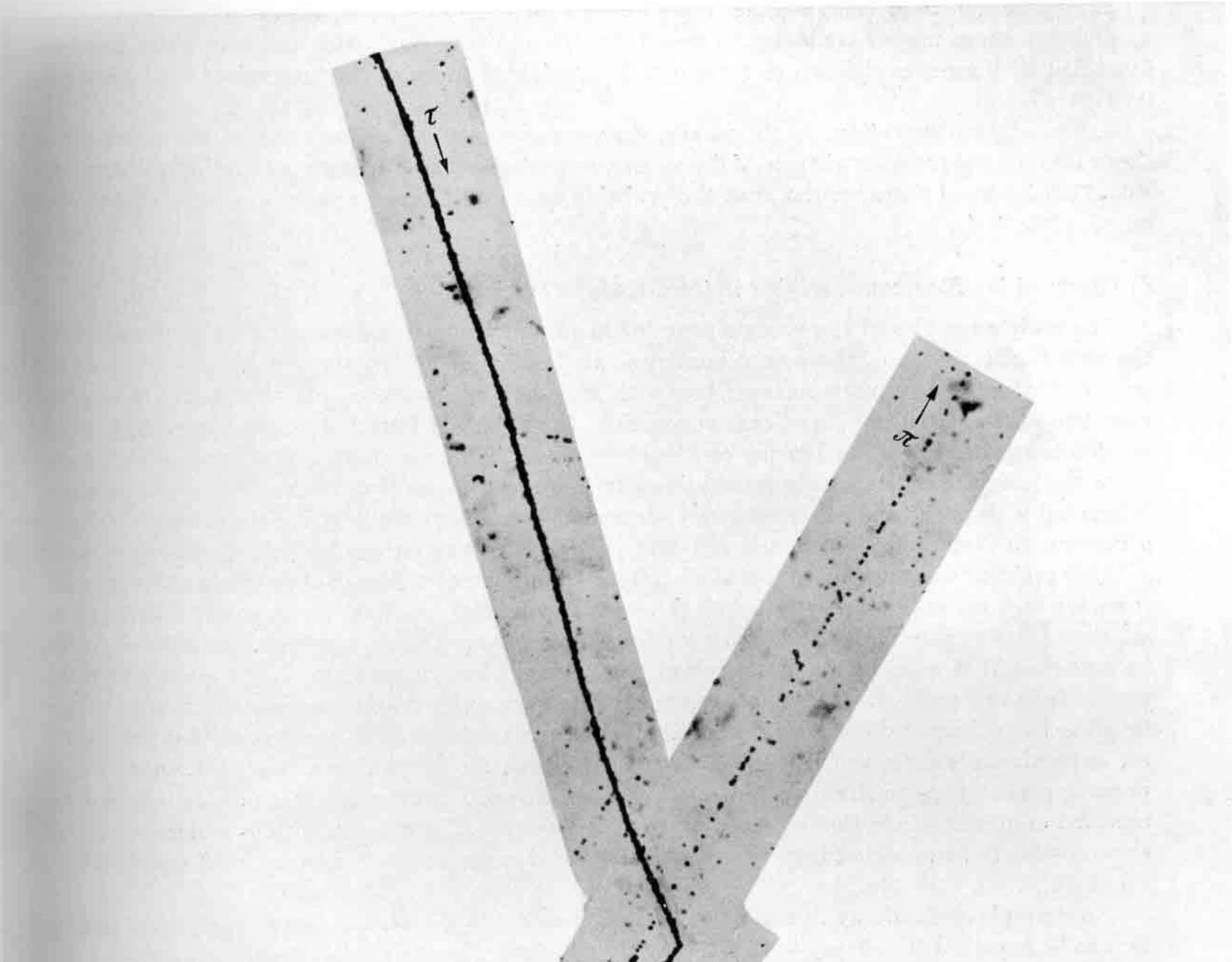


PLATE 9–3

Ilford G 5 emulsion.

HODGSON; Phil. Mag. **42**, 1060 (1951).

It may be seen from Table 9–5 that there were six secondary particles, associated with events τ_1, τ_4, τ_{10} and τ_{11}, whose masses could be compared, by the above method, with particles which had been identified with some confidence as π-mesons. The weighted mean of the four values so obtained was $0{\cdot}98 \pm 0{\cdot}03$.

4. The direct observations on the mass of the τ-mesons were in good accord with the assumption of decay into three π-particles whereas, if the secondary particles were μ-mesons, a significant discrepancy would exist several times greater than the probable errors of the measurements; see the observations on τ_6, Plate 9–4.

d) Charge of the *K*-mesons decaying in the τ-mode in emulsion

The early examples of the τ-mode recorded in photographic emulsions gave little information on the sign of the charge of the parent particles. If the charges of the three secondary π-mesons are known, that of the primary follows; but with glass-backed emulsion, the probability of arresting even two of the secondary particles is very small. In the period from 1949–1953, the problem was of great interest because of its bearing on the strength of the interaction of these mesons with nuclei. Were the heavy mesons strongly interacting like the π-mesons, so that the negative particles always interacted with nuclei and never, or rarely, decayed at rest? Or were they weakly interacting like the μ-mesons, so that both positive and negative particles decayed on reaching the end of their range?

This problem was eventually solved with the introduction of stacks of stripped emulsions in which there is a high probability of arresting all the secondary particles; it was thus shown that all, or almost all, the parent mesons decaying in the τ-mode, after being arrested in emulsion, are positive. It may be remarked that even before this solution had been reached, it was possible to make a statistical approach to this problem. Thus, among the first forty secondary π-mesons arrested, twenty-six were found to be positive and fourteen negative, a result compatible with the assumption that the positives are approximately twice as frequent as the negative; and, therefore, that at least the majority of the primary particles are positive. A similar conclusion followed from the fact that no slow electrons were reported originating from the point of arrest of the τ-mesons. By analogy with μ- and π-mesons, such electrons are to be expected from the atomic capture of negative heavy mesons, with a probability of about 10%.

No example of the decay at rest of a negative K-meson in the τ-mode has been observed hitherto. It is to be expected that decay in flight, possibly very near the end of the range, can occur, but there will then be an absence of conservation of momentum among the three secondary π-mesons. The important fact that negative K-particles can decay in this mode was established by experiments with Wilson chambers where the K-mesons commonly decay 'in flight' (van Lint and Trilling 1953).

3. ACCURATE MASS MEASUREMENTS ON τ-MESONS

Later measurements in the more favourable conditions which followed the introduction of stripped emulsions gave a striking demonstration of the reliability of the early results and conclusions. In stacks of emulsions, it was possible to arrest all the three secondary mesons, to identify them as π-mesons

(Continued at top of page 298)

PLATE 9–4 ▸

In this event, τ_6, the track of the primary particle is 8 mm long, so that its direction of motion is unambiguous and good mass measurements are possible. The mean of the values obtained by the methods (g, R) and $(\bar{\alpha}, R)$ was 965 ± 100. The three secondary tracks are co-planar to within 2°, two of them being longer than 2 mm. The values of the grain-density and the relative directions of motion of the secondary particles are only consistent with the assumption that the three particles are of equal mass; i.e. that they are either π- or μ-mesons. If they are assumed to be μ-mesons, the corresponding value for the mass of the τ-meson deduced from the conservation laws, is $774 \pm 12\ m_e$; if π-mesons, 998 ± 15. Only the second of these assumptions is consistent with the mass value obtained by direct measurement viz. $965 \pm 100\ m_e$.

Decay of a τ-meson

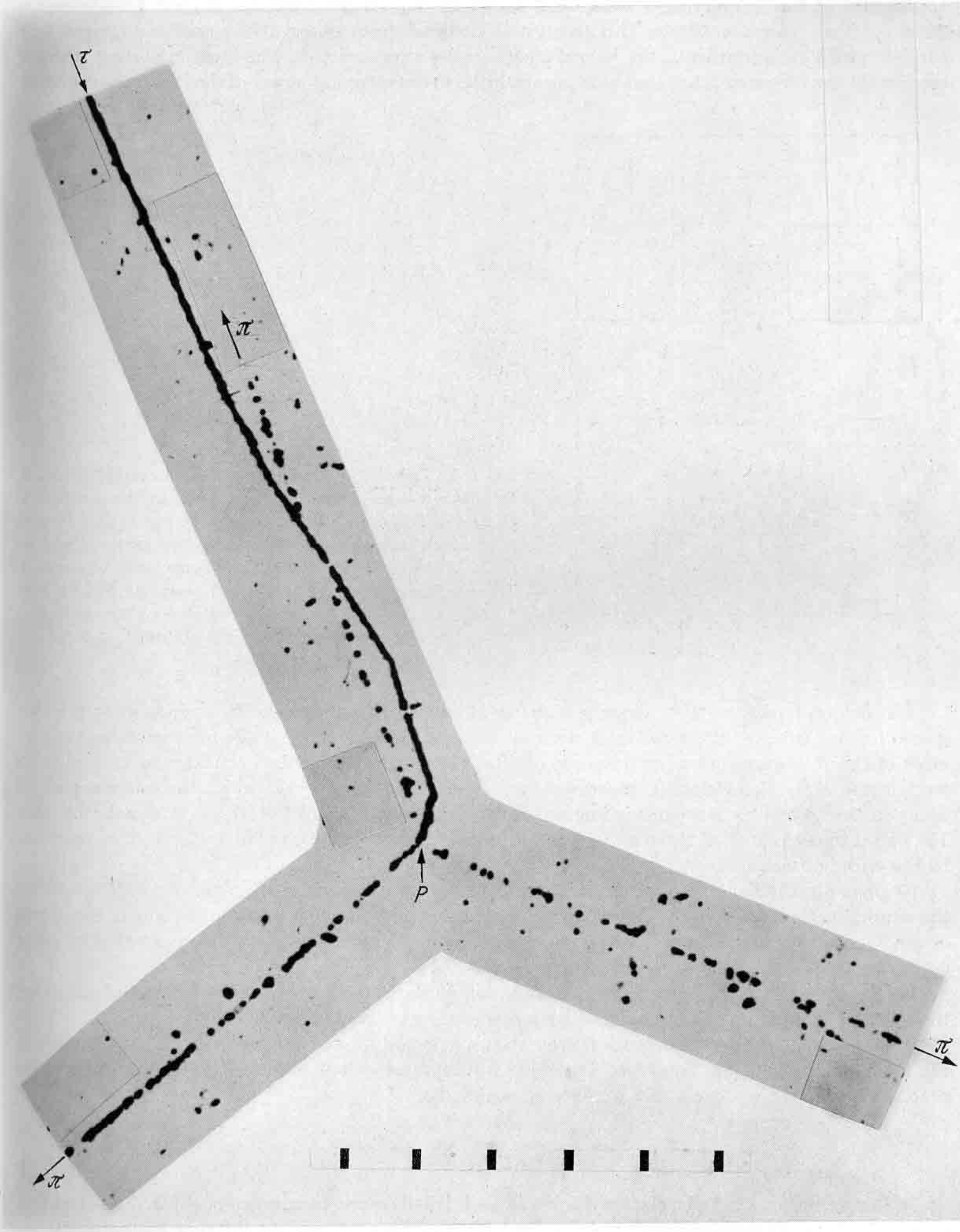


PLATE 9–4

Ilford G5 emulsion.

CECCARELLI, DALLAPORTA, MERLIN and ROSTAGNI (1952).

by the effects observed at the end of the range, and to make accurate estimates of their energy by measuring their ranges. A value thus obtained for the mass of the parent meson, based on an application of the conservation laws, and assuming $m_\pi^+ = 273{\cdot}1 \pm 0{\cdot}2\ m_e$, $m_\pi^- = 272{\cdot}5 \pm 0{\cdot}4\ m_e$, is $965{\cdot}9 \pm 1{\cdot}0\ m_e$; (AMALDI 1956). This result was deduced from observations on 100 τ-mesons, from each of which at least two of the secondary π-mesons were arrested. The most important source of error in this result is that associated with uncertainties in the stopping-power of the emulsions employed.

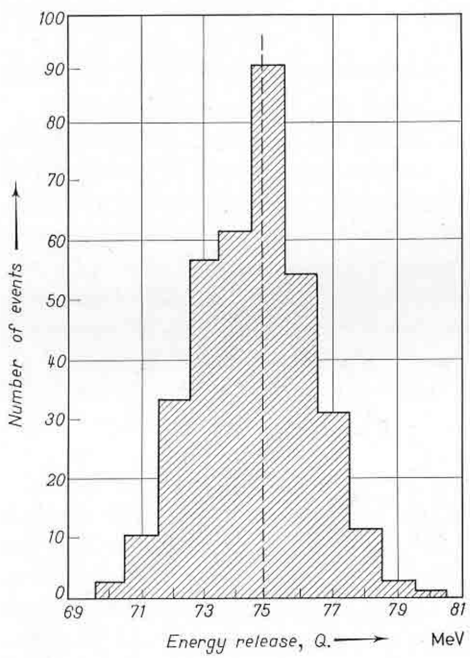


Fig. 9–1. Distribution in the values of the energy release, Q, for 400 τ-mesons observed in stripped emulsions exposed to an artificial K^+-meson beam. Only those events were accepted from which at least two of the secondary particles were arrested in the emulsion, so that their range could be measured. The emulsions were not calibrated, and the energies were deduced from the range-energy relation of BARONI *et al.* (After BALDO-CEOLIN *et al.* 1957.)

The determination of the energy release, Q, combined with an accurate knowledge of the rest-mass of the π-mesons, offers the most accurate method at present available for measuring the rest-mass of the K^+-mesons, and provides a good illustration of the technical considerations involved in work of the highest precision. If measurements are confined to events in which the common plane of decay of the secondary π-mesons is inclined to that of the surface of the emulsion at not more than 15°, and if the ranges of all three π-mesons can be directly determined, the following factors contribute to the errors of measurement:

(i) Errors in the true range of the π-mesons. It has been estimated by HADDOCK (1956), that for the approximation, as commonly employed, in which the range is taken to equal the sum of the lengths of the chords to the track, the true ranges of the π-mesons are commonly underestimated by about 0·5%, with a corresponding error in the energy of $\sim$0·25%.

(ii) Straggling in range contributes a fluctuation of about 0·5% to individual values of the range, but such effects can be greatly reduced by measurement on large samples.

(iii) Errors in the assumed range-energy relation, including any associated with uncertainties in the stopping-power of the emulsion. In addition, the value of m_K is subject to uncertainties in the precise value of the rest-mass of the π-meson; see p. 229.

PLATE 9–5 ▶

In this event, τ_7, all the tracks are short and no detailed measurements are possible. The identification depends on (a) the co-planarity of the three secondary tracks, and (b) the very marked scattering of the τ-meson at points near the centre of disintegration, a feature which provides strong evidence that the particle was approaching the end of its range. In such an event, the only useful evidence is provided by the relative directions of motion of the secondary particles in their common plane which enable the details of the partition of energy among the three particles to be calculated.

Decay of a τ-meson

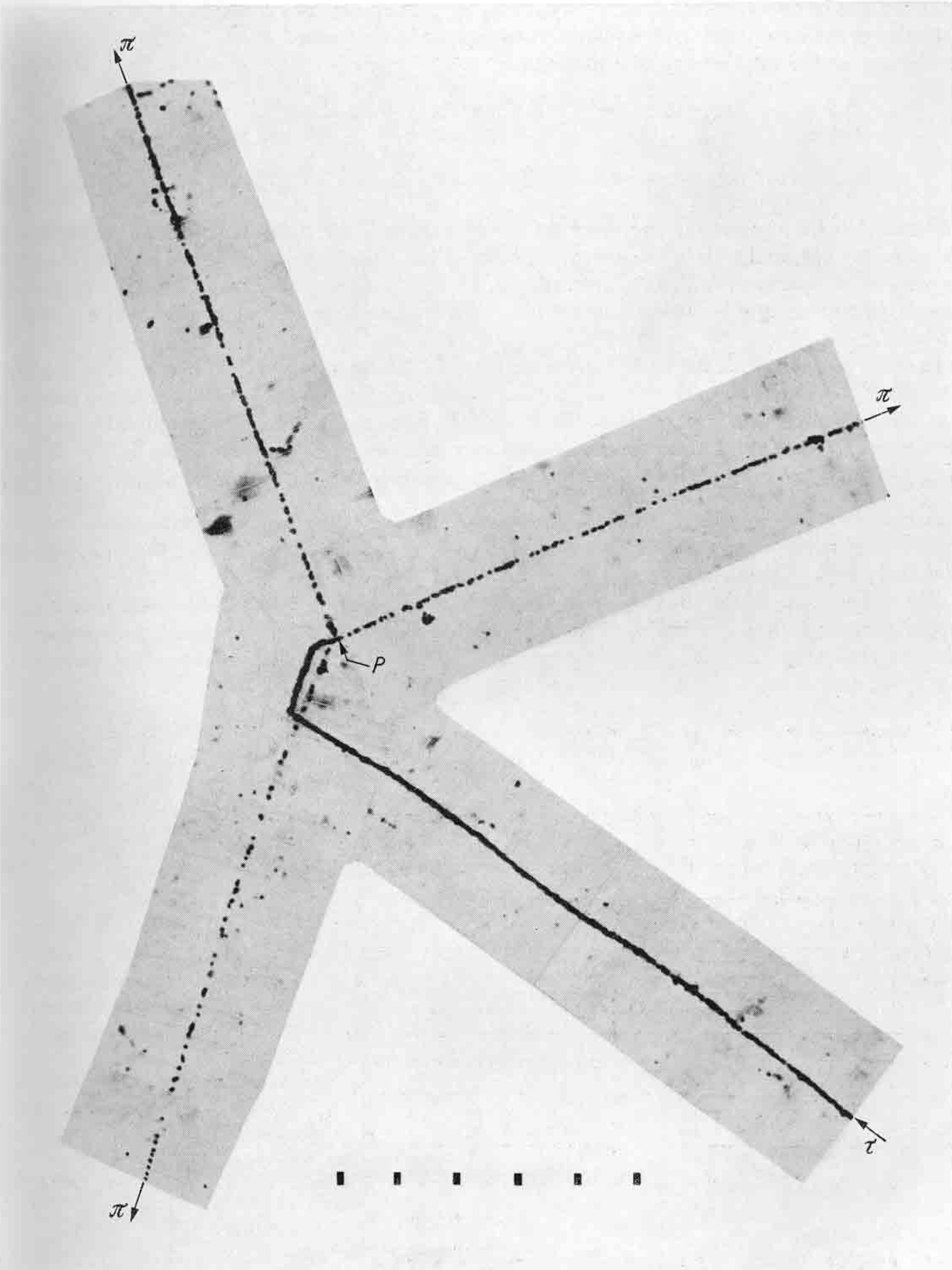


PLATE 9–5

Ilford G5 emulsion.

M. G. K. MENON (unpublished).

Of the above sources of error, (i) and (iii) are the most important, and in order to reduce them, the following approach was made by BACCHELLA *et al.* (1957): Let p be the momentum of a secondary π-meson, and α the angle between the directions of emission of its two partners, in a particular example of the τ-mode of decay. Then $p_1/\sin\alpha_1 = p_2/\sin\alpha_2 = p_3/\sin\alpha_3 = m_\pi \,.\, c \,.\, \lambda$, where λ is a constant for the particular event considered, and m_π is the rest-mass of the π-meson.

Writing for the total energy of a π-meson

$$E_\pi = (p^2 c^2 + m_\pi^2 \,.\, c^4)^{\frac{1}{2}} = m_\pi \,.\, c^2 \,(1 + \lambda^2 \,.\, \sin^2\alpha)^{\frac{1}{2}},$$

it follows that

$$m_K \,.\, c^2 = 3 m_\pi \,.\, c^2 + Q = m_\pi \,.\, c^2 \left\{ \sum_{n=1}^{n=3} (1 + \lambda^2 \,.\, \sin^2\alpha_n)^{\frac{1}{2}} \right\}.$$

It follows that for any assumed value of the energy release Q, the value of λ for any particular event can be calculated, and thence the energy of each of the three π-mesons. The values so determined can then be compared with the observed ranges; and from an assembly of such data, a range-energy curve is defined. A number of such curves may thus be determined for a few chosen values of Q near 75 MeV.

In order to distinguish the most acceptable value of Q, measurements are also made of the lengths of track, R_μ, of the μ-mesons from $\pi \rightarrow \mu$ decay, as recorded in similar conditions in the same emulsions, and measured by the same methods and with the same restrictions as were applied to the secondary π-mesons. The initial energy of these μ-mesons is known to be 4·12 MeV; see p. 229. The mean range of π-mesons of energy $4{\cdot}12 \times \frac{m_\pi}{m_\mu}$ can therefore be determined, for the precise conditions of the experiment, with high precision. The value so obtained can then be compared with that deduced from the different range-energy curves corresponding to different values of Q, and the most acceptable value deduced by interpolation.

The range energy curve thus determined by BACCHELLA *et al.* is shown in Fig. 9–2. In it, a number of points are separately distinguished which were rejected because the corresponding π-mesons showed evidence that they had lost energy by interactions 'in flight'. The corresponding value of Q is $75{\cdot}0 \pm 0{\cdot}2$; and of $m_K = 966{\cdot}3 \pm 0{\cdot}7\, m_e$, assuming $m_\pi^+ = m_\pi^- = 273{\cdot}25 \pm 0{\cdot}15\, m_e$.

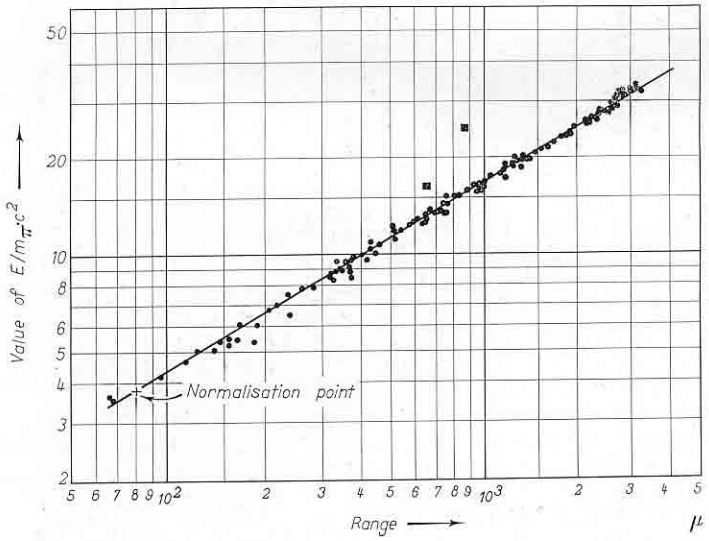


Fig. 9–2. Range-energy relation as deduced by the method of BACCHELLA *et al.* (1956). The 'normalisation-point', deduced from the mean range of μ-mesons from π-μ decay, is distinguished thus: +. The points marked thus, ■, are due to π-mesons which showed evidence of interacting with nuclei 'in flight'. (After BACCHELLA *et al.* 1956.)

PLATE 9–6 ▸

The τ-meson reaches the end of its range at the point P and decays into three particles of which the initial directions of motion are co-planar. One of the three secondary particles stops at Q and emits a μ-meson which in turn decays, at the point R, into an electron. The μ-meson dips steeply in the emulsion and this decreases its apparent range through fore-shortening. In a similar event, τ_8, observed by BARONI *et al.* (1953), the μ-meson left the emulsion before decaying.

First observation of the successive decay $\tau \to \pi \to \mu \to \beta$

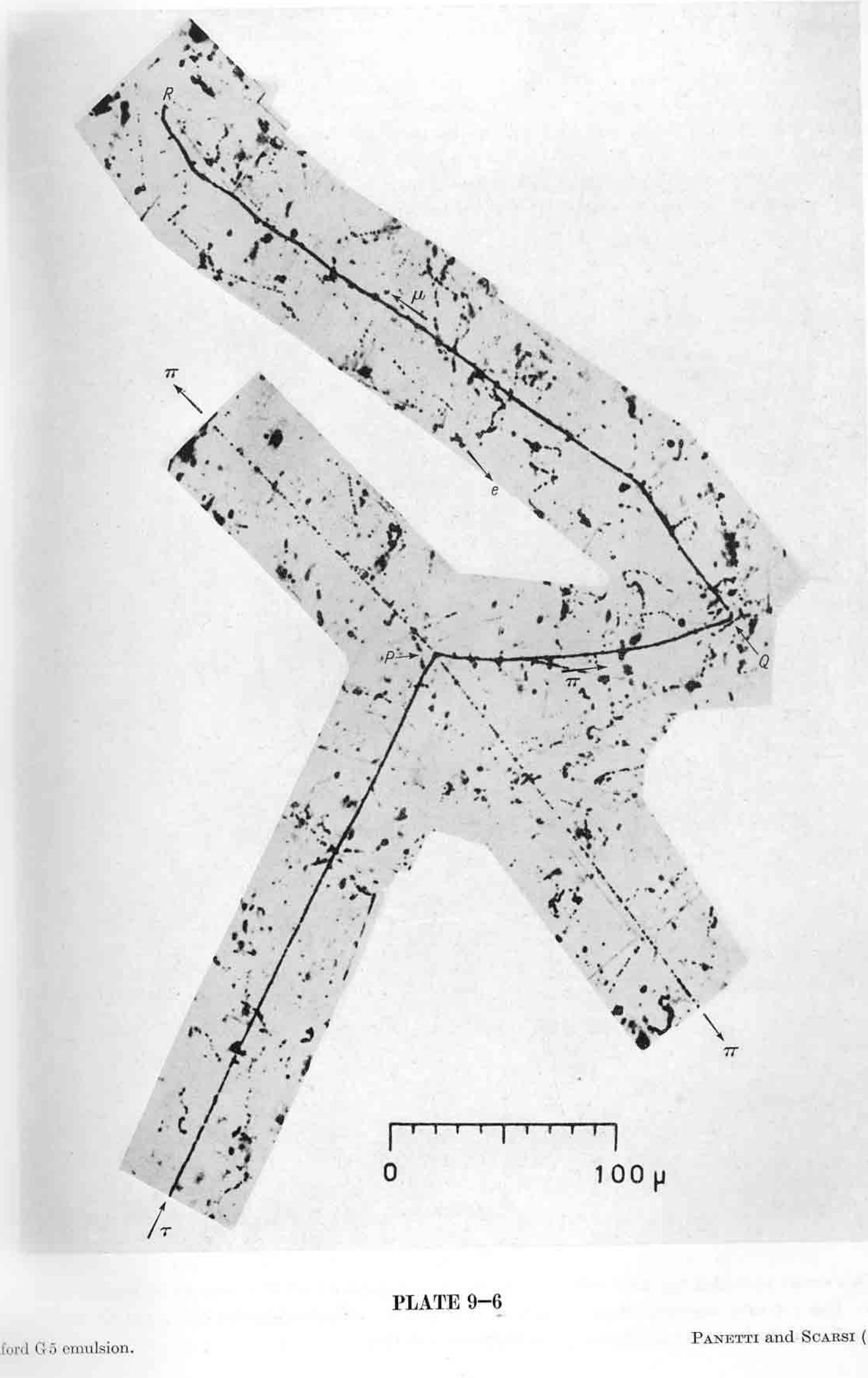


PLATE 9–6

Ilford G5 emulsion.

PANETTI and SCARSI (1953).

Direct production of a meson in a nuclear collision

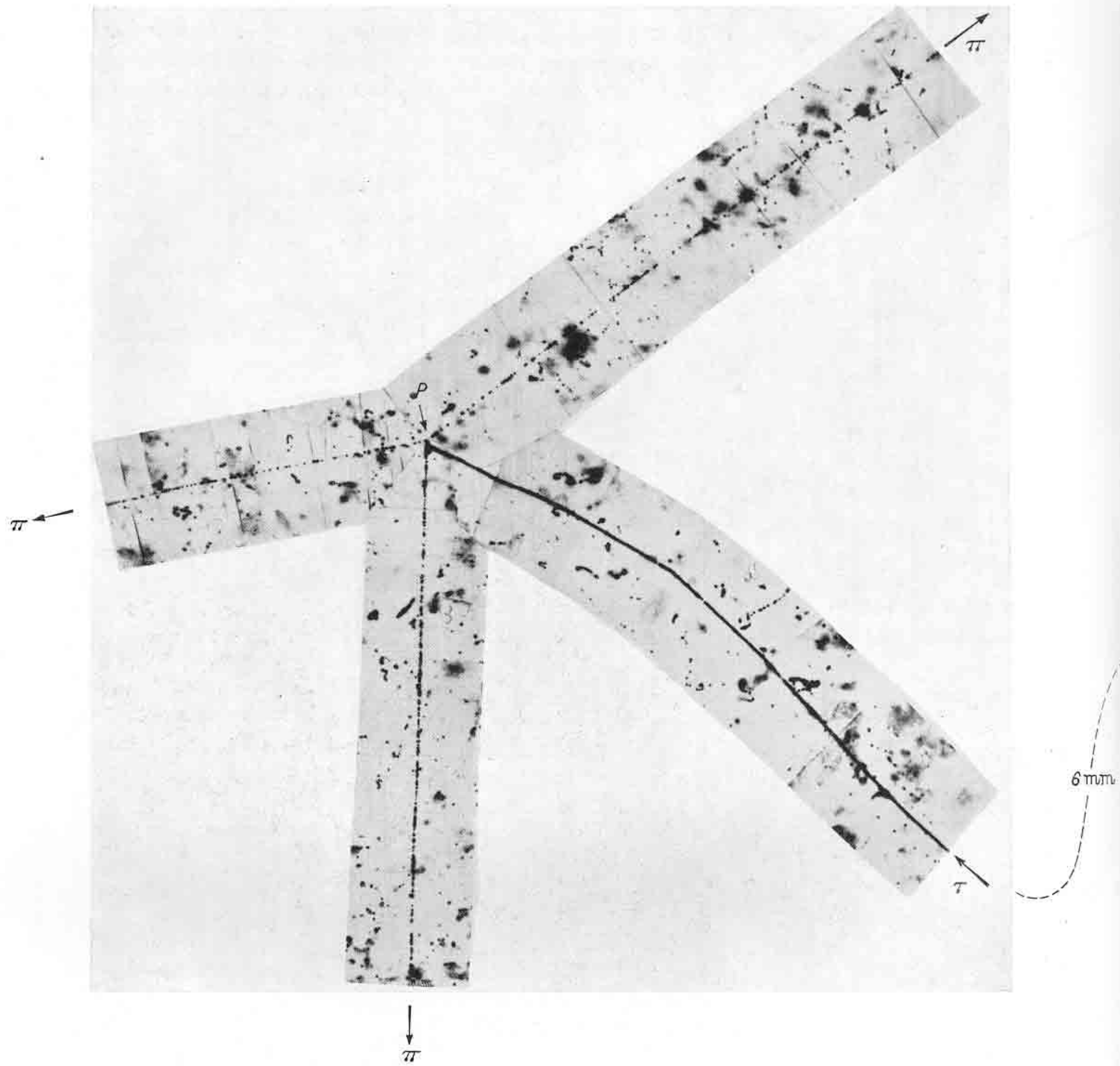


PLATE 9–7

Ilford G 5 emulsion. CECCARELLI, DALLAPORTA, MERLIN, QUARENI and ZORN (1953)

PLATES 9–7 and 9–8

Ilford G 5 emulsion. CECCARELLI, DALLAPORTA, MERLIN, QUARENI and ZORN (1953).

This event provided the first evidence for the direct production of τ-mesons in nuclear disintegrations. The τ-meson emerges from a nuclear encounter in the emulsion at the point O, and stops in the emulsion at the point P, its total range being $\sim$7 mm.

4. DISTRIBUTION IN ENERGY OF THE SECONDARY π-MESONS

The distribution in energy of the secondary π-mesons has an important bearing on the spin and parity of the parent τ-mesons, and therefore on the question of the identity of the K-mesons decaying in different modes (DALITZ 1953, FABRI 1954).

Figs. 9–3 and 9–4 shows the distribution in energy of π^--mesons, originating in the decay of τ^+-mesons, together with the expected theoretical distributions for various combinations of spin and parity (HADDOCK 1956). It appears that the most acceptable combination is 0^-, i.e., zero spin and odd parity. This result was of great interest since, on the assumption that parity is conserved in the different modes of decay, it was suggested that such a heavy meson could not disintegrate into two π-mesons in the χ-mode ($K_{\pi 2}$), and therefore that there are differences between the heavy mesons decaying in the different modes.

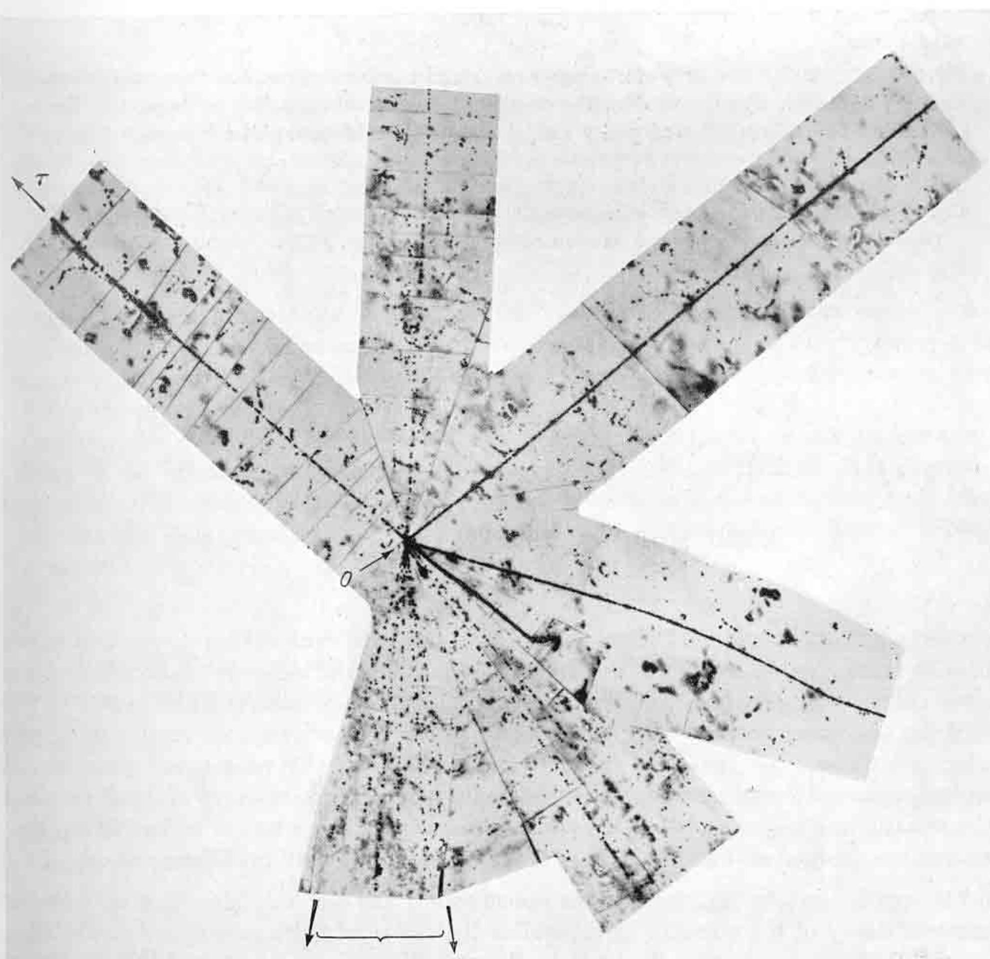


PLATE 9–8

Ilford G 5 emulsion. CECCARELLI, DALLAPORTA, MERLIN, QUARENI and ZORN (1953).

6. DIRECT PRODUCTION OF τ-MESONS IN NUCLEAR DISINTEGRATIONS

A second important problem bearing on the question of the strength of the interaction of τ-mesons with nuclei, which was of great interest during the early period, was that of their origin. Could they, like π-mesons, be directly produced in nucleon-nucleon collisions? Or were they, like the μ-mesons, products of the decay of other particles? Two events—due to CECCARELLI *et al.* (1953), (see Plates 9–7 and 9–8) and to PETERS (1953), —made an important contribution to this problem. They each showed a τ-meson emerging from a 'star', and appeared to prove the direct production of τ-mesons in nuclear disintegrations, apart from the reservations referred to on p. 256, that there may be other particles involved, which provide a link in a decay sequence which leads to the τ-meson, but which are unobserved because of their very short lifetime.

The final solution of this problem, which showed that both the π- and μ-mesons provided inadequate analogies, and that the phenomena were more complicated than had been anticipated, was provided by the experiments of FOWLER *et al.* (1953) on the associated production of K-mesons and hyperons: see p. 353.

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PLATE 9–9

▶

This photograph shows an early example of the decay of a heavy meson with the emission of a secondary π^+-meson of low energy. The π-particle, of energy 41·5 MeV, is identified by its observed decay $\pi \rightarrow \mu \rightarrow e$. The μ-meson is heavily scattered at point Q, as a result of Coulomb forces in a collision with a nucleus.

It is generally assumed that events of this type are due to an alternative mode of decay of the τ-meson $\tau^+ \rightarrow \pi^+ + 2\,\pi^0$, $Q = 84$ MeV. Confirmatory evidence for this interpretation might be obtained by determining the maximum energy E_π(max) of the π-mesons. This should extend up to 53 MeV, see Fig. 9–5, p. 305, a value appreciably greater than the corresponding maximum from the normal mode of decay; viz. $\sim$48 MeV.

Decay of a *K*-particle with the emission of a secondary π-meson.
Alternative mode of decay of the τ-meson

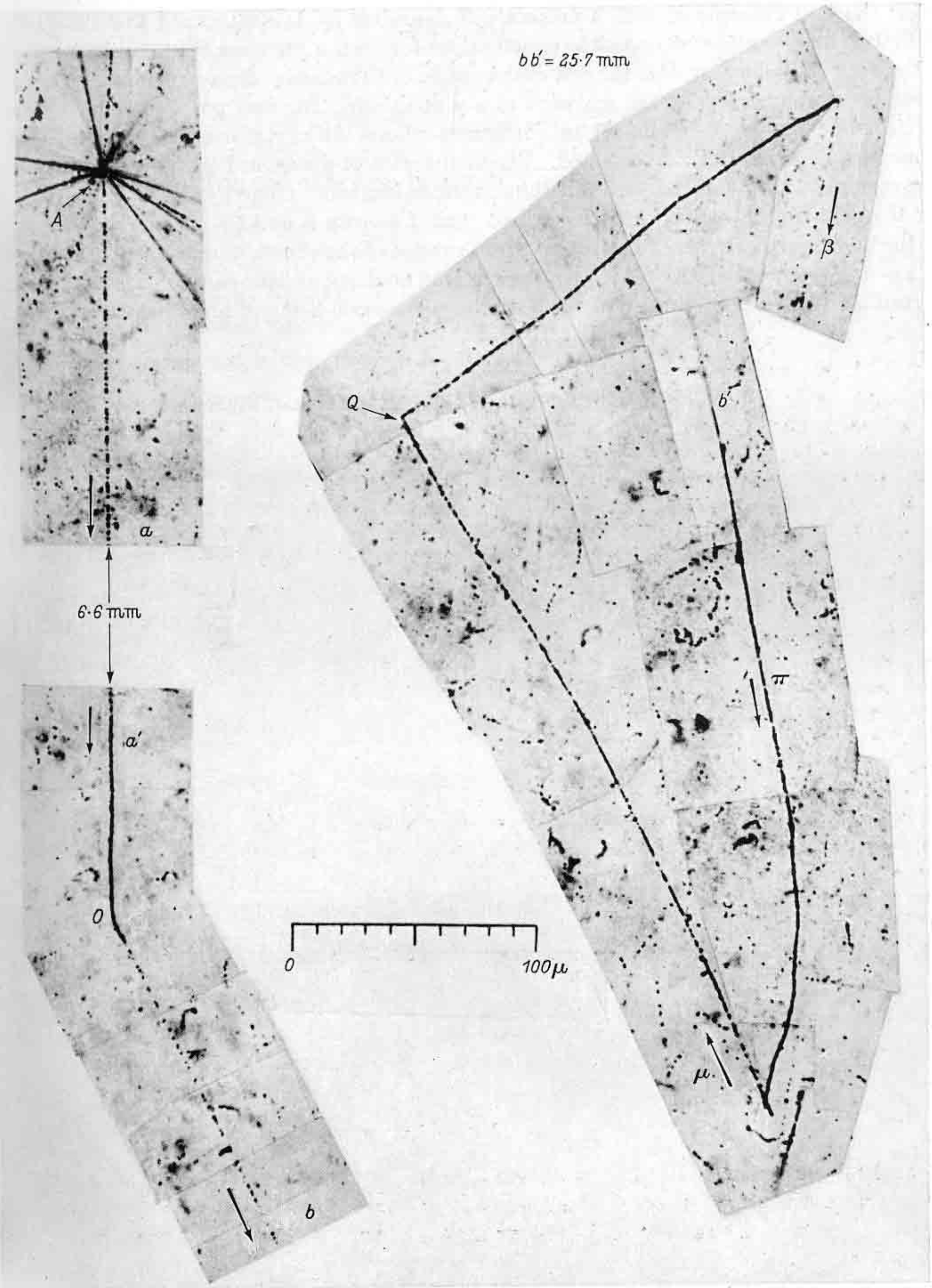


PLATE 9–9

Ilford G 5 emulsion.

DI CORATO, DILWORTH, and SCARSI; Nuovo Cim. Suppl. **11**, p. 285 (1954)

Radiative decay of the τ-meson; $\tau \rightarrow 3\pi + \gamma$

In most of the examples of the decay of a τ-meson in emulsion, the particle comes to rest and there is a balance of momentum with a release of energy equal to $\sim$75 MeV. Rarely, in emulsion, the τ-meson may decay in flight. A few events have been described, however, in which the meson appears to reach the end of its range, yet there is an absence of a momentum balance among the three secondary particles; the first example of such a process was described by DANIEL and YASH PAL (1954).

At first sight, there are two possible explanations for such a phenomenon; it might be attributed, either to decay in flight very near the end of the range, or to radiative decay in which the three charged π-mesons are accompanied by the emission of a γ-quantum. The two possibilities can, however, be distinguished in stacks of emulsion, in conditions where the energies and momenta of the three π-mesons can be accurately determined. For in the case of decay in flight, the total energy of the three π-mesons will, owing to the contribution from the kinetic energy of the parent τ-meson, be greater than the normal value for decay at rest; but if a γ-ray is emitted, it will be less.

By the above methods, it has been shown that several of the events in question are due to the emission of a γ-ray—to the 'radiative decay' of the τ-meson analogous to the similar process for the π-meson which results in a small proportion of the secondary μ-mesons being of low range; see p. 246.

Decay in flight of a K-meson in the τ-mode

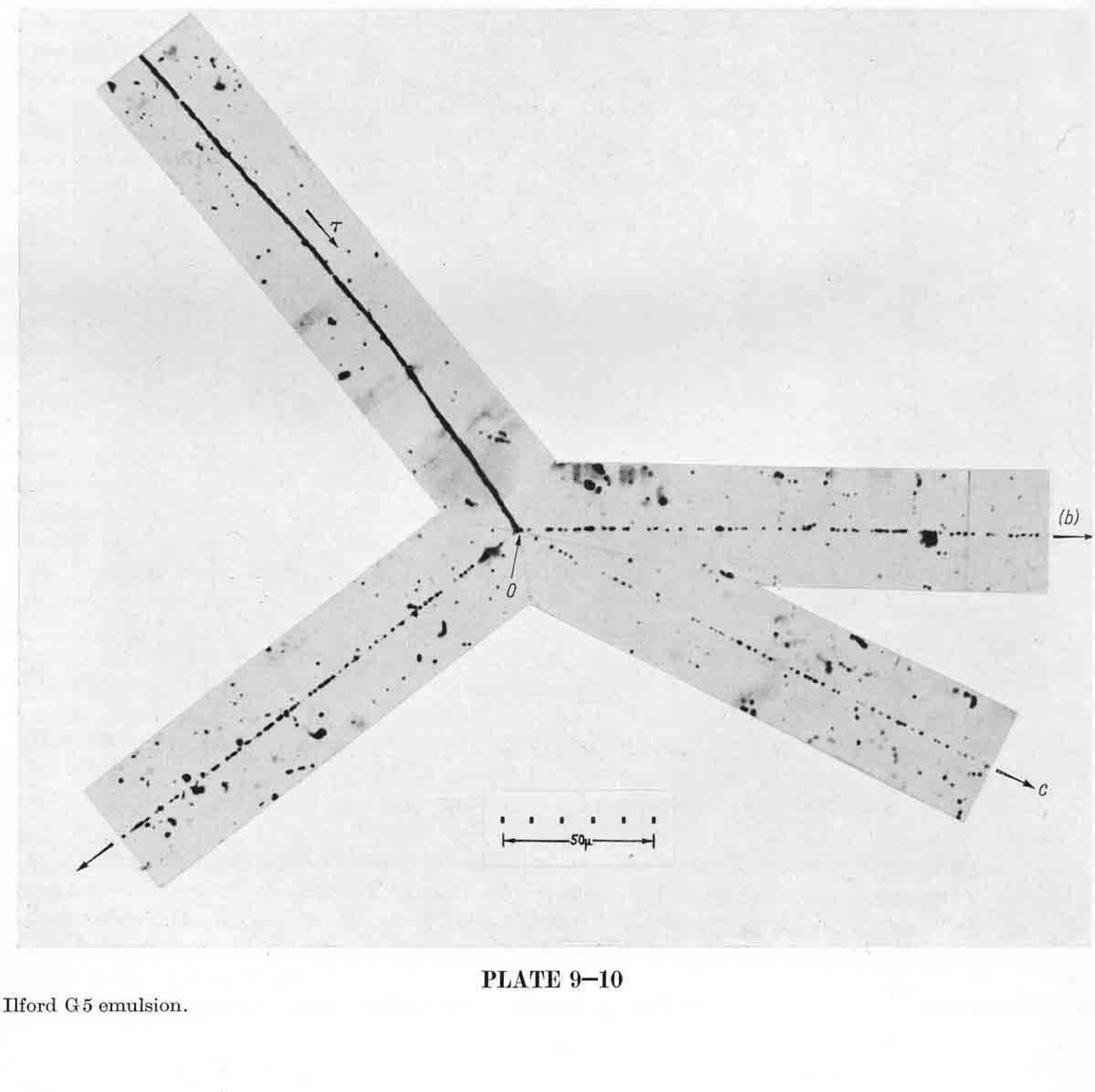


PLATE 9–10

Ilford G5 emulsion.

First observation of the decay 'at rest' of a charged *K*-meson

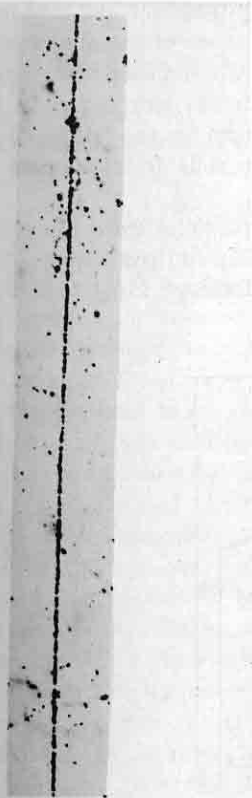
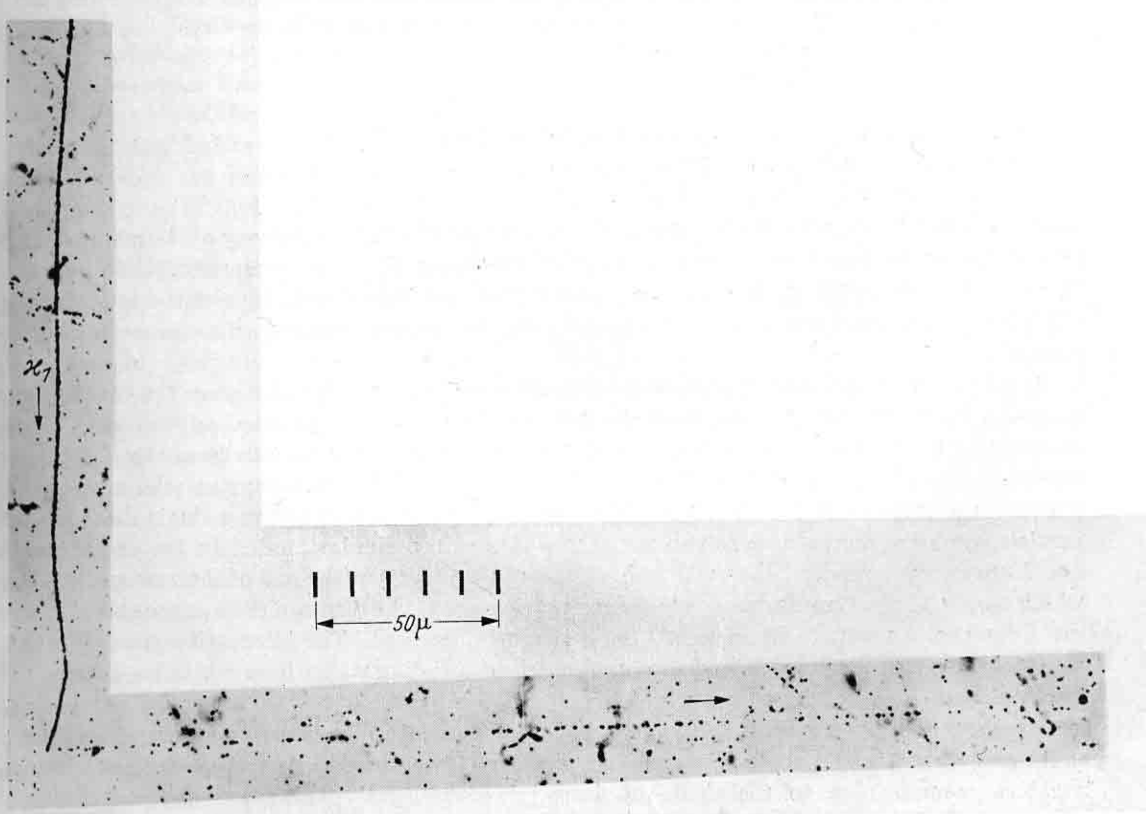


PLATE 10–1

Ilford G 5 emulsion.

C. O'Ceallaigh; Phil. Mag. **42**, 1032 (1951).

The 'event' was discovered during an experiment to determine the distribution in energy of the electrons emitted in the decay of μ-mesons. The secondary particle produced a track 2·2 mm long. The observed value of the scattering parameter, $\bar{\alpha}$, corresponded to a momentum of 250 MeV/c, i.e. a value several times greater than the maximum for the electrons formed in the β-decay of the μ-meson. The track of the primary particle, of length $\sim$4 mm, was therefore scrutinised, and measurements gave a value for the mass $\sim 1320 \pm 250\ m_e$. The nature of the secondary particle could not be established, but since its momentum is greater than the value for the π-mesons formed by decay in the $K_{\pi 2}$-mode, it may be assumed that the event represents the decay of a heavy meson into a μ-meson, or an electron. It is now recognised to be, most probably, an example of the mode $K_{\mu 2}$.



Decay of a *K*-meson

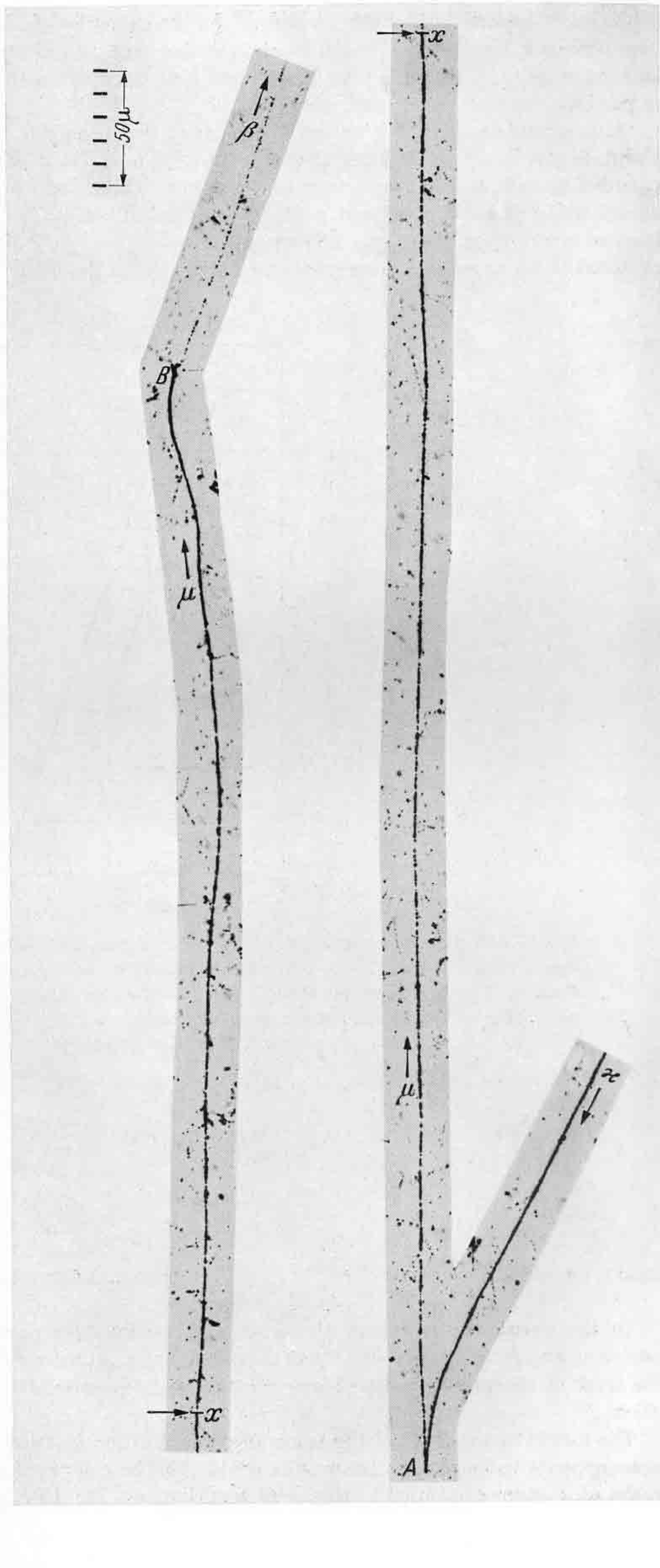
PLATE 10–2

Ilford G 5 emulsion.
C. O'Ceallaigh; Phil. Mag. **42**, 1032 (1951).

This photograph shows the second example of the decay of a heavy meson to be found in a photographic emulsion. It appears, at first sight, to represent the transformation $\pi \to \mu \to \beta$, but the μ-meson has a range of $\sim 1100\ \mu$, much greater than any value hitherto observed as a result of the decay of a π-particle at rest. Measurements on the track of the secondary particle showed the mass to be between 200 and 300 m_e. Taken in conjunction with its observed decay, presumably into an electron, this appeared to give decisive evidence that the secondary particle was indeed a μ-meson, for the direct β-decay of a π-meson had never been directly observed.

For the following reasons, it was very difficult to admit that the event represents the transformation $\pi \to \mu \to \beta$: There is indeed a small probability of a π-meson decaying before being brought to rest in an emulsion, and such a 'decay in flight' can produce a μ-meson of exceptional range—see p. 244—but for the range to be longer than the normal values, the μ-meson must be thrown forward, and not backward, in the line of motion of the parent particle. The evidence provided by the tracks strongly indicates, however, that the particle was either 'at rest' when it decayed, or that it was moving in a direction nearly opposite to that in which the μ-meson was ejected.

The evidence that the event was of a novel type was confirmed by measurements on the track of the primary particle which gave a value for the mass of $1125 \pm 200\ m_e$.



explanation appears improbable, however, for no examples of the process: $\tau^- \rightarrow \pi^- + \pi^+ + \pi^-$ have been observed for mesons arrested in an emulsion, and the alternative mode $\tau'^- \rightarrow \pi^- + 2\pi^0$ should be even more rare. Again it may be stressed that in experiments with magnetically analysed beams of particles, such ambiguities do not arise.

Although the form of the energy spectrum of the secondary particles is not yet sufficiently well known to give information about the accompanying neutrals, it shows that the $K_{\mu 3}$-mode is not to be regarded as the radiative decay of heavy mesons in the mode $K_{\mu 2}$, in a process analogous to those known to occur for both π- and τ-mesons; see pp. 246 and 308. This is indicated by the fact that, from such a process, the γ-rays are commonly of low energy. Further, the $K_{\mu 3}$-mode would then be expected to occur much less frequently, compared with the mode $K_{\mu 2}$, than is observed.

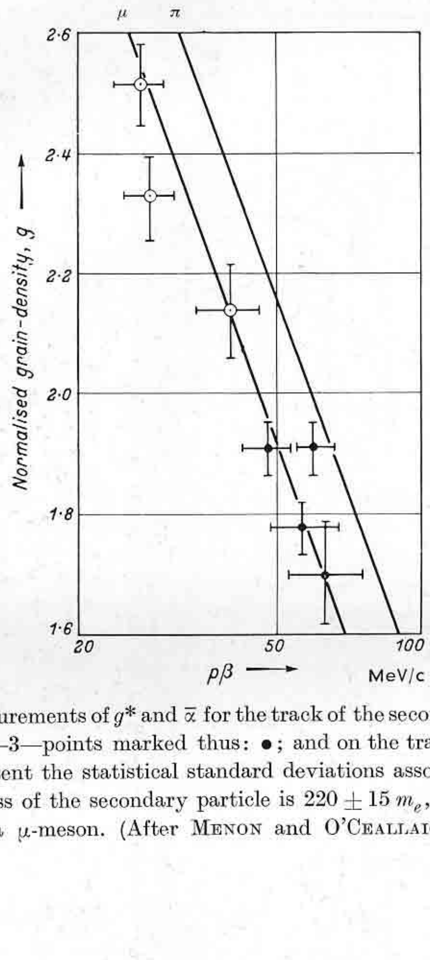


Fig. 10–2. Results of measurements of g^* and $\bar{\alpha}$ for the track of the secondary particle of the heavy meson shown in Plate 10–3—points marked thus: •; and on the track of a μ-meson—marked thus, ⊙. The bars represent the statistical standard deviations associated with each measurement. The estimated mass of the secondary particle is $220 \pm 15\, m_e$, very strong evidence that it was a μ-meson. (After MENON and O'CEALLAIGH 1954.)

PLATE 10–3

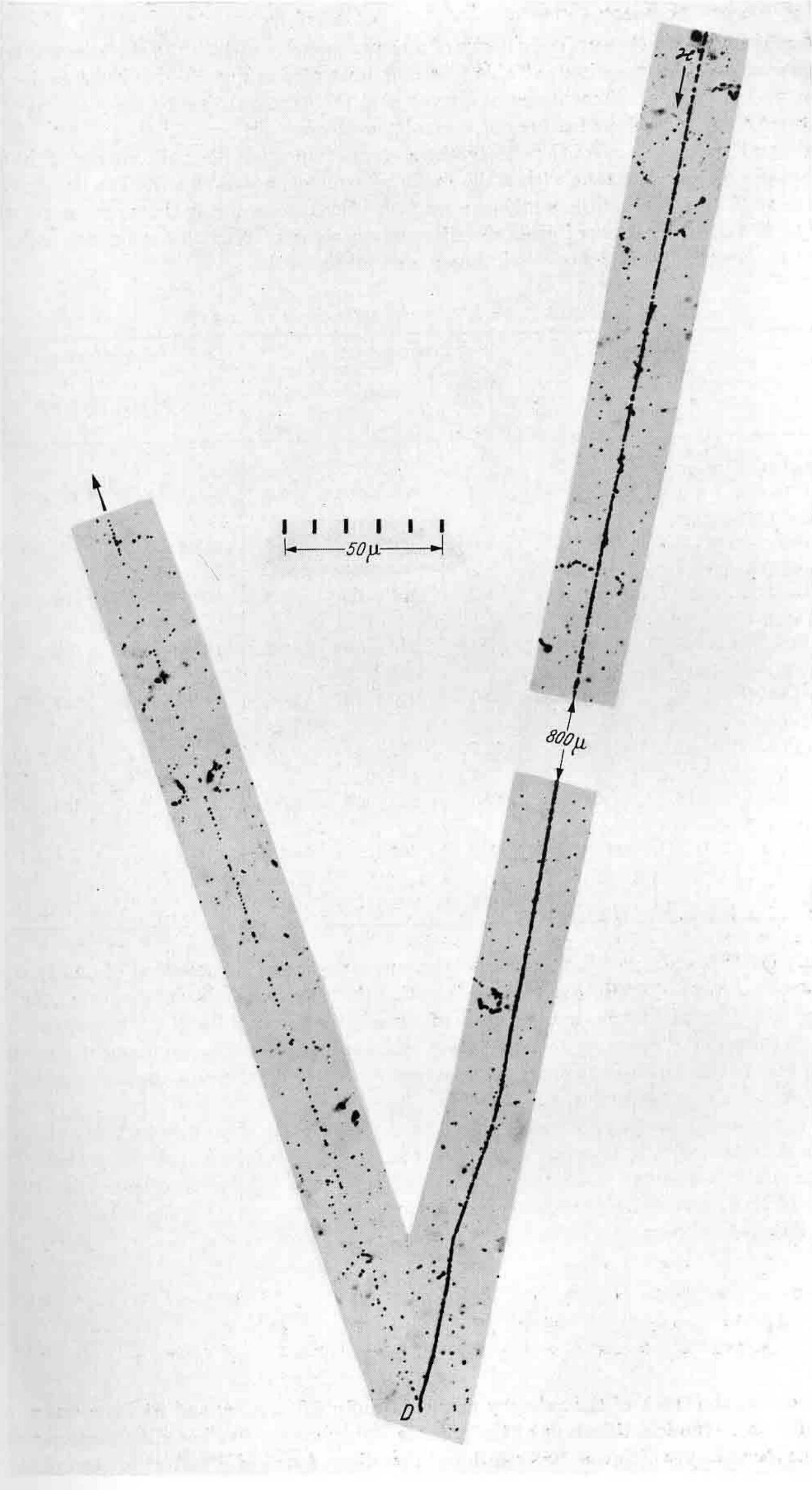
▶

Ilford G 5 emulsion. MENON and O'CEALLAIGH; Proc. Roy. Soc. A **221**, 292 (1954).

In this event, the length of the track of the secondary particle was 9 mm. Measurements of scattering and grain-density show that the particle was a μ-meson ejected with an energy of $\sim$34 MeV. The track of the primary particle was 1·5 mm long, and estimates of the mass gave the value $1000 \pm 400\, m_e$.

The length of the track of the secondary was sufficiently great to permit three independent mass measurements to be made. The results could then be compared with those obtained with the long tracks of μ-mesons recorded in the same emulsion; see Fig. 10–2 above.

Disintegration of a heavy meson in the mode $K_{\mu 3}$



b) The mode $K_{\pi 2}$ or χ; $K^+_{\pi 2} \rightarrow \pi^+ + \pi^0$

The early evidence for the two-body decay of a heavy meson, in which the single secondary charged particle is a π-meson, is summarised in Table 10–2 and illustrated in Fig. 10–3. It includes five examples, in addition to the original observations of MENON and O'CEALLAIGH (1953).

There were three important features of the early evidence:

In assessing the significance of the observations, it was important that the energy of the secondary particles appeared to be constant within the limits of error of measurement. The demands made by the problem on the precision of the methods were very exacting, requiring the most careful and critical approach to the determination of grain-density and scattering. Had the secondary π-mesons been distributed in energy, the evidence would have been much weaker.

Table 10–2. Early examples of the decay $\chi \rightarrow \pi + \pi^0$

Reference	Primary particle			Secondary particle		
	length of track (mm)	mass (m_e)	range (mm)	g^*	$p\beta$	mass (m_e)
a) MENON and O'CEALLAIGH Proc. Roy. Soc. A **221**, 292 (1954) . .	2·6	900 ± 200	7·6	1·14 ± 0·025	187 ± 17	
b) MENON and O'CEALLAIGH Proc. Roy. Soc. A **221**, 292 (1954) . .	0·6	1000	19·5	1·094 ± 0·016	162 ± 9	
c) MENON and O'CEALLAIGH Proc. Roy. Soc. A **221**, 292 (1954) . .	4·3	1200 ± 230	6·5	1·15 ± 0·03	172 ± 17	
d) BONETTI *et al.* Proc. Roy. Soc. A **221**, 318 (1954) . .	1·47	1340 ± 400	2·5	1·06 ± 0·04	200 ± 33	300 ± 50
e) BØGGILD, HOOPER and SCHARFF Nuovo Cim. Suppl. **12**, 223 (1954) . .	30·0	970 ± 210	58·0	1·02 ± 0·02	167 ± 8	
f) BALDO *et al.* Nuovo Cim. Suppl. **12**, 220 (1954) . .	42·5	964 ± 60	21·0		160 ± 10	270 ± 33
g) BALDO *et al.* Nuovo Cim. Suppl. **12**, 220 (1954) . .	36·5	943 ± 60	24·0		159 ± 9	276 ± 30
h) APPA RAO and MITRA Proc. Ind. Acad. Sci. **41**, 30 (1955) . .	5·0	937 ± 200	40·5		$E = 110 \pm 10$ MeV; interacts	
i) PADUA (1955)	16·6	965 ± 110	20·5		166 ± 15; interacts	

Secondly, after the discovery of charged hyperons, and the transformation of one type according to the equation $\Sigma^{\pm} \rightarrow n + \pi^{\pm}$, it was realised that there was the possibility of confusion, for the energy of the π-mesons formed by the decay at rest of such an hyperon is 94 MeV. It was not sufficient, therefore, to show that a decaying K-particle was more massive than the π-meson; it was necessary to prove also that it was less massive than the charged hyperon. In three of the four original examples of MENON and O'CEALLAIGH, this condition was observed.

In the examples (h) and (i) in Table 10–2, the identity of the fast secondary particle as a π-meson was made almost certain by its observed interaction with a nucleus which it disintegrated. The energy of the π-meson in these two events, as determined by scattering measurements, was 108 ± 5 MeV, and 106 ± 10 MeV, respectively, values which correspond to a mass of 967 ± 20 m_e for the χ-meson, assuming its mode of decay to be correctly represented: $\chi^+ \rightarrow \pi^{\pm} + \pi^0$.

PLATE 10–4

▶

In this event, the track of the primary particle is only 630 μ long, and its mass was estimated to be 1380 ± 600 m_e. The identification of the particle as a χ-meson was based on measurements of the track of the secondary which was 19·5 mm long. The observations of $\bar{\alpha}$ and g^* are shown in Fig. 10–3.

First observation of the disintegration of a heavy meson in the $K_{\pi 2}$-mode

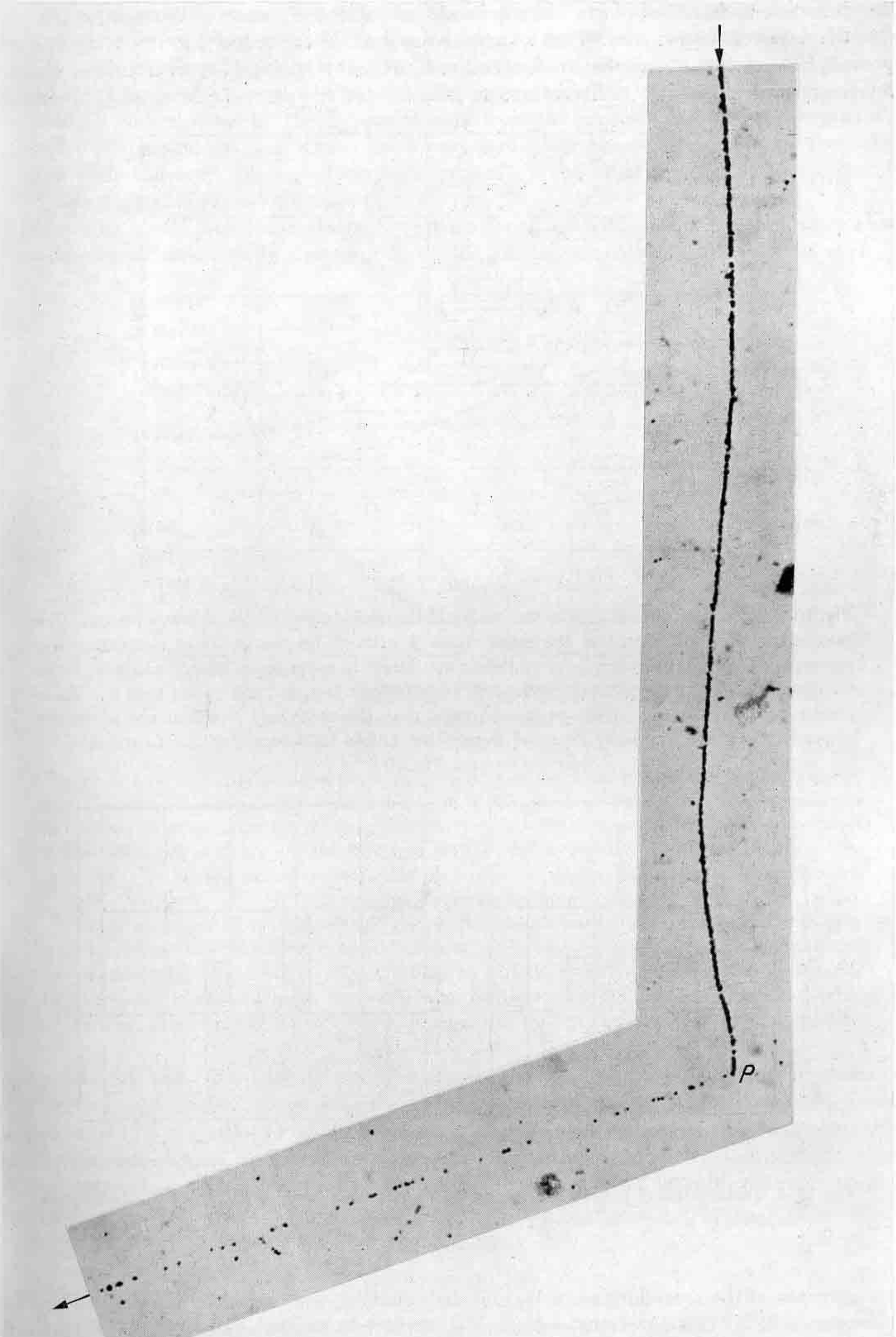


PLATE 10–4

Ilford G 5 emulsion.

MENON and O'CEALLAIGH; Proc. Roy. Soc. A 221, 292 (1954).

which decay in different modes; see Fig. 10–12. In particular, the mesons decaying in the τ-mode, of which the masses are accurately known from an application of the conservation laws, can be compared with the $K_{\mu 2}$, $K_{\pi 2}$ and other modes. This method is particularly powerful for, as emphasised in Sect. 5, any difference in mass causes a relatively large change in range, $\Delta M/M \sim 2\Delta R/R$, and the results are independent of small errors in the range-energy relation; see p. 164.

The results of an application of this method, due to BIRGE *et al.* (1956) are shown in Table 10–5 which gives the masses of the different types, assuming $m_\tau = 966\, m_e$. The table also includes the values deduced from the conservation laws. It may be seen that there is no significant difference between the results of the two methods; see p. 328.

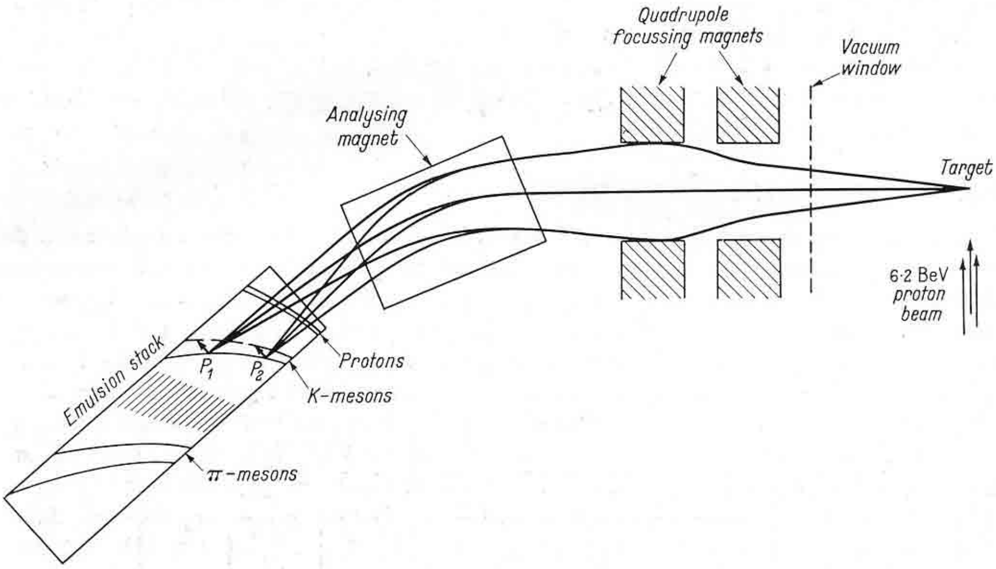


Fig. 10–11. Horizontal section through magnets and stack, to show disposition of apparatus for experiments to compare the masses of K-particles by the (p, R) method. The plane of the individual emulsions is vertical so that all the particles recorded in one plate are of approximately the same momentum, whilst the value slowly changes in passing across the stack (after BIRGE *et al*, 1956). The resulting difference in range of the different types of particles, and of the spread in range due to straggling and inhomogeneity in momentum, are indicated in the figure. The use of strong-focussing magnetic fields resulted in a great increase in the available intensities of secondary particles and was a technical advance of great importance.

In addition to determining the ratio of the masses of mesons decaying in the different modes, a comparison of each with the mass of the proton can also be made. The method is based on measuring the ranges of K-mesons and protons of nearly the same momentum. A small difference in the mean momentum between the K-mesons and protons at a given point of entry into the stack was present in the first experiments by this method. The protons and K-mesons differ in velocity and specific ionisation, and there are corresponding small differences in their loss of energy, and in their trajectories, in traversing the path in air through the magnetic fields. Such effects may be greatly reduced by interposing helium or hydrogen gas, contained in polyethylene bags, in the path of the particles.

PLATE 10–5 ▸

A heavily ionising particle emerges from the disintegration at the point A, and reaches the end of its range at the point B where it decays. The measured mass of the particle was $1150 \pm 200\, m_e$, proving it to be a heavy meson. The particle was emitted at an angle of 160° with respect to the line of motion of the parent particle which produced the original disintegration, and with an energy of $\sim$16 MeV. The track of the secondary particle is too short to allow significant measurements. The particle was recorded in plates exposed in high altitude balloon flights, made from Cagliari, Sardinia in June 1952.

First observation of the direct creation of a slow heavy meson

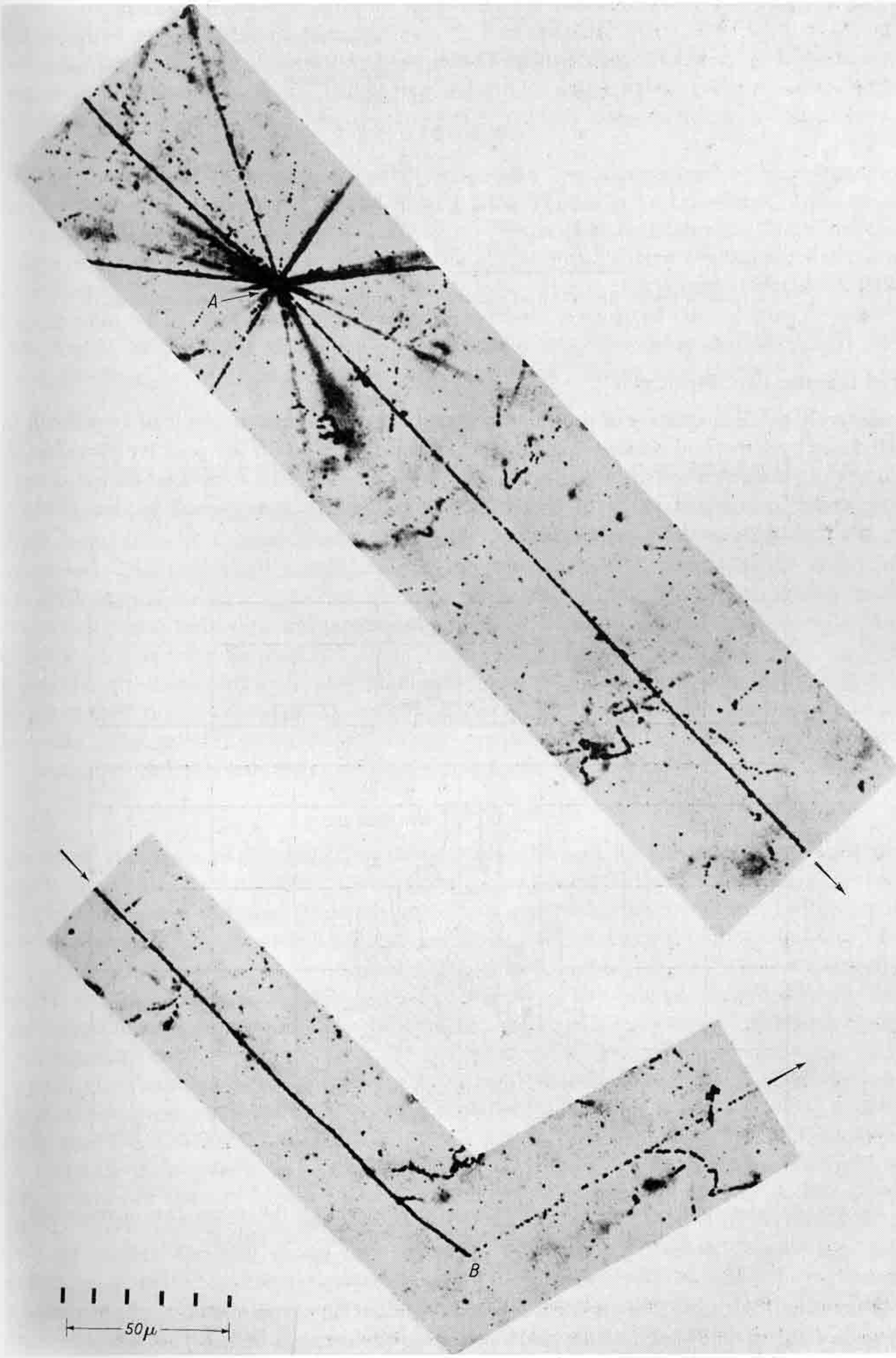
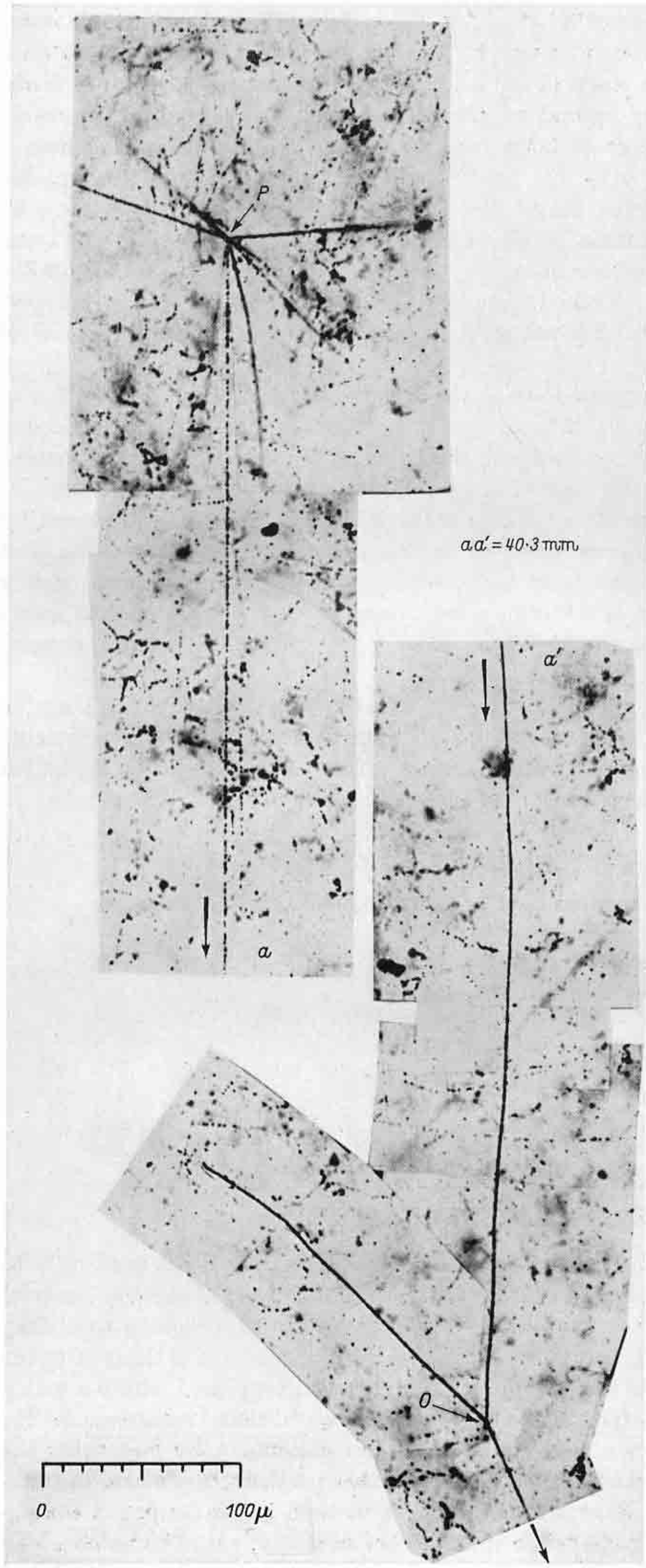


PLATE 10–5

Ilford G 5 emulsion. LEVI-SETTI and TOMASINI; Nuovo Cim. **9**, 1244 (1952).



This event was found during a re-examination and scrutiny of a large number of 'stars'. It was recognised that the particle '*a*' was approaching the point of disintegration *O*, and that its track was less scattered than one due to a π^--meson; cf. Plates 5–6 to 5–8. The particle was traced back to the parent 'star', *P*, and its measured mass was found to be $970 \pm 90\ m_e$.

The event is typical of those due to the nuclear capture of K^--mesons in which only a small fraction of the available energy appears among the charged products of the disintegration.

PLATE 10–7

Ilford G 5 emulsion.

di Corato, Locatelli, Mignone, and Tomasini; Nuovo Cim. Suppl. **12**, 270 (1954).

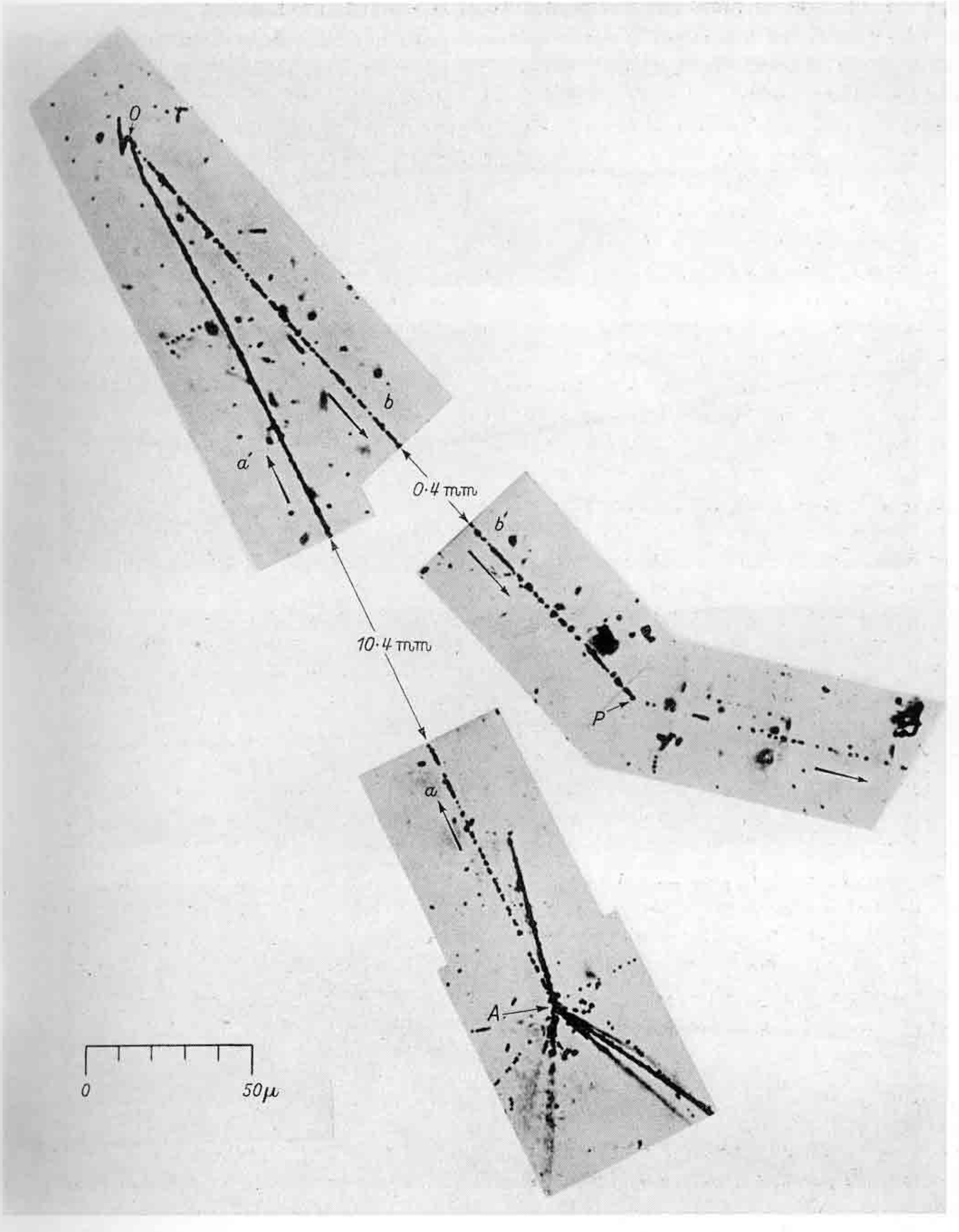


PLATE 10–8

Ilford G 5 emulsion. DI CORATO, LOCATELLI, MIGNONE, and TOMASINI; Nuovo Cim., **11**, Suppl. 2, 270 (1954).

This event was the first to be observed in which a charged hyperon is emitted from a disintegration produced by the nuclear interaction of a K^--meson at the end of its range. The measured mass of the K-meson was $1170 \pm 230\ m_e$. The hyperon decays, at the point P, into a secondary particle of which the track is too short to allow accurate measurements, but which can be shown to be less massive than a K-meson. If it is assumed to be a π-meson, the release of energy, Q, assuming the mode of decay to be $Y \rightarrow n + \pi$ is found to be 95 ± 20 MeV. The particle is therefore almost certainly of type Σ. The short track from O, heavily scattered, cannot be identified. The event provided valuable evidence for the close association of K-mesons and hyperons; see p. 338.

Stars due to the capture of K^--mesons in emulsion

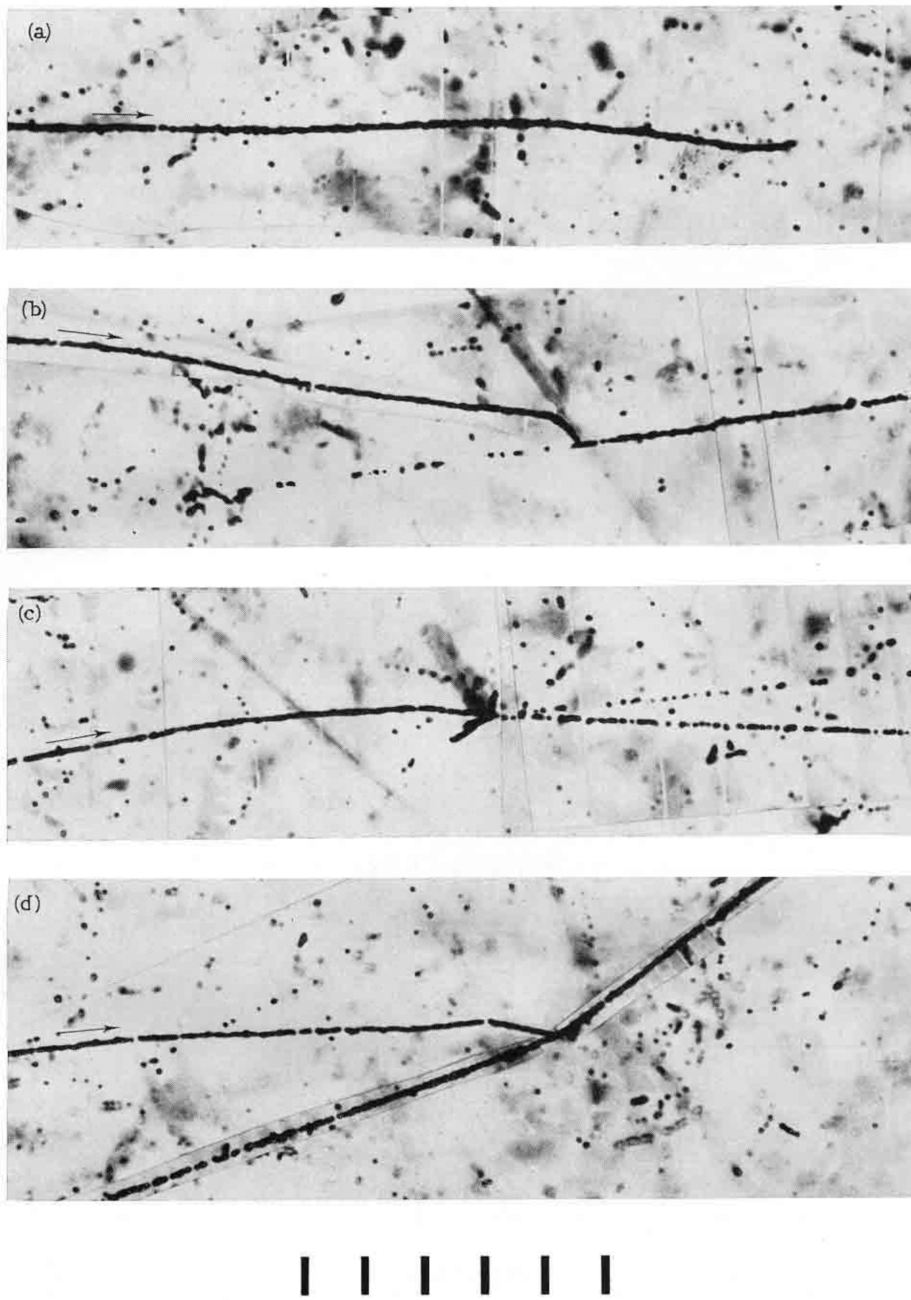


PLATE 10–9

Ilford G5 emulsion. Bristol (unpublished).

Four examples of the capture of K^--mesons by nuclei in emulsion.

In (a), no secondary charged particles can be distinguished; such events are sometimes designated K_ϱ.

In (b), a π-meson and a hyperon recoil from one another in opposite directions, the event represents the interaction with a free proton $K^- + p \rightarrow \Sigma^+ + \pi^-$.

In (c) and (d) are characteristic interactions accompanied by the emission of several singly charged particles.

Disintegrations due to the capture of K^--mesons by nuclei in emulsion

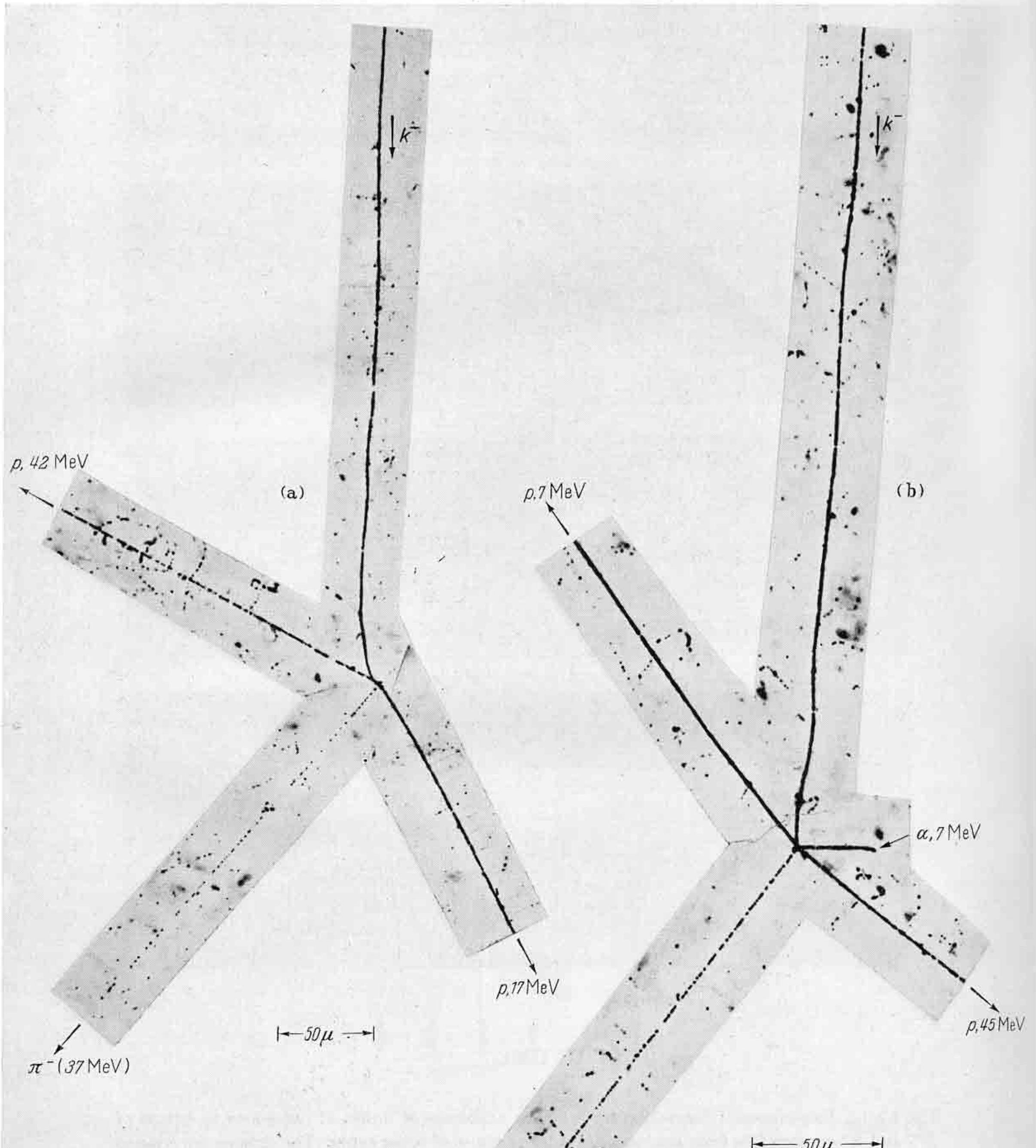


PLATE 10–10

Ilford G5 emulsion. Bristol (unpublished).

Sequence of events involving a negative **K^-**-meson

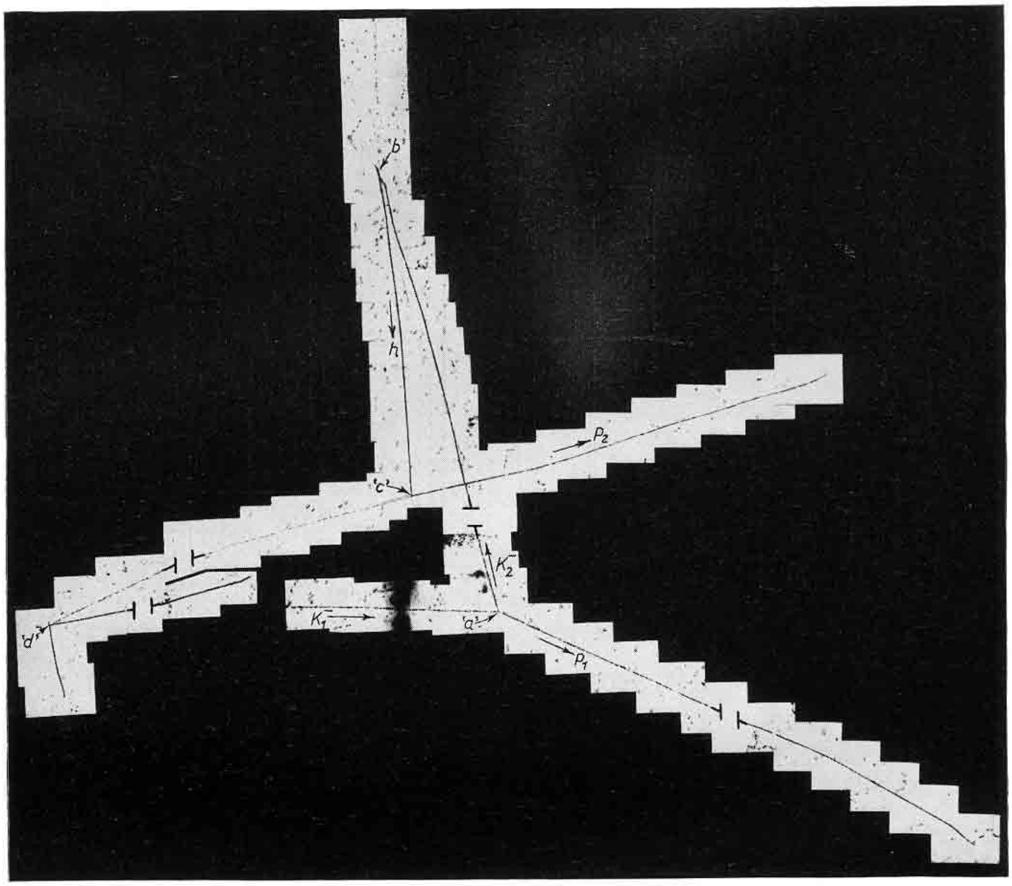
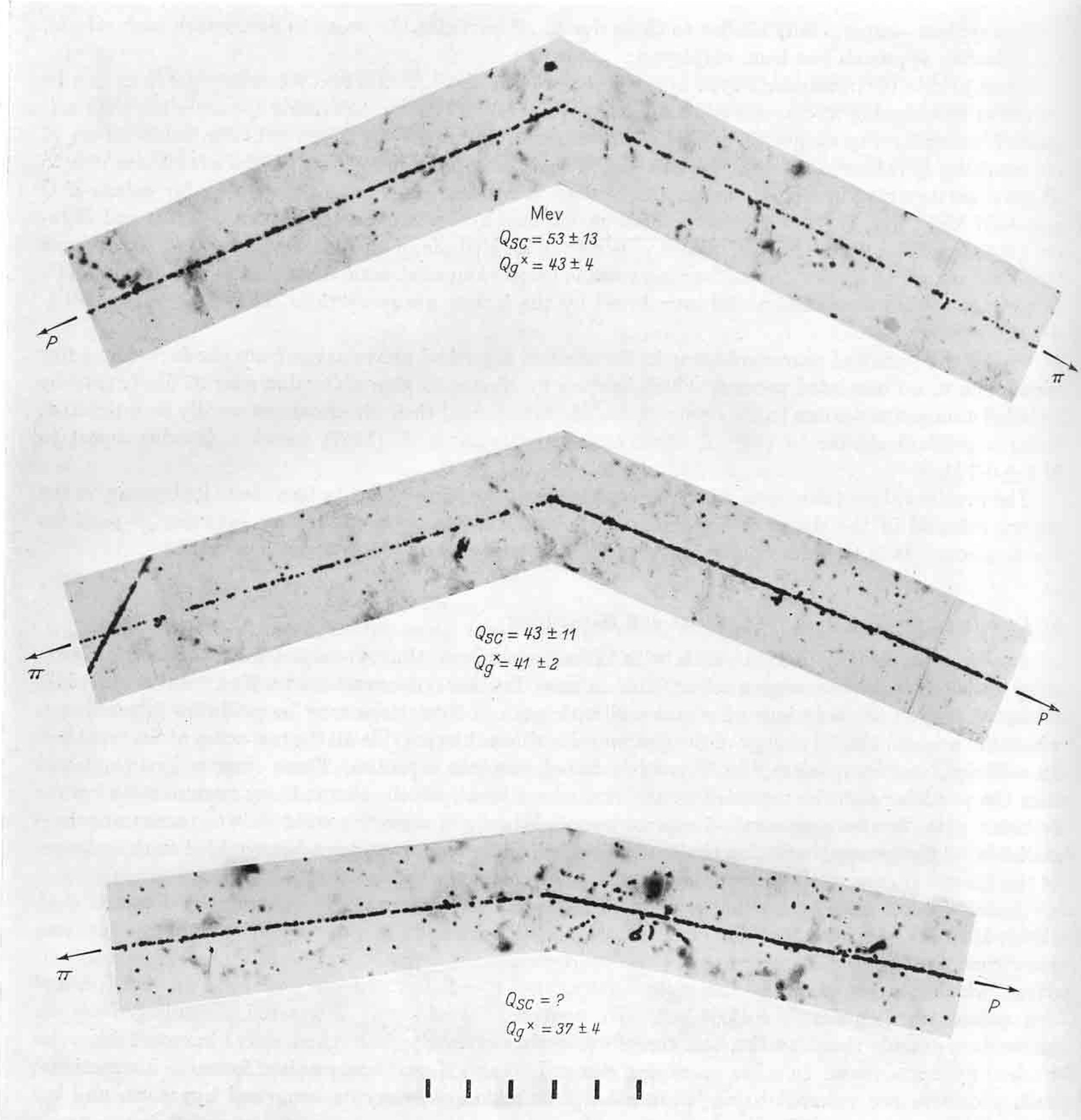


PLATE 10–11

Ilford G5 emulsion. OLIVER and LEIPELT.

A negative K-meson interacts with a proton at the point 'a' and projects it, track p_1, and itself recoils, coming to the end of its range at 'b'. Following the capture of the K^--meson by the nucleus of a light element in the emulsion, four charged secondary particles result. One of them is a hyper-fragment, track h, which reaches the end of its range at 'c' and there decays into a proton, track p_2, a second proton of very short range and a negative π-meson which is captured by a nucleus at 'd'. The hyper-fragment was probably either $_\Lambda He^4$ or $_\Lambda He^5$.



Ilford G5 emulsion. **PLATE 11–1** YASIN (1954).

Three early examples of the characteristic V-events due to the decay of low-energy Λ^0-particles. The observations were made in individual plates, and the proton and π-meson of each event were identified by the $(g^*, \bar{\alpha})$ method; see p. 162. The Q-values were then estimated either from the observed energies as determined by scattering, or from the observed grain-densities, the corresponding values being indicated as Q_{sc} or Q_g, respectively.

Much more precise values of Q can be determined in stacks of stripped emulsions where the energies can be deduced from the ranges of the particles; see p. 352, Fig. 11–1.

It may be remarked that most of the examples of the decay of Λ^0-particles found in stacks of emulsions have a wide angle between the directions of emission of the proton and the meson. This follows because the observed Λ^0-particles are of low energy; if of higher energy, the secondary π-mesons have a large probability of escaping from the stack. In those methods of search for Λ^0-particles which depend upon following back a π^--meson to its point of origin, high energy events are therefore found only rarely.

First observations on the decay of Σ-particles

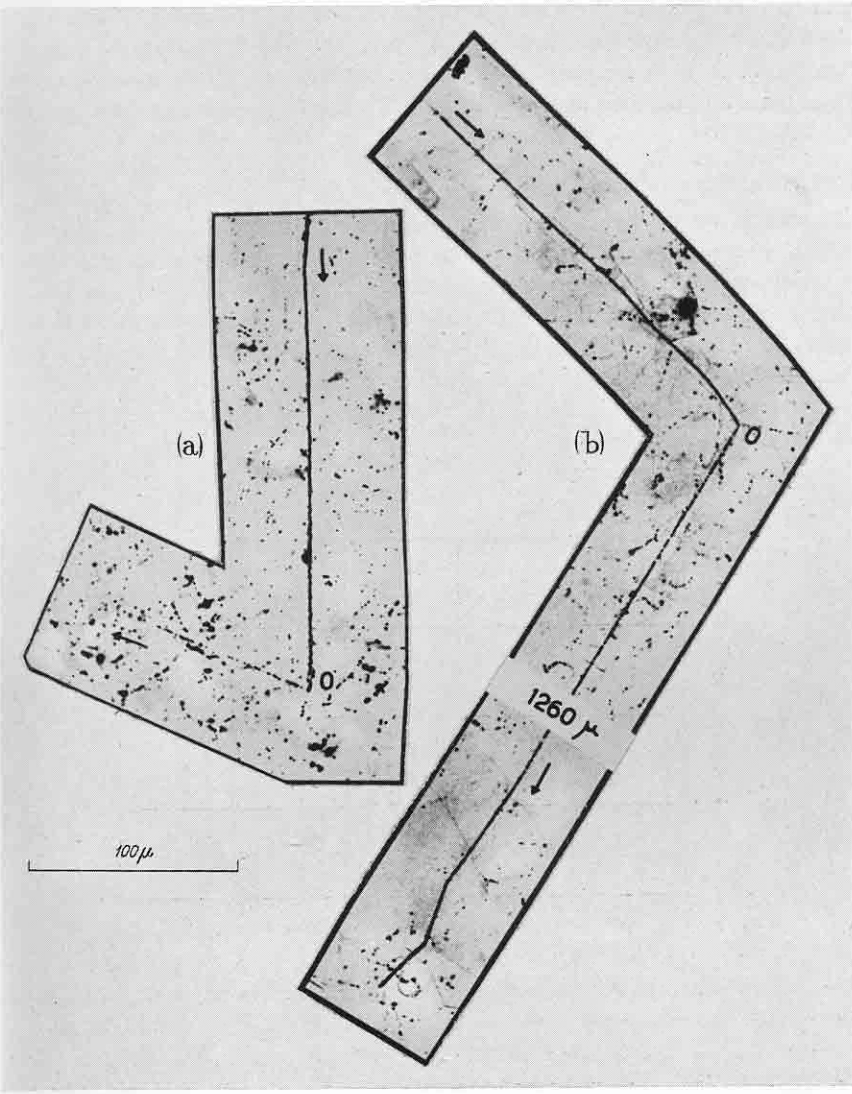


PLATE 11–2

Ilford G 5 emulsion. BONETTI, LEVI-SETTI, PANETTI and TOMASINI (1953).

The event (a) shows the first tracks identified as due to the decay of a hyperon; a particle comes to rest at O and decays with the emission of a fast secondary. The observation was made before the introduction of stripped emulsions, and the track of the secondary was too short (120 μ) to permit a definite identification. It was possible to show, however, that the particle, of minimum ionisation, was not an electron. The identification of the primary was made by mass measurements on its track which was ~1 cm long. The value thus obtained was 2500 ± 345, thus making it reasonable to exclude an interpretation in terms of the decay of K-mesons.

The event (b) shows the first example of the decay of a Σ^+-particle according to the equation $\Sigma^+ \rightarrow p + \pi^0$. The observed range of the proton was $1{\cdot}67 \pm 0{\cdot}02$ mm and the computed mass of the parent particle $2320 \pm 6\, m_e$, assuming the above mode of decay. The value determined by scattering measurements using the constant-sagitta method was $2500 \pm 620\, m_e$.

3. MASSES OF Σ^+ AND Σ^--HYPERONS

Experiments to establish the detailed properties of the Σ-particles were greatly assisted by the artificial production of homogeneous beams of K^--mesons. We have seen—see p. 338—that Σ-particles were then found to be a frequent product of the nuclear capture of K^--mesons, and accurate determinations of mass and lifetime became possible. The methods employed are as follows:

a) From an analysis of the modes of decay

Using K^--mesons as a source of Σ-particles, the early evidence for the modes of decay $\Sigma^+ \rightarrow p + \pi^0$, or $\Sigma^+ \rightarrow n + \pi^+$, $\Sigma^- \rightarrow n + \pi^-$ was confirmed, and it was shown that the two modes of decay of the positive particles occur with nearly equal frequency; see Fry *et al.* (1957) and Barkas *et al.* (1957). The measurements on the energy of emission of the charged secondaries allowed the masses of the parent particles to be determined. Thus, Fig. 11–2 shows the distribution in range of the protons found in early examples of the decay at rest of the Σ^+-particle in the mode $\Sigma^+ \rightarrow p + \pi^0$. The mass thus deduced is $2327 \pm 1\ m_e$, in accord with the less accurate value found by measuring the energy of the charged π-meson formed in the mode $\Sigma^+ \rightarrow n + \pi^+$.

(Continued at top of page 360)

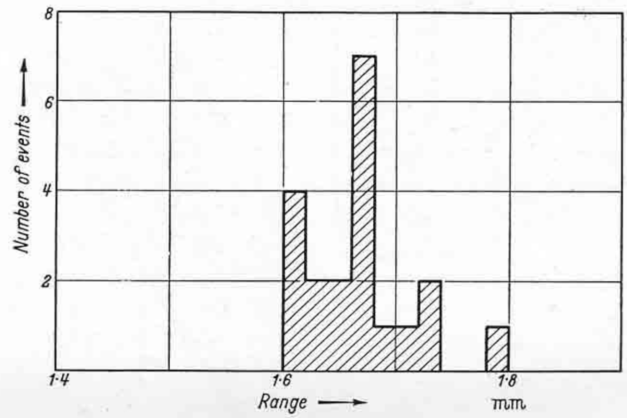


Fig. 11–2. Distribution in range of protons produced in the first twenty events attributed to the mode of decay:

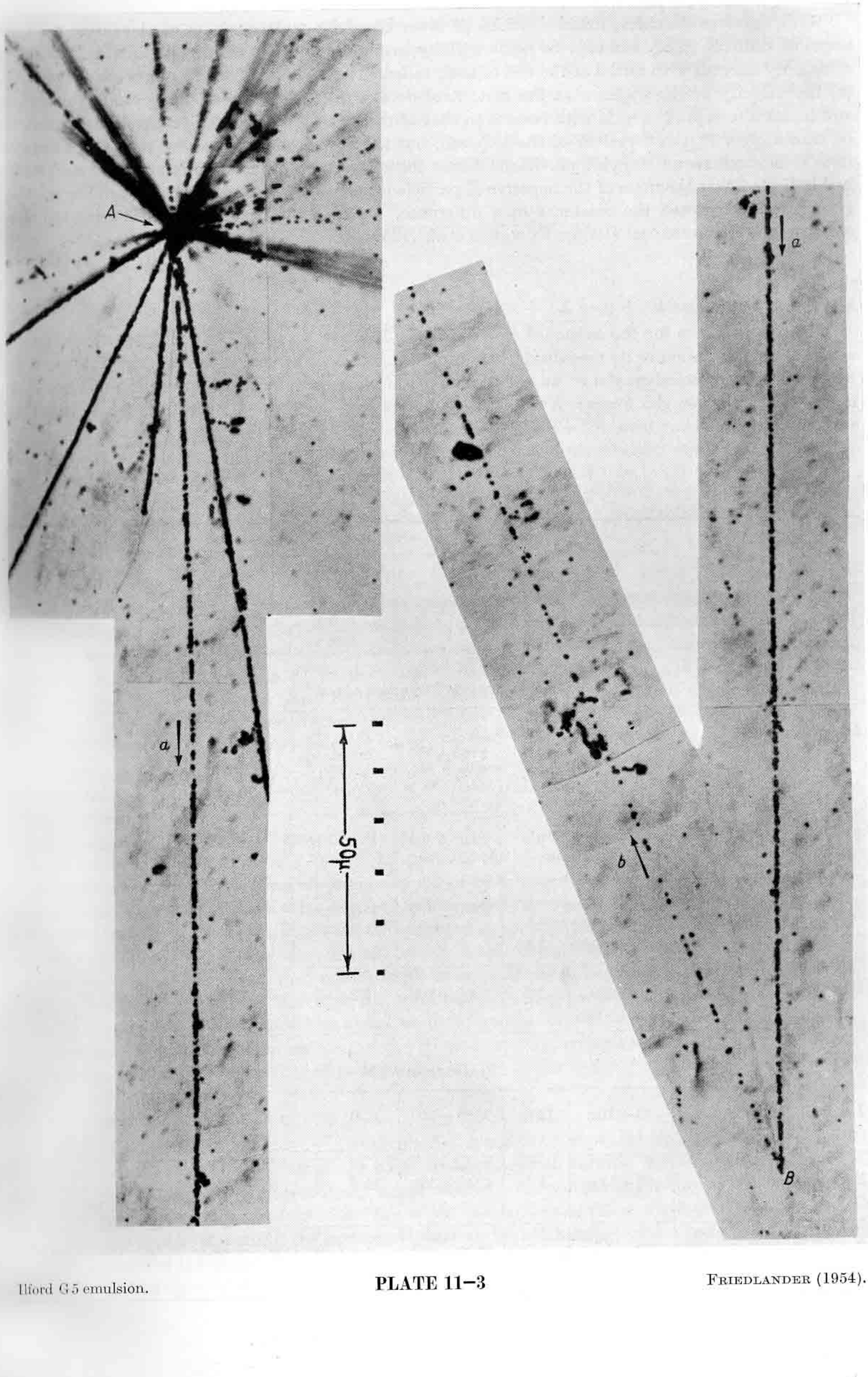
$$\Sigma^+ \rightarrow p + \pi^0.$$

The presence of a homogeneous group of secondary particles is well displayed. The spread in the values is a little greater than that expected, for a strictly homogeneous group, from 'straggling' alone. This effect may be due, at least in part, to variations in the density of the emulsions employed; the values of the density were commonly not stated.

PLATE 11–3. Early example of the decay in flight of a charged hyperon ▸

The charged hyperon, track *a*, is emitted from the star *A*, and after a path of 4·7 mm decays 'in flight' at the point *B*. Its mass as determined by the ($\bar{\alpha}$, g^*) method is $2760 \pm 500\ m_e$. The greatly increased speed of the secondary particle, track *b*, as compared with that of the primary, is made manifest by the difference in grain-density in the two tracks. The secondary 'dips' too steeply to allow accurate scattering measurements, but it can be established that the particle is less massive than a proton. Assuming it to be a π-meson, its energy can be deduced from the grain-density. The Q-value for a reaction of type $\Sigma^{\pm} \rightarrow n + \pi^{\pm}$ can then be computed. The value thus obtained was $\sim$ 100 MeV.

Early example of the decay in flight of a charged hyperon



Ilford G5 emulsion.

PLATE 11–3

FRIEDLANDER (1954).

the reaction $K^- + p \rightarrow \Sigma + \pi$ is observed shows that all, or a very large fraction, of the K^--mesons captured by free protons in emulsion do interact with them. It follows that a process analogous to that occurring with π-mesons does not occur, or is infrequent.

The above result shows that in its lowest orbit round a proton, a K^--meson interacts more rapidly than does a π^--meson. This may be partly due to the smaller 'radius' of the orbits of the K-meson, due to its greater mass, and the increased probability that the meson will be in the immediate neighbourhood of the proton; but it strongly suggests that the K-meson interacts with the proton not less strongly than does the π-meson.

Similar observations of the interaction of K^--mesons with free hydrogen have been made in experiments with bubble-chambers—particularly with hydrogen bubble-chambers—and have given similar results, although the precision with which masses can be deduced is considerably less than in work with emulsion. The most striking advantage of the bubble-chamber is made apparent in experiments with the neutral particles, particularly in the proof of the existence, and studies of the properties, of the K^0- and Σ^0-particle; see p. 369. This allows the relative frequency of the reactions giving different hyperons to be determined. It has thus been shown by ALVAREZ *et al.* (1957) that the hyperons resulting from the capture of K^--mesons by protons, are produced in the approximate proportions $\Sigma^-:\Sigma^+:\Sigma^0:\Lambda^0 = 4:2:2:1$, a result which has an important bearing on the isotopic-spin states operative in the reactions; see, for example, FRANZINETTI and MORPURGO (1957).

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STEINBERGER; Rochester Conf. p. VI—23 (1956); see also BUDDE *et al.*; Phys. Rev. **103**, 1827 (1956).
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PLATE 11–4

▶

These two events were the first to be interpreted as due to the nuclear interaction of negative hyperons Σ^-. Both particles are emitted from 'stars' and reach the end of their ranges in the emulsion. The track length of the primary particle of event A is 7 mm and the estimated mass of the particle $2250 \pm 400\, m_e$. Two charged secondary particles appear to be emitted from the point D, one, s, of very short range; the other, t, dips steeply in the emulsion and appears to be a proton. The event is therefore attributed to a nuclear interaction.

In event B, the measured mass of the primary particle which originates in a star and produces a track, b, 4·6 mm long, is $2440 \pm 300\, m_e$. The secondary particle, emitted from the point E, has a mass near or equal to that of the proton, and an energy certainly greater than 50 MeV. This follows from the observed length of the track, observations on scattering, and the grain-density at the point of exit from the stack. For reasons discussed on p. 364, the event is attributed to the nuclear capture of a negative hyperon rather than to the spontaneous decay of the particle.

First observations of the nuclear capture of negative hyperons

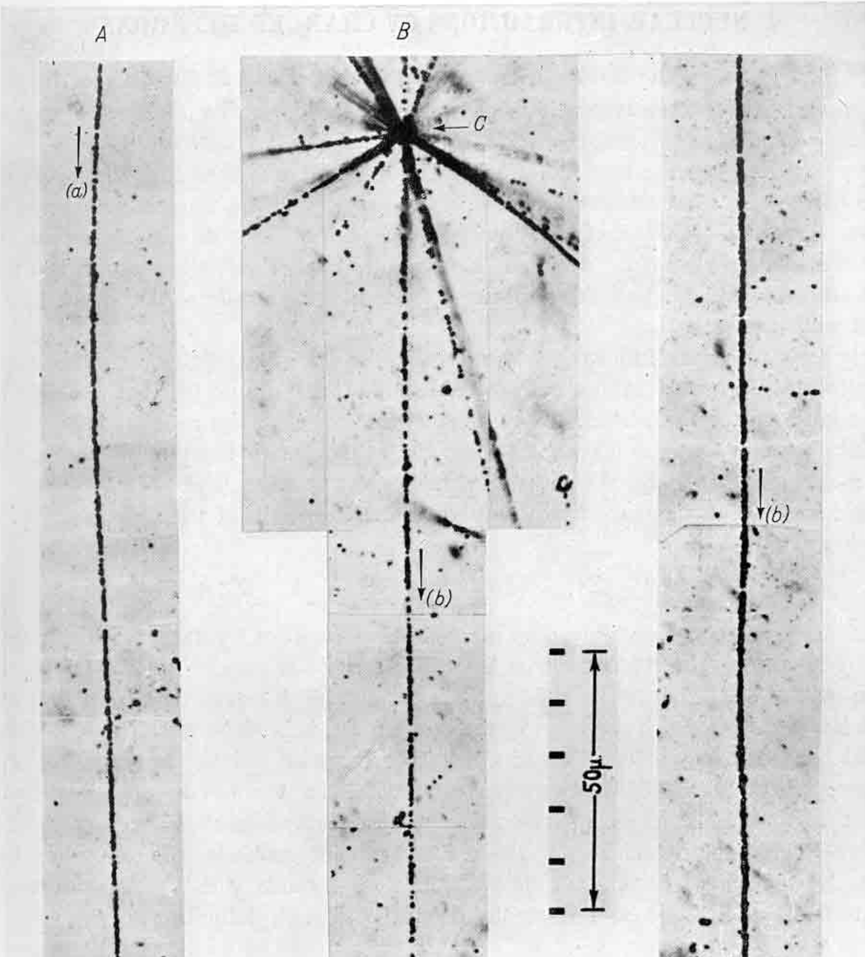

PLATE 11–4

Ilford G5 emulsion.

(A) Johnston and O'Ceallaigh (1954). (B) Friedlander (1954).

4. NUCLEAR INTERACTIONS OF CHARGED HYPERONS

a) Early observations

Two of the early events involving charged hyperons could not be attributed to the decay of a particle of mass $\sim 2330\,m_e$ in either of the modes discussed above. In that from Dublin—see Plate 11-4—two secondary particles appeared at the end of the range. It was therefore suggested that the event corresponded to the effects of an interaction of a Σ^--particle with a nucleus. In the event Bristol (2) Table 11-2—see Plate 11-4—the secondary particle was a proton with an energy of 100 ± 15 MeV. If it represented the spontaneous decay of a hyperon, $Y \to p + \pi^0$, the mass of the parent particle must have been $\sim 2900\,m_e$. It therefore appeared preferable to attribute this event also to a nuclear interaction of a Σ^--particle.

These early examples were followed by many others which allowed the general features of the disintegrations produced by Σ^--particles to be established. It was found (a) that in about a third of the events, an energetic proton is emitted, $E \sim 30$ to 100 MeV, (b) that the number of 'prongs' associated with the disintegrations is commonly small—less than that due to the nuclear capture of π^--mesons, and (c) that π-mesons are rarely, if ever, emitted.

The above features can be readily explained if it is assumed that the essential interaction is one of charge-exchange:

$$\Sigma^- + p \to n^0 + \Sigma^0; \qquad \Sigma^0 \to \Lambda^0 + \gamma; \qquad \text{or} \qquad \Sigma^- + p \to n + \Lambda^0.$$

Proof that such reactions do indeed occur following capture by free protons was provided by experiments by ALVAREZ *et al.* (1957), with a hydrogen bubble-chamber; see p. 369. If such a process occurs within a nucleus, the Λ^0-particle failing to escape from it, the resulting disintegration should be similar to that of a hyperfragment. Support for this picture was provided by two observations in which the nuclear interaction of a negative hyperon led to the emission of a hyperfragment; see CECCARELLI *et al.* (1955); SCHEIN *et al.* (1955). In the event described by SCHEIN, the hyperfragment was a ${}_{\Lambda}H^4$-nucleus. Further, since any observed nuclear interaction of the hyperon must be with a nucleus for which $Z \gtrless 6$, the resulting disintegrations will commonly be of the type referred to as 'non-mesic' (see p. 392). The absence of secondary π-mesons and the presence of energetic protons, characteristic of 'non-mesic' decay, is thus explained.

b) Characteristics of the disintegrations due to the capture of Σ⁻-particles

We have seen that the nuclear capture of K^--particles frequently leads to the emission of Σ-particles, some of which may be positively charged, some negative. In order to make a detailed study of the disintegrations due to K^--capture, and the nature of the primary interactions, it was therefore necessary to identify the secondary Σ-particles with high efficiency.

In the case of Σ^+-particles which decay at the end of the range, identification can usually be based on measurements on the secondary particles. For the decay mode $\Sigma^+ \to p + \pi^0$, recognition is easy; for the mode $\Sigma^+ \to \pi^+ + n$, attention must be paid to the conditions of the experiment, and the efficiency with which tracks of low grain-density are detected for various values of the 'dip'; but there are no

(Continued at top of page 366)

PLATE 11–5. Effects observed at the end of the range of Σ⁻-hyperons ▶

Characteristic phenomena observed at the end of the range of Σ^--hyperons due to Auger electrons and the disintegration of the capturing nucleus.

(a) A rare example from which three charged secondary particles are emitted by the disintegrating nucleus;

(b) Auger electrons;

(c) Chance juxtaposition of tracks of an electron and a proton;

(d) Single charged secondary particle; and

(e) Two charged secondaries.

Effects observed at the end of the range of Σ^--hyperons

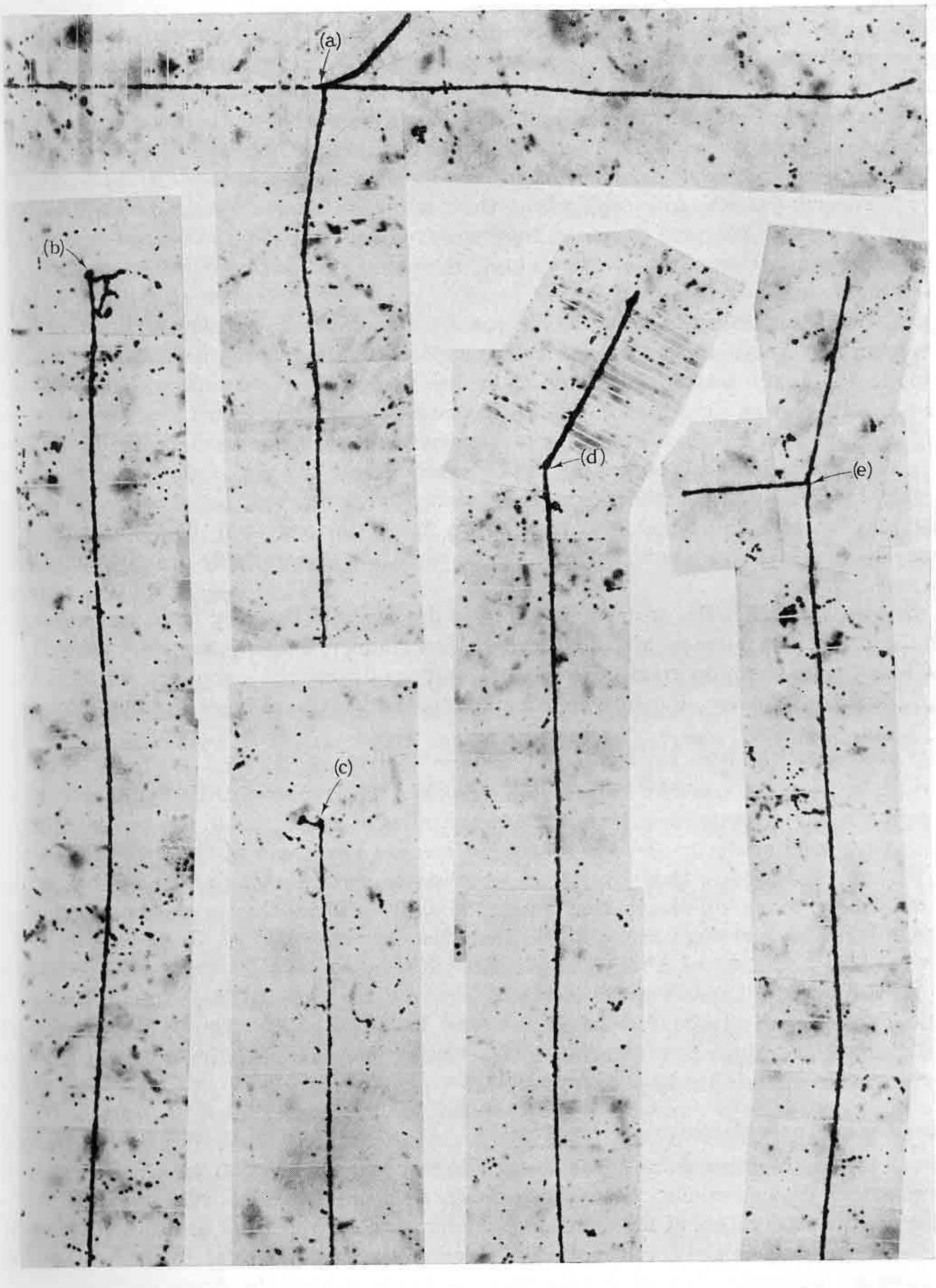

PLATE 11–5

Ilford G5 emulsion.

Bristol (1958) (unpublished).

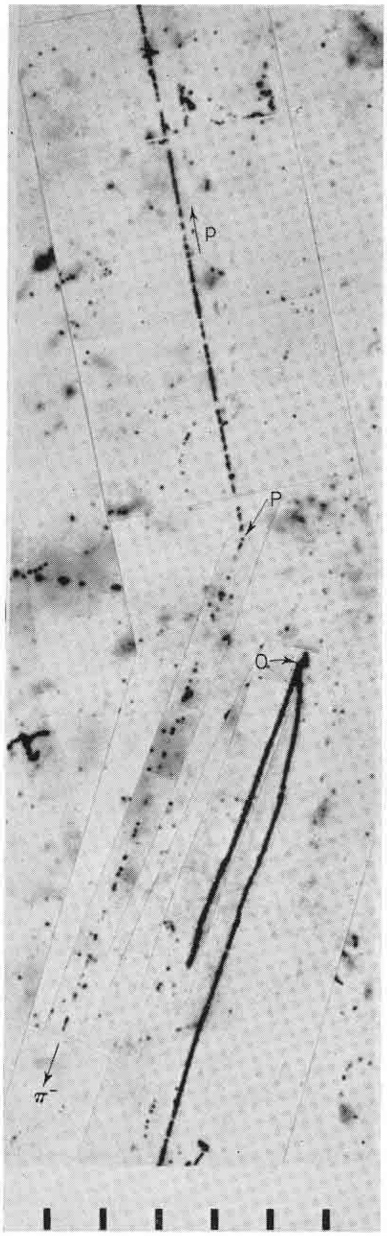

PLATE 11–6

Λ^0-decay associated with K^--capture

This event was found in a stack of K5 emulsions exposed to a beam of K^--mesons from the Berkeley bevatron. A K^--meson reaches the end of its range at the point O, and is captured by a nucleus. From the resulting disintegration, a single heavily ionising particle is emitted. An associated short recoil track, or an Auger electron, can also be distinguished. In addition, a Λ^0-particle was produced which, after travelling 26 μ, decayed into a proton and π^--meson at the point P. The centre of disintegration due to the nuclear capture of the K^--meson lies in the plane containing the tracks of the π^--meson and proton from the decay of the Λ^0-particle, to within the limits of error of measurement. Further, the momenta of the π-meson and of the proton, transverse to the assumed line of flight of the Λ^0-particle, are equal and opposite. Evidence for the association is thus very strong. The π^--meson was clearly identified by a 'star' it produced at the end of its range. The energies of the π-meson and the proton, as determined from their ranges, were $28{\cdot}4 \pm 0{\cdot}5$ MeV, and $23{\cdot}1 \pm 0{\cdot}2$ MeV, respectively, and the angle between their directions of motion $120 \pm 1°$. The corresponding Q-value for the Λ^0 decay is then found to be $36{\cdot}7 \pm 0{\cdot}6$ MeV, and the kinetic energy of the Λ^0-particle only 15 MeV.

Ilford K5 Emulsion. Bristol (unpublished).

Associated production of a *K*-meson and an hyperon

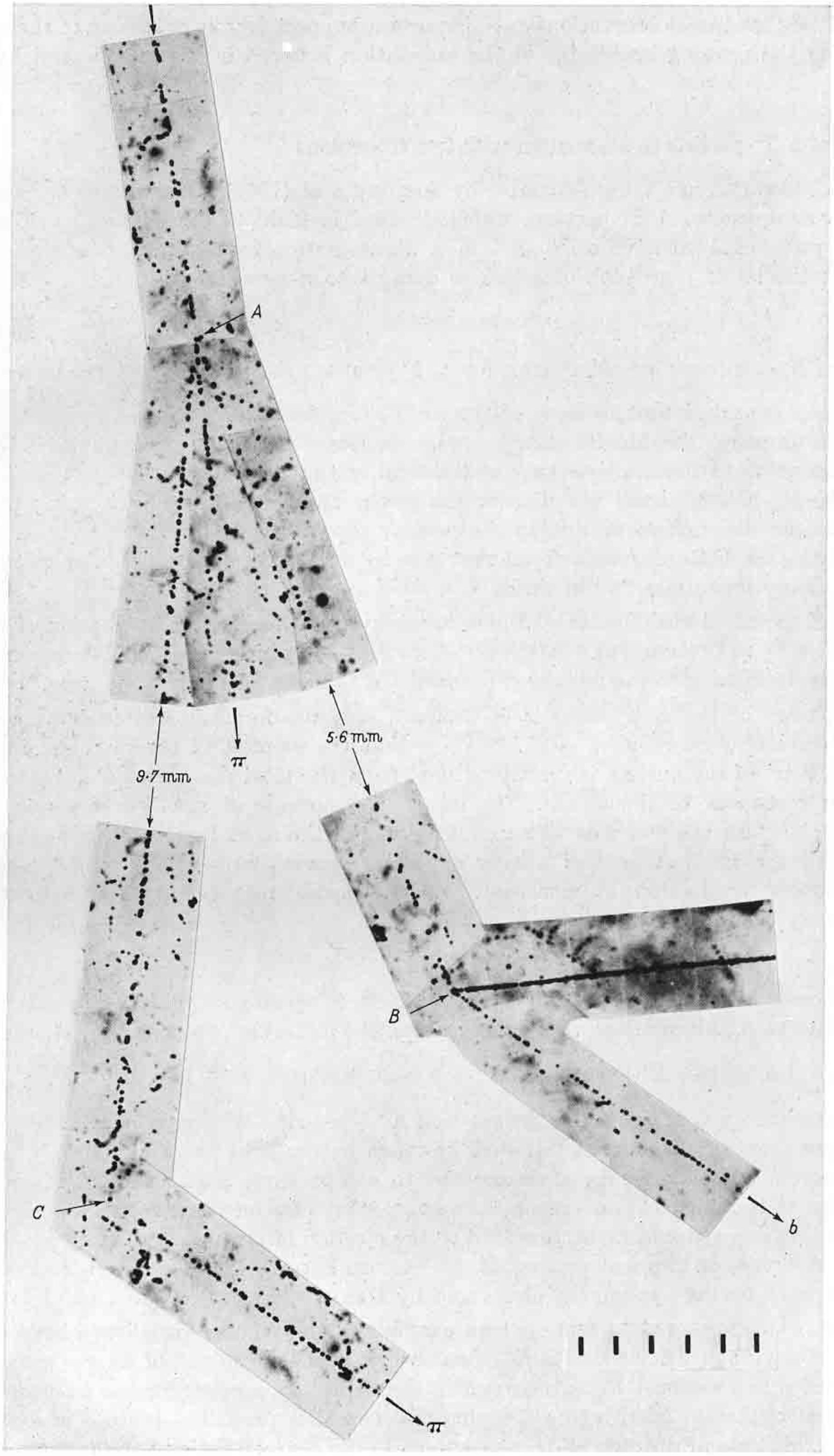

PLATE 11–7

Ilford G 5 emulsion.

FRIEDLANDER, KEEFE, and MENON; Nuovo Cim. **1**, 694 (1955).

Nuclear interaction of a fast *K*-meson

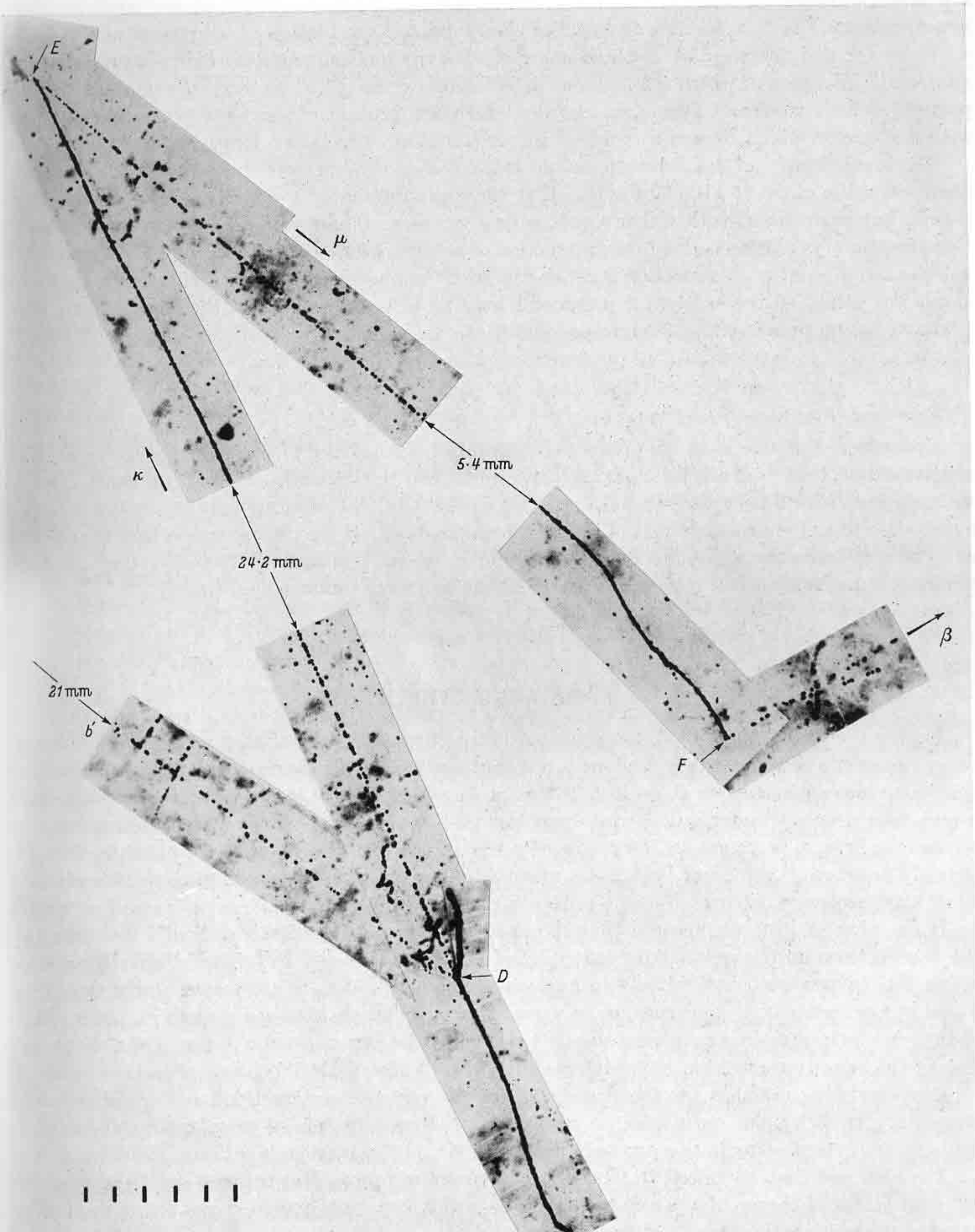

PLATE 11–8

PLATES 11–7 and 11–8. Associated production of an hyperon and a *K*-meson

This remarkable event shows the great richness of the phenomena it is possible to record with stacks of emulsions. It was found in a stack of dimensions 20 cm × 15 cm × 5 cm, exposed at 95,000 ft for 4 hours. A fast particle which enters the stack makes a nuclear collision at the point A, and from the resulting disintegration, three particles emerge; viz. (a) a hyperon, which after a range of about

(Continued overleaf)

Associated production

$$\underset{S=(0)}{\pi^-} + \underset{(0)}{p} \to \underset{(+1)}{K^+} + \underset{(-1)}{\Sigma^-}; \quad |\Delta S| = 0, \text{ allowed}$$

$$\to \underset{(-1)}{K^-} + \underset{(-1)}{\Sigma^+}; \quad |\Delta S| = 2, \text{ forbidden}$$

$$\to \underset{(+1)}{K^0} + \underset{(-1)}{\Lambda^0}; \quad |\Delta S| = 0, \text{ allowed}$$

$$\to \underset{(-1)}{\bar{K}^0} + \underset{(-1)}{\Lambda^0}; \quad |\Delta S| = 2, \text{ forbidden.}$$

Pair production

$$\underset{(0)}{p} + \underset{(0)}{p} \to \underset{(+1)}{K^+} + \underset{(-1)}{K^-} + \underset{(0)}{p} + \underset{(0)}{p}; \quad |\Delta S| = 0, \text{ allowed.}$$

Ξ^--Production

$$\underset{(0)}{p} + \underset{(0)}{p} \to \underset{(-2)}{\Xi^-} + \underset{(+1)}{K^0} + \underset{(+1)}{K^0} + 2\pi^+ + \underset{(0)}{p}; \quad |\Delta S| = 0, \text{ allowed.}$$

Nuclear capture

$$\underset{(-1)}{K^-} + \underset{(0)}{p} \to \underset{(-1)}{\Sigma^+} + \underset{(0)}{\pi^-}; \quad |\Delta S| = 0, \text{ allowed}$$

$$\underset{(-1)}{K^-} + \underset{(0)}{p} \to \underset{(-1)}{\Sigma^-} + \underset{(0)}{\pi^+}; \quad |\Delta S| = 0, \text{ allowed.}$$

Decay

$$\underset{(-1)}{\Lambda^0} \to \underset{(0)}{p} + \underset{(0)}{\pi^-}; \quad |\Delta S| = 1, \text{ slow}$$

$$\underset{(+1)}{K^+} \to \underset{(0)}{\pi^+} + \underset{(0)}{\pi^0}; \quad |\Delta S| = 1, \text{ slow}$$

$$\underset{(-2)}{\Xi^-} \to \underset{(-1)}{\Lambda^0} + \underset{(0)}{\pi^-}; \quad |\Delta S| = 1, \text{ slow.}$$

Other reactions of creation and decay can be similarly treated and show no deviation from these simple rules. We shall see that they also embrace the phenomena met in the interaction of fast heavy mesons with nuclei treated in Sect. 14.

(Continued on page 381)

PLATE 11–9. First observation in emulsion of the simultaneous production of a pair of K-mesons ▸

One of the K-mesons, of negative charge, reaches the end of its range at A where it reacts with a peripheral proton to produce a Σ-particle and a π-meson; these two particles recoil from one another at an angle of $\sim 160°$. The Σ-particle, after a range of 1·67 mm, decays at the point B into a π-meson of energy 82 ± 3 MeV; this is substantially less than the value expected in the decay of a Σ-particle at rest, and it was therefore suggested that the particle decayed in flight when about 200 μ from the end of its range. The range of the Σ-particle, 1·67 mm instead of $\sim 0{\cdot}8$ or $\sim 0{\cdot}7$ mm found for interactions with protons at rest, and the fact that the tracks of the two secondary particles are not precisely collinear, shows that the proton which captured the K^--meson was not free; the Σ-particle received its increased energy of ejection as a result of the Fermi momentum of the proton.

This and similar events gave important support for the suggestions of GELL-MANN and others on the conservation of 'strangeness'. It appeared remarkable that whereas the associated production of K^+-mesons and hyperons had frequently been observed, the first heavy particle observed to be created in association with a K^--meson was a second K-particle—the charge of the latter in this example was unknown, but the mass, deduced from simultaneous estimates of scattering and grain-density along the track, was $875 \pm 65\ m_e$. The track of the particle leaves O in a direction nearly horizontal in the photograph, and to the left.

First observation in emulsion of the simultaneous production of a pair of *K*-mesons

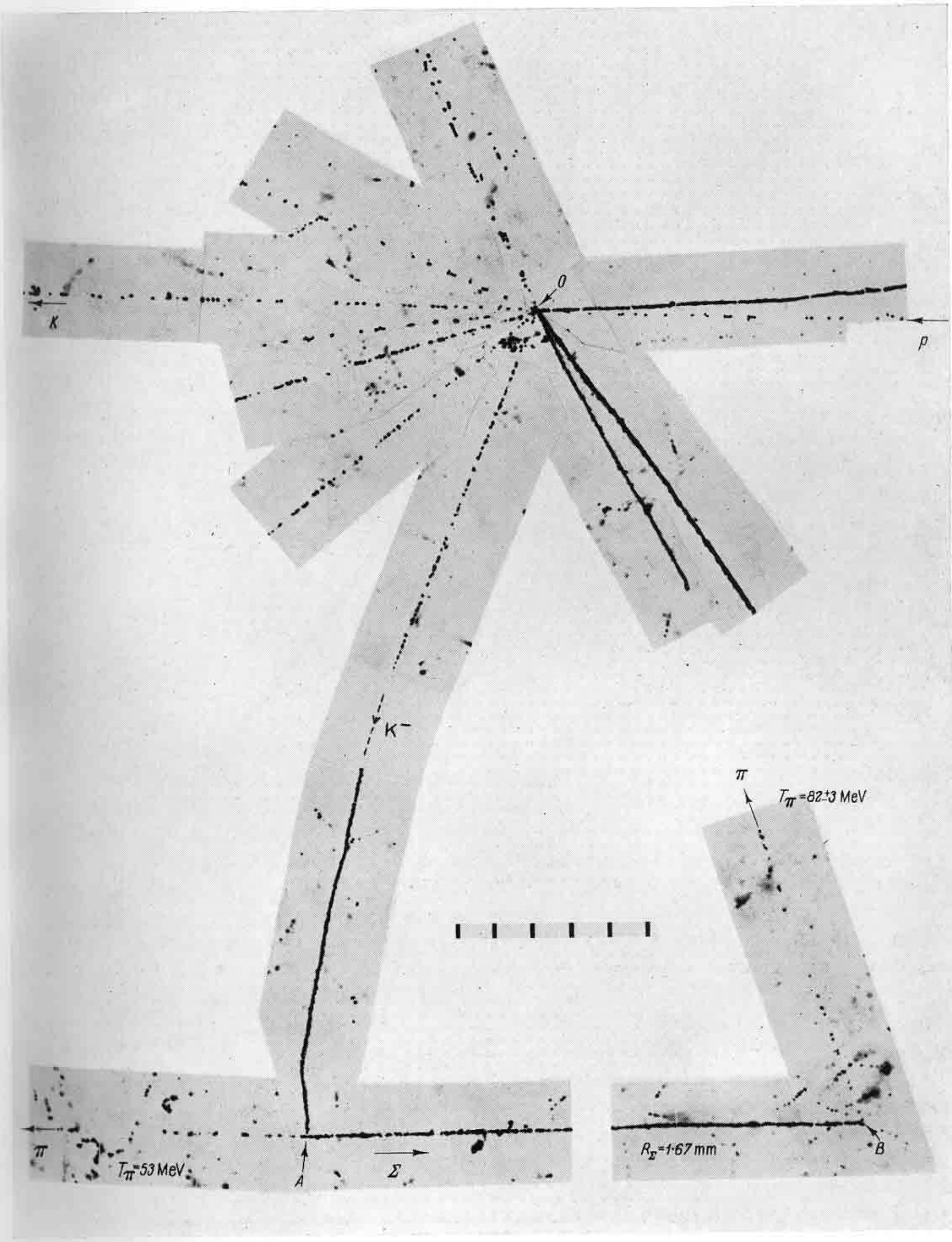

PLATE 11–9

Ilford G 5 emulsion.

FRIEDLANDER, KEEFE and MENON; Nuovo Cim. **2**, 666 (1955).

Delayed disintegration of a nucleus at the end of its range

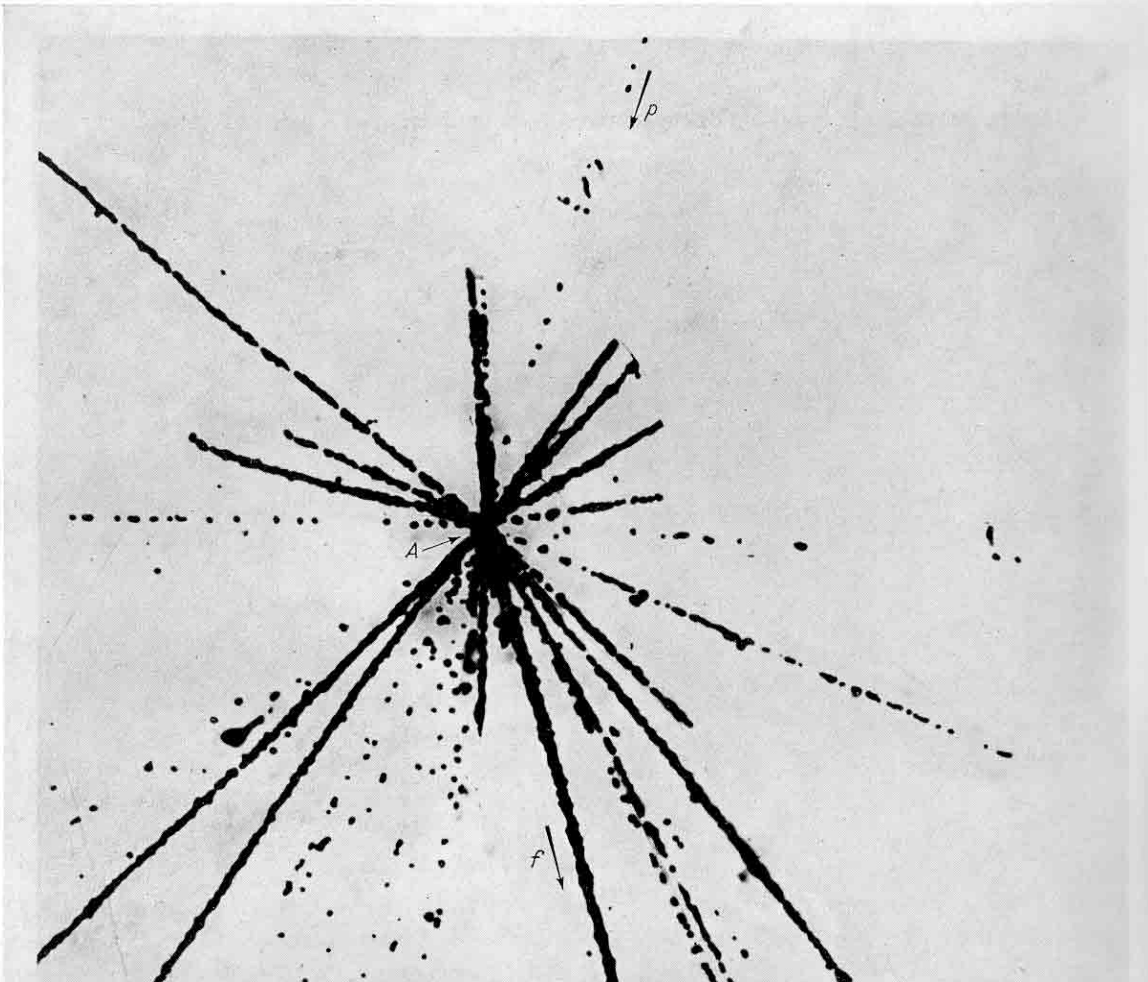

PLATE 11–10

Ilford G5 emulsion.

DANYSZ and PNIEWSKI (1953).

It may be remarked that not all the particles listed in Table 11–5 have been discovered. Thus the $\bar{\Lambda}^0$ is the only anti-hyperon for which there is good evidence; see p. 418. The particles $\bar{\Sigma}^+ \bar{\Sigma}^- \bar{\Sigma}^0$, anti-particles to the Σ-hyperons, would transform into anti-nucleons: $\bar{\Sigma}^+ \rightarrow \pi^+ + \bar{n}$; $\bar{\Sigma}^- \rightarrow \bar{p} + \pi^0$; or $\rightarrow \pi^- + \bar{n}$. The threshold energy for their production involves the creation of a nucleon and anti-nucleon pair, and is correspondingly higher than for the ordinary hyperons. If the basic ideas on which the GELL-MANN-NISHIJIMA scheme is based are in general valid, there appears to be no room for elementary particles of unit charge other than those given in Table 11–5.

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10. THE DISCOVERY OF HYPERNUCLEI

Λ^0-particles as components of nuclei

The original discovery suggesting that hyperons can exist not only as free particles, but also bound within nuclei, was due to DANYSZ and PNIEWSKI (1953). They observed a heavy nuclear fragment, of charge $\sim 5e$, emitted from a nuclear disintegration recorded in a photographic plate exposed to the cosmic radiation; see Plate 11–10. The particle appeared to reach the end of its range where it disintegrated with the emission of three, possibly four, charged particles. Such particles, when ejected from disintegrations, are now referred to as hyperfragments; or, more generally, as hypernuclei.

The striking feature of the observation was that the disintegration occurs at the end of the range, when the parent particle was at rest, or moving with very low velocity. The secondary disintegration could not therefore be due to a collision of the fragment with another nucleus. Instead, it was attributed

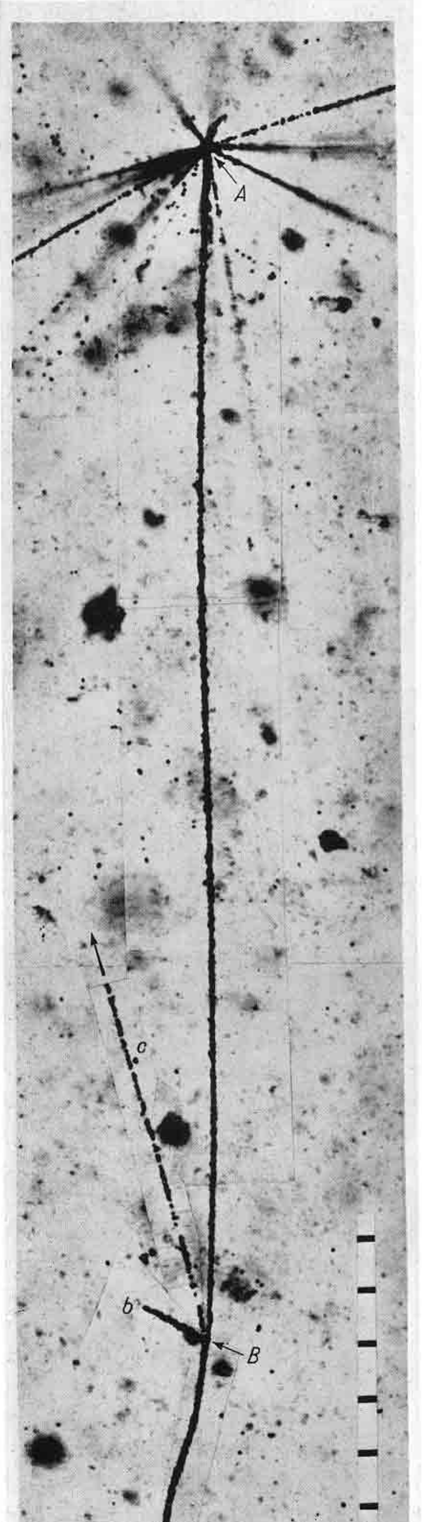
(Continued on page 383)

PLATE 11–10

First observation of the 'delayed' disintegration of a nucleus. A nuclear fragment, f, of charge $\sim 5e$, reaches the end of its range at B and disintegrates with the emission of three fast charged particles. It is possible that the track (3) is due to a π-meson. If so, the total release of kinetic energy in the disintegration is about 40 MeV, in good accord with the assumption of a Λ^0-particle as a component of the nuclear fragment.

The similar phenomena observed later commonly involved fragments of smaller charge, most of them with $Z = 1$ or 2. Heavier fragments, such as that shown above, are much rarer, but it seems probable that the order of discovery was influenced by the fact that for particles with $Z = 4$ or 5, the direction of motion is very easily established because of the pronounced taper of the track. Other examples of small charge must have been seen without their significance having been recognised.

Delayed disintegration of a heavy nuclear fragment



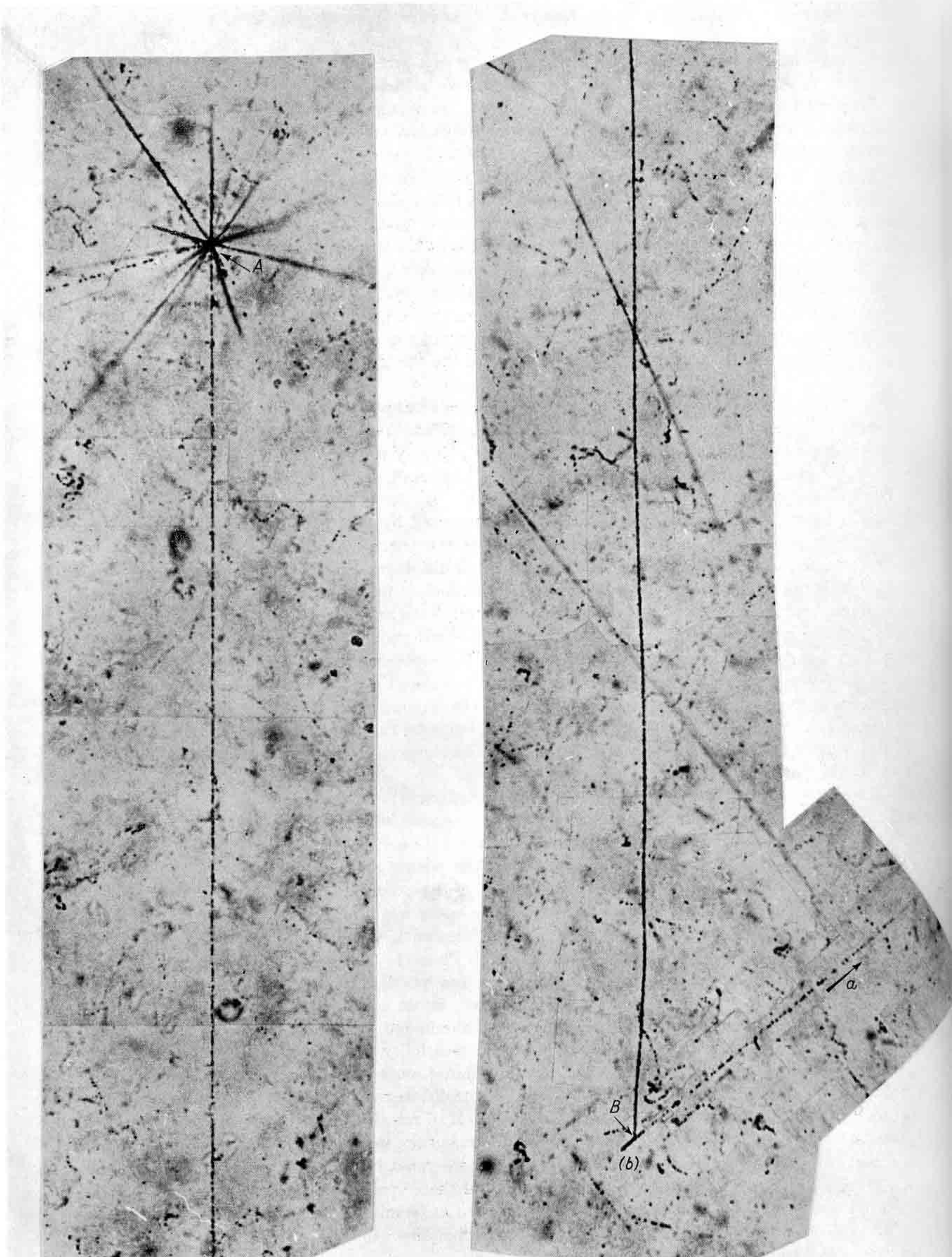
In this example of the apparent delayed disintegration of a nuclear fragment, the emitted particle appears to be of effective charge $Z = 2$. On the other hand, there are three charged particles emerging from the secondary disintegration at B. If indeed the nuclear fragment was doubly charged, then one of the tracks must have been produced by a negative particle, and another, say track b, by a particle of charge $2e$. There was, however, no evidence to suggest that any of the three tracks was that of a π^--meson. The most likely interpretation is that the nuclear fragment was in fact of charge $Z = 3$. In addition, it must be assumed that one or more neutrons were ejected, in order to conserve momentum in the secondary disintegration.

PLATE 11–11

Ilford G5 emulsion.

TIDMAN, DAVIS, HERZ and TENNENT (1953).

First observation of the decay of $_{\Lambda}H^3$



First observation of the decay of $_{\Lambda}H^3$

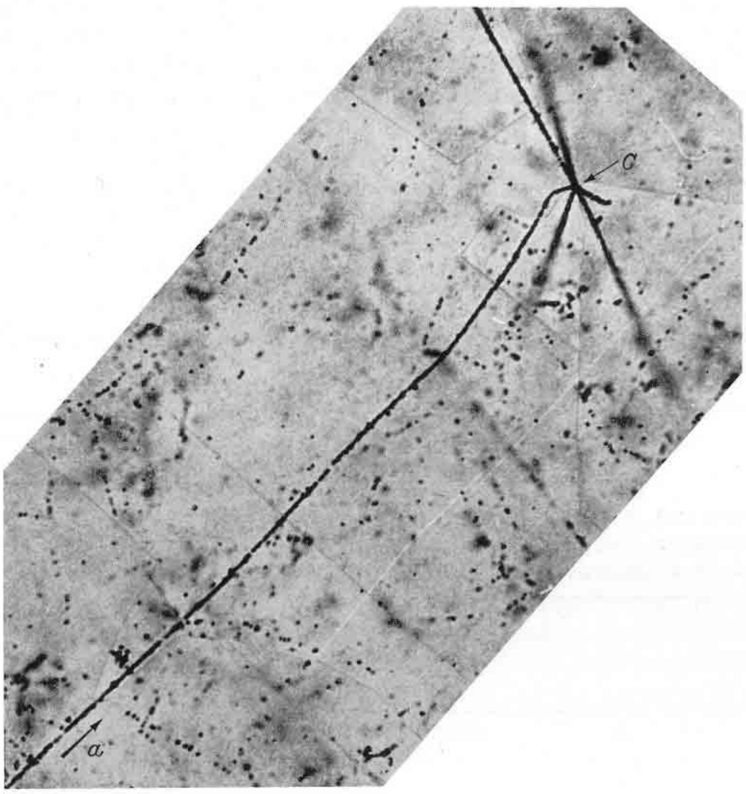


PLATE 11–12

Ilford G5 emulsion.

BONETTI, LEVI-SETTI, PANETTI, SCARSI and TOMASINI (1954).

PLATE 11–12. First observation of the decay of $_{\Lambda}H^3$

This example of the delayed disintegration of a nucleus was observed in a stack of emulsions, and allowed a very complete analysis. The nuclear fragment of charge e, emitted from a disintegration at A, comes to rest at B after a range of $\sim$ 13 mm. Its mass can be measured and the result is $\sim$5500 m_e, approximately the mass of the triton. At the end of its range, it disintegrates into two particles which recoil from one another. The fast particle is a negative π-meson, which is arrested after a range of 23·8 mm and produces a secondary disintegration. The laws of conservation of charge and mass-number then require that the short, heavily ionising particle, recoiling from the π-meson, is a He^3 nucleus. With this assumption, its observed range is consistent with a momentum equal and opposite to that of the π-meson, and the total release of energy is $\sim$41·5 MeV. The disintegration is therefore represented $_{\Lambda}H^3 \rightarrow He^3 + \pi^- + 41{\cdot}5$ MeV.

The observations allow the binding energy of the Λ^0 within the triton to be computed.

PLATE 11–13. Capture of a K^--meson by O^{16} with the emission of a $_{\Lambda}Li^7$ hyperfragment ▸

This observation gives a remarkable demonstration of the detailed conclusions which can be drawn, in favourable conditions of observation, from single events recorded in photographic emulsion, and displays the power of the photographic method in the study of hyperfragments.

A negative K-meson entered the emulsion, top left, from the Berkeley accelerator and reached the end of its range at the point A, where it was captured by an oxygen nucleus. The latter disintegrated into a $_{\Lambda}Li^7$ hyperfragment, together with two α-particles, tracks (i) and (ii), a proton, track (iii), and a π^--meson. The hyperfragment reached the end of its range at the point B, where it spontaneously decayed according to the equation: $_{\Lambda}Li^7 \rightarrow \pi^- + He^4 + He^3$; $Q = 35{\cdot}9 \pm 0{\cdot}5$ MeV. These detailed features of the analysis were established in the following way, from the measurements given in the accompanying table.

Track	Range μ	Angle in common plane	Energy (MeV) from range	Momentum (MeV/c) from range
π^-	10,060	$0 \pm 0{\cdot}3$	$24{\cdot}1 \pm 0{\cdot}45$	$85{\cdot}5 \pm 1$
iv	33·1	$144{\cdot}5 \pm 1$	$6{\cdot}9 \pm 0{\cdot}1$	$227 \pm 1{\cdot}5$
v	23	307 ± 1	$4{\cdot}9 \pm 0{\cdot}1$	165 ± 2

Dealing first with the decay of the hyperfragment, the directions of motion of the three secondary particles were co-planar to within the errors of measurement. It is therefore reasonable to assume that no neutral particles were emitted, and that the hyperfragment decayed at rest. The observed range of the π^--meson defines its momentum; the momenta of the two particles of short range, tracks (iv) and (v), then follow from an application of LAMI's theorem. The values thus found were 227 ± 16 MeV/c for the particle which produced track (iv), and 165 ± 16 MeV/c for track (v). If the track (iv) was produced by an α-particle, its range should be between 28 and 41 μ, the actual value being 33 μ. If, on the other hand, it was really due to He^3, its range should be between 48 and 74 μ; any assignment other than He^4 gives a value for the range widely different from that observed. A similar approach can be made in the identification of the particle which produced track (v). It may thus be shown to have been He^3, although the evidence is not quite so strong as for track (iv).

Accepting the evidence that the longer track was indeed due to an α-particle, its range now gives a more precise estimate of its momentum than that deduced previously; the value thus found was $227 \pm 1{\cdot}5$ MeV/c. It then follows from the conservation of momentum that track (v) corresponds to a particle of momentum 165 ± 2 MeV/c. If the particle was indeed He^3, its range should then have been 23 ± 1 μ; or $14 \pm 0{\cdot}5$ μ if He^4; and 98 ± 3 μ if H^3. The observed range 22·8 μ therefore establishes the conclusion that tracks (iv) and (v) were due to He^4 and He^3 as indicated. It follows that the hyperfragment was $_{\Lambda}Li^7$ which decayed according to the equation above. Using the energies of the particles as determined from the ranges, the binding energy of the Λ^0-hyperon was found to be $5{\cdot}2 \pm 0{\cdot}5$ MeV. This appears to have been the first example of a $_{\Lambda}Li^7$ hyperfragment in which the identification could be made without the uncertainty whether or not a single product nucleus had been formed in an excited state.

Proceeding now to the parent disintegration, the interpretation that it was due to capture by O^{16}, $K^- + O^{16} \rightarrow He^4 + He^4 + {_{\Lambda}Li^7} + H^1 + \pi^-$, depends upon the following consideration: in addition to the secondary π-meson and the hyperfragment emitted from the point A, there are three heavily ionising particles of short range, of which the lines of motion are narrowly inclined in projection. Two of them, of which the points of arrest are labelled (i) and (ii), can only just be distinguished in the photograph. Attributing tracks (i) and (ii) to α-particles, and track (iii) to a proton, the vector sum of the momenta of the four nuclear fragments is 230 ± 10 MeV/c, with a component of only 8 ± 10 MeV/c, transverse to the line of motion of the associated π-meson. This π-meson escaped from

Capture of a K^--meson by O^{16} with the emission of a $_{\Lambda}Li^7$-hyperfragment

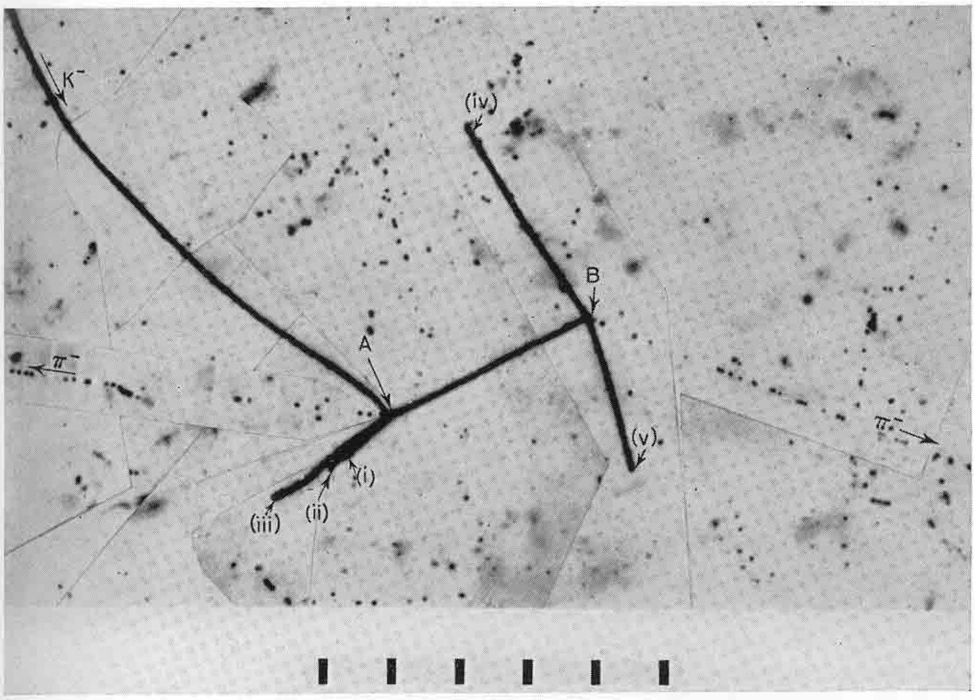


PLATE 11–13

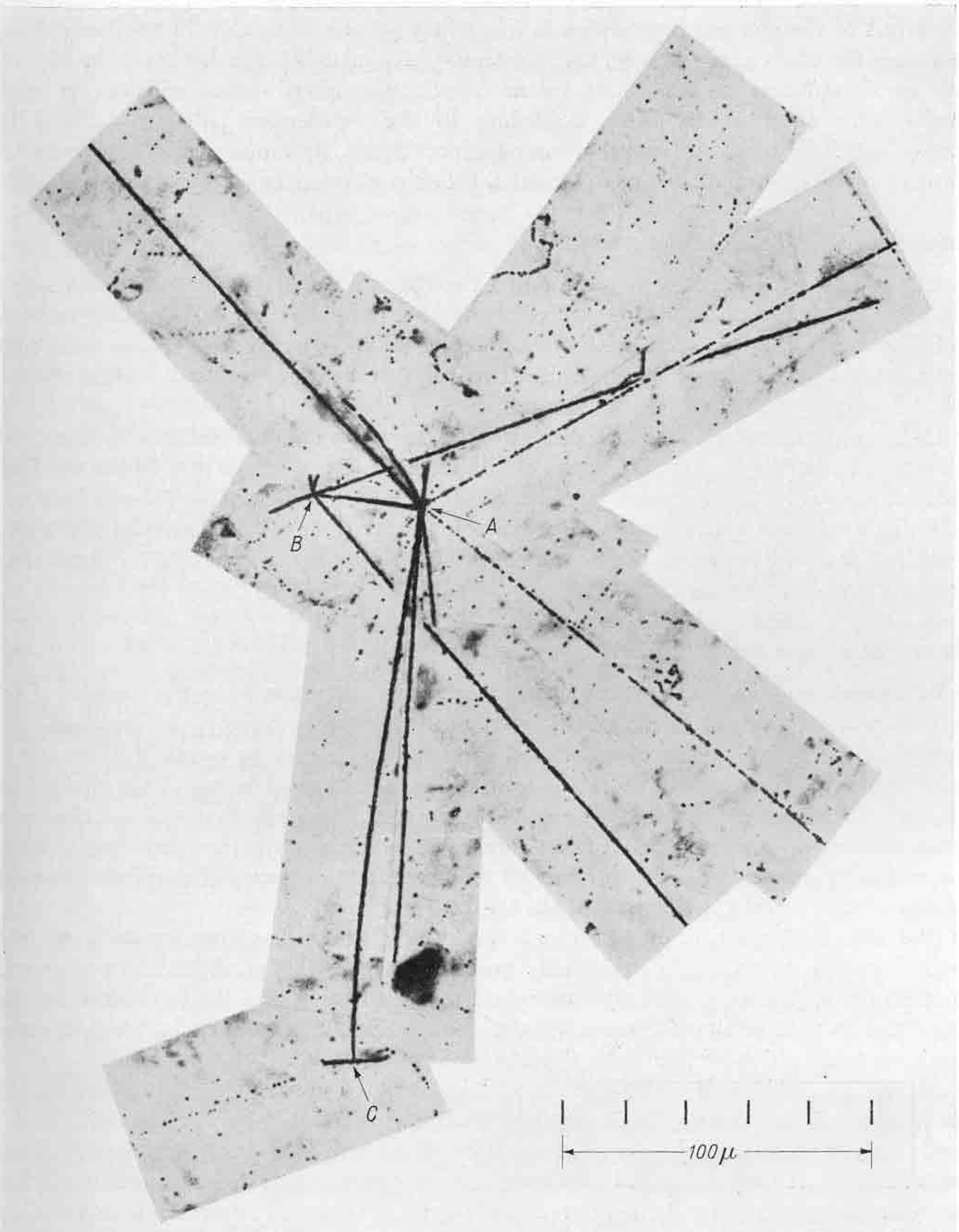
Ilford K5 emulsion. FOWLER (1958).

the stack so that its energy could not be accurately determined from the range; the sign of its charge was also ambiguous; but assuming no neutral particles to have been emitted from the disintegration, the momentum of the π-meson must be equated to the vector sum of the momenta of the heavy charged particles, viz. 230 ± 10 MeV/c. The corresponding energy, E_π, is 124 ± 9 MeV. The total release of energy, assuming the disintegration to be correctly represented by the equation above, is then found to be 497 ± 9 MeV. Since the release of energy is so closely in accord with that corresponding to the rest-mass of the K^--meson, viz. ~ 494 MeV, with good evidence for a balance of momentum, it is reasonable to assume tentatively that no neutrons were emitted.

Assumptions about the identity of the charged particles other than those indicated above, disturb the balance of momentum. In such analyses, however, the possibility of the ejection of a neutron of suitable momentum, can generally not be excluded. This is so in the present example. If, however, the range of the π-meson had been accurately determined, it would have been possible to resolve this ambiguity.

On the basis of the above evidence, it is very probable that the disintegration was indeed due to capture by O^{16}. This gives additional support for the view that the hyperfragment was $_{\Lambda}Li^7$. Had the π-meson ejected from A been arrested in the stack, its energy could have been defined within ~ 2 MeV, and this would have allowed an accurate estimate of the total release of energy; the mass of the K^--meson, would then have followed with an accuracy of $\sim 4\ m_e$. In the absence of this information, we may assume the mass of the K^--meson and thence define the energy of the π-meson. The value thus obtained is 124 ± 1 MeV. This value appears to indicate that the Λ^0-particle was produced directly in this instance and not, as frequently happens, as a result of the formation of a Σ-particle and its subsequent interaction with nucleons; e.g. $\Sigma^- + p \rightarrow \Lambda^0 + n$. In such an event, the π-meson cannot have an energy greater than ~ 90 MeV; even allowing for the Fermi momentum of the nucleons, it is not possible to account for such a high energy as ~ 124 MeV, except in terms of direct production of Λ^0-particles, unless very special assumptions are introduced; see FOWLER (1958).

Non-mesic decay of a hyperfragment



Ilford G 5 emulsion. **PLATE 11–14** Bristol (unpublished).

This event was observed in a stack of emulsion into which had been injected 4·5 BeV π-mesons from the Berkeley accelerator. From the disintegration at A, a hyperfragment of charge about $5e$ was emitted, which reached the end of its range and decayed in the non-mesic mode at the point B. The 'taper' in the track of the hyperfragment can be readily distinguished. From the same disintegration, a Li^8 nucleus is also emitted which decays at the point C.

The photograph illustrates an advantage of high-energy disintegrations for studies of the decay of hypernuclei of large mass-number. Although they occur rarely, they are sometimes emitted from disintegrations of silver or bromine with considerable kinetic energy. They then decay at a point well resolved from that of the centre of the primary disintegration, whereas, if produced by the nuclear capture of K^--mesons, the two centres are frequently, in effect, superimposed. Compare also Plate 11–10.

Neutral π^0-meson from the decay of a hypernucleus

A K^--meson reached the end of its range at the point O, and from the resulting disintegration a hyperfragment was emitted which came to rest at P. By its decay, the latter led to the ejection of a particle of short range, and a close-pair of electrons which must, almost certainly, be attributed to the alternative mode of decay of a π^0-meson.

In such events, it is possible, in principle, to estimate the energy of the pair by scattering measurements, and its mean direction with respect to the line of motion of the parent π^0-meson; the latter is defined by the direction of the single recoil track. The energy of the π^0-meson then follows, together with its momentum. Assuming that the hyperfragment decayed at rest into two particles only, the nature of the recoil track can thus be estimated from its range and momentum. In favourable examples, the hyperfragment could thus be identified. The present event can reasonably be attributed to the hyperfragment ${}_{\Lambda}He^4$; ${}_{\Lambda}He^4 \rightarrow He^4 + \pi^0$; $Q = 61{\cdot}1$ MeV; range of recoiling $He^4 \sim 9\ \mu$.

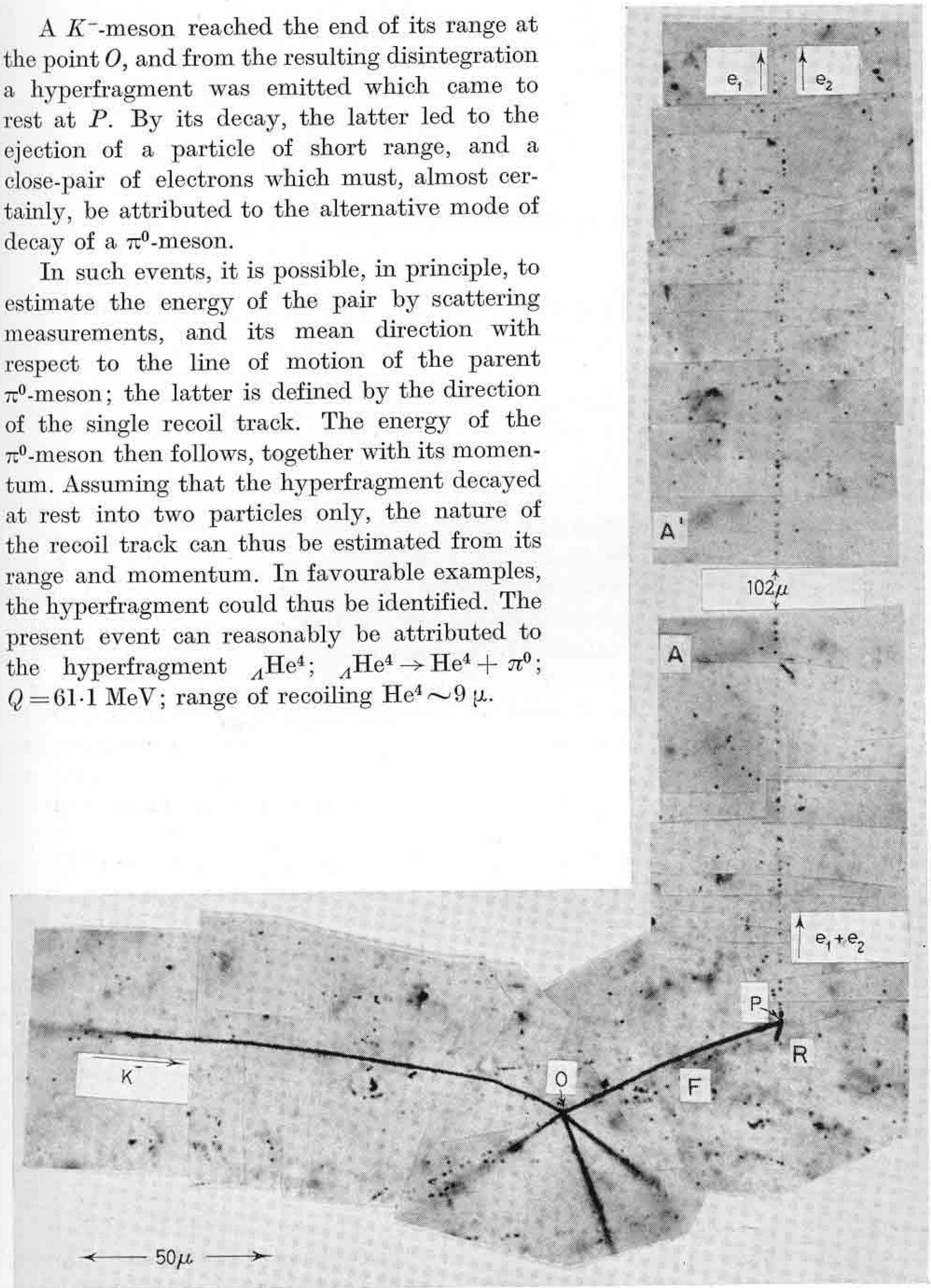


PLATE 11–15

Ilford G5 emulsion.

LEVI-SETTI and SLATER (1958)

PLATE 11–16. Decay of a hypernucleus $_{\Lambda}He^4$ in flight

This plate shows an early example of the decay of a hyperfragment in flight. Decay in flight in emulsion occurs much less frequently than decay at rest because most hyperfragments are emitted with low velocity, $\sim 0{\cdot}1$ c, especially when they are produced by the nuclear capture of K^--mesons. They are then stopped in a time of $\sim 10^{-11}$ sec; see p. 88.

The example shown was found in Copenhagen in a stack of emulsions flown at 90,000 ft over Southern England. The parent star (not shown) was small, type $(4+2n)$, but the hyperfragment was emitted with a kinetic energy of ~ 120 MeV, and travelled ~ 5 mm before decaying at the point O where its residual range was about 350 μ.

The analysis described below shows that the disintegration may be represented: $_{\Lambda}He^4 \rightarrow H^1 + H^1 + H^2 + \pi^-$; $Q = 29{\cdot}6 \pm 0{\cdot}6$ MeV:

a) Measurements of δ-ray density and multiple scattering showed that the parent particle was of charge $Z = 2$, and was near the end of its range (350 ± 100) μ at the point of interaction or decay. In particular, the δ-ray density, N_δ, passed through a maximum value, of magnitude corresponding to $Z = 2$, and fell thereafter, showing clearly the approach to the end of the range; see Fig. 5–10, p. 169.

b) All the secondary charged particles were arrested in the emulsion, so that their ranges could be accurately measured. The π^--meson was identified by the four-prong star which it produced at the end of its range.

c) If the heavily ionising particles are attributed to protons and deuterons, as indicated in the Plate, then the vector sum of the momenta of the secondary particles is 429 ± 2 MeV/c, and it lies approximately 1° from the measured direction of the primary. This small departure in direction may be attributed to the scattering of the primary particle, $\sim 2°/100$ μ, which prevents the determination of its line of motion with precision. Assuming that the momentum of the parent $_{\Lambda}He^4$-particle is 429 ± 2 MeV/c at the point of decay, its residual range is 240 ± 5 μ, in good agreement with the value estimated from the δ-ray and scattering measurements.

It may be emphasised that the evidence for the assumed mode of decay is not decisive, but it is very strong. Thus, it is possible that the tracks attributed to protons and deuterons have been wrongly identified, although they must all be hydrogen isotopes of one kind or another in order to conserve charge. But any assignment other than that adopted is inconsistent with zero transverse momentum, and with the residual momentum of the parent particle.

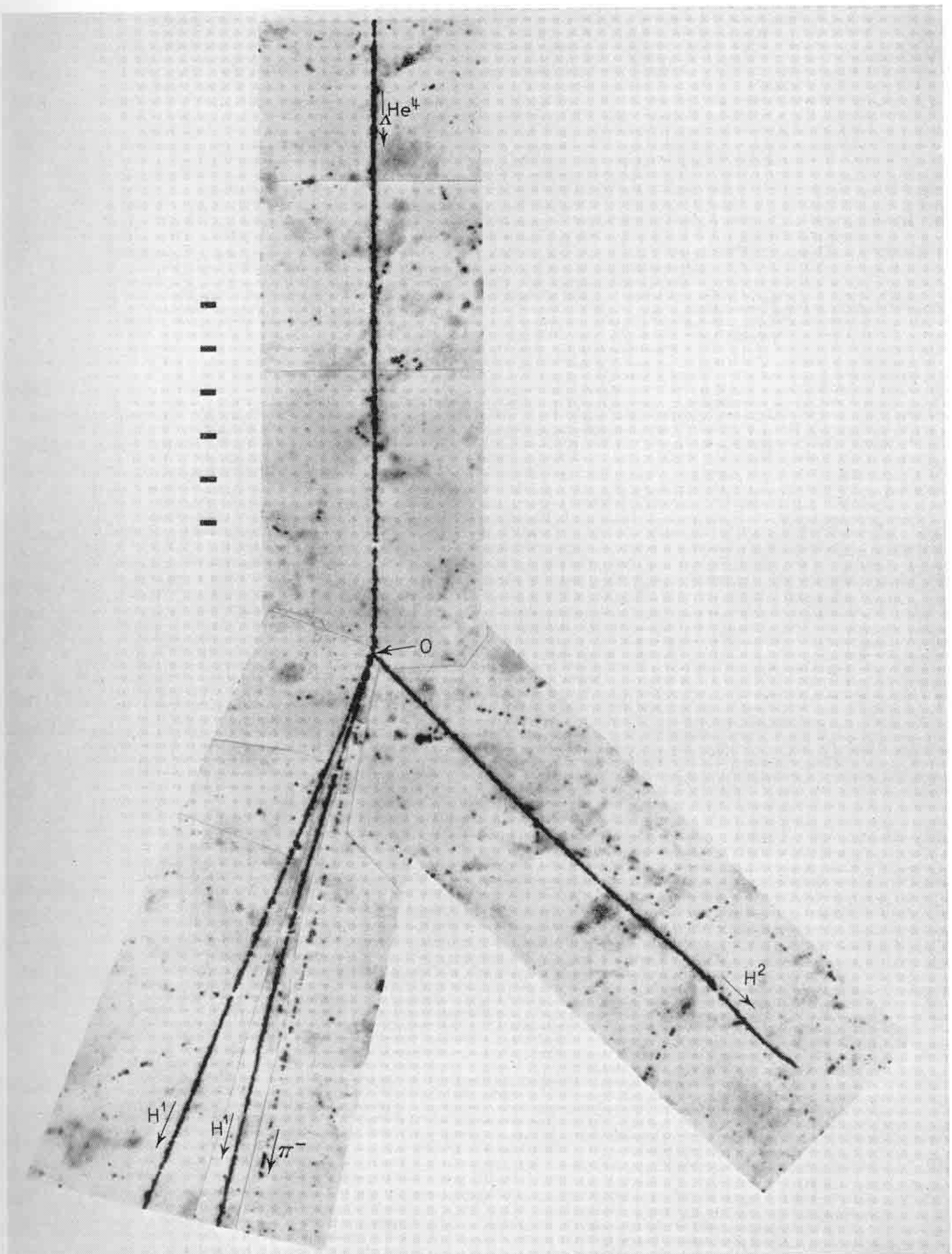
Another possibility is that a neutron was emitted, together with three protons. This possibility cannot be excluded; but it is improbable that in such a case an apparent balance of momentum would be observed. The further possibility of $_{\Lambda}He^5$ as an interpretation can be rejected because there is too great a visible release of energy.

Similar objections can be brought against the interpretation of the event in terms of the nuclear interaction of the hyperfragment; the existence of a momentum balance is then very improbable. It may be remarked that, in general, hyperfragments are of such low velocity and short lifetime that the probability of a nuclear interaction is much smaller than decay in flight. The final support for the suggested interpretation came from the consistency between the value of the mass of $_{\Lambda}He^4$ thus obtained, and those deduced from examples of the disintegration at rest of this nucleus. The value deduced, from the above interpretation, for the energy of binding of the Λ^0-particle was $1{\cdot}9 \pm 0{\cdot}6$ MeV, in good accord with subsequent measurements.

It may be remarked that the fact that this hyperfragment decayed in flight facilitated the analysis, for it ensured that there were no short tracks for which it is frequently difficult to determine accurately the range and the direction of motion. Although the π-meson was rather less energetic than is commonly observed in the mesic mode of decay of hyperfragments, it is the errors associated with the straggling of this particle which contributed most to the final error in the determination of the binding energy. This is frequently so in measurements of the mass of hyperfragments made in favourable conditions of observation.

Details of the measurements are given below, and allow the value of the binding energy to be computed as an exercise in the technical methods.

Decay of a hypernucleus $_\Lambda He^4$ in flight



Ilford G 5 emulsion. **PLATE 11–16** Fowler and Hansen (1956).

	Assumed nature	Range (microns)	Energy (MeV)	Momentum (MeV/c)	Projected angle	Dip angle
Primary	$_\Lambda He^4$	—	—	—	0·0 ± 0·6	0.0 ± 1.0
1	*D*	136	5·70 ± 0·05	14·6 ± 0·7	316·2 ± 1	−8·1 ± 1·5
2	π	10,050	23·6 ± 0·5	84·5 ± 0·8	12·9 ± 0·3	+43·8 ± 0·5
3	*P*	565	10·2 ± 0·1	139 ± 0·7	16·1 ± 0·5	−25·5 ± 0·8
4	*P*	898	13·4 ± 0·1	158·7 ± 0·8	22·7 ± 0·5	+8·1 ± 0·8

Decay of hypernuclei at rest and in flight

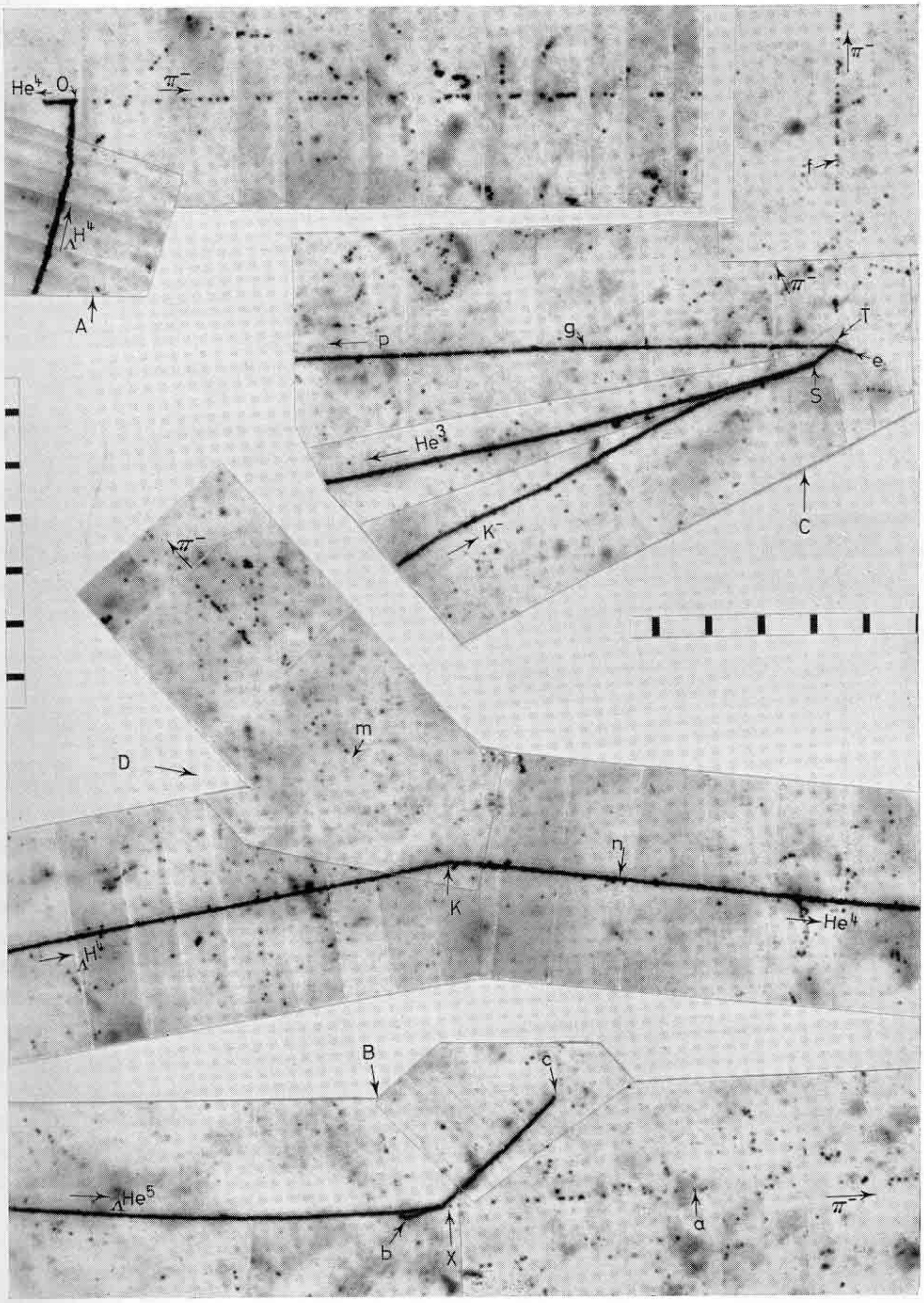


PLATE 11–17

A Ilford G 5; B, C and D Ilford K 5 emulsion. Bristol (unpublished).

Annihilation of an artificially produced anti-proton

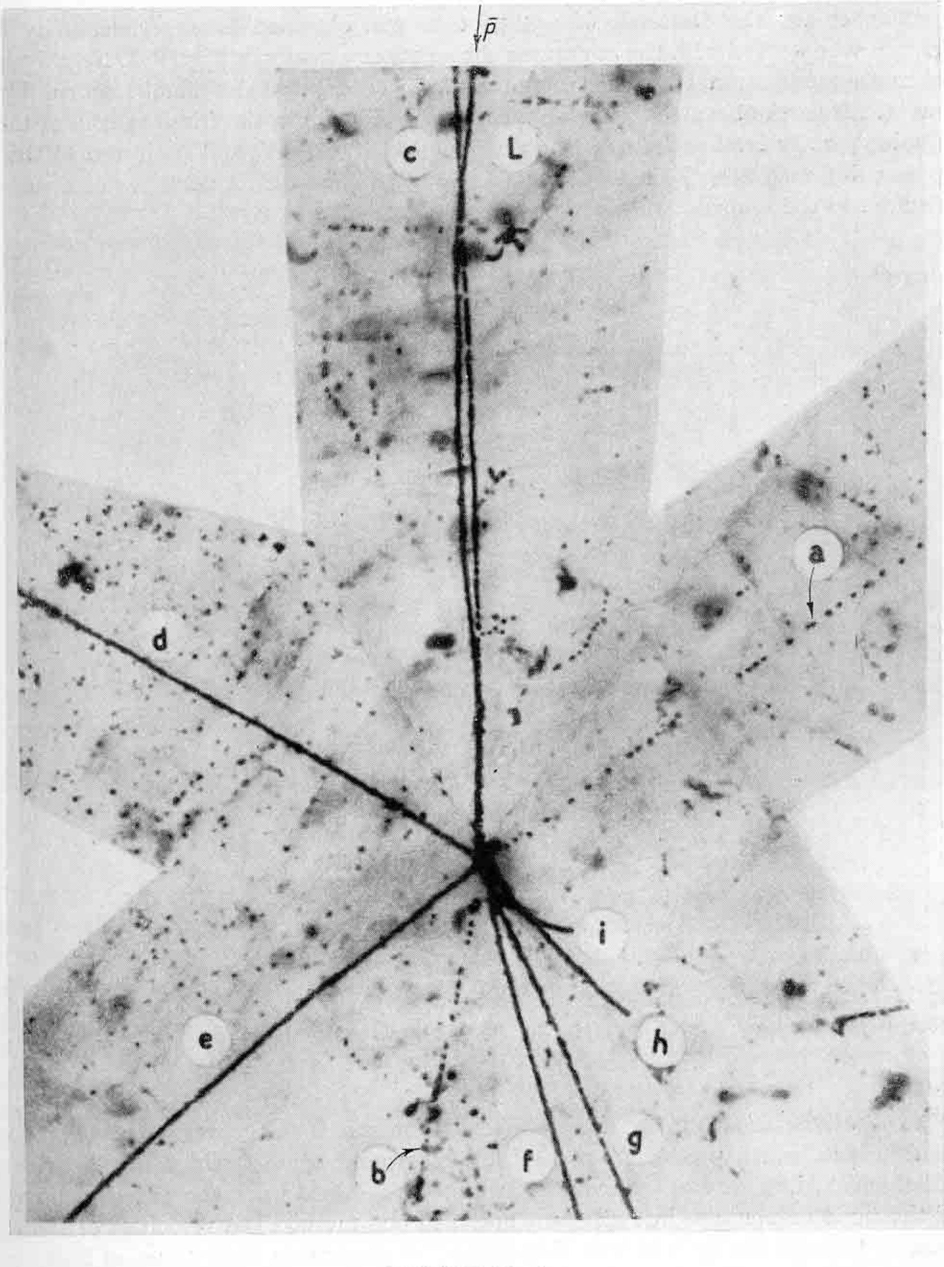


PLATE 12–1

Ilford G 5 emulsion.

CHAMBERLAIN *et al.* (1956 a).

The photomicrographs show the first observed example in emulsion of the annihilation of an artificially produced anti-proton.

Disintegration due to the annihilation of an anti-proton

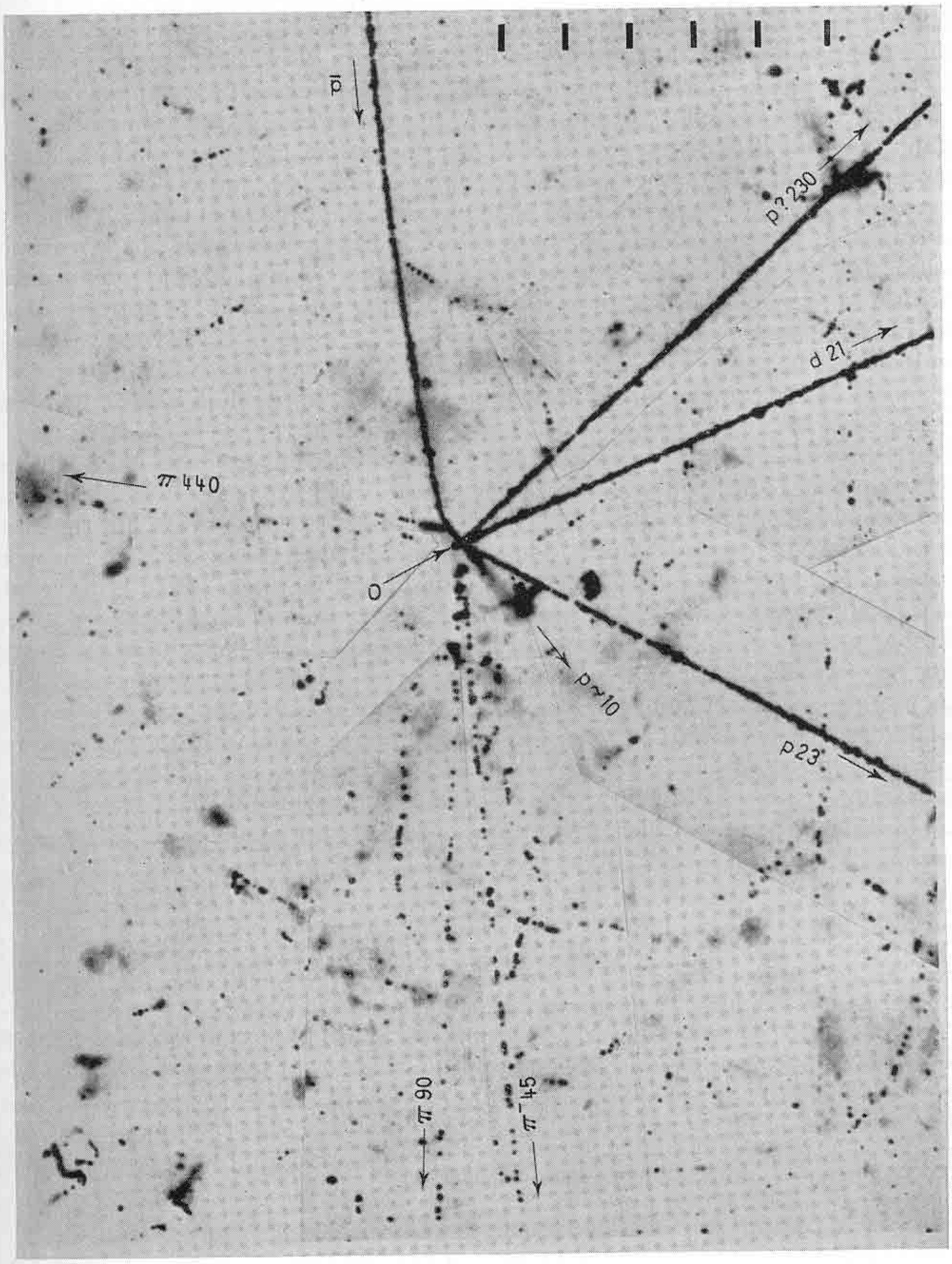


PLATE 12–2

Ilford G 5 emulsion.

Bristol (unpublished).

An anti-proton, $\bar{p}$, generated artificially in the Berkeley bevatron, enters an emulsion and is annihilated at the end of its range at the point O. The nature of the secondary particles, and their energies in MeV are indicated. The total visible release of energy is greater than that corresponding to the rest-mass of the incident particle alone.

Annihilation of an anti-proton

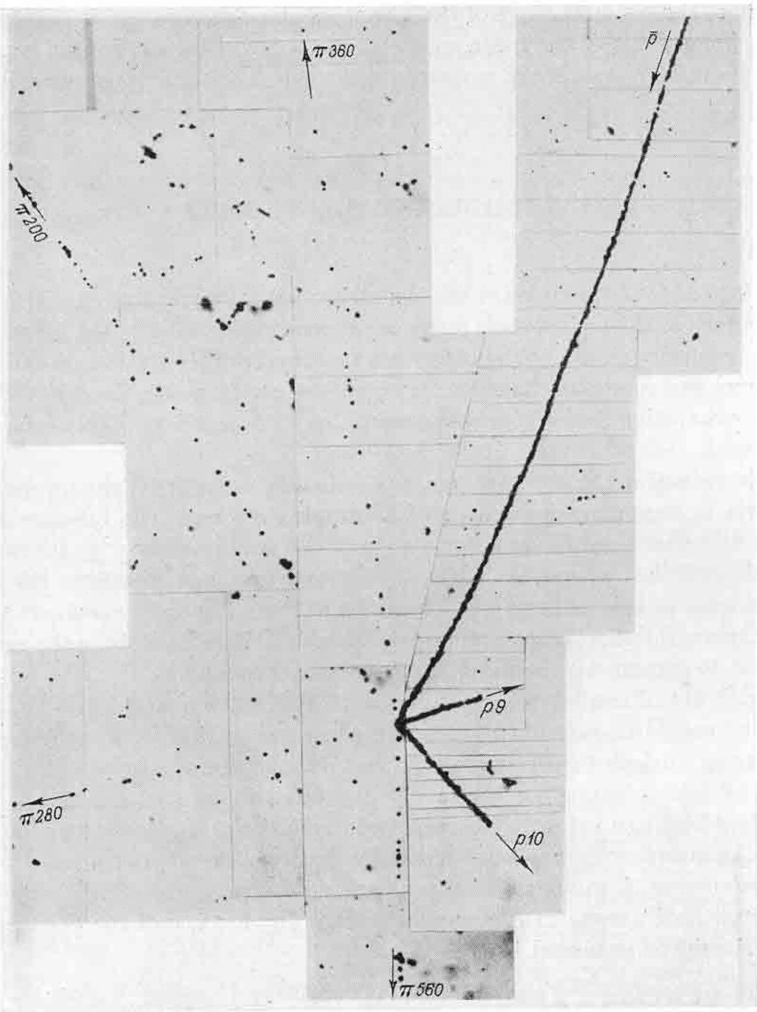


PLATE 12–3

Ilford G 5 emulsion. BIRGE *et al.* (1956).

The products of the disintegration and their estimated energy are indicated. Four charged π-mesons are emitted, the total visible release of energy being 1·4 BeV. The low energy of the accompanying disintegration suggests that none of the secondary π-mesons produced in the act of annihilation have been absorbed. The number associated with the track of each secondary particle indicates its measured energy in MeV.

First observation in photographic emulsion of an event attributed to the creation and annihilation of an anti-proton

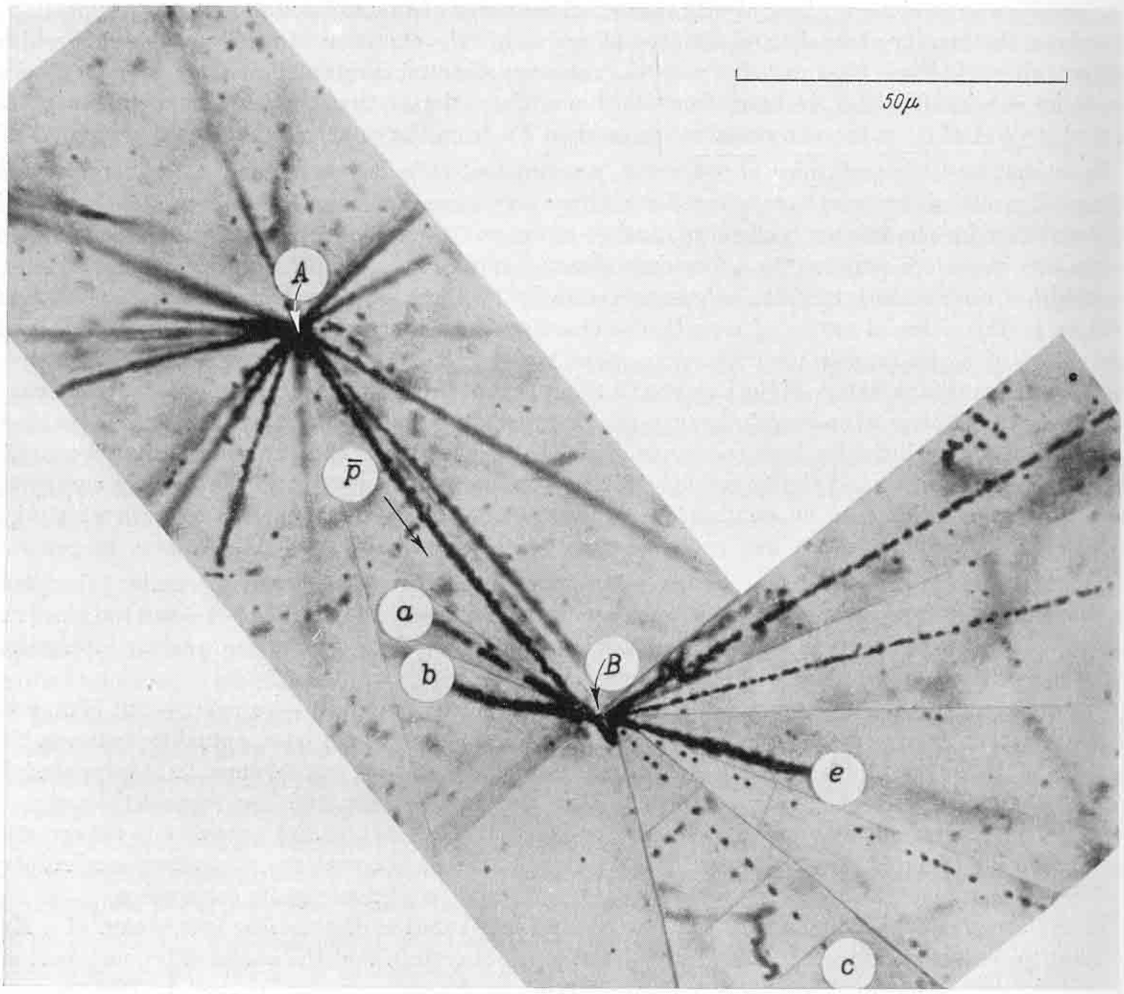


PLATE 12–4

Ilford G5 emulsion. AMALDI *et al.* (1955).

This photomicrograph shows the first event recorded in emulsion which was attributed to the annihilation of an anti-proton. From a disintegration at A, a track labelled $\bar{p}$ emerges. It appears to be scattered through $\sim 90°$ near the end of the range, and to come to rest at a point indistinguishable from the centre of a second disintegration at B. The 'star' at B is now known to be similar in character to those undoubtedly due to the nuclear capture of anti-protons. The point of uncertainty is whether the track $\bar{p}$ came to rest at the apparent point of scattering where, by chance, a short range track from B also terminated.

1. INTRODUCTION

THERE are several reasons for making detailed studies of the characteristics of the disintegrations of complex nuclei produced by the impact of fast protons and other particles. In addition to the intrinsic interest and importance of understanding the processes involved, they have a bearing on the interpretation of many important phenomena investigated by the photographic method, such as the 'stars' due to the annihilation of anti-nucleons, or to the collisions of mesons and hyperons with nuclei. The early work was confined to studies of cosmic radiation, for there alone, at the time, were found particles of sufficient energy. In this early period, the important problem of the multiplicity of production of mesons in nucleon-nucleon collisions was of great interest, and studies of the characteristics of the stars allowed tentative conclusions to be drawn on this question, conclusions which were finally established by direct observations with cloud and bubble chambers. Before describing the experimental methods, it will be convenient to give an outline of the principal processes believed to take place in the disintegrations due to fast protons. This provides a suitable background against which to discuss the main features of the observations:

A silver or bromine nucleus can be regarded as an assembly of about a hundred nucleons, spherical in form and between four and five nucleons in diameter. The observed characteristics of the disintegrations produced by protons of a given energy will depend on the impact parameter which defines the line of motion of the incident particle with respect to the centre of the nucleus, and thence the number of nucleons with which the incident proton, and the secondary particles it produces, are likely to interact. Roughly, the disintegrations can be divided into two classes; those involving central penetration of the nucleus, and peripheral collisions. In the former, the nuclear thickness, for the heavier atoms of the emulsion, can be taken to be four or five; and for peripheral collisions, from one to three, the two groups being approximately equally frequent. In collisions with the lighter nuclei (C, N, O), the nuclear thickness for central collisions will be of the order of three. Fluctuations in the numbers of secondary particles, from collisions defined by a given impact parameter, also contribute to the diversity of the effects observed.

When a fast proton with an energy of a few BeV collides with a nucleus, it commonly interacts with one of the nucleons, and several π-mesons, charged and uncharged, are created in the impact. It is an important feature that the conservation laws of momentum and energy require that, from an 'inelastic' collision, between two nucleons, both shall emerge with considerable kinetic energy.

The mesons created in the first nucleon-nucleon collision commonly have velocities in the relativistic region, and they sometimes escape from the nucleus without imparting more than a small fraction of their kinetic energy to the nucleons lying near their line of motion. They may also produce other mesons in collisions with nucleons, but little of their energy is expended in the production of recoiling nucleons. On the other hand, the recoiling protons from the first collision are often of lower velocity; they frequently interact with other nucleons in the nucleus, and the recoiling particles from these collisions interact in turn. In a sufficient thickness of nuclear matter, such processes would result in a nucleon-cascade, the original energy of the recoiling nucleon being rapidly shared with a number of others. The essential point is that the probability that a proton of energy E shall make a collision in a given length of path in nuclear matter varies approximately as $1/E$. Just as the specific ionisation of a charged particle increases rapidly as it approaches the end of its range, so a fast nucleon, $E < 200$ MeV, has an increased probability of losing energy in collisions with other nucleons as its velocity is reduced. The two problems are closely analogous, and result from the increased time of collision as the velocity is reduced, and the correspondingly more favourable conditions for the transfer of momentum.

(Continued on page 427)

PLATE 13–1. Nuclear collisions of protons of energy 52 and 145 MeV ▶

Secondary disintegrations produced by protons of energy, (a) 145 MeV, and (b), 52 MeV, emitted from nuclear disintegrations. The thinly ionising track associated with the disintegration (b) is due to an electron, possibly produced by the β-decay of the residual nucleus. The 'stars' are both of type $2 + 0_p$. β-decay of a product nucleus occurs only rarely.

Nuclear collisions of protons of energy 52 and 145 MeV

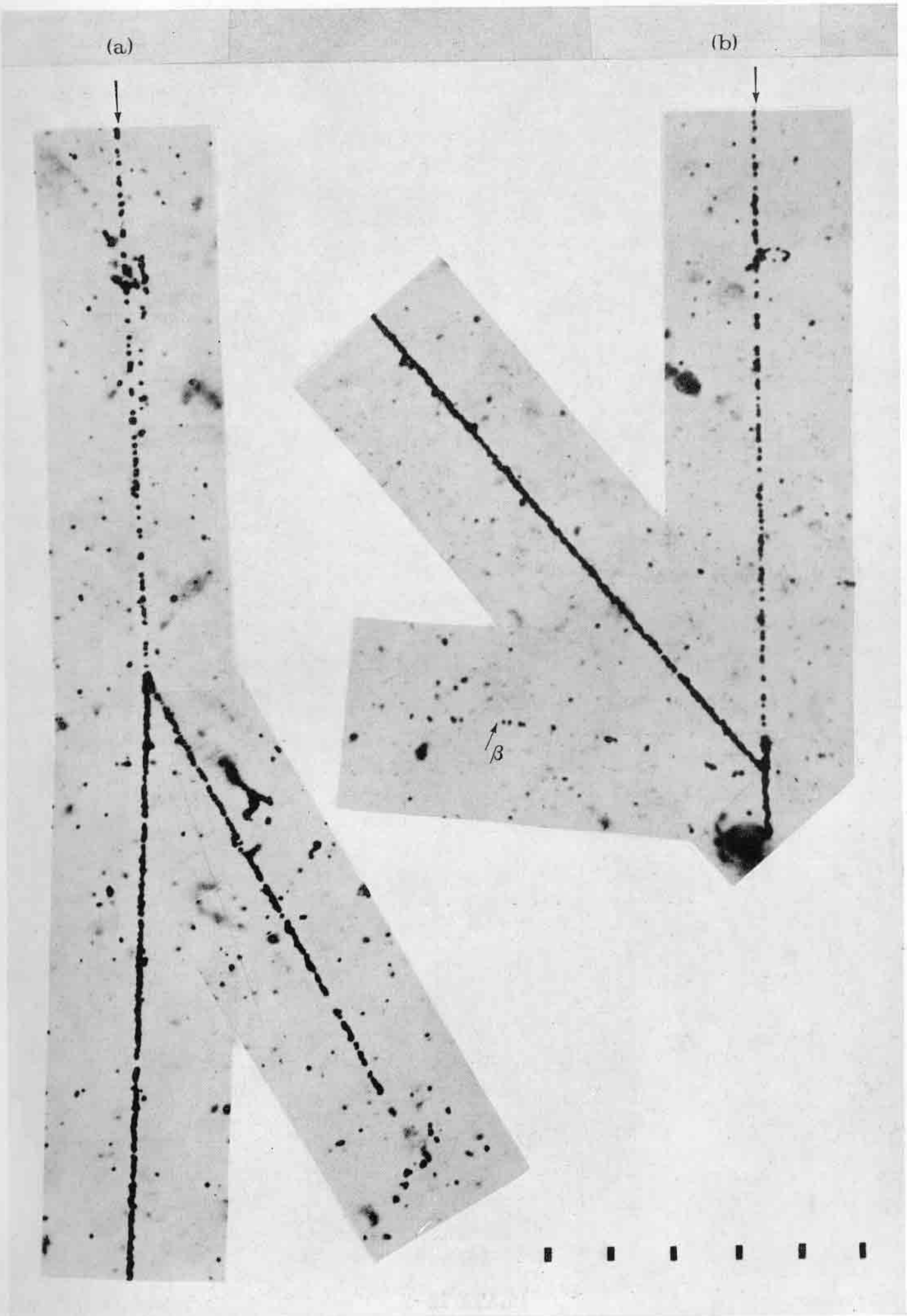
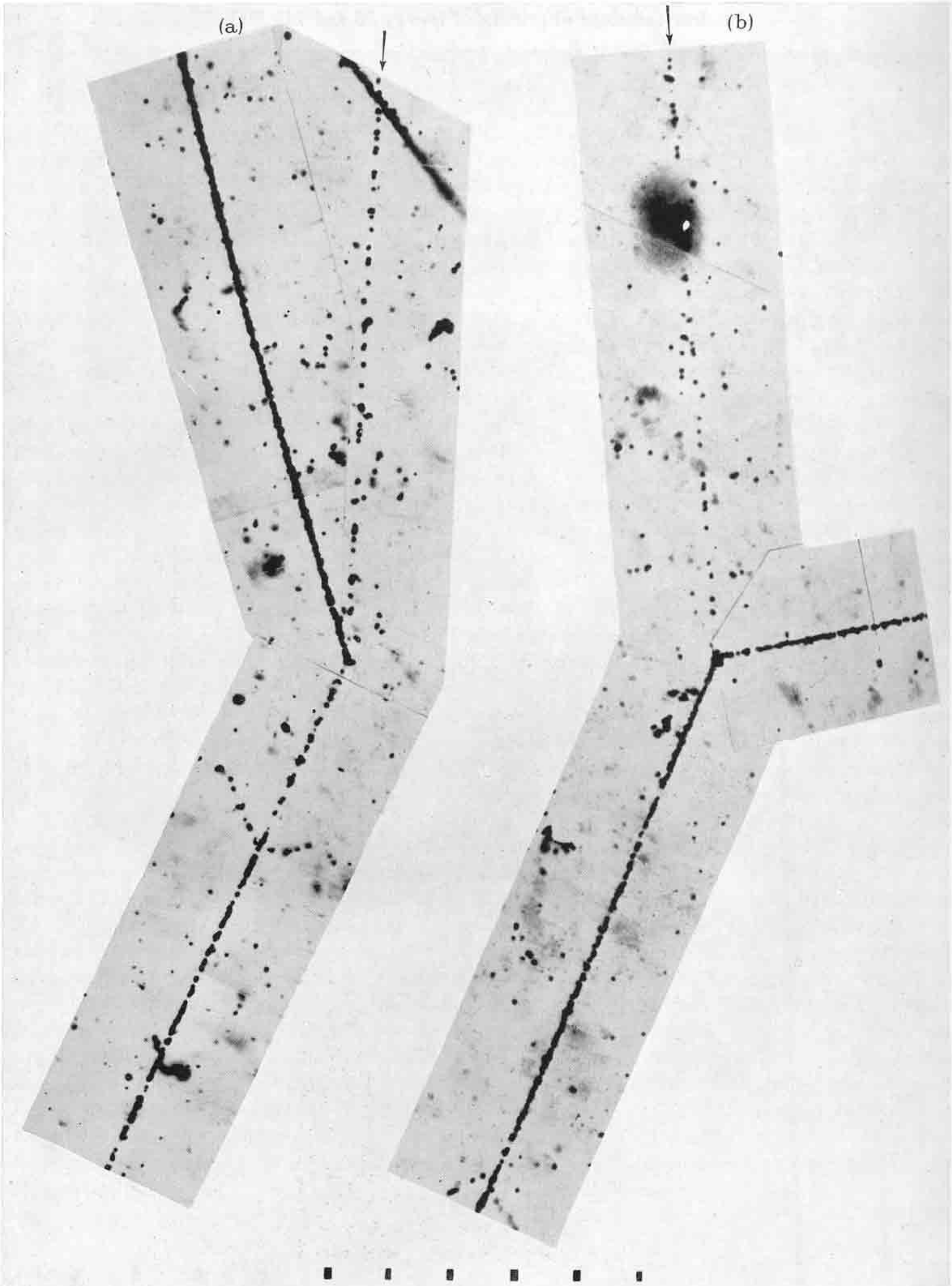


PLATE 13–1

Ilford G 5 emulsion. Bristol (1952) unpublished.

Nuclear collisions of protons of energy 90 and 270 MeV



Ilford G5 emulsion. **PLATE 13–2** Bristol (1952) unpublished

Disintegrations produced by protons of energy (a) 90 MeV, and (b) 270 MeV.

The protons were identified by measurements of $\bar{\alpha}$ and g. The identification of the protons as the parent particles depends on the fact that they emerged from more energetic disintegrations; their directions of motion were therefore unambiguous. The 'stars' are both of type $2 + 0_p$.

Nuclear interaction of protons of energy 255 MeV and 600 MeV

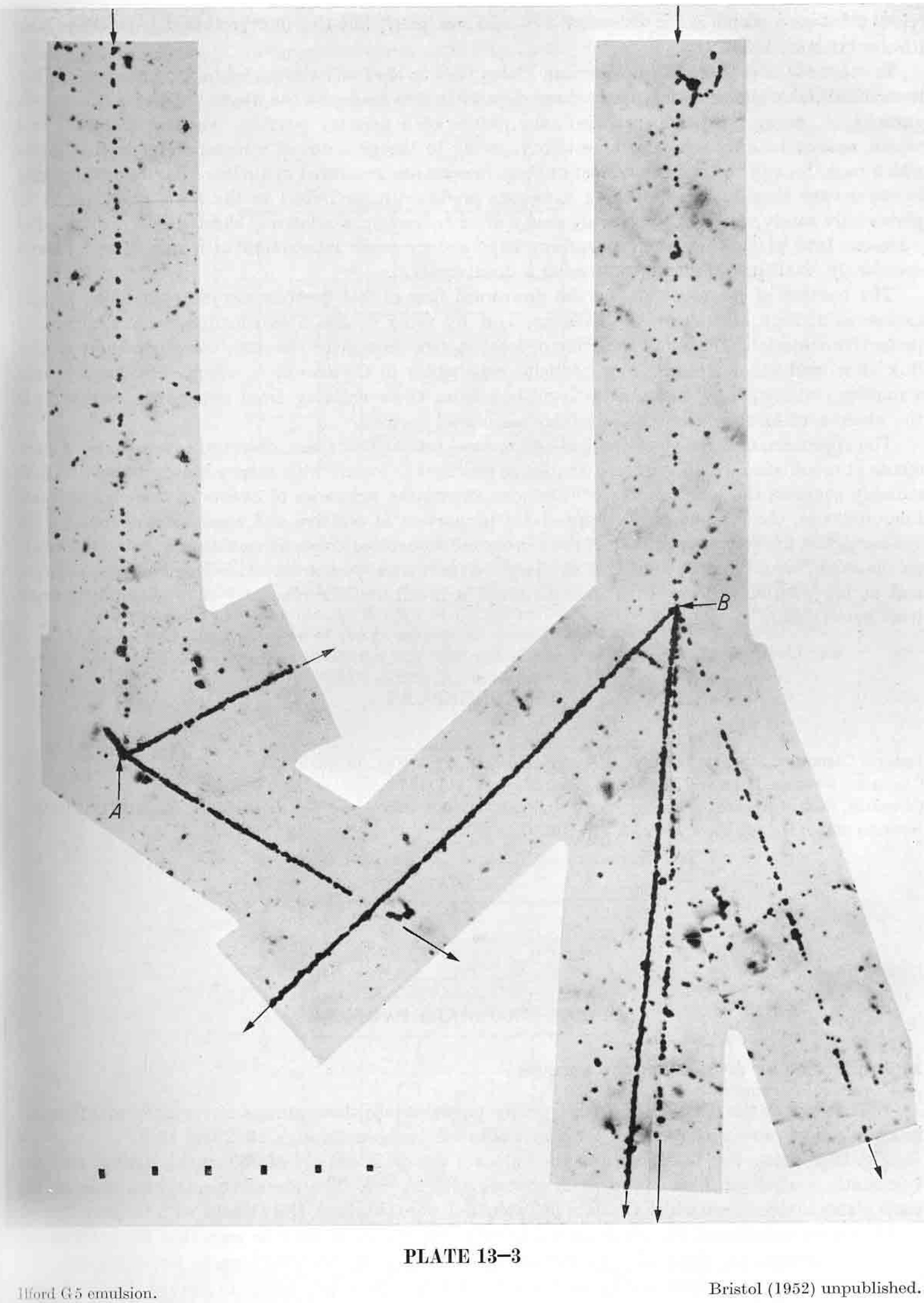


PLATE 13–3

Ilford G5 emulsion. Bristol (1952) unpublished.

(*A*) 'Star' of type $3 + 0_p$, produced by a proton of energy 255 MeV, and (*B*) 'Star' of type $4 + 0_p$, produced by a proton of energy 600 MeV.

Nuclear interaction of a proton of energy 570 MeV

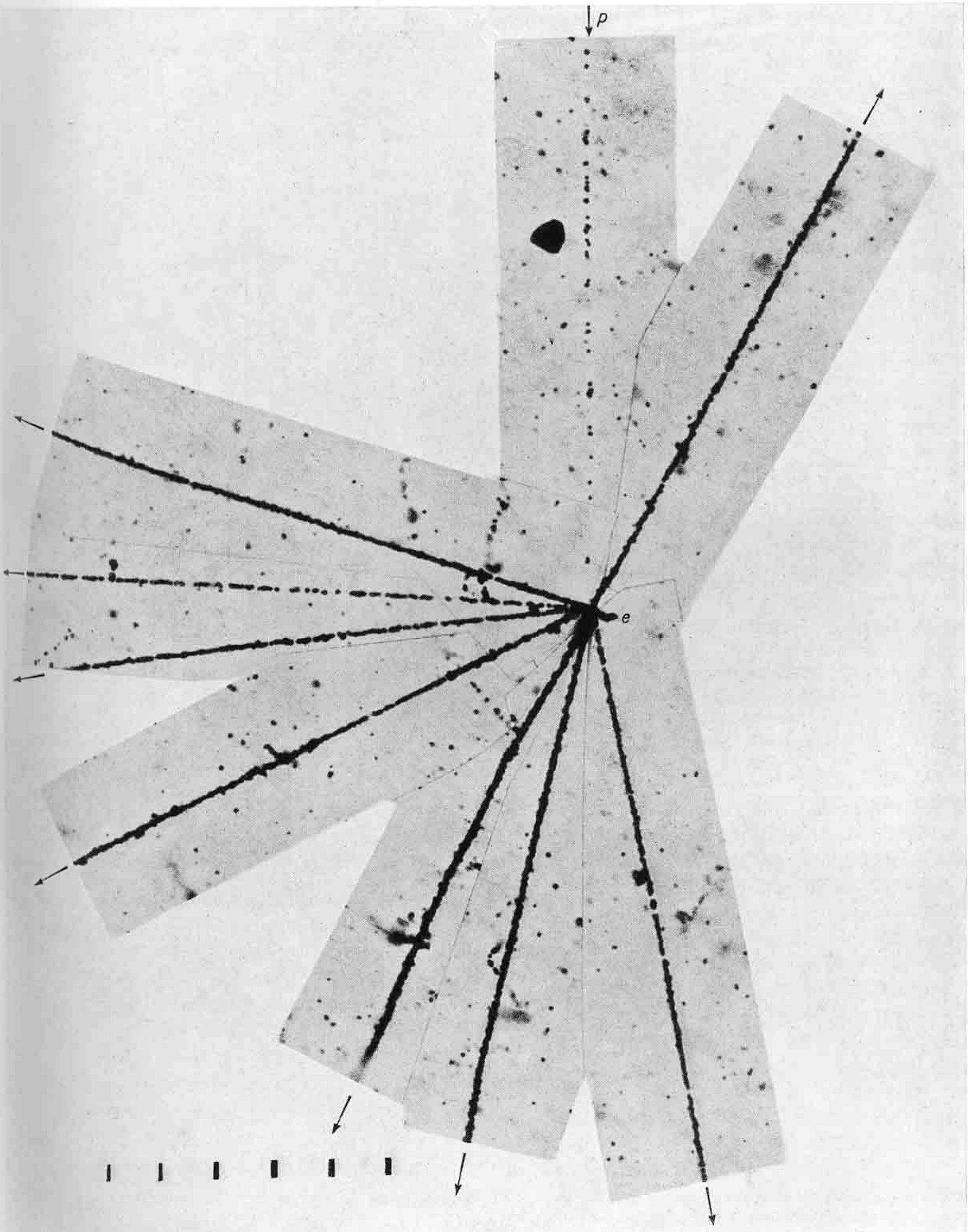


PLATE 13–4

Ilford G5 emulsion. Bristol (1952) unpublished.

A proton of the cosmic radiation, of energy 570 MeV, makes a nuclear collision, and produces a 'star' of type $9 + 0_p$.

Nuclear interaction of a proton of energy 1 BeV

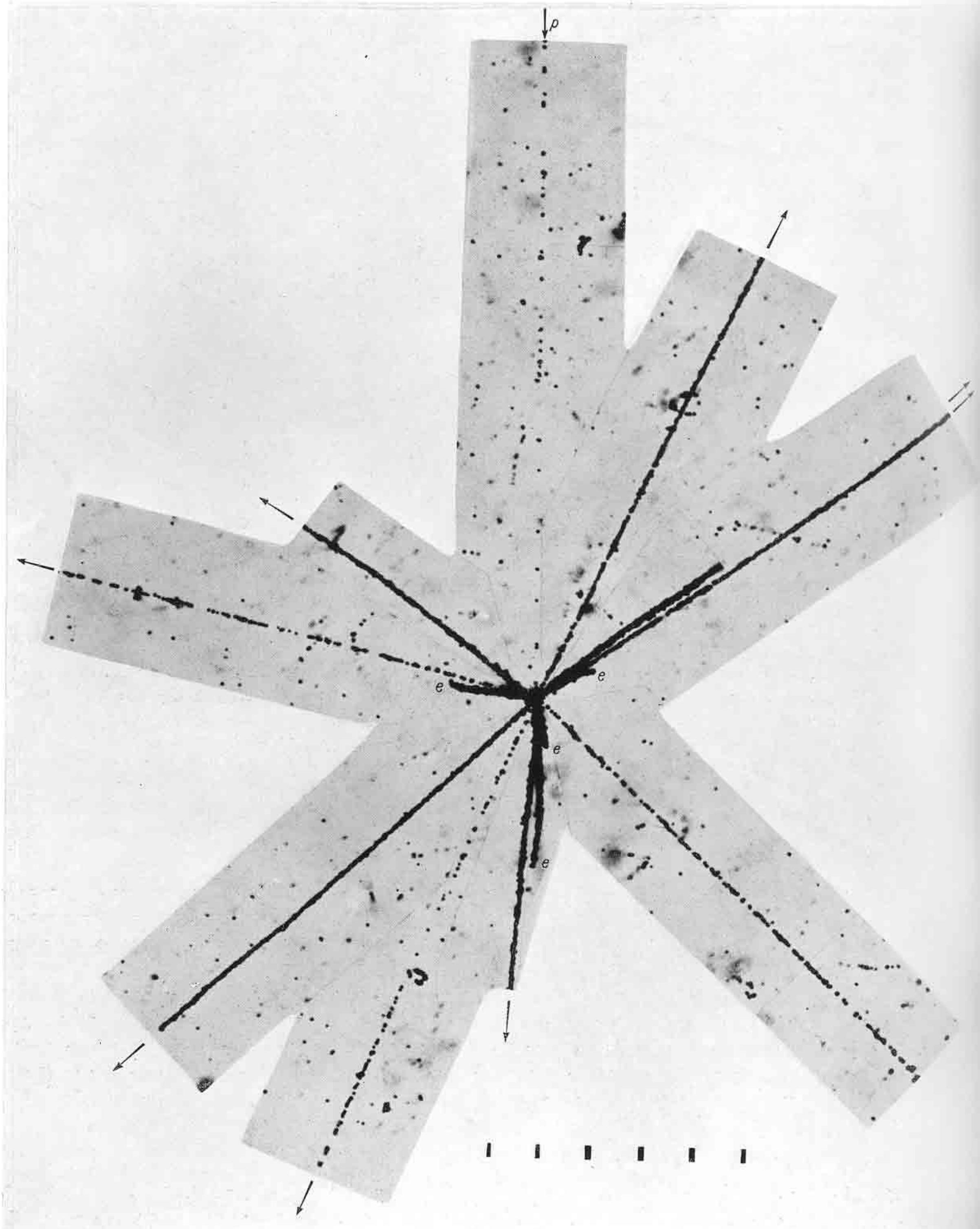


PLATE 13–5

Ilford G5 emulsion. Bristol (1952) unpublished.

A proton of energy 1 BeV produces a 'star' of type $13 + 0_p$. Four of the secondary charged particles, e, are of short range, and come to rest in the emulsion.

Nuclear interaction of a 4 BeV proton

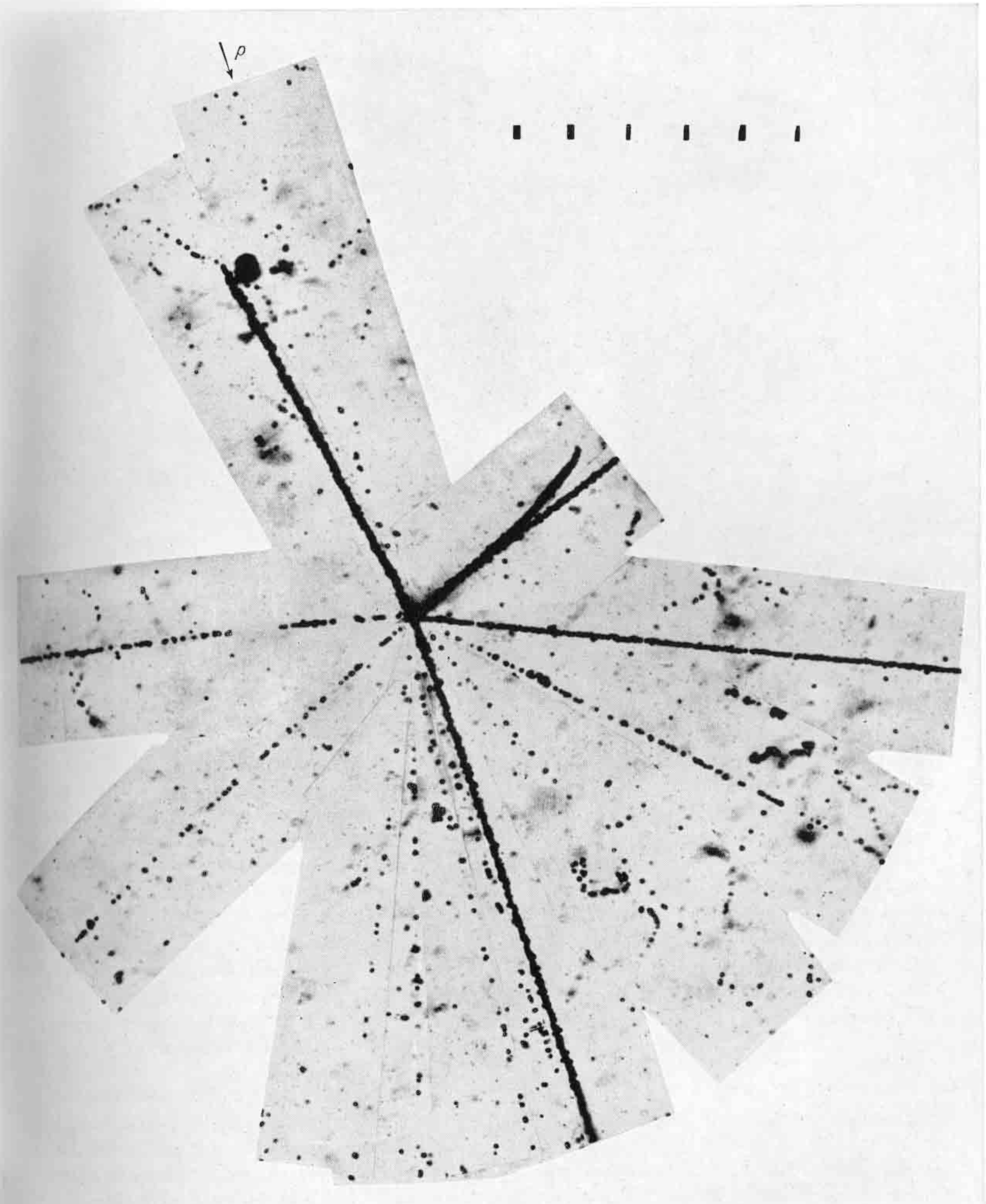


PLATE 13–6

Ilford G5 emulsion. Bristol (1952) unpublished.

The proton produces a 'star' of type $8 + 5_p$. Artificially accelerated protons of this energy were made available when the Berkeley proton-synchrotron came into operation.

Nuclear disintegration produced by a proton with energy 8 BeV

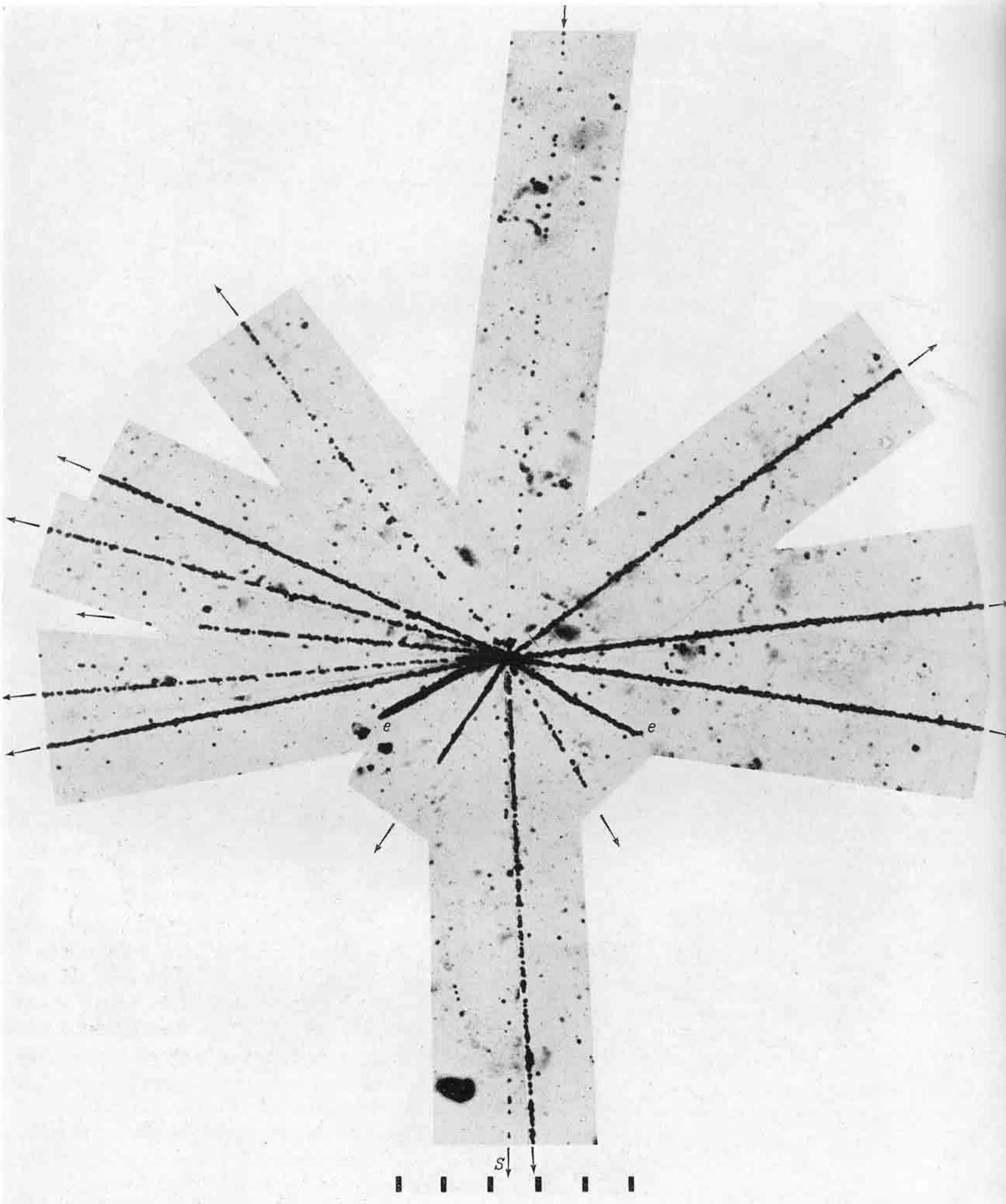


PLATE 13–7

Ilford G5 emulsion. Bristol (1952) unpublished.

The proton produces a 'star', of type $14 + 1_p$, by collision with a nucleus of silver or bromine.

Nuclear collision of a proton with energy 8 BeV

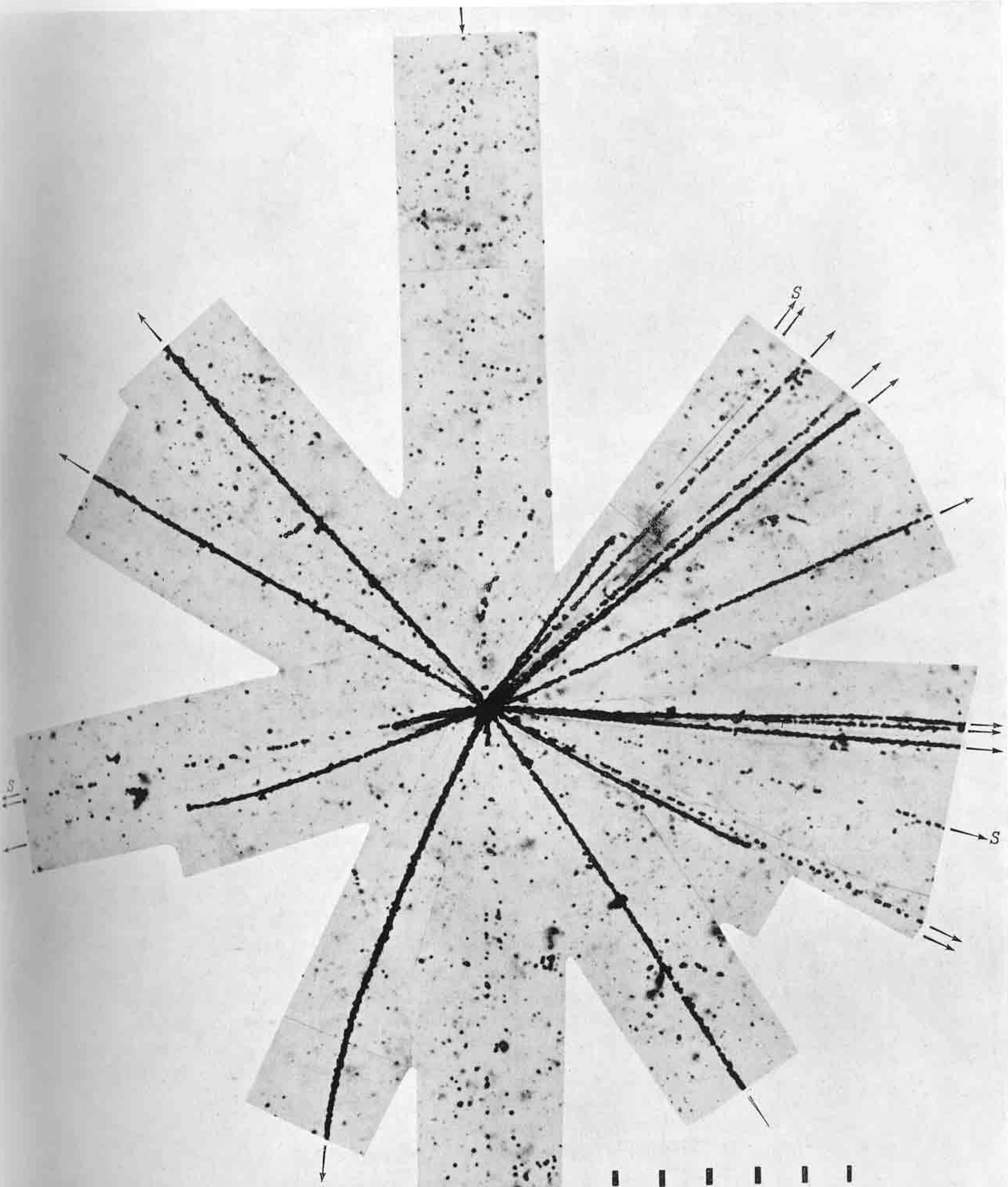


PLATE 13–8

Ilford G 5 emulsion.

Bristol (1952) unpublished.

The proton produces a 'star' of type $16 + 5_p$ by collision with a silver or bromine nucleus. Most of the shower particles, and several of those which produce 'grey' tracks also, are probably due to mesons. With protons of this energy less than one tenth of the mesons are K-particles.

Disintegration of a silver or bromine nucleus by a proton of energy 30 BeV

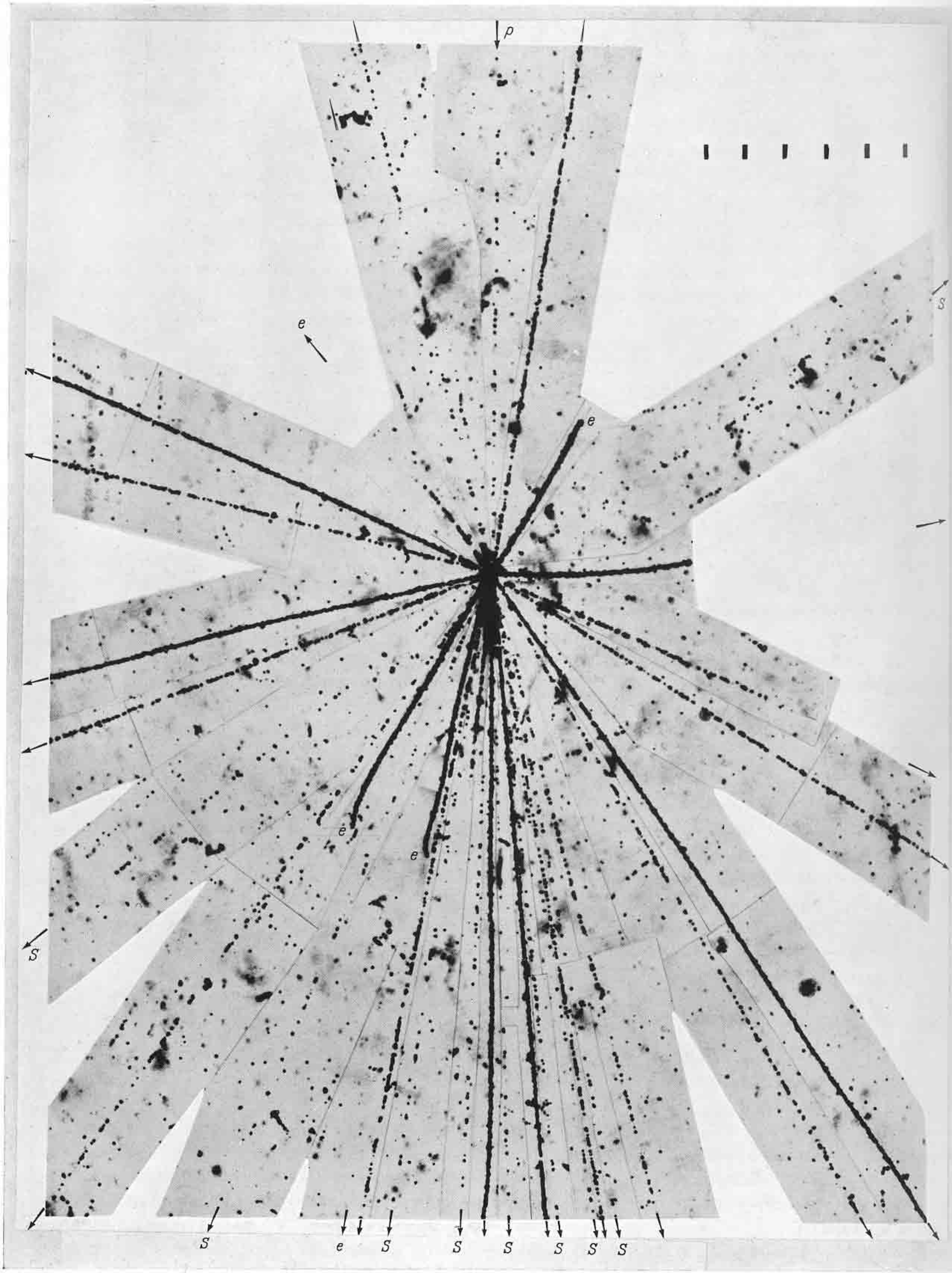


PLATE 13–9

Ilford G5 emulsion.

Bristol (1952) unpublished.

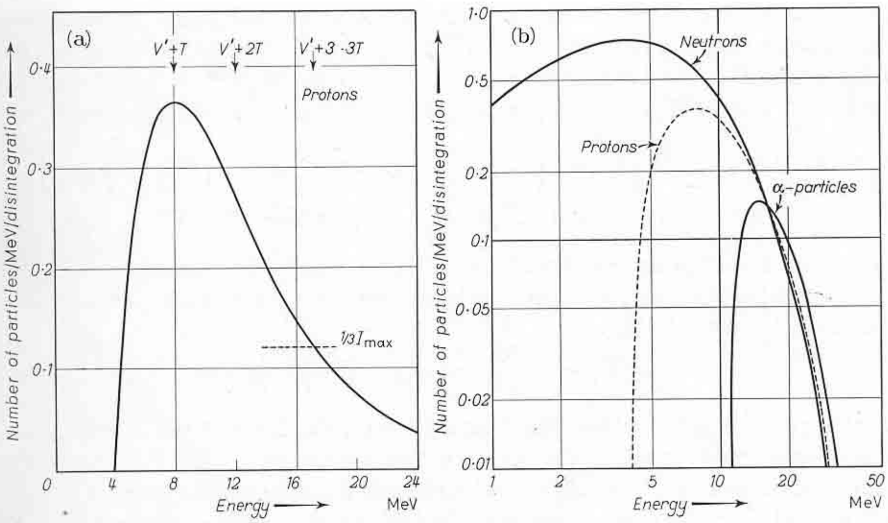


Fig. 13–18. Energy spectra for particles of different types according to elementary evaporation theory. The curves have been computed from the formula of Eq. (13–ii), assuming a 'temperature' of 4 MeV. In (a), the spectrum for protons is shown on a linear scale, assuming the effective barrier height, V', to be 4 MeV. The maximum occurs at an energy $V'+T$, i.e. at 8 MeV; the mean energy, summed over the whole evaporation spectrum, is at $V'+2\,T$. The intensity falls to one third the maximum value at $E = V' + 3{\cdot}3\,T$.

In (b), the spectra for neutrons, protons and α-particles are shown on logarithmic scales. They again correspond to $T=4$ MeV, and the values of V' have been taken as 11 MeV for α-particles, 4 MeV for protons, and 0 for neutrons. These spectra may be compared with those shown in Fig. 13–11. In particular, the experimental spectra decrease in intensity at higher energies much less rapidly than would be expected if the evaporation process were the only source of the particles.

For both figures, the intensities per MeV per disintegration correspond to a typical 'star' from which eight neutrons, four protons and 1·6 α-particles are emitted by evaporation.

where ε is the Fermi energy, $\sim$20 MeV; N is the number of particles in the nuclear volume; and α is an appropriate constant. T is a quantity with the dimensions of energy which can be equated to the product of Boltzmann's constant and the nuclear temperature, but in what follows, it will be convenient to refer to it as the nuclear temperature.

With this model, the number of particles incident per unit time on the nuclear surface which have sufficient energy to penetrate the potential barrier of effective height V' MeV, can be determined. A relation for the number of particles escaping per unit time then follows. For our present purpose it is a reasonable approximation to omit the $+1$ term in the denominator of Eq. (13–i), corresponding to a transition to Boltzmann statistics. In making the calculations, it is assumed that any nucleon which meets the nuclear surface at an angle less than a certain critical value, θ_c, escapes, whilst for larger angles of incidence it undergoes total internal reflection. θ_c is given by the relation:

$$\sin\theta_c = \frac{\lambda_I}{\lambda_0} = \left\{\left(\frac{p^2}{2M} - \varepsilon - B - V'\right)\Big/(p^2/2M)\right\}^{\frac{1}{2}} = \{(E - V')/(E + B + \varepsilon)\}^{\frac{1}{2}},$$

◀ **PLATE 13–9. Disintegration of silver or bromine by a proton of energy 30 BeV**

The proton produces a 'star' of type $22 + 9_p$. It will be seen that even with protons of this energy the directions of emission of the shower particles are still widely dispersed. The shower particles are indicated by the letter S, whilst e denotes a particle which reaches the end of its range in the emulsion in the field of view. Protons of about this energy will be produced artificially when the great proton-synchrotron at Geneva comes into operation.

Emission of a carbon nucleus from a disintegration

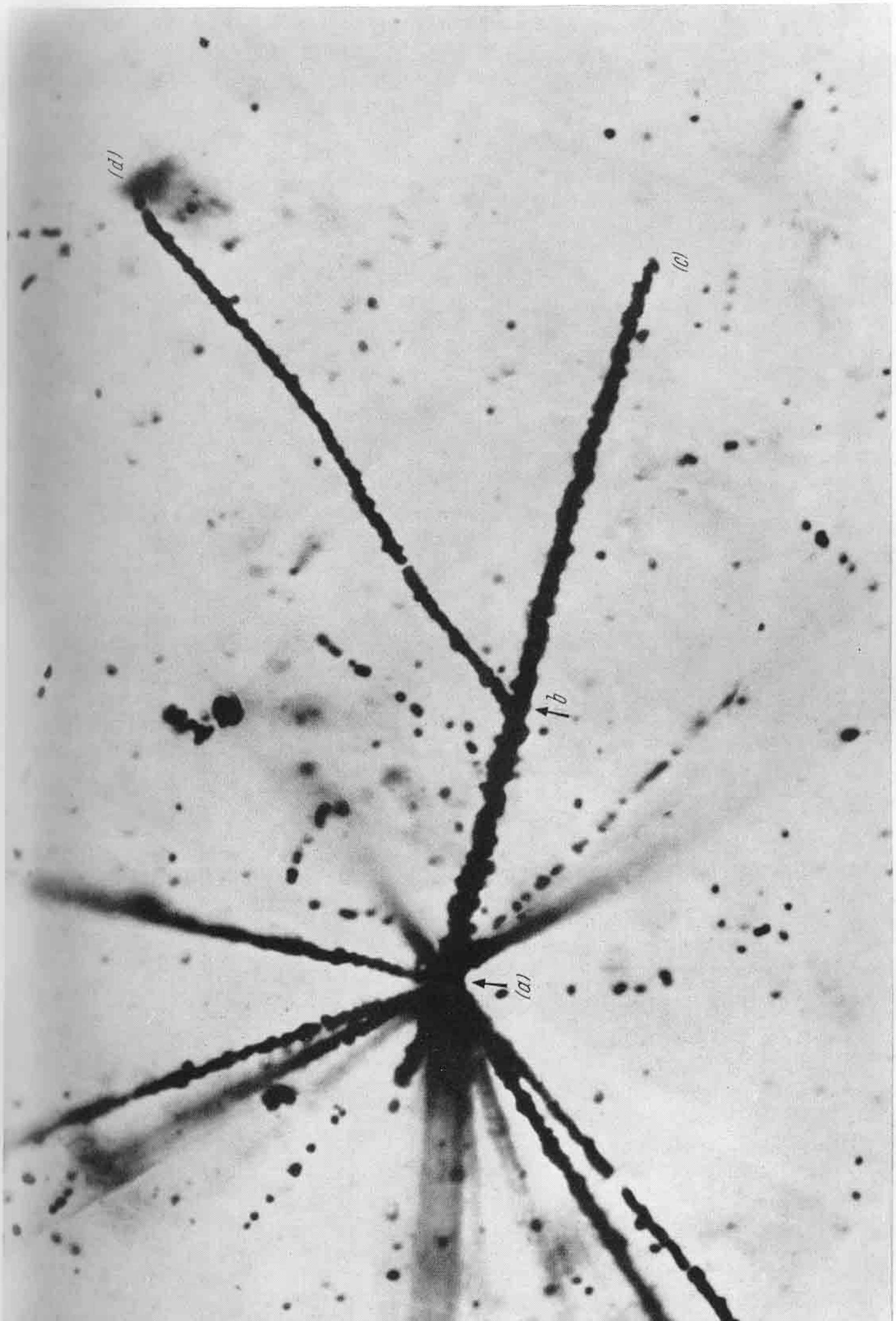


PLATE 13–10

Ilford G 5 emulsion. FOWLER (unpublished).

A heavy nuclear fragment is emitted from the disintegration at (*a*). It collides with a proton at (*b*) and reaches the end of its range at (*c*).

Hammer tracks

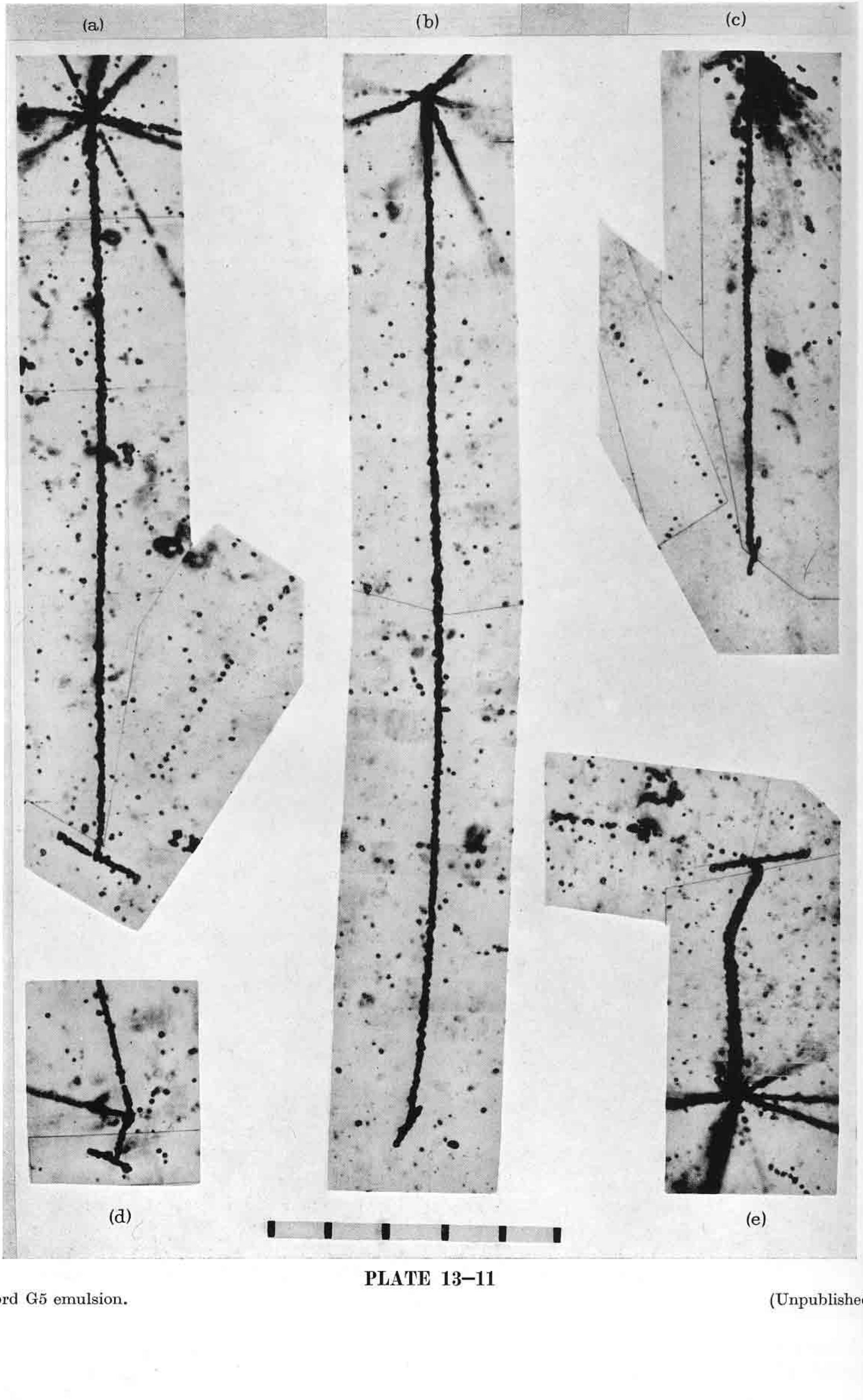


PLATE 13–11

Ilford G5 emulsion. (Unpublished).

Hammer tracks due to Li^8 and B^8 nuclei

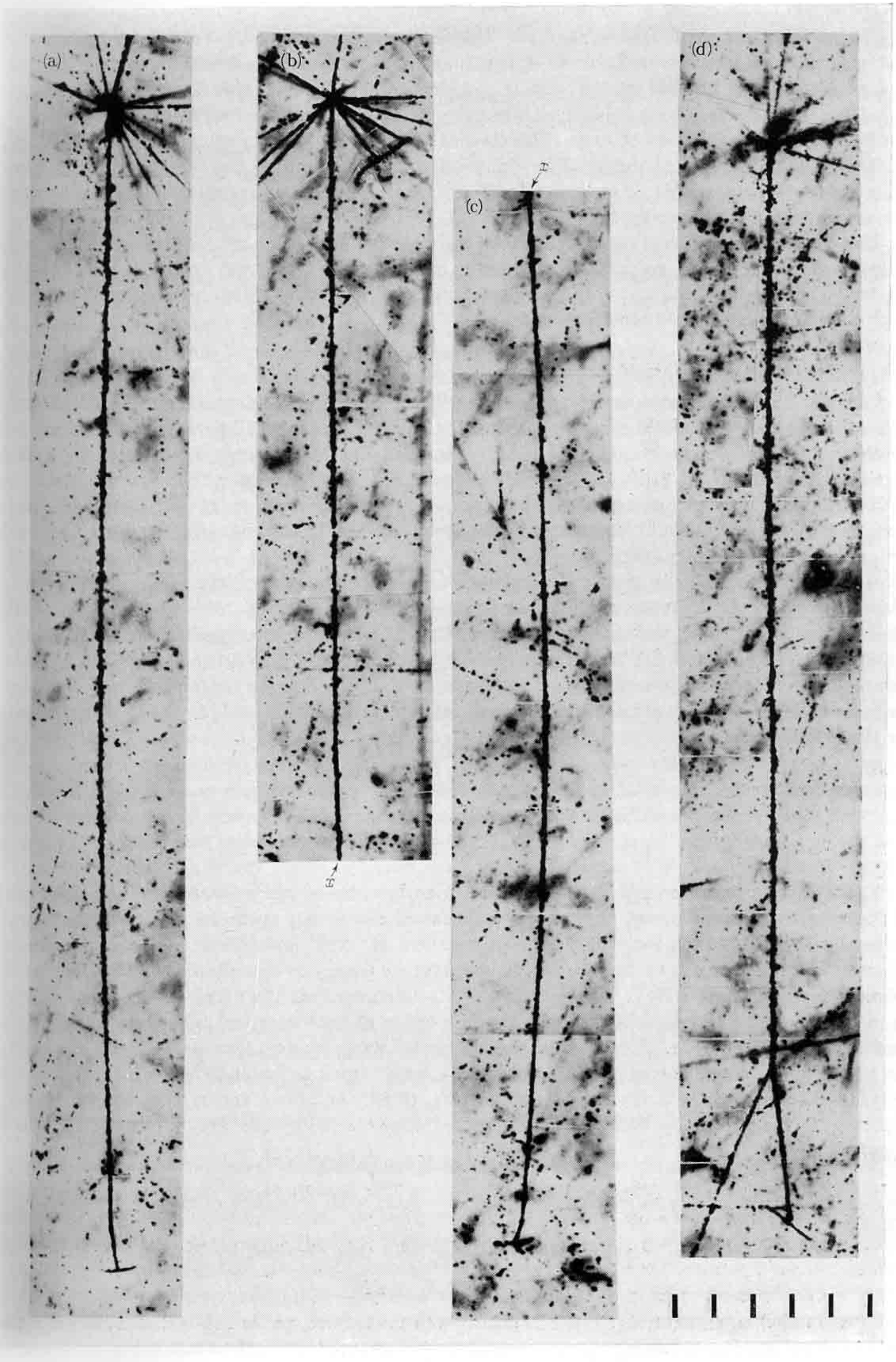


PLATE 13–12

Ilford G 5 emulsion. (Unpublished, 1956).

Emission of a Be^8 nucleus from a disintegration

Pairs of α-particles with nearly the same range and direction are sometimes emitted in nuclear disintegrations. Each is due to the emission of a Be^8 nucleus in its very short-lived ground state, from which it transforms into two α-particles with a very small release of energy.

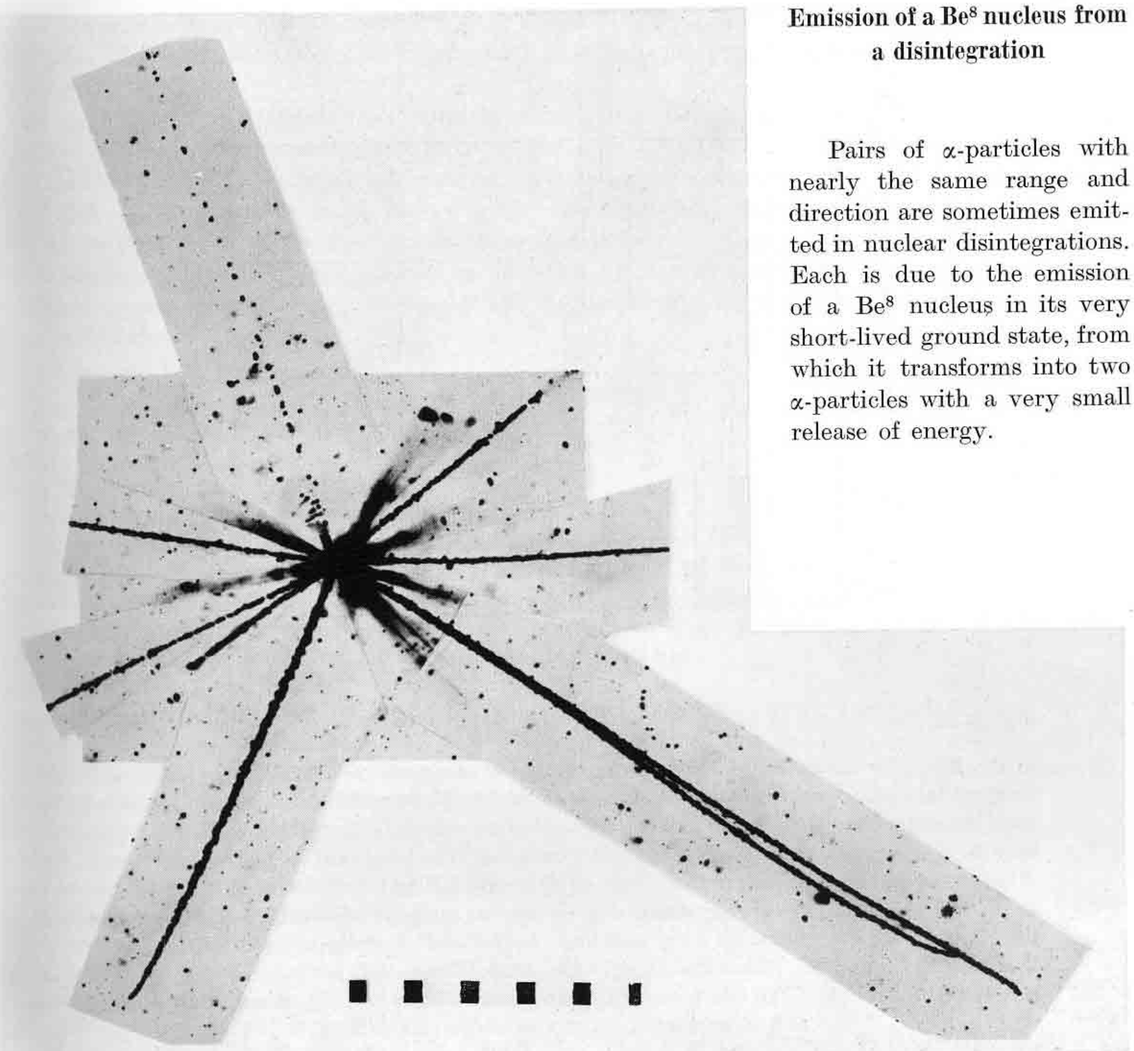


PLATE 13–13

Ilford G5 emulsion.

D. H. Perkins (unpublished).

Table 13–7. Frequency of emission of heavy fragments of long range

Type of fragment	Number observed with $R > 100\ \mu$	Energy at $R = 100\ \mu$ (MeV)	Number observed with $E > 64$ MeV
$Li^{6,7}$	336	29	106
Li^8	56	31	18
$Be^{7,9,10}$	52	43	16
B^8	4	56	4
$B^{10,11}$	17	64	17

(After Skjeggestad and Sørensen, 1958)

For a spherical nucleus, there is no general analytical solution giving the differential angular distribution, but in the limit when $KR \to \infty$, it is identical with that for the disc. Except in cases of a combination of k' large with K small, however, the overall width of the angular distribution from a sphere will not differ greatly from that of a disc, but the subsidiary maxima may often be absent. This is so if the nucleus is assumed to have a Gaussian distribution in density, with KR and $k'R$ both small; then $\overline{\theta^2} \times \overline{r^2} = 2$, where $\overline{\theta^2}$ and $\overline{r^2}$ represent the root mean square values for the angle of diffraction and distance of a nucleon from the nuclear centre.

In illustration of the effects due to diffraction scattering, Fig. 14–3 shows the results of experiments on the elastic scattering of 7·7 MeV deuterons by carbon and nitrogen. They were determined by experiments of the type illustrated in Fig. 4–6, p. 131, using gaseous targets. It may be seen that the general form of the angular distribution of the scattered intensity is similar for the two types of nuclei, corresponding to the similar values of R, and independent of detailed features of the structure of the two types. Curve (iii), in the same figure, shows the calculated distribution assuming an optical model for an impenetrable sphere with $kR = 3$. The similarity in the three distributions is clearly displayed. It may be remarked that for 8 MeV deuterons, assuming a potential well, $V = 40$ MeV, the refractive index is large. Effects due to reflection, which have not been taken into account in the previous discussion, may then be important. The curves for scattering from oxygen and nitrogen nuclei follow closely numerous experimental points which are not shown. For angles less than about 40°, the intensity rises rapidly owing to Coulomb scattering.

REFERENCES

Burge, Burrows, Gibson and Rotblat; Proc. Roy. Soc. A **210**, 534 (1952).
Fernbach, Serber and Taylor; Phys. Rev. **75**, 1352 (1949).
Gibson and Thomas; Proc. Roy. Soc. A **210**, 543 (1952).

Characteristic early examples of disintegrations due to fast μ-mesons

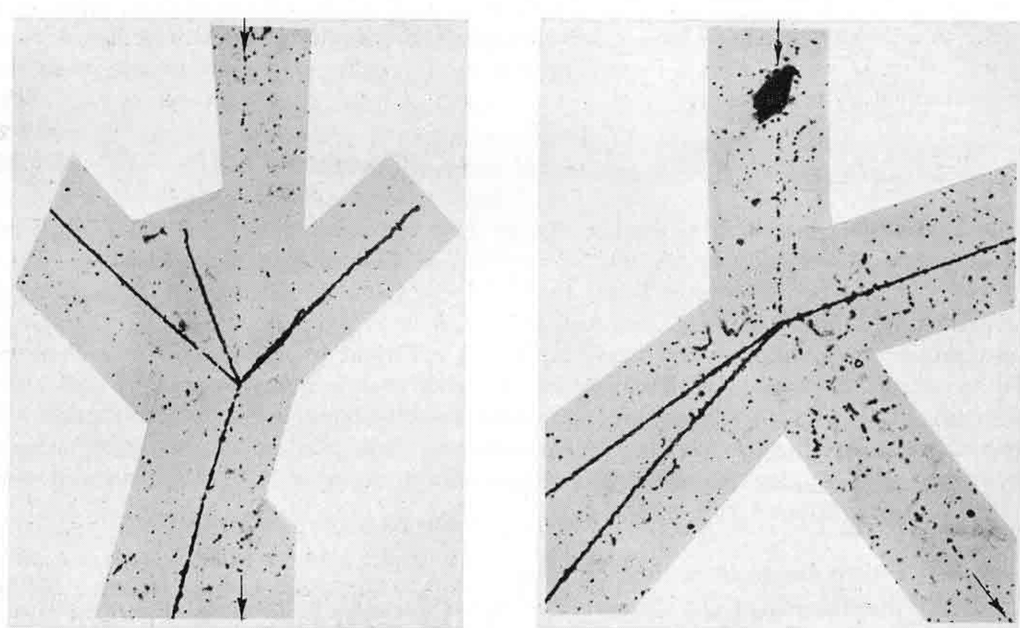


PLATE 14–1

Ilford G 5 emulsion. George and Evans (1950).

The two events were among the first observed which could be attributed to fast μ-mesons. The emulsion was poured and developed underground at a depth of 60 m of water equivalent. In each event, the μ-meson emerges from the collision; that on the right is unusual in that the deviation in the direction of motion is large.

Meson production by fast μ-meson

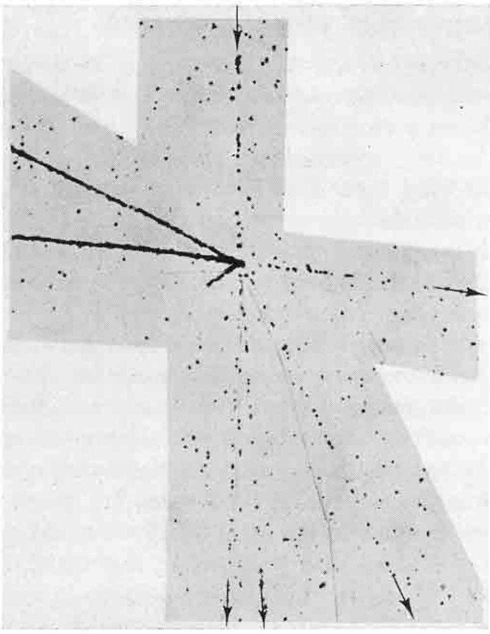


PLATE 14–2

Ilford G5 emulsion. GEORGE and EVANS (1950).

In this rare event, observed in the same conditions as those described in the caption to Plate 14–1, the primary particle interacts with a nucleus and several fast particles, almost certainly π-mesons, are created.

through loss of energy by ionisation, before interacting with a nucleus. This explanation of the main features of the observations was in good accord with the number of events of the different types, and with the slow change in the μ-meson intensity with depth.

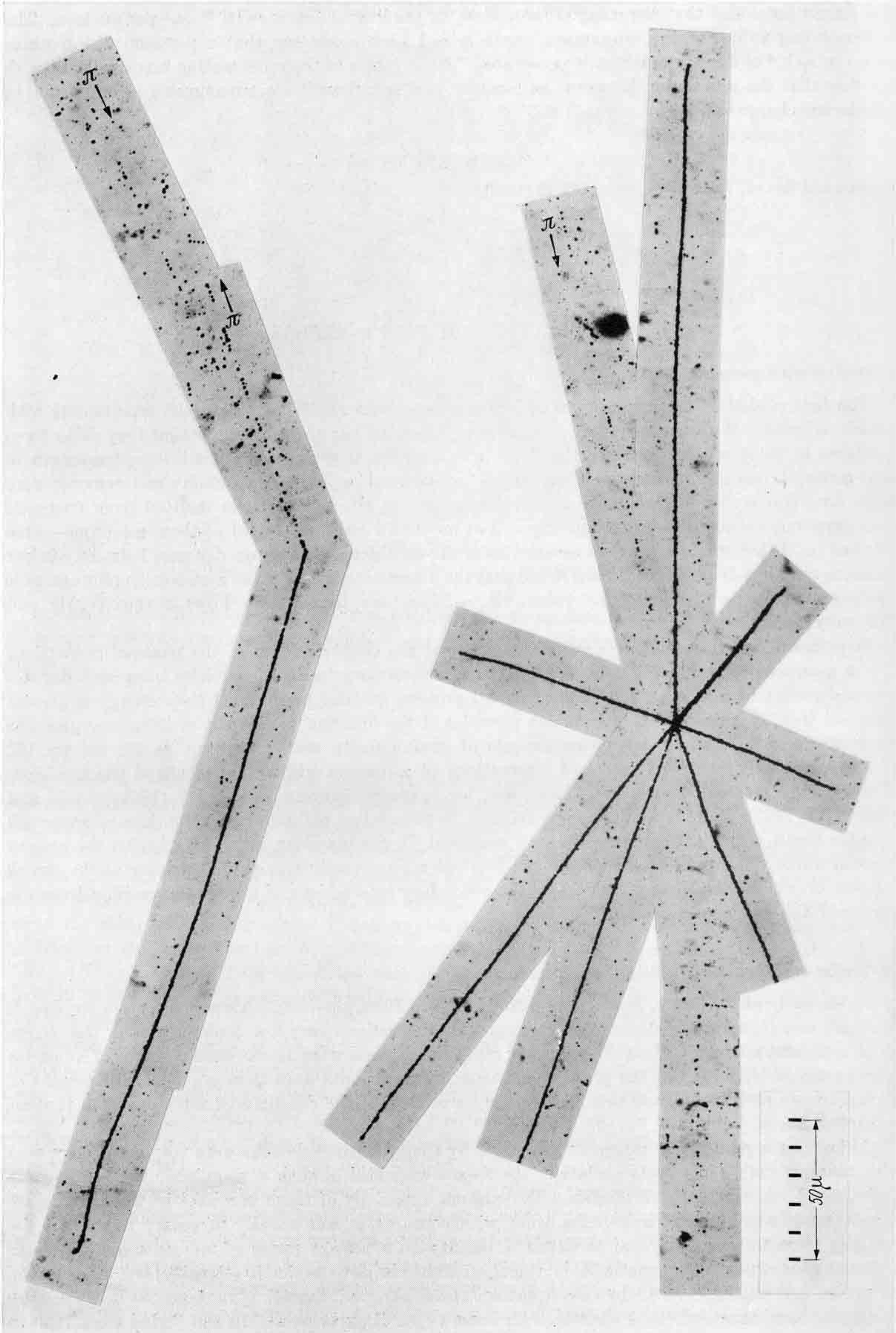
In order to obtain an estimate of the energy of the μ-mesons producing the stars of the type 1_p, GEORGE and EVANS assumed that the scattering of the μ-meson occurred through interaction with a single proton, the recoil of this particle, and its interaction with other nucleons of the nucleus, giving rise to the observed disintegration. The energy of recoil could then be estimated from the 'size' of the resulting star—the number, N_h, of heavily ionising particles emitted—using the relation $\overline{E} = 37 N_h + 4 N_h^2$; see p. 464. They concluded that the energies of the μ-mesons are commonly between 1 and 10 BeV, a result in good accord with the energy distribution of the 'hard component' at sea-level and underground.

In spite of the success of the above picture of the nature of the interaction of μ-mesons with nucleons, later evidence suggests that the collisions are commonly inelastic. Thus, in similar experiments in controlled conditions with fast electrons, collision with a proton may create a π-meson, the electron being little deviated. By analogy, one may anticipate that the interaction of the μ-meson with a nucleon creates a π-meson; the latter is commonly absorbed by the associated nucleus which is thus disintegrated.

Because of the complexity of the phenomena, it is difficult to maintain that any particular disintegration recorded in plates exposed underground was due to a μ-meson, and not to one of the locally produced π-mesons which may sometimes be of considerable energy. There is, however, no doubt as to the origin of most of the stars of a given class observed in such an experiment.

By comparing the number of observed disintegrations in a given volume of emulsion, and from a given exposure, with the known intensity of fast μ-mesons at the same depth underground, GEORGE

Early examples of nuclear collisions of π-mesons of energy 79 and 280 MeV



(a) (b)

PLATE 14–3

Ilford G 5 emulsion.

Lock and Yekutieli (1952), unpublished.

1956, more than fifty investigations were made with emulsions, using artificially generated π-mesons with energies ranging from low values up to $\sim$4·5 BeV; for a list of references see p. 495.

Studies of the interactions of π^+- and π^--mesons of different energy in emulsion have been made with two principal objectives. First, to help in establishing the details of the interactions of π-mesons with protons, the latter being present as hydrogen nuclei in the emulsion; and secondly, for studies of the interactions of the particles with heavier nuclei. The latter have an important bearing on the interpretation of the processes involved in high-energy nuclear disintegrations, for π-mesons frequently result from interactions between elementary particles. When these occur in a complex nucleus, the secondary interactions of the escaping mesons may play an important rôle in determining the nature of the phenomena observed. Such considerations are important, for example, in interpreting 'stars' due to the interaction of anti-protons with nuclei (see p. 412).

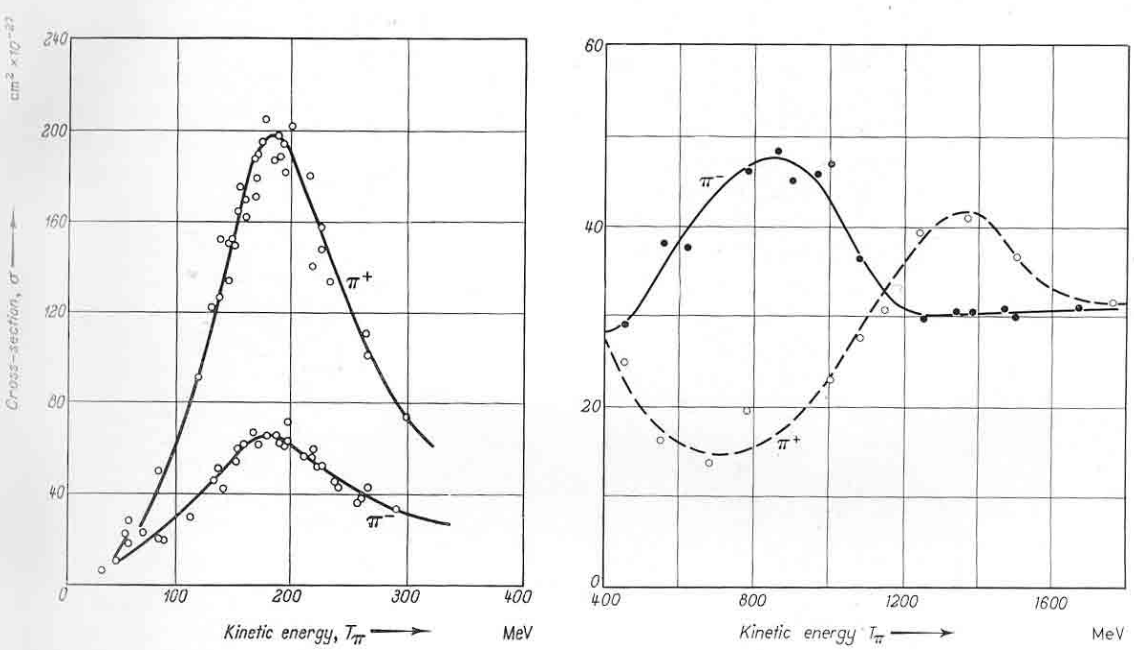


Fig. 14–4. Variation with energy, T_π, of the total cross-sections for the interactions of positive and negative π-mesons with protons. The interactions of the negative particles involve both elastic scattering and 'charge-exchange'. The results have been compiled from the work of many authors; see, for example, ANDERSON (1956) and MESCHERYAKOV (1956); COOL *et al.* (1956).

◂ **PLATE 14–3. Early examples of nuclear collisions of π-mesons of energy 79 and 280 MeV**

In both these events, the identification of the nature and energy of the incident π-mesons is unambiguous, for both were created by cosmic radiation in nuclear disintegrations in the emulsion. In (a), the meson originated as the secondary particle of a disintegration of type $(6+4p)$. The meson was scattered nearly backwards along its original direction of motion as a result of a nuclear collision, emerging with energy $\sim$67 MeV. The event cannot be attributed to a collision with a free hydrogen nucleus as the recoiling proton manifestly does not balance the change in momentum of the meson.

In event (b), a meson of energy 240 MeV, emitted from a disintegration of type $(5+2p)$, produces a secondary disintegration. The heavily scattered secondary particle, of small specific ionisation, was of low mass. It was probably an electron produced by the β-decay of the nuclear fragment left after the evaporation of part of the struck nucleus. Consideration of conservation of energy makes it unlikely that a neutral π-meson was produced in the collision, and the event probably represents the nuclear capture of a fast π-meson. The β-decay of a product nucleus is rarely observed.

Nuclear collision of a π-meson of energy 350 MeV

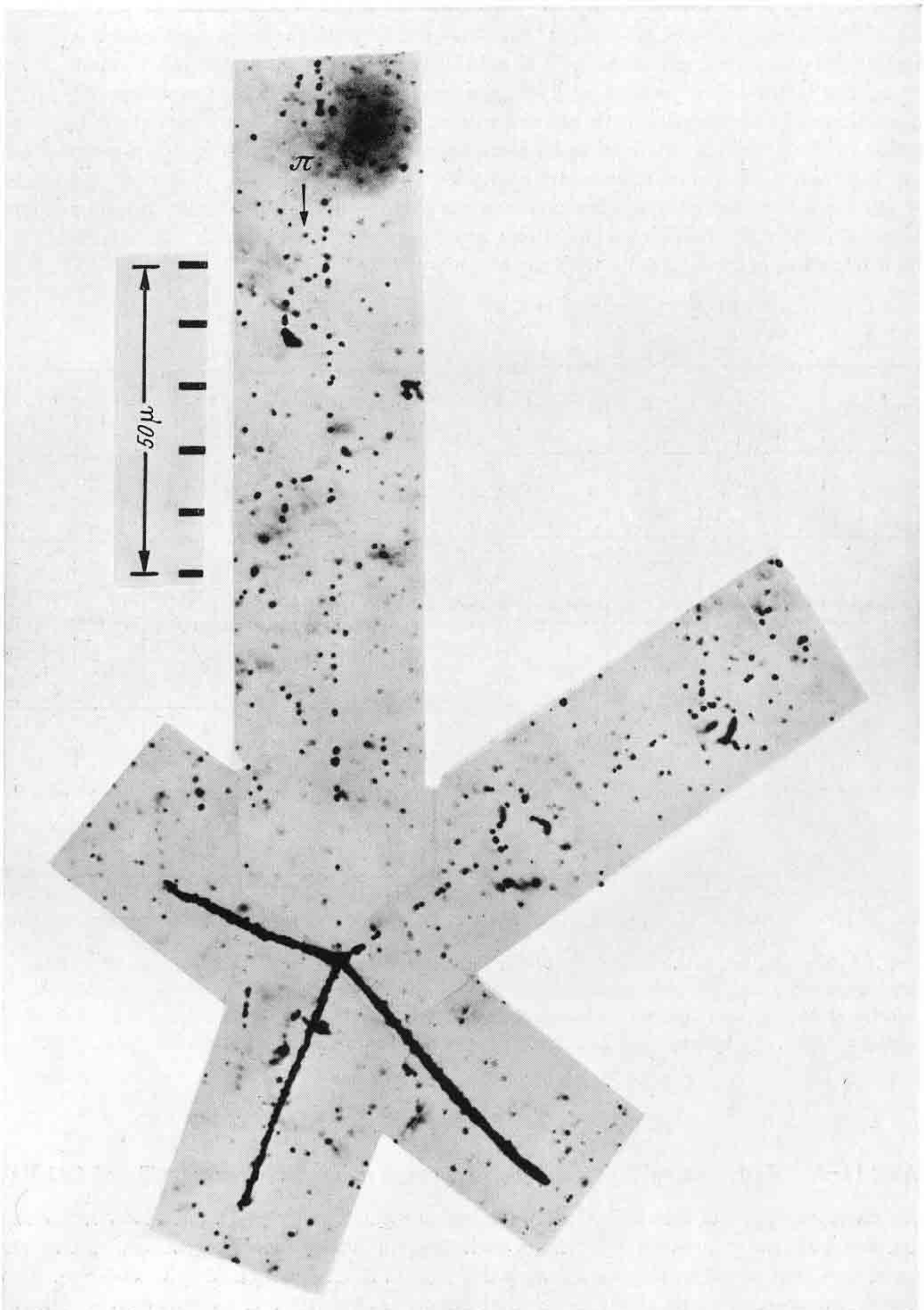


PLATE 14–4

Ilford G 5 emulsion. LOCK and YEKUTIELI (1952), unpublished.

A π-meson of energy 350 MeV, produced as a secondary particle from a disintegration of type $10+5p$, makes a nuclear collision from which three heavily ionising particles of short range are emitted together with a fast particle which cannot be identified. This secondary particle was probably a π-meson, and the event an example of the 'inelastic scattering' of a fast meson. Compare Plate 14–12.

Early example of the nuclear collision of a π-meson of energy 560 MeV

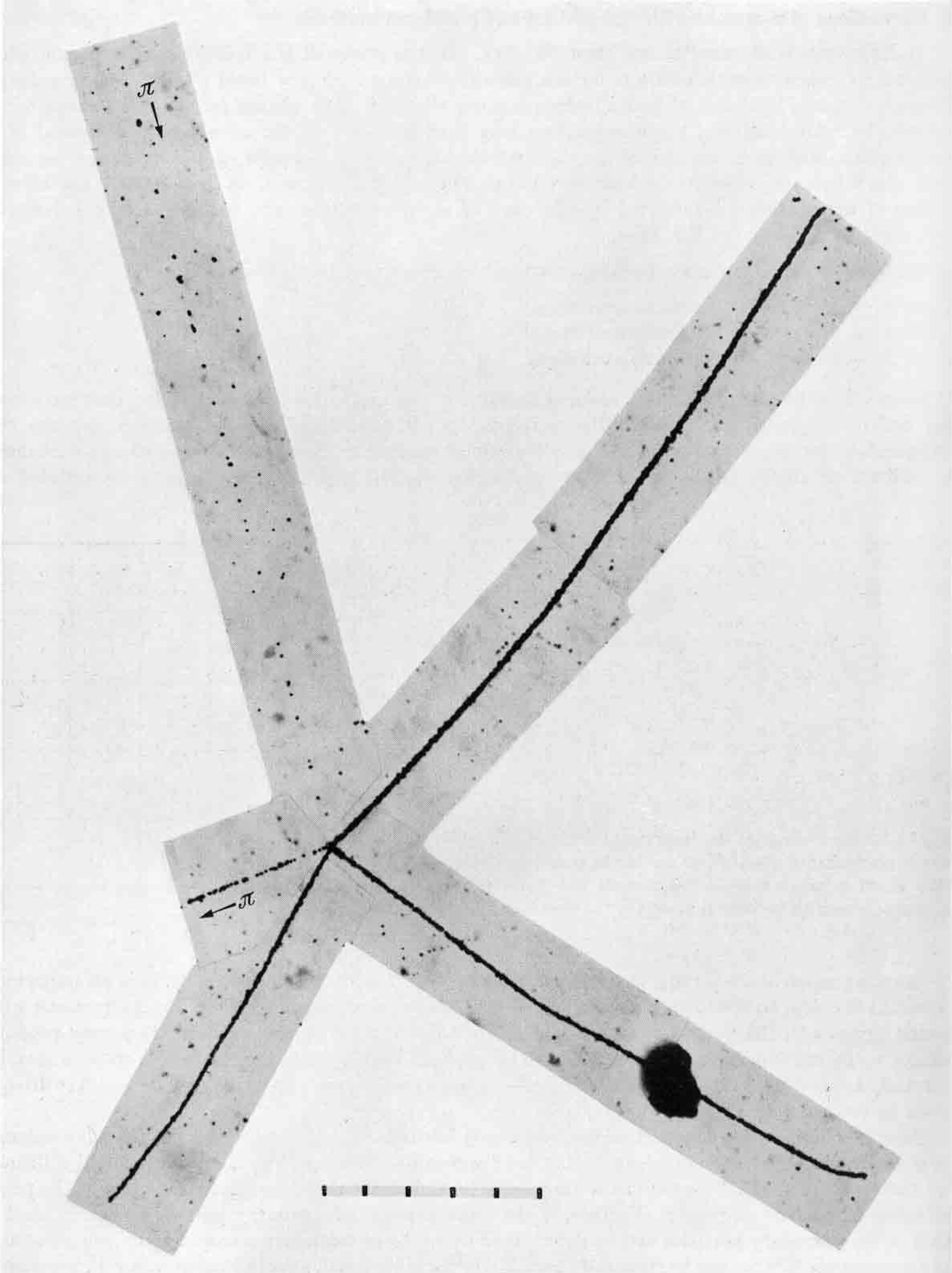


PLATE 14–5

Ilford G 5 emulsion. LOCK and YEKUTIELI (1952), unpublished.

The π-meson, of energy 560 MeV, was emitted from a parent disintegration of type $5 + 1n$. The event, closely similar in appearance to that shown in Plate 14–4, probably represents the inelastic collision of a π-meson with a nucleus without meson production.

Early example of the nuclear collision of a π-meson of energy 640 MeV

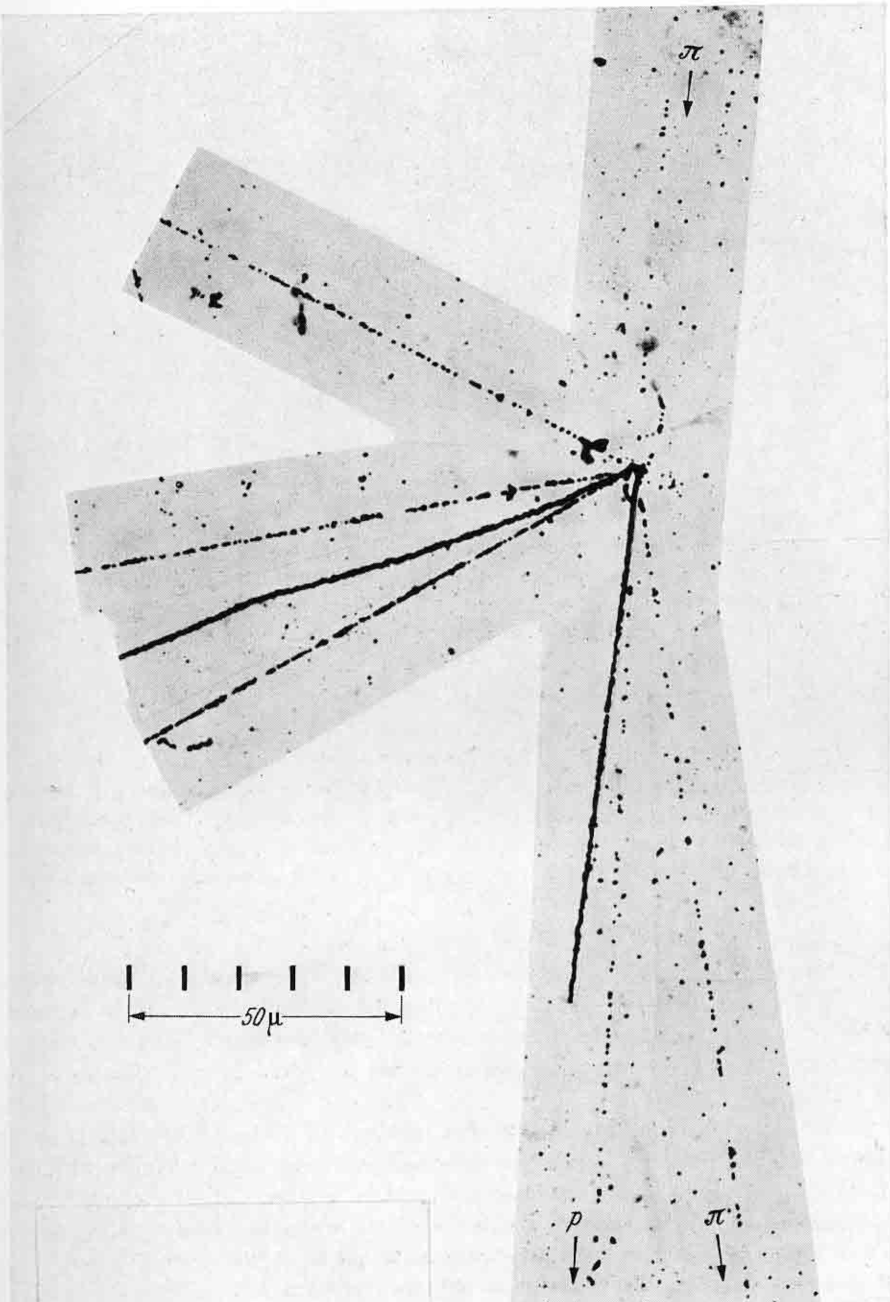


PLATE 14–6

Ilford G 5 emulsion. LOCK and YEKUTIELI.

The incident meson leads to the ejection from the struck nucleus of a proton, p, of energy 380 MeV and a π-meson of 40 MeV. The other tracks were too short to allow the particles which produced them to be identified.

Early example of the 'inelastic' scattering of a π-meson of energy 750 MeV

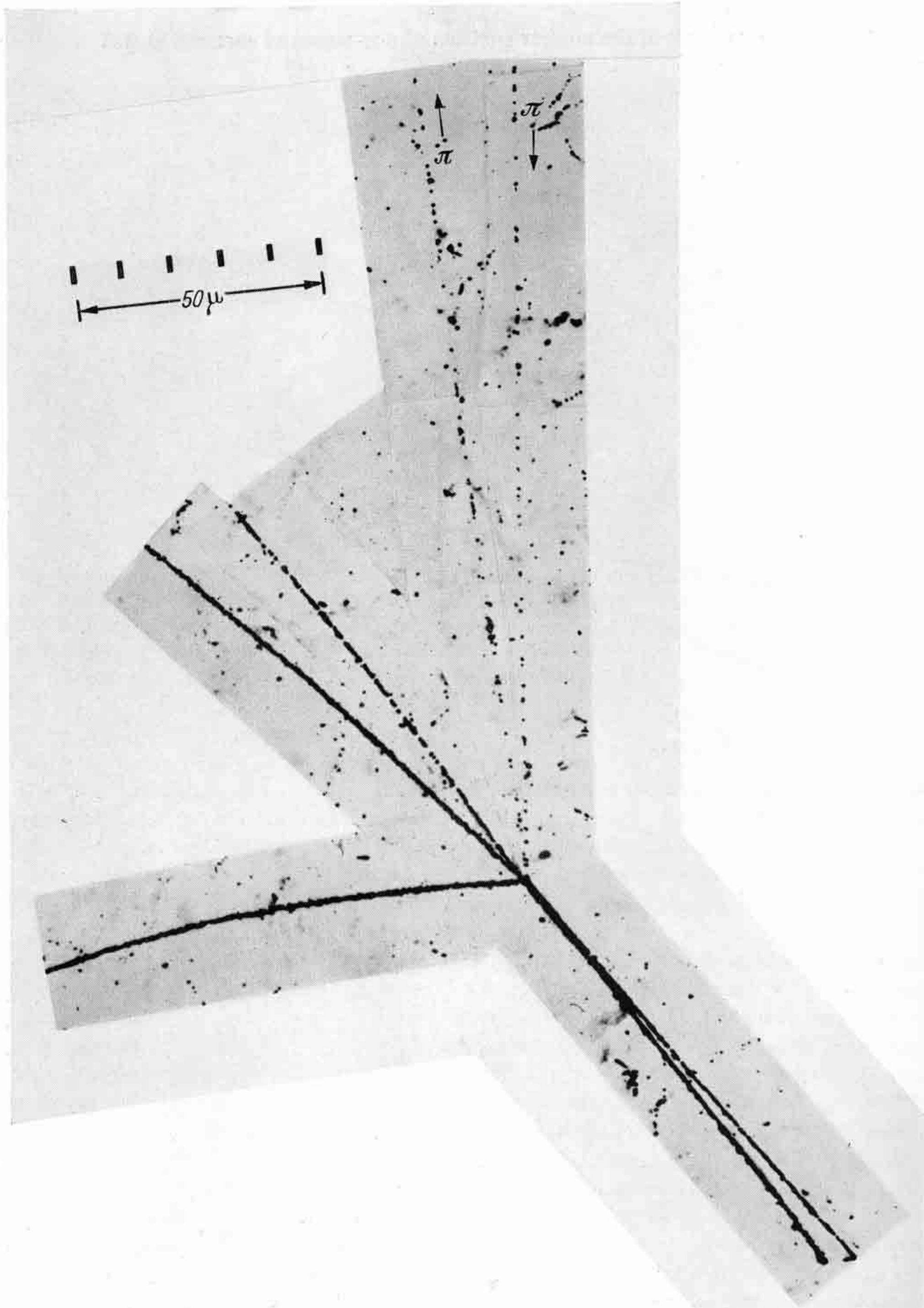


PLATE 14–7

Ilford G5 emulsion.

LOCK and YEKUTIELI.

The disintegration is accompanied by the ejection of a π-meson of energy ~70 MeV which emerges in a direction at 167° to the line of motion of the parent particle. It is probable that a neutral π-meson was also emitted.

'Elastic' scattering of a π-meson at energy 825 MeV

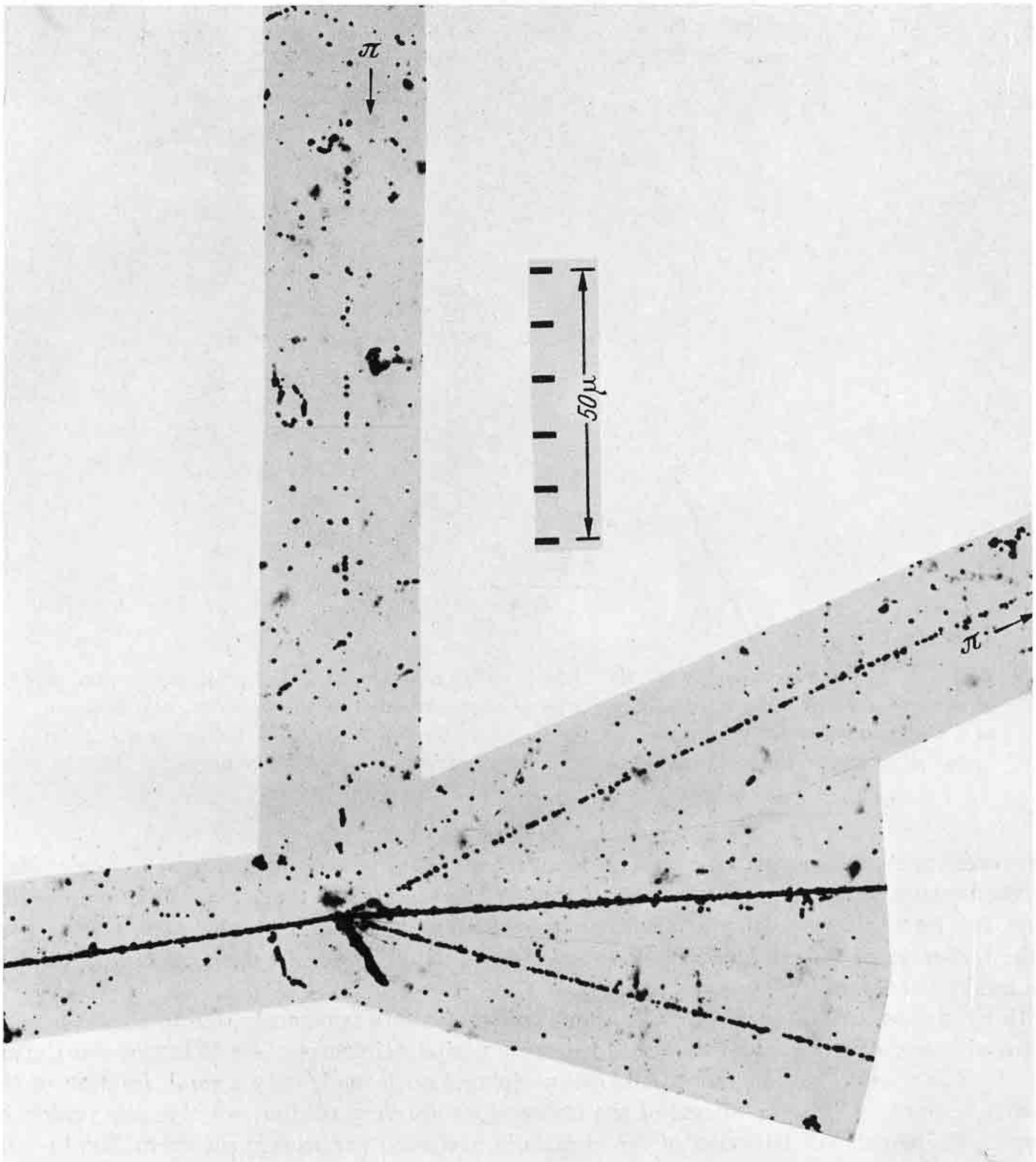


PLATE 14–8

Ilford G 5 emulsion. LOCK and YEKUTIELI (1952), unpublished.

A π-meson of energy 825 MeV collides with a nucleus and disintegrates it. Among the secondary particles is a π-meson of energy 17 MeV. In view of the small amount of visible energy in the disintegration, it is reasonable to suppose that a π^0-meson was also emitted.

Early example of the nuclear interaction of a π-meson of energy 3·8 BeV

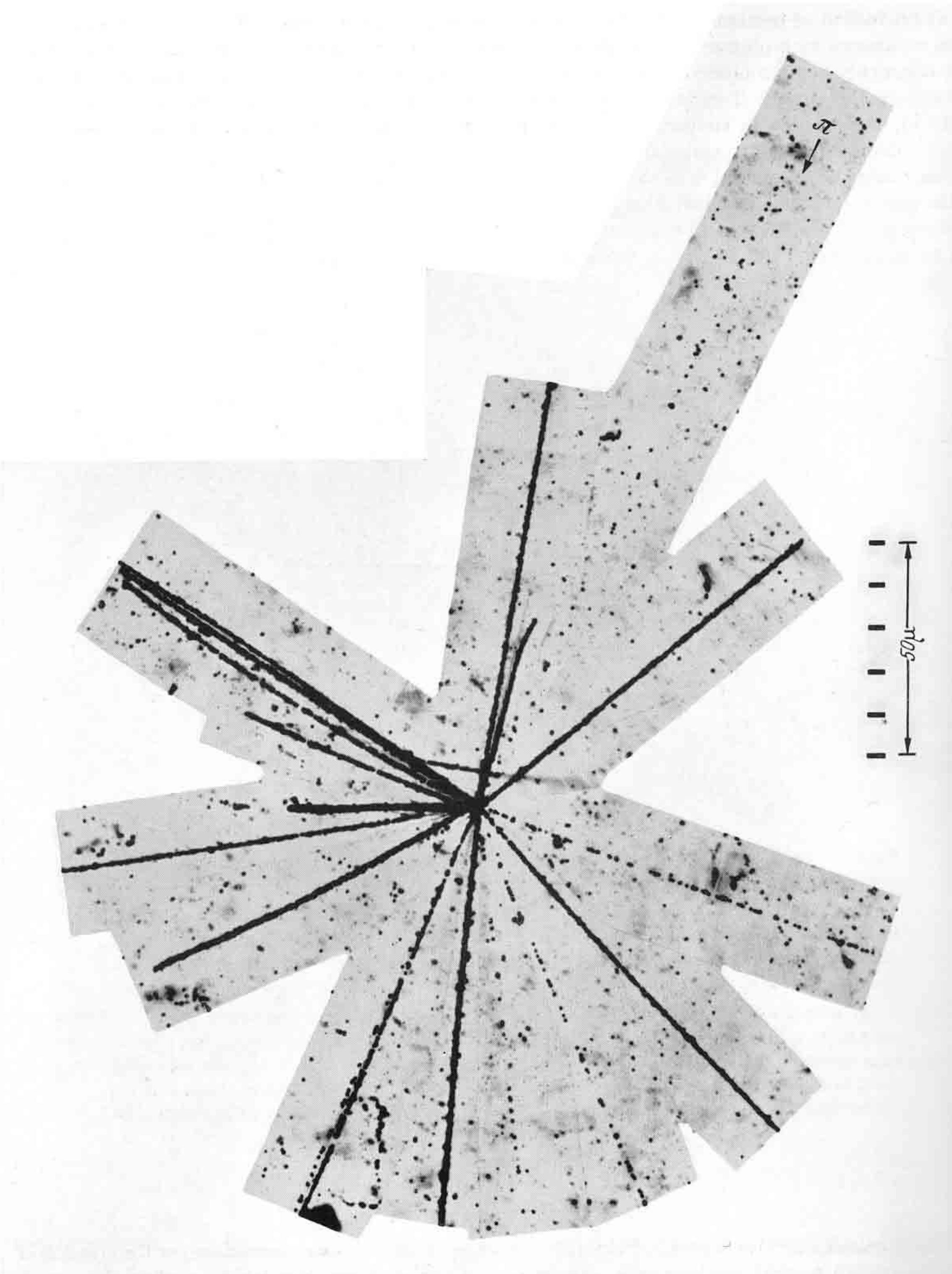


PLATE 14–9

Ilford G 5 emulsion. LOCK and YEKUTIELI (1952), unpublished.

A π-meson of energy 3·8 BeV, emitted from a disintegration of type $7 + 10p$, produces a secondary disintegration of type $18 + 1\pi$. It is probable, but not established, that several of the lightly ionising secondary particles are π-mesons.

Characteristic disintegrations due to 4·5 BeV π^--mesons

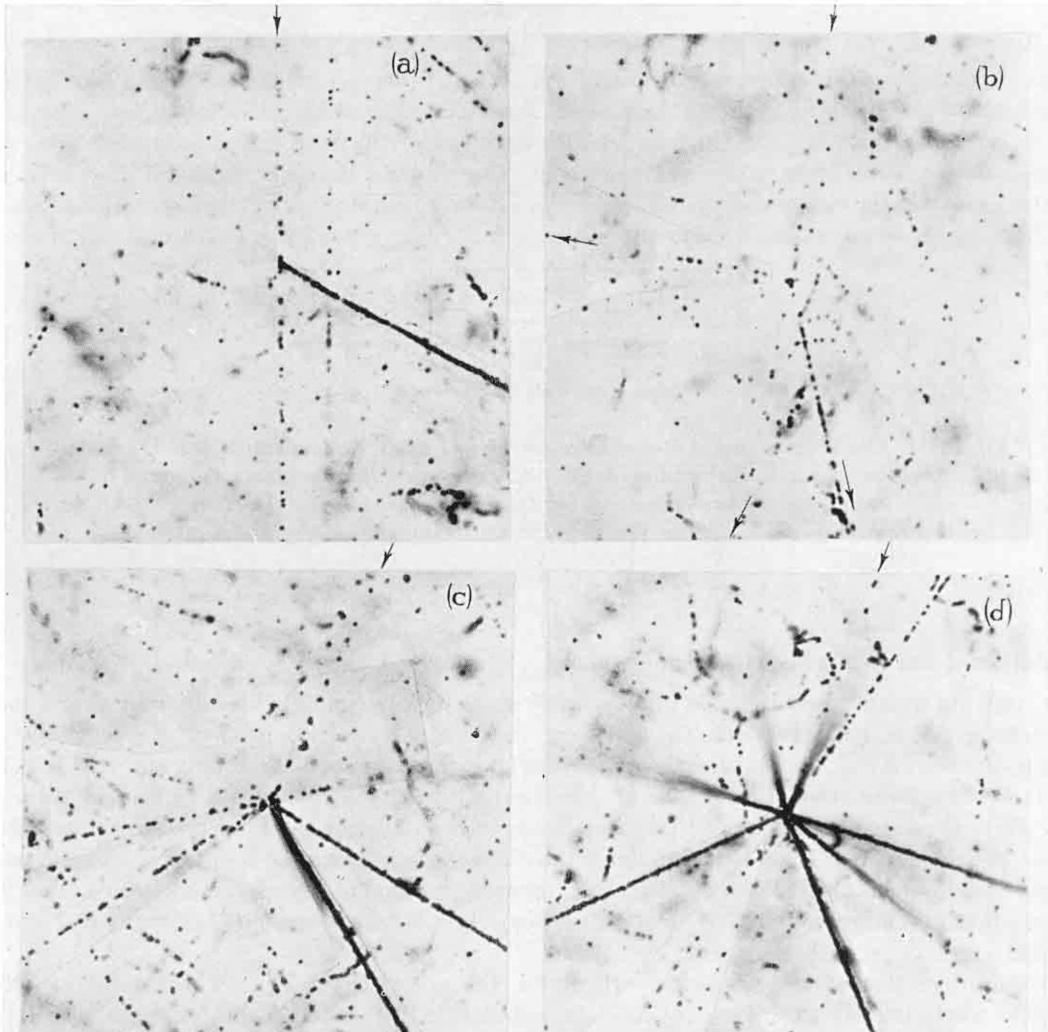


PLATE 14—10

Ilford G 5.

Bristol (unpublished).

of such events has been made by ALY *et al.* (1959). They found that the angular distribution of the mesons produced in the collision could be accounted for predominantly in terms of interaction of the incident pion with a single nucleon, and symmetrical backward and forward emission of mesons in the centre-of-momentum frame of this collision. The centre-of-momentum angular distribution was approximately isotropic, as in the case of the pion-proton collisions described above.

Early examples of the inelastic collision of π^--mesons with emulsion nuclei are shown in Plates 14–4 to 14–9. They were taken from plates exposed to cosmic radiation, the π-mesons being identified by mass measurements. It was shown by LOCK and YEKUTIELI (1952) that, in those events in which the π-meson escapes from the struck nucleus, the change in momentum and energy cannot be accounted for in terms of a collision with a single nucleon of the nucleus. The observations can, however, be explained in terms of two or three such collisions. The average energy of the π-mesons emerging from the disintegrations after scattering is $\sim$40 MeV; the value appears to be insensitive to the magnitude of the primary energy for $T_\pi < 500$ MeV.

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For other references, see Table 14–1, p. 495.

◄ **PLATE 14–10. Characteristic disintegrations due to 4·5 BeV π^--mesons**

The wide variety in the character of the 'stars' is well displayed. It is due to the many variables involved in the collision; a) the closeness of the collision, whether central or peripheral; b) the nature of the struck nucleus, whether light (C, N, O) or heavy (Ag, Br); and c) the secondary interactions of the π-mesons and other particles resulting from the primary interaction with a nucleon or nucleons. Some of the events show the production of several charged π-mesons as a result of an interaction with a single nucleus. Such observations did not give decisive evidence for the multiple production of π-mesons in single pion nucleon collisions, however, for the view that several nucleons of the target nucleus might have been involved in the collision could not be excluded.

4. NUCLEAR INTERACTIONS OF FAST POSITIVE K-MESONS

a) Elastic and inelastic scattering: charge-exchange

We have seen that when a fast π-meson collides with a nucleus, it can take part in a variety of processes, including elastic scattering, charge-exchange, plural production of mesons and the associated production of heavy mesons and hyperons. At kinetic energies < 400 MeV, however, the processes of elastic scattering and charge-exchange, together with those in which the meson is absorbed, its rest-energy contributing to the nuclear disintegration, are dominant. Further, there is little difference

(Continued on page 502)

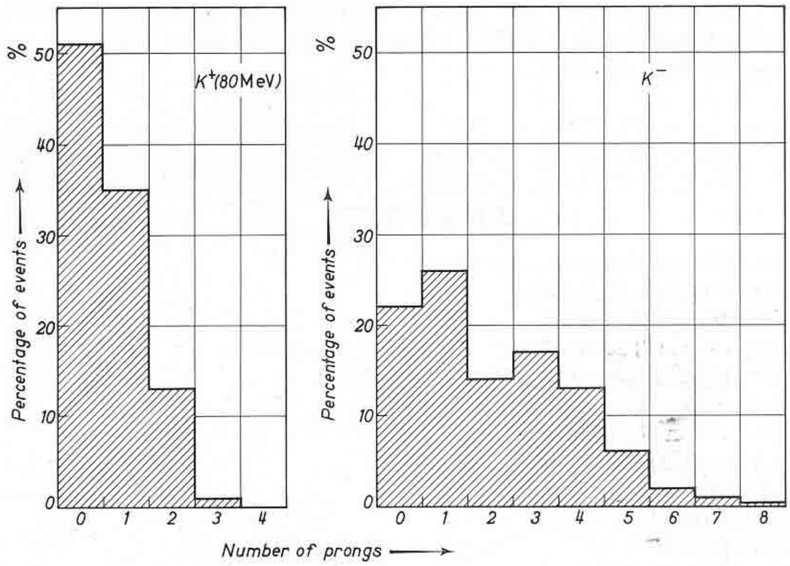

Fig. 14–14. Distribution in the number of prongs from the interaction of K-mesons with nuclei in emulsion: a) from the collision of 80 MeV positive particles, K^+; b) from K^--mesons at rest. N_h represents the number of secondary stable particles with range $>5\ \mu$, and with ionisation $>1{\cdot}4\ g_p$. It does not include any π-mesons and Σ-hyperons which sometimes emerge from stars due to K^--capture, but not from the K^+-mesons. N_h is therefore a measure of the nuclear excitation.

PLATE 14–11. Nuclear collisions of K^+-mesons of energy $\sim$ 60 MeV ▸

The photographs show typical examples of the nuclear collisions of K^+-mesons of moderate energy. In every case, the track of the meson is indicated by an arrow. The striking feature of the collisions is the very low average value of the release of energy. This is a consequence of the fact that the meson is either scattered, or it suffers charge-exchange, an unobserved K^0-meson then emerging from the encounter; the meson is never absorbed; its rest-energy does not therefore contribute to the disintegration.

a) Elastic collision with a silver or bromine nucleus. There is no observable change of grain-density following the collision, so little communication of energy to the struck nucleus. The track of the latter appears as a short track or 'blob'.

b) Elastic collision with a light nucleus, of carbon, nitrogen or oxygen. The track of the recoiling nucleus, of range $\sim 3\ \mu$, is clearly seen and its momentum can therefore be estimated. The resultant momentum diagram can be constructed, assuming the recoiling nucleus to be of nitrogen, carbon, or oxygen. The events where the recoil particle is of much greater range are attributed to collisions either with free hydrogen or with a loosely bound proton in the struck nucleus.

c) Charge-exchange. The track of the K-meson suddenly terminates, the last grain being indicated by an arrow.

d) Inelastic scattering of K-meson with resulting disintegration of low energy. The track of the secondary K-meson dips at a large angle, and this over emphasises the increase in grain-density.

Nuclear collisions of K^{+}-mesons of energy $\sim$60 MeV

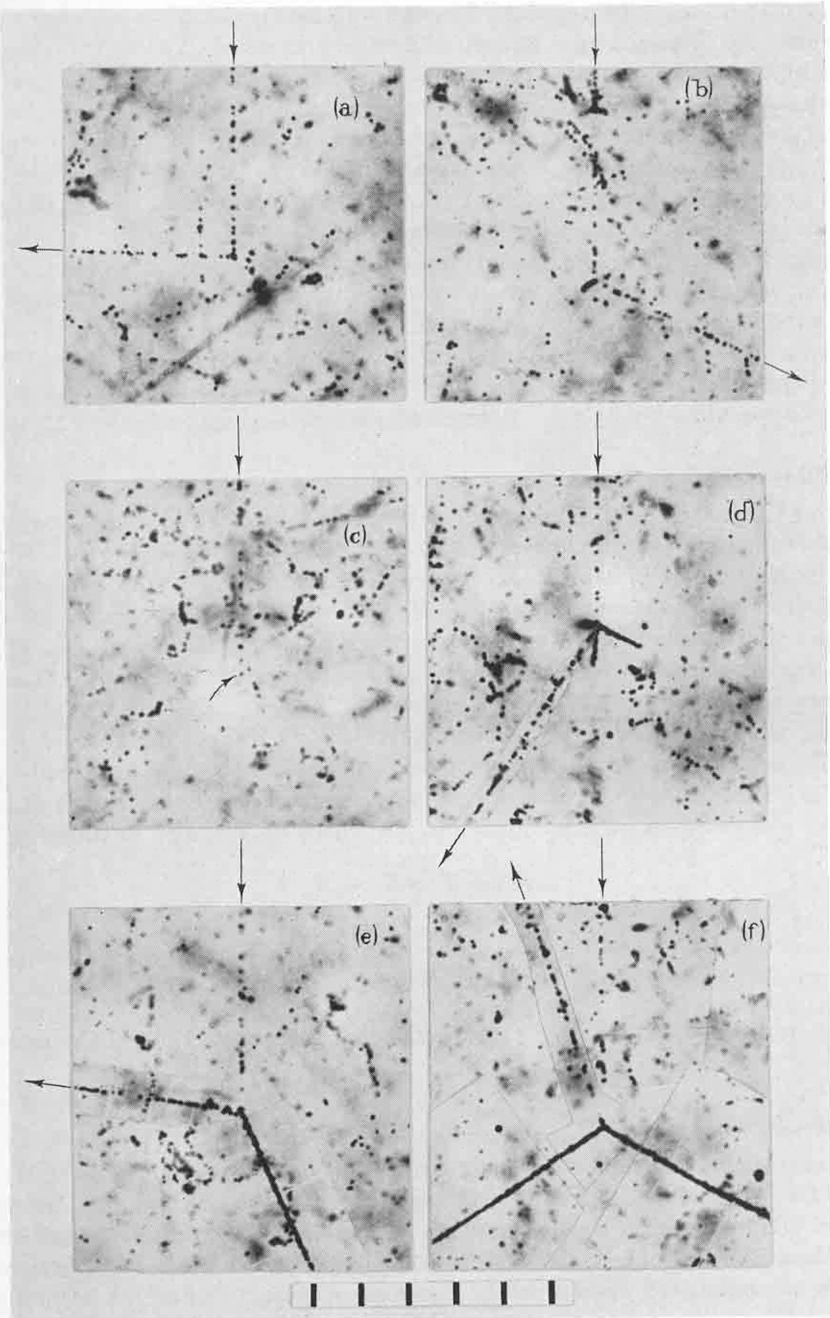

PLATE 14–11

Ilford G5 emulsion.

Bristol (1956) unpublished.

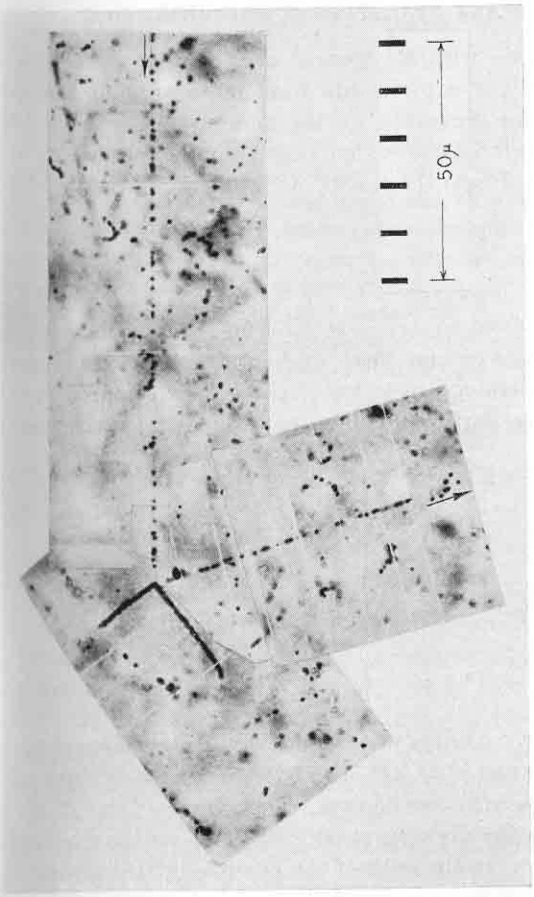

PLATE 14–12

Collision of a K^+-nucleus with a C^{12}-nucleus

A K^+-meson collides with a carbon nucleus and disintegrates it into three α-particles: $K^+ + C^{12} \rightarrow K^+ + 3\,He^4$. The observations allowed it to be shown that the momentum of the incident K-meson equalled the vector sum of the momenta of the secondary particles, and permitted a determination of the Q-value for the reaction. The tracks of two of the three α-particles are superposed and cannot be separately distinguished.

Ilford G 5 emulsion. ANDERSON *et al.* (1956).

escaping; the nucleus is, as it were, too opaque to the passage of the π-mesons; whereas, for the K^+-mesons, the interaction is of an appropriate intermediate strength, which allows the incident radiation to interact in sufficient intensity without modifying too seriously that which emerges.

d) Modes of decay of scattered particles

The early observations on the elastic collisions of positive K-mesons were made at a time when several modes of decay had been established, but the identity or difference of the parent particles of the different modes was still uncertain. It therefore appeared that in respect of their behaviour in elastic collisions, a further test might be applied. It was found, however, that all the decay modes were represented among the K-mesons finally arrested after undergoing such collisions, and that they appeared in the same proportions as commonly observed. It was apparent that, in this respect also, no distinction could be made between K^+-mesons decaying in different modes.

An experiment based upon similar considerations was undertaken by WIDGOFF *et al.* (1956). When 6 BeV protons bombard a uranium target, some K^+-mesons are emitted nearly backward against the direction of the incident beam. A simple application of the conservation laws shows, however, that these K-mesons cannot have been produced in this direction in the primary nucleon-nucleon collision; most of them must have been scattered by interaction with nucleons before escaping from the parent nucleus. WIDGOFF *et al.* showed that for these scattered K-mesons also, the different modes of decay appear with the same relative frequencies as in other experiments.

Disintegrations due to the nuclear interaction of neutral *K*-mesons

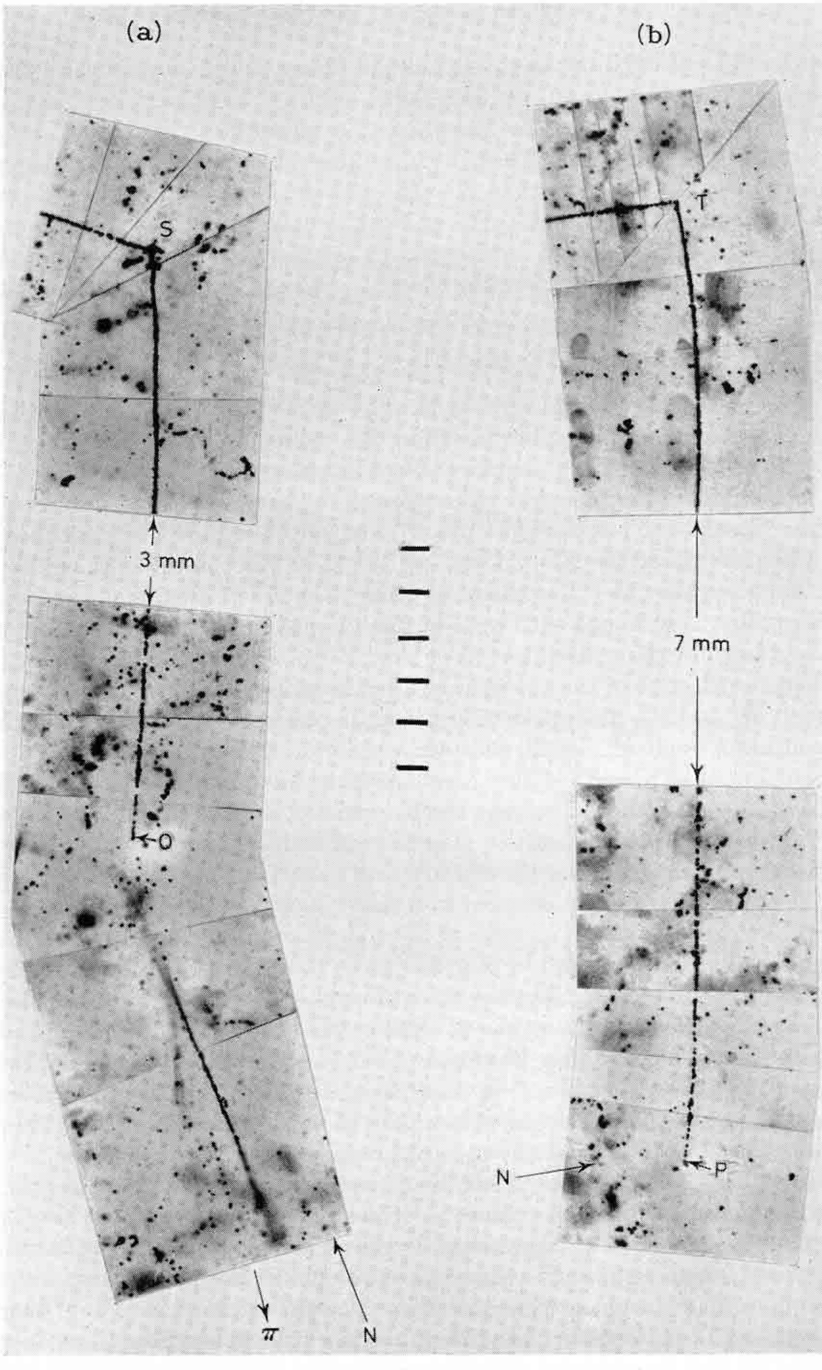

PLATE 14–13

Ilford G 5 emulsion.

passage of a beam of K_2^0-mesons through a sufficient thickness of material to ensure the absorption of the $\bar{K}^0$-component involves a time long compared to the mean lifetime of the K_1^0-mode. The regeneration of the short-lived component K_1^0, cannot therefore be readily demonstrated, for it decays too rapidly after its formation. The experiment would be facilitated if absorbing screens of much greater density than that of any ordinary matter in terrestial conditions were available; or if it became possible to work with particles of very great energy, so that advantage could be taken of the relativistic dilation of the time-scale of a moving particle as in experiments on π^0-mesons; see p. 278.

Since a direct demonstration of the correctness of the above conception of a particle mixture cannot at present be attempted, tests of a less decisive character have been made: Suppose that a beam of neutral K-mesons is generated by the impact of fast protons on a target: At the low values of proton energy commonly employed, ~4 BeV, most of the neutral K-mesons will be formed in association with Λ^0 or Σ-hyperons, and they will be of strangeness $+1$, see p. 378, and will be expected to interact with nuclei only by elastic scattering, or by charge-exchange, as in the case of K^+-mesons. It follows that if some of the original neutral particles are found, in practice, to interact with nuclei and to give rise to Σ or Λ^0-hyperons, or K^--mesons, particles with strangeness -1, this would, at first sight, appear as a gross violation of the principle of the conservation of strangeness, corresponding to $|\Delta S| = 2$. The difficulty does not arise, however, if the conception of a particle-mixture changing in composition with the passage of time is adopted. Evidence of such a kind is not so powerful as that which would be provided by an experiment of the type of PAIS and PICCIONI, because the argument depends on the correctness of the initial assumption of the conservation of strangeness in the production of the neutral particles; but it can, nevertheless, be very impressive.

The first evidence for the nuclear interactions of K^0-mesons was obtained by FRY *et al.* (1956), who made exposures of G 5 emulsion stacks to neutral particles from the Berkeley bevatron. The emulsions were exposed at such a distance from the target that the number of short-lived K^0-particles which could have survived to reach the stack must have been very small. In the resulting plates, however, four nuclear disintegrations were found, due to neutral particles, from which charged hyperons or heavy mesons emerged. FRY *et al.* attributed these disintegrations to a long-lived component of the neutral K-mesons.

The remarkable feature of the above observations was the frequency with which the Σ- and K-particles were produced. At first sight, the disintegration might have been attributed to fast neutrons from the target, and stars from this process do occur. The experiments indicated, however, that of the stars occurring in the stack and due to fast particles, about one in ten had an associated K-meson or Σ-particle. This proportion is very much greater than that found for disintegrations due to neutrons of energy ~200 MeV. The observations can, however, be readily understood if there is a neutral K-meson flux through the plates with a component of strangeness -1.

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◄ **PLATE 14–13. Disintegrations due to the nuclear interaction of neutral *K*-mesons**

Two examples of the nuclear interaction of neutral K-mesons in which particles of strangeness -1 are produced. In each case the direction of the flux of any neutral particles coming from a target bombarded by 4·5 BeV protons is indicated by an arrow labelled N.

In (a), an event occurred at the point O, and from it, there were emitted a Σ^--hyperon and a charged π-meson. The hyperon reached the end of its range at the point S and produced a characteristic disintegration; see p. 364. The second particle was a π-meson, of which the energy was determined by measurements of scattering. It is reasonable to assume that the event was due to the interaction of a neutral K-meson with a neutron of a nucleus according to the equation $\bar{K}^0 + n \to \Sigma^- + \pi^+$.

In the event (b), a Σ^+-hyperon originates suddenly at the point P and decays at the point T at the end of its range, in the mode $\Sigma^+ \to p + \pi^0$. The event may be attributed to an interaction with a free proton according to the equation $\bar{K}^0 + p \to \Sigma^+ + \pi^0$.

Nuclear interactions of particles of energy 100 and 200 BeV

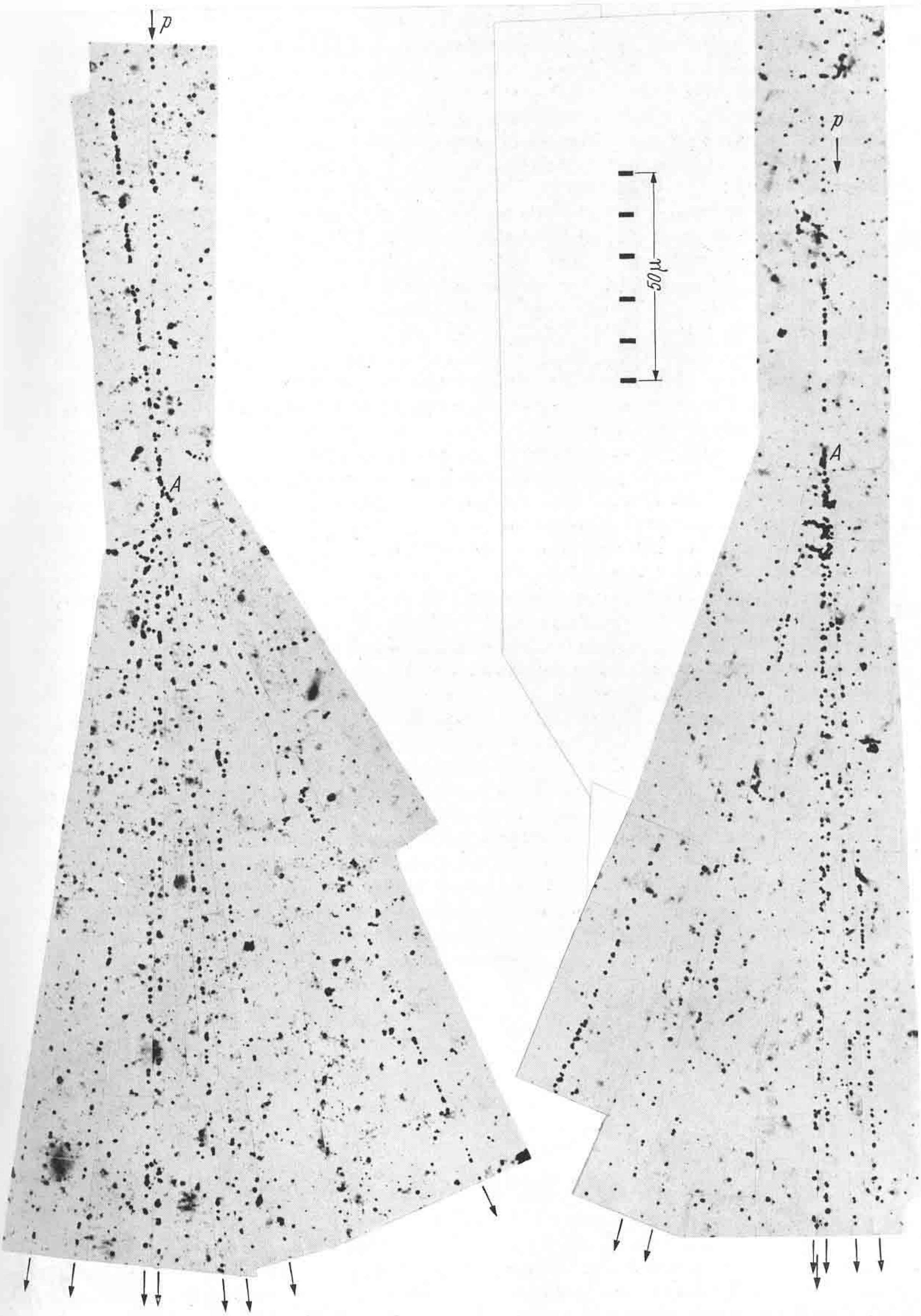


PLATE 15–1

Ilford G5 emulsion.

DANIEL, DAVIES, MULVEY and PERKINS (1952).

(Continued from page 520)

of primary particles is little contaminated by π-mesons and other secondary particles resulting from nuclear interactions in the atmosphere. A high-energy disintegration observed in a stack, and due to a singly charged particle entering it from outside, must therefore, almost certainly, be due to a primary cosmic-ray particle. Further, in favourable conditions of measurement, a detailed study of such disintegrations may be made, including an analysis of the effects produced by the secondary charged particles in traversing the stack, and the development of the soft cascades resulting from the π^0-mesons and their decay.

The above advantages are limited by the fact that the sensitive volume in which the high energy collisions may occur and be recorded is relatively small. Thus, consider a stack with a depth equal to about one interaction-length (30 cm) and a surface area 200 cm^2. These values are very small compared with the effective interaction volume in counter experiments, which commonly consists, in effect, of a column of atmosphere several hundred metres in horizontal extent. In a stack of volume 6 litres, flown for 6 hours at 100,000 ft, for example, one can expect to detect only two events of energy greater than 10,000 BeV/nucleon, whereas a typical large array of counters at sea-level will, on the average, detect several events of energy greater than 10^7 BeV every day. These figures make clear the great advantage which would follow from making experiments of long duration such as may be secured by means of satellites.

Successful experiments with satellites must await the solution of the recovery problem; in the meantime, valuable information can be obtained in flights with high-flying aircraft which permit times of exposure at altitudes above 10 km for periods of 1000 hours. The usefulness of such exposures is greatly increased by the fact that fast nucleons penetrate, on the average, to much greater depths in the atmosphere than was at one time believed. The nuclear collisions of protons of great energy are frequently very elastic, only about 30% of the energy of the incident nucleon appearing among the secondary particles. Such a nuclear collision therefore, does not necessarily lead to the removal of a proton, only to a reduction of its energy. Using aircraft, great loads can be carried, and for some types of experiment it is then an advantage to use emulsion interleaved with lead, and thus to ensure the more rapid development of the electron-cascades whereby high-energy events may be recognised; see Plate 15–20, p. 570.

It may be remarked that in spite of the complexity of the processes occurring in the atmosphere, most of the disintegrations observed in plates exposed to cosmic radiation at mountain altitudes are produced by protons and neutrons, present in approximately equal numbers; see Table 13–1, p. 429. This is due to the fact that most of the particles are of relatively low energy, a few BeV, and any π- and K-mesons which may have been produced with them will commonly have decayed in flight. The proportion of mesons among the charged particles entering a stack is therefore small.

The above considerations are modified if attention is confined to particles of very great energy, for the mesons then survive for much longer periods through the relativistic dilation of the time-scale. They are then commonly removed in the atmosphere by interactions with nuclei rather than by decay. As a result, the charged particles of great energy entering a stack exposed at altitudes less than $\sim$18 km are not made up exclusively of protons and electrons of the soft cascades.

PLATE 15–2. 'Jets' due to the nuclear collision of 200 BeV and 300 BeV protons ▸

Two events of type $1 + 18p$ and $2 + 36p$, respectively. The small number of heavily ionising particles associated with each suggests that they are probably due to peripheral collisions. It was possible to identify one of the secondary particles from the event on the left as a π-meson. Only about half the secondary fast particles have been reproduced in each of the mosaics.

'Jets' due to the nuclear collision of 200 BeV and 300 BeV protons

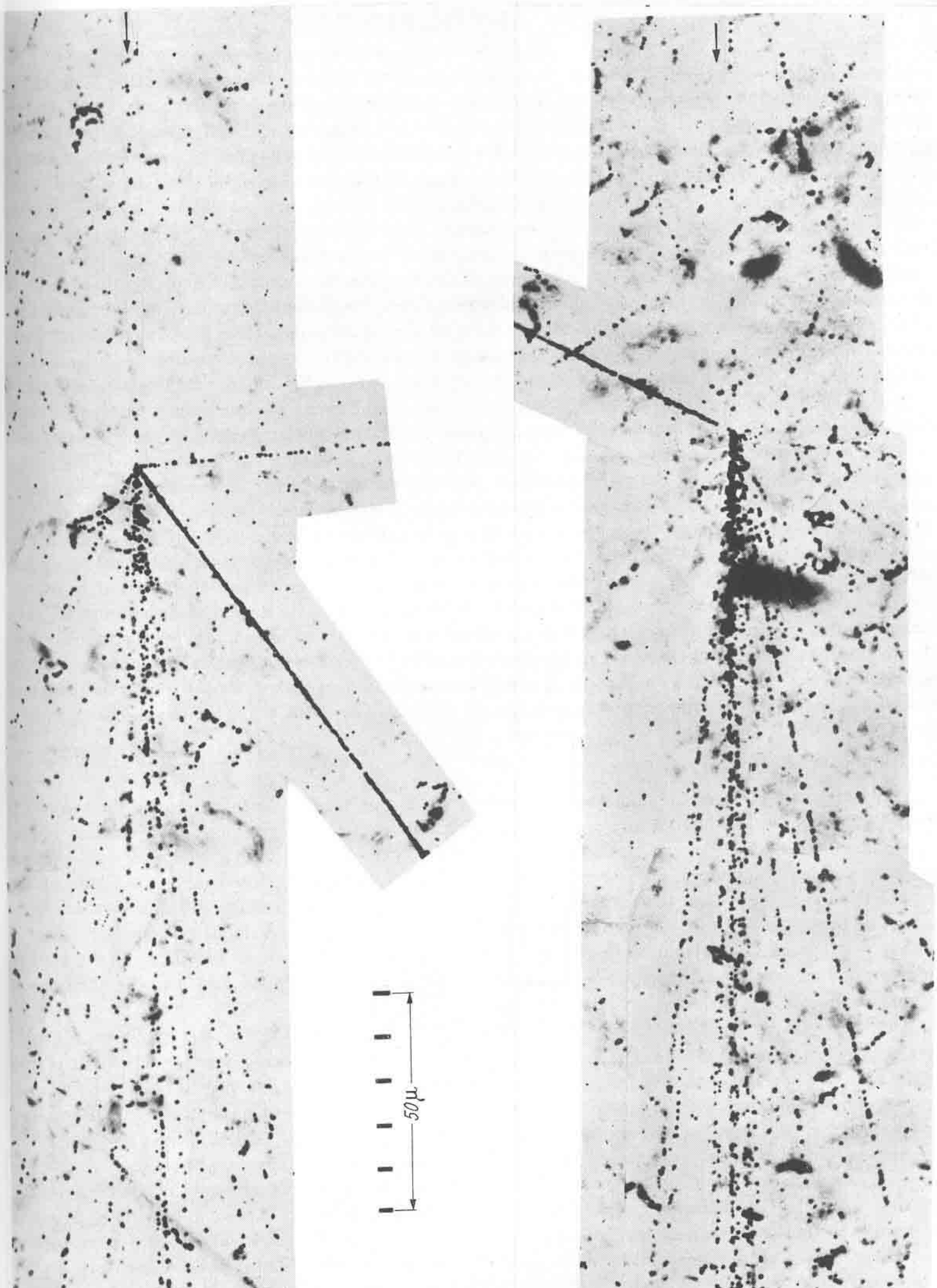


PLATE 15–2

Ilford G 5 emulsion.

DANIEL, DAVIES, MULVEY and PERKINS (1952).

The nucleus may then be widely dispersed into its component nucleons, and a star with a large value of N_h will accompany the jet. On the other hand, in glancing collisions, little energy may be given to the parent nucleus. It is then reasonable to assume that there is a forward-backward symmetry, in the angular distributions and energy of the secondary particles in the C-system.

c) Selection bias

In the investigation of 'jets', it is very important to avoid selection bias. At the lower energies, $\sim$100 BeV, events are detected by 'direct' area scanning. It is then impossible, in practice, to avoid a bias in favour of 'stars' with large values of N_h and n_s. For higher primary energies, an unknown bias exists, for the detection of the secondary soft cascade depends, first, on the geometry of the event, and secondly on the mean energy of the secondary particles. It is found in practice that the average value of N_h for jets above 1000 BeV is much smaller than in events found by unbiassed scanning at much lower energies; Fig. 15–1. In high-energy collisions, the resulting jets are frequently of low multiplicity, and the question then arises—does the method of detection favour events in which more than the average number of π^0-mesons, and thence of photons, are produced? Such a bias is believed not to be serious, however, especially in very large stacks, since energetic secondary particles, whatever their nature, have themselves an appreciable probability of producing jets, and thus of reinforcing the main soft cascade.

3. THE ENERGY OF PARTICLES PRODUCING JETS

a) Angular distribution of secondary particles

In studying nuclear collisions in the region of very high energies, it is important to estimate the energy of the primary particle responsible for a given jet, for this quantity has a decisive influence on the conclusions drawn from the observations about the energy and angular distribution of the secondary products in the C-system of the nucleon-nucleon collision. Since direct measurements are impossible by present techniques, the estimate is commonly based on the angular distribution of the secondary particles; if the median angle is η, the energy E_p, of the primary particle, is given approximately by the relation: $E_p \approx 2\,\frac{m_p \cdot c^2}{\eta^2} \approx \frac{2}{\eta^2}$ BeV. This method depends on the assumptions:

(a) that the secondary particles result effectively from a collision with a single nucleon;

(b) that they are unmodified by secondary collisions in escaping from the nucleus of which the target nucleon was a part; and

(c) that the secondary particles are emitted symmetrically and with equal probability forwards and backwards in the C-system of the primary interaction.

The plausibility of these assumptions and the conditions in which they should be valid, have been considered by a number of authors (Wataghin 1941, 1943; Kaplon and Ritson 1952; Heitler and Terreaux (1953); Cocconi 1954; Roessler and McCusker 1953). The first important feature to remark is that a considerable fraction of the collisions of protons of high energy with emulsion nuclei are likely to involve either (a) complete penetration of a nucleus without interaction, or, (b), an interaction with one nucleon only. Thus, assume that in passing through a nucleus, a nucleon may lose some of its energy without a significant change in direction. The approach given on p. 474 then allows the relative numbers of interactions of a primary nucleon in traversing nuclei of different types to be calculated for any assumed value of σ, the nucleon-nucleon cross-section for such collisions. The results

PLATE 15–3. 'Jets' from high-energy nuclear collisions ▶

The event on the left, of type $4 + 50\alpha$, is due to an α-particle of energy $\sim$3000 BeV, i.e. $\sim$800 BeV per nucleon; that on the right, to a particle of charge e and energy $\sim$600 BeV. In each case, the photographs of the central core have been made with a single setting of the microscope, and only a proportion of the tracks can be distinguished.

'Jets' from high energy nuclear collisions

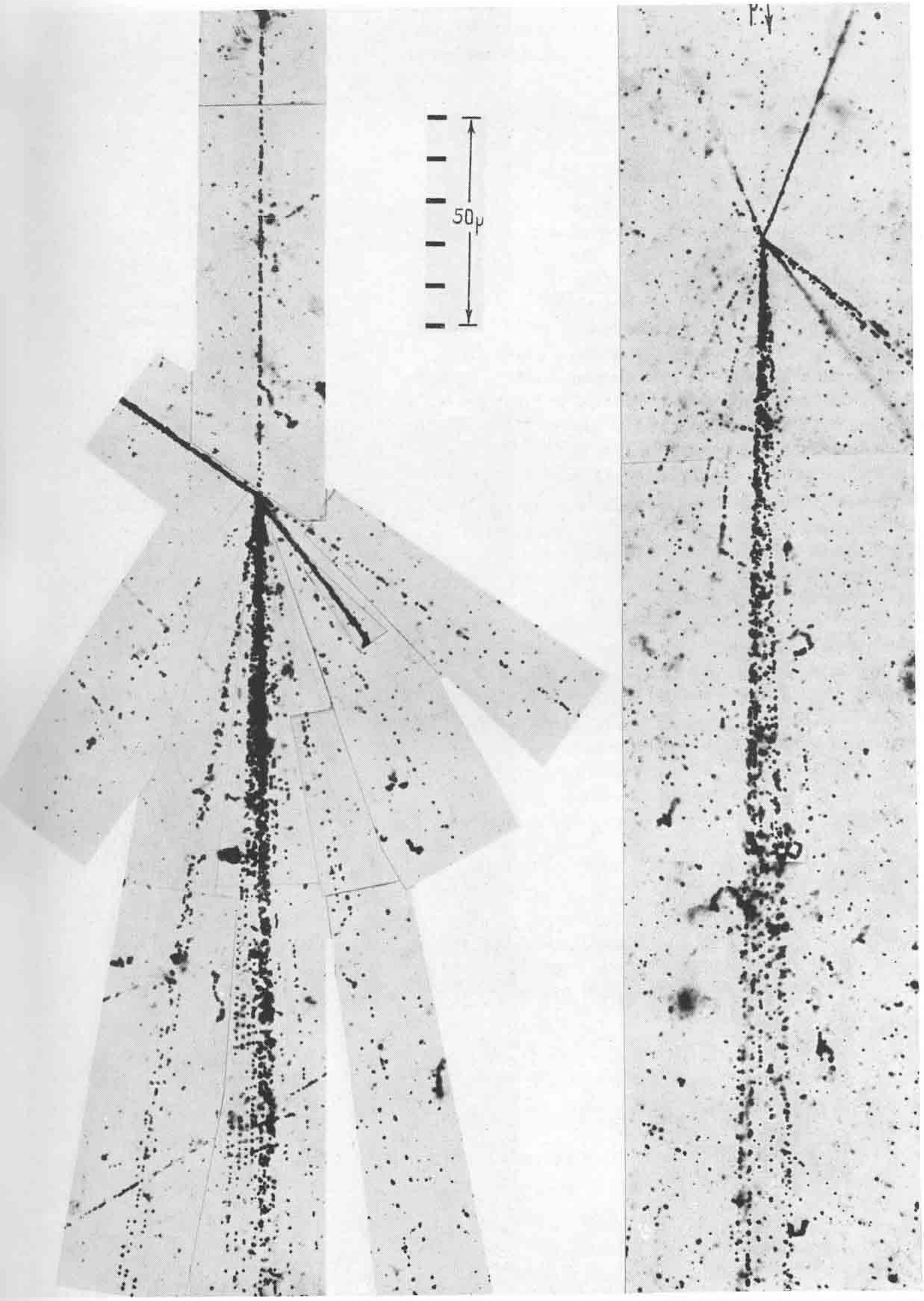


PLATE 15–3

Ilford G5 emulsion.

Daniel, Davies, Mulvey and Perkins (1952).

Nuclear interaction of the secondary particle from a 'jet'

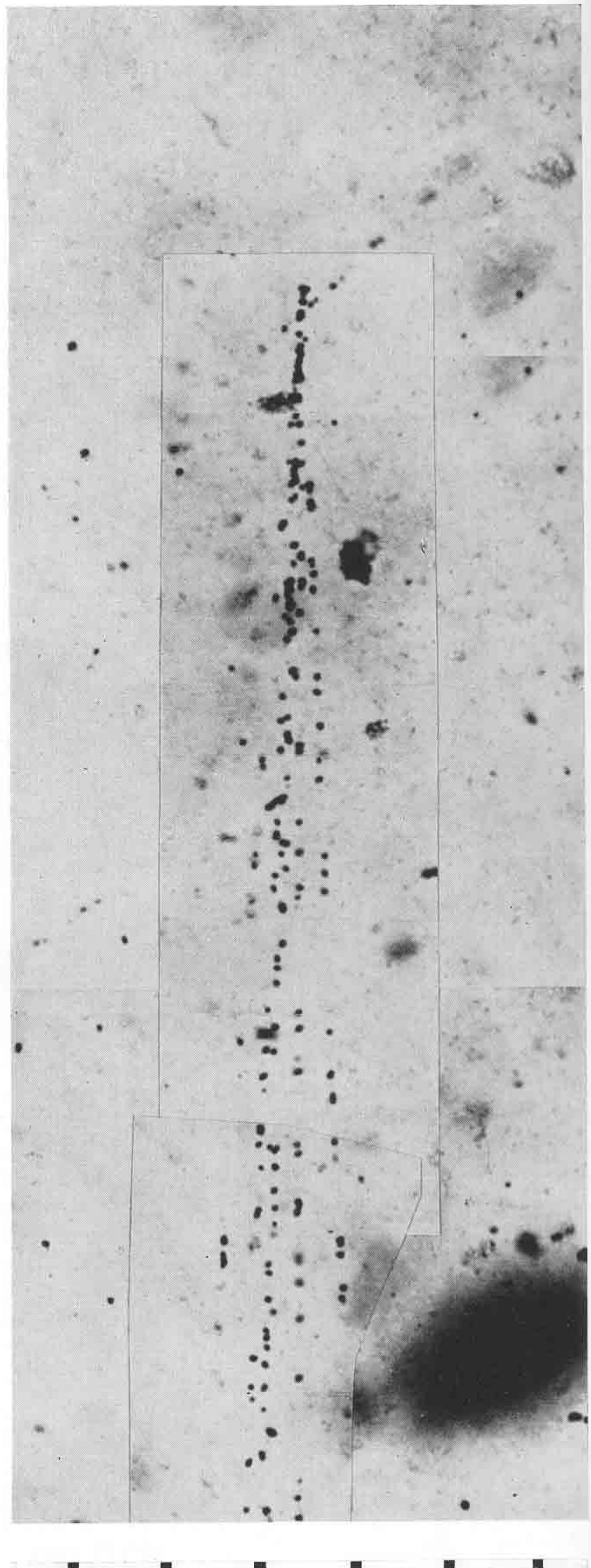


PLATE 15–4

A secondary interaction, of type $0+6n$, involving a neutral particle of energy ~ 500 BeV, produced in the event shown in Plate 15–8, p. 544. The assumed association of the two events is based on the fact that the secondary interaction occurred among the tracks forming the main 'jet', and the median line of the secondary particles was coincident with the direction of the neighbouring shower particles. The nature of the neutral particle which produced the disintegration is uncertain. It might be attributed either to a neutron, a π^0-meson, a γ-ray, or a heavy neutral meson.

PLATE 15–4

Ilford G5 emulsion.

Bristol (1952) unpublished.

c) Determination of γ_c from observations on secondary particles

Consider a secondary particle of mass m_s, velocity β_s, energy $\gamma_s \cdot m_s \cdot c^2$, and direction of motion θ relative to the primary particle, all quantities being measured in the L-system; and let $\bar{\beta}_s$, $\bar{\gamma}_s$ and $\bar{\theta}$, be the corresponding quantities in the C-system. It may then be shown that

$$\tan\theta = \frac{\sin\bar{\theta}}{\gamma_c \cdot (\cos\bar{\theta} + \beta_c/\bar{\beta}_s)}. \qquad \text{Eq. (15–iii)}$$

If we now consider two secondary particles emitted with equal and opposite momenta in the C-system, and with directions $\bar{\theta}$ and $\pi - \bar{\theta}$, it follows that

$$\tan\theta_1 \cdot \tan\theta_2 = \frac{1-\cos^2\bar{\theta}}{\gamma_c^2\{(\beta_c/\bar{\beta}_s)^2 - \cos^2\bar{\theta}\}}. \qquad \text{Eq. (15–iv)}$$

If, for a given jet, the values of $\bar{\theta}$ are broadly and symmetrically distributed over the interval from 0 to π, the quantity $(1-\cos^2\bar{\theta})/\{(\beta_c/\bar{\beta}_s)^2 - \cos^2\bar{\theta}\}$ is of the order unity for most pairs of secondaries; it follows that

$$-\log\gamma_c = 1/n \sum \log\tan\theta, \qquad \text{Eq. (15–v)}$$

a relation involving all the measured angles of the secondary charged particles in the L-system (Castagnoli *et al.* 1953).

A simpler method, which has been frequently used, and which often gives results only a little less reliable, is to determine the median angle of the secondary charged particles, η, corresponding to $\bar{\theta} = \pi/2$; thus

$$\tan\eta = \frac{\bar{\beta}_s}{\beta_c} \cdot \frac{1}{\gamma_c} \simeq \frac{1}{\gamma_c}. \qquad \text{Eq. (15–vi)}$$

It can, however, only be applied when the values of $\bar{\theta}$, and hence θ, are widely distributed. If, for example, as sometimes occurs (see Fig. 15–12) the values of $\bar{\theta}$ and $\pi - \bar{\theta}$ correspond to angles near the forward and backward directions of motion in the C-system, a large gap may result in the distribution of values of θ, and a reliable estimate of η is then not possible; in the same circumstances, however, it is possible to apply the relation (15–v).

In some events represented in Fig. 15–12, especially those of low multiplicity, the mean value of $\log\tan\theta$ does not appear to give a reliable estimate for the primary energy. Thus, for the events of type $(0+11p)$, $(4+5p)$ and $(0+2p)$, the primary energy according to this method appears to exceed 100,000 BeV, whereas the energy of the soft cascade, and of secondary nuclear interactions, are, in each event, only a few thousand BeV. A more realistic estimate of the primary energy, corresponding to a value η' for the quantity $1/\gamma_c$, can be made by assuming that in these examples there have been large disparities in the numbers of *charged* particles in the forward and backward cones, respectively, with more particles ejected forwards than backwards. Conversely, in the events of type $(0+4p)$ and $(1+6\alpha)$, there are more secondary particles emitted backwards than forwards. Where there *are* both backward and forward particles present (including identified neutral pions), the appropriate value for η' is obtained by finding the mean value of $\log\tan\theta$ separately for the forward and backward cones, and taking $\log\tan\eta'$ as the mean. In the events of type $(4+5p)$ and $(0+2p)$, there are apparently no backward tracks, and the most likely primary energy will then correspond to an assumed mean backward angle of $\sim 45°$. Finally, in the event of type $(1+6\alpha)$, discussed later in detail, there is no clear distinction between particles in the backward and forward hemispheres, and the estimate of the primary energy depends entirely on the angular distribution from a secondary interaction $(8+80p)$, also represented in Fig. 15–12. It may be remarked that the backward cone of particles associated with the event shown in Plate 15–13, p. 559, was only found by close scrutiny. In some conditions, such tracks may be overlooked, especially if they dip steeply.

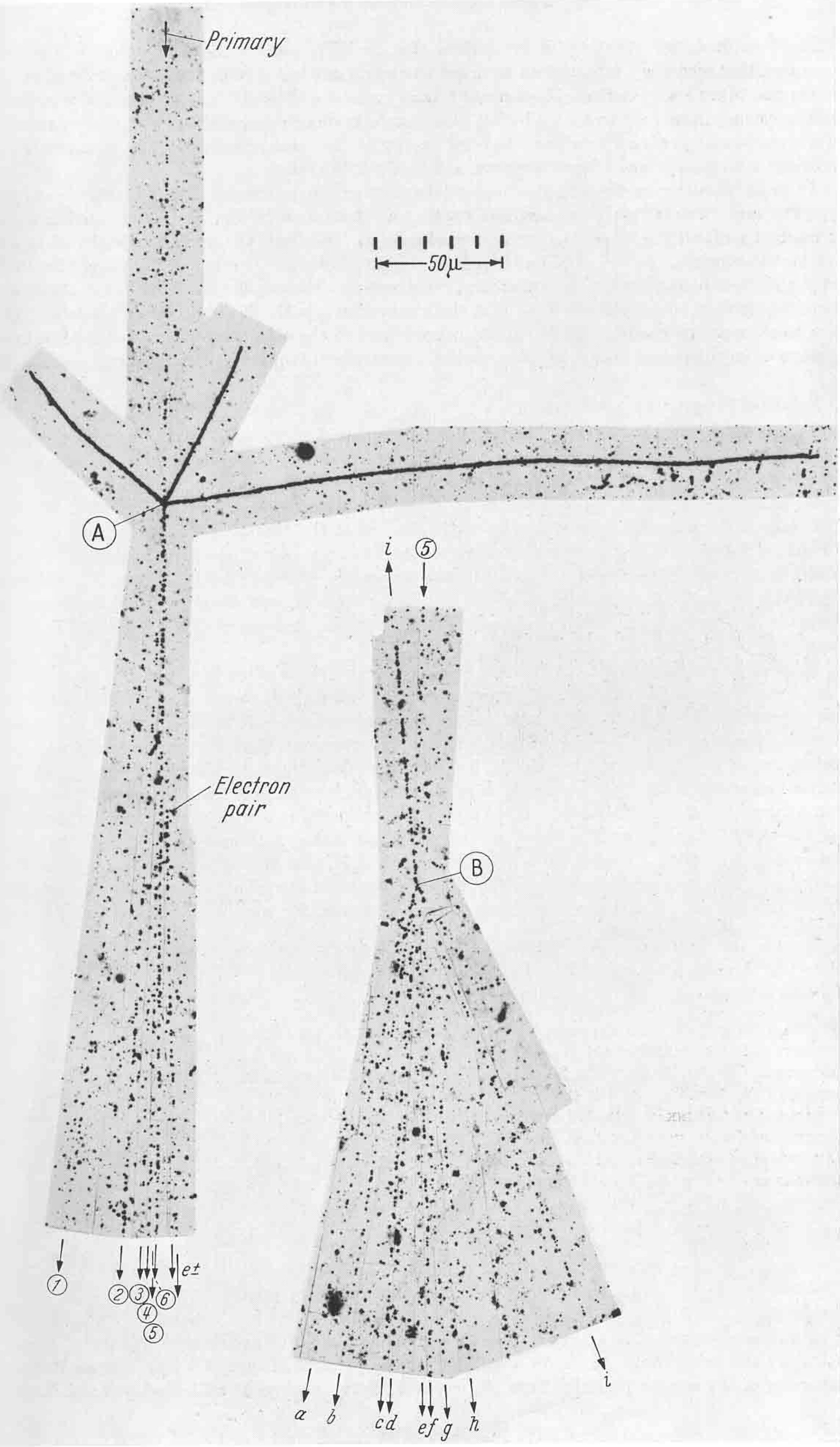
In some events it has been possible to test the value of the energy of a primary particle, deduced by the methods outlined above under the assumption $N=1$, by other measurements. It has thus been shown that there is commonly an agreement, within the errors, between the results of the

(Continued at top of page 532)

PLATE 15–5. 'Jet' of energy 1000 BeV ▶

Ilford G5 emulsion. Powell (1950).

Photomicrograph of a jet, A, due to a particle with energy $\sim$1000 BeV, and the effect of a nuclear collision, B, involving one of the secondary particles. Note the electron-pair associated with the primary event.



Primary
50μ
A
i
5
Electron
pair
B
1
2
3
4
5
6
e±
a
b
c d
e f
g
h
i

different methods for events with low values of n_s and N_h, i.e. for those in which it is reasonable to assume that secondary interactions have not played an important rôle; see EDWARDS *et al.* (1958).

On the other hand, central collisions with heavy nuclei commonly involve secondary interactions with nucleons; these lead to a broadening of the angular distributions of the secondary particles and to a corresponding reduction in the estimated energy of the primary particle. For examples of central collisions with heavy nuclei, see BRISBOUT and McCUSKER (1958).

In order to allow for the effects of secondary interactions in central collisions with heavy nuclei, HEITLER and TERREAUX (1953), and McCUSKER and ROESSLER (1953), assume the incident particle to interact with all the nucleons near its line of motion. In effect, the nucleus is regarded as a fluid, in which the incident particle and its secondary products bore out a tunnel, of radius $\sim 1{\cdot}3 \times 10^{-13}$ cm, projecting the nuclear matter lying near the line of motion. The angular distributions of the secondary particles are then computed assuming that the interaction is with all the projected nucleons regarded as a single massive particle. The angular distributions of the secondary particles are then found to be more widely dispersed than in nucleon-nucleon interactions of the same primary energy; see Eq. (15–ii).

d) Nature of the primary particles

It has been remarked above that in emulsions exposed at great altitude, the primary particles will consist almost exclusively of protons and heavier nuclei uncontaminated by secondary π-mesons. At lower altitudes, however, say below 60,000 ft, and for events due to particles of great energy, ambiguities arise because of the presence of charged π-mesons which survive for much longer than their normal life-span owing to the relativistic dilation of the time-scale. It is difficult to calculate the actual fraction, Φ_π, of π-mesons among the high-energy particles entering a stack because the estimates depend on parameters which are not accurately known. Making reasonable assumptions about the elasticity of the nucleon-nucleon collisions, however, and assuming that the energy made available is effectively divided among only three π-mesons, it appears that $\Phi_\pi(E > 10^4$ BeV) is not more than about 0·1 at an altitude $\sim$15 km.

It must be remarked that the fraction of high-energy events actually found in a stack which are due to π-mesons may be considerably greater than the value given above. For whilst the interactions due to protons may be relatively elastic, only a small proportion, $\sim$30%, of the energy of the primary particle appearing in the form of secondary π- and other mesons, those due to π-mesons may be completely inelastic. They may, for example, frequently result in the sharing of all the energy of the incident π-meson among many secondaries. If so, a much larger fraction of the primary energy contributes to the formation of the soft cascade; there is then a corresponding increase in the probability of detecting the event, if recognition is based on observing this feature. It may be remarked that, when a π-meson collides with a nucleus, it is possible, in principle, that it may sometimes retain most of its energy, but undergo charge-exchange; if so, a large fraction of the primary energy may be transformed almost directly into a soft-cascade. No evidence, however, for such a process involving a π-meson of great energy has hitherto been reported.

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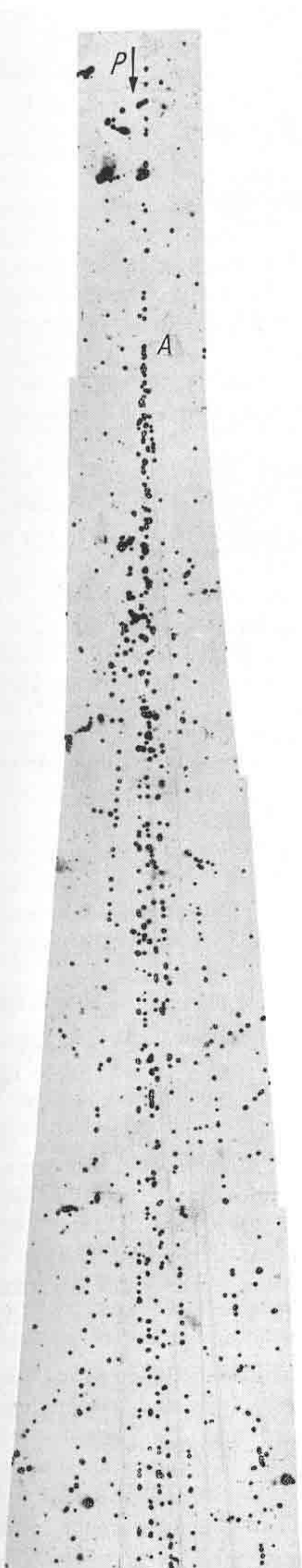
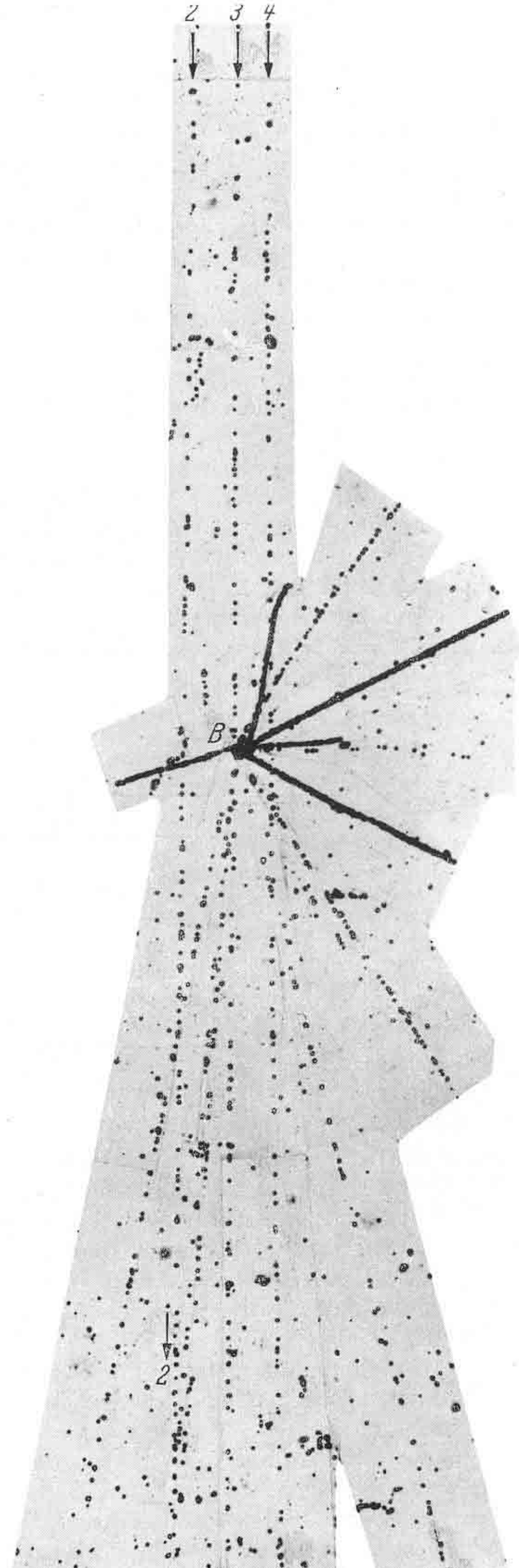
PLATE 15–6. Interaction of a secondary particle from a jet ▸

A nuclear interaction of a primary particle of energy 1000 BeV occurs at the point A. One of the secondary shower particles, 3, makes a collision, at the point B, of type $(7 + 5p)$. The greater angular dispersion of the shower particles from the event of lower energy is well displayed; cf. Plate 15–5.

Interaction of a secondary particle from a 'jet'





Ilford G 5 emulsion.

PLATE 15–6

Table 15–2

	No. of secondary stars produced by	
	neutral	and charged secondaries
MULVEY (1954)	1	4
LAL *et al.* (1954)	2	9
BRISBOUT *et al.* (1956) } EDWARDS *et al.* (1958) }	12	48
LOHRMANN and TEUCHER (1958)	8	51
Total	23	107

c) Identification of particles in the outer fringe

(i) *Direct mass measurements*

The methods described in the previous paragraph are indirect and provide no evidence for the nature of the particles of the inner core which are not pions. The particles of the outer fringe may, however, permit a more direct approach. They are of much lower energy, being projected 'backwards' in the C-system of the primary interaction, and in favourable cases significant measurements of scattering are possible. In principle, direct mass-measurements would be of great value, for when dealing with the results of nucleon-nucleon collisions, the samples of particles in the outer fringe and the inner core—corresponding very nearly to particles emitted backwards and forwards in the C-system, respectively—must be closely similar:

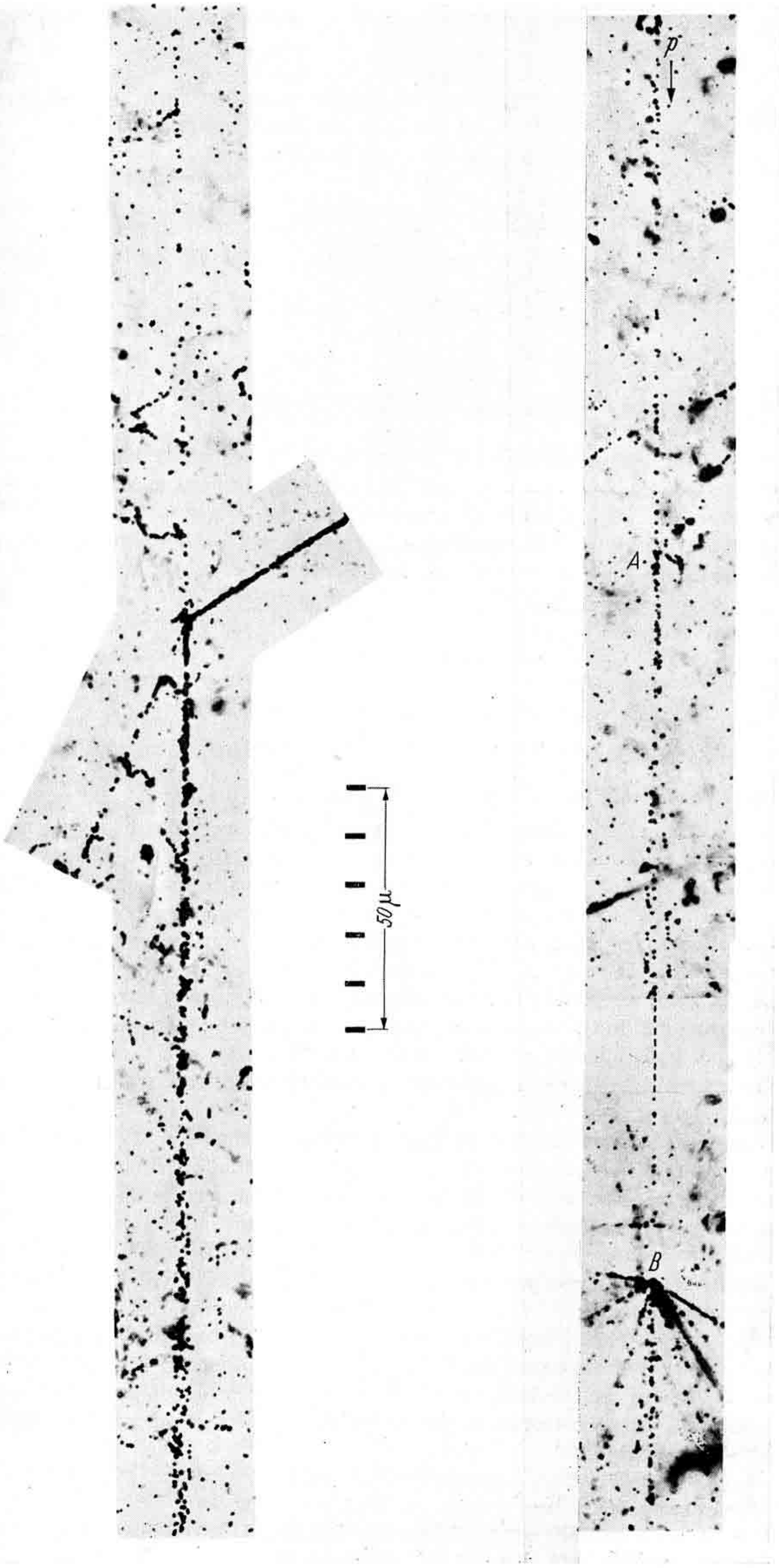
In order to distinguish particles of different mass among those of the outer fringe of jets, DANIEL *et al.* (1952) took advantage of the small changes in grain-density which occur for values of $p\beta/mc$ between 2 and 10; see, for example, Fig. 5–4, p. 162. Working with glass-backed plates, and the correspondingly short lengths of track, they found approximately equal numbers of π-mesons and heavier particles (K-mesons and protons) among the charged secondary particles of the outer fringe. Their results were subject to large statistical errors, and should be treated with reserve.

Fig. 15–3 shows the results of later measurements on tracks of particles in the outer-fringe of jets produced by protons and α-particles of energy $\sim$1000 BeV (EDWARDS *et al.* 1958). The events were recorded in stacks of emulsion; measurements were confined to tracks longer than 1 cm in each emulsion, and to plates in which 'spurious scattering', as determined by measurements on neighbouring tracks due to particles of great energy, could be proved to be negligible. It was thus possible to determine the quantity $p\beta$ with a statistical error of $\sim 10\%$ for values < 10 BeV/c; and to measure the blob-density to within $\sim 1{\cdot}5\%$. With these methods, among 20 particles with $p\beta < 7$ BeV/c, for which discrimination between π-mesons and heavier particles was possible in principle, it was reasonable to attribute about a third to protons or K-particles, but no final conclusions were possible, on account of the statistical errors, and the serious uncertainty in the precise form of the relation between b^* and $p\beta c$.

PLATE 15–7. 'Jets' produced by particles of energy 1000 and 2000 BeV ▸

Two events, of types $1+9p$ and $0+4p$, produced by particles of energy 1000 and 2000 BeV, respectively. A secondary particle from the event at A on the right, makes a nuclear interaction at B, and produces a disintegration of type $7+13p$. Events of this type show conclusively that the number of shower particles resulting from a nuclear interaction gives a very unreliable indication of the energy of the primary particle. The greater angular dispersion of the secondary particles in the interaction of lower energy is well displayed.

'Jets' produced by particles of energy 1000 and 2000 BeV

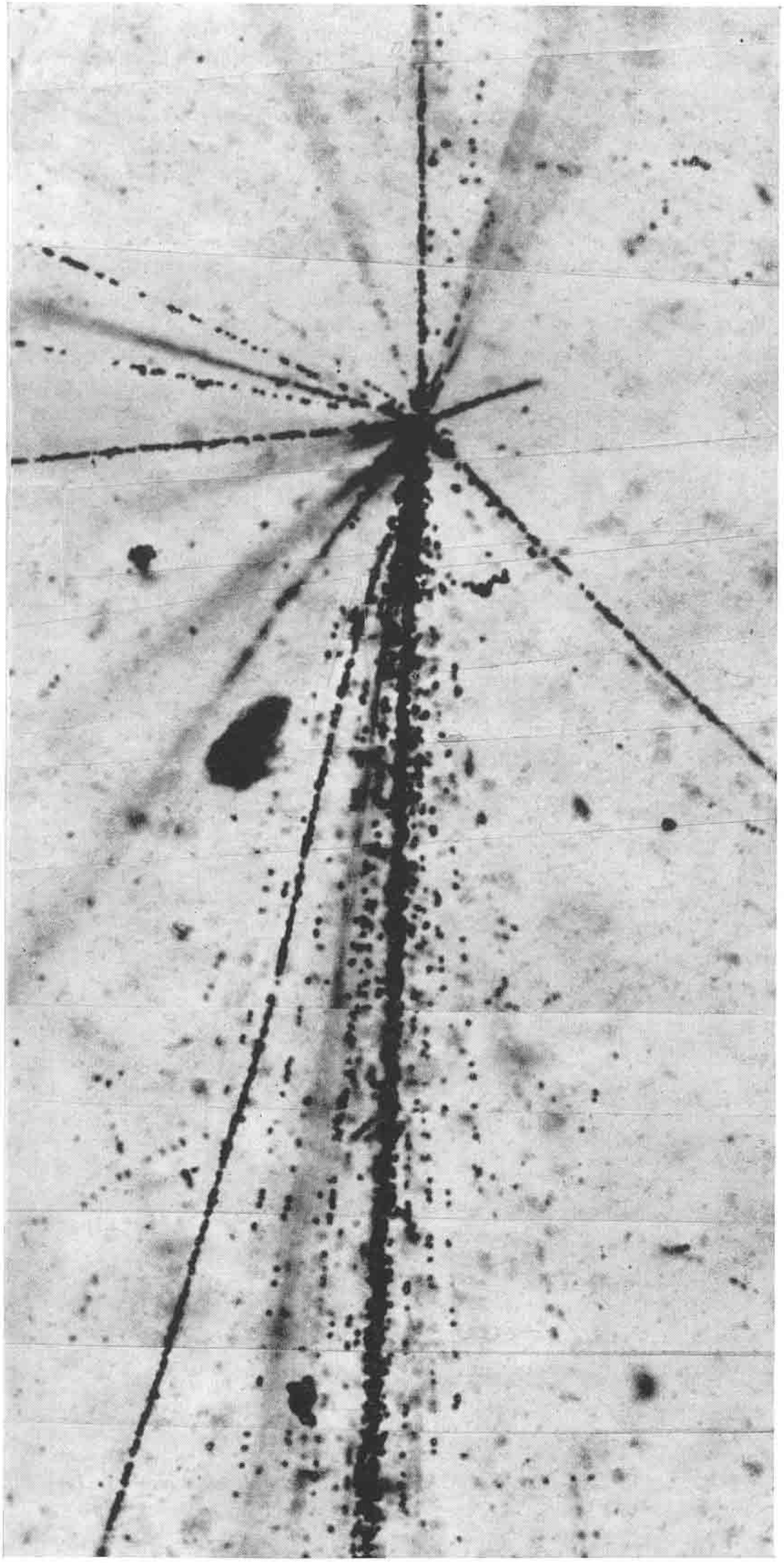


Ilford G5 emulsion.

PLATE 15–7

DAVIES *et al.* (1952).

Nuclear interaction of a primary proton of energy 30,000 BeV



PLATES 15–8 and 15–9

In this event, of type $(22 + 76p)$, recorded in a stack of plates exposed in a balloon flight at 90,000ft, about half the shower particles are in the central core, and cannot be individually resolved. The track of the primary particle, p, is coincident with the axis of the main core of secondary particles. The track of the heavily ionising particle, immediately to the left of the primary, was produced by an outgoing proton which came to rest in the emulsion. The 'core' can be traced through the emulsion and glass of 22 plates, and the development of the soft-cascades due to the decay of π^0-mesons can thus be studied.

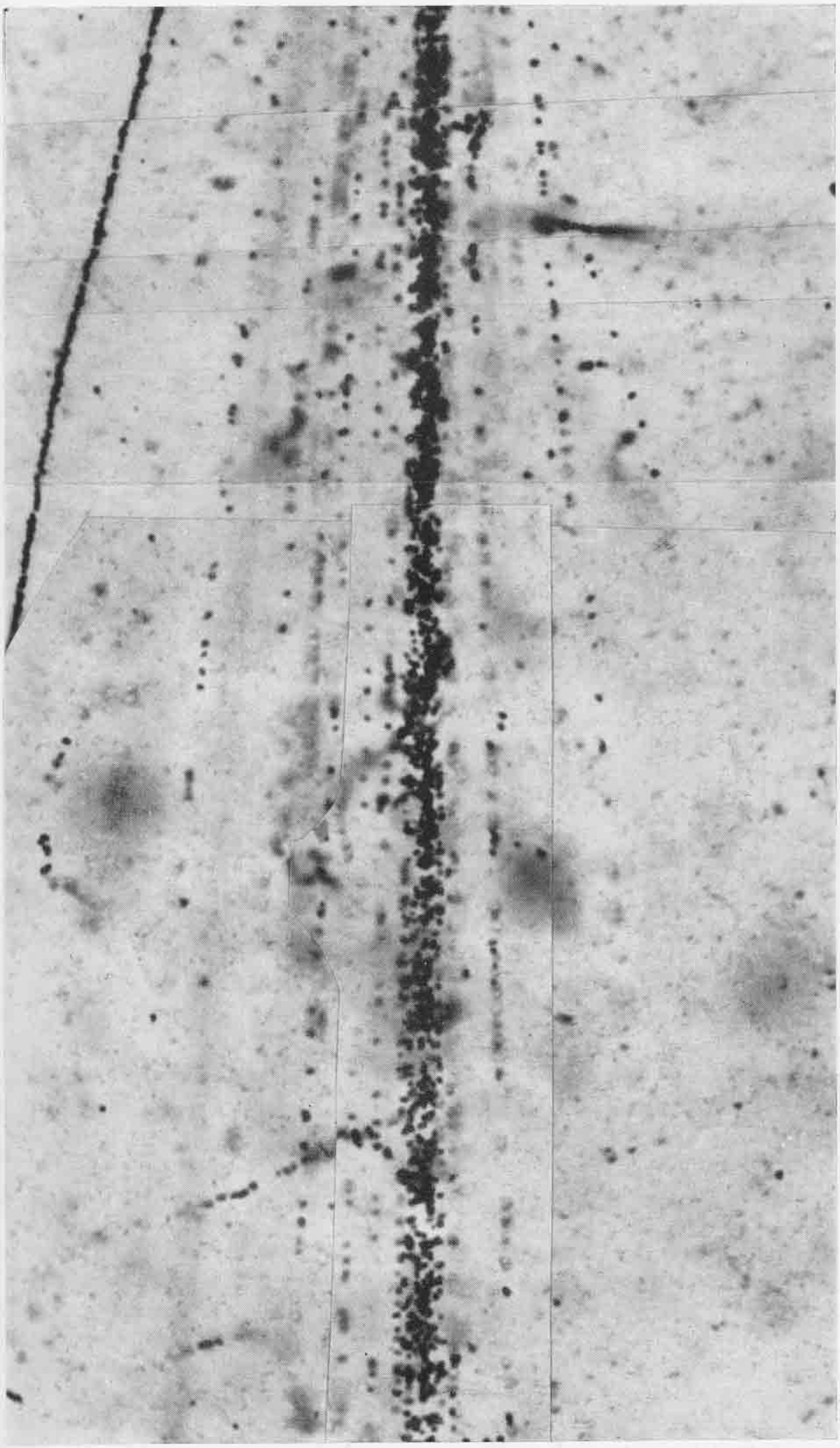


PLATE 15–9

Ilford G5 emulsion.

Bristol (1952) unpublished.

'Jet' of mesons from nuclear interaction of great energy

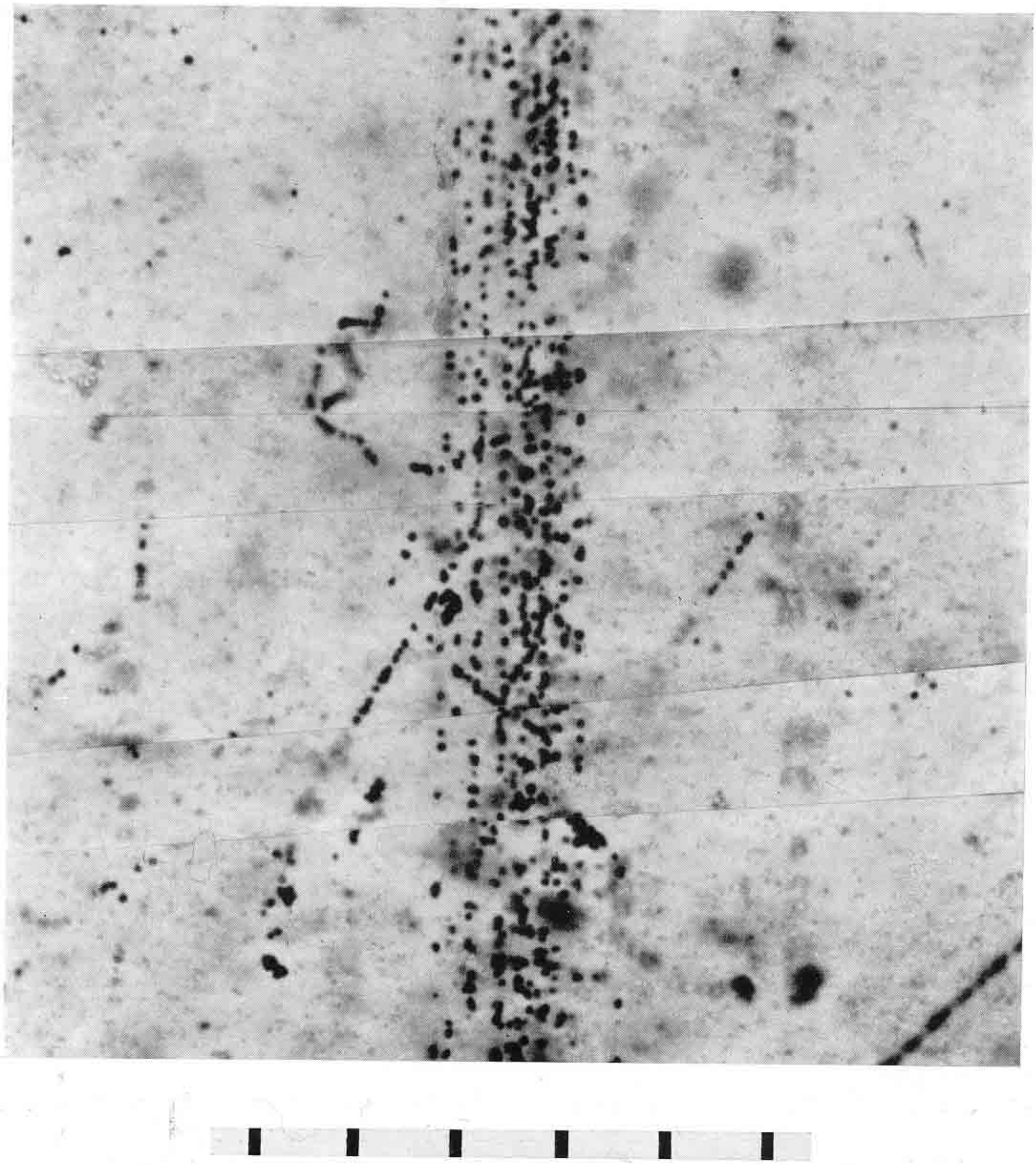


PLATE 15–10

Ilford G 5 emulsion.

Bristol (1952) unpublished.

In this plate, the particles of the central core of the event shown in Plates 15–8 and 15–9, here seen at a point about 3 mm from the centre of disintegration, can be individually resolved. Events of this type can usually be readily followed through the plates of a stack because of the dense core, and the tracks due to associated electrons of the soft component.

In experiments with monoenergetic beams of stable particles, the attenuation length, λ_{att}, of the particles—the distance in matter over which the number of particles with the given energy is reduced by a factor e—is equal to the nuclear interaction length, λ_{int}. In contrast, when dealing with an energy *spectrum* of incident particles, the attenuation length will be defined as the distance over which the number of particles above a given energy, E_0, falls by a factor e. The ratio $S = \lambda_{att}/\lambda_{int}$ is then always ≥ 1, the equality holding only when all interactions result in catastrophic absorption (see GREISEN and WALKER 1953). The extent to which S exceeds unity depends on the distribution of the primary energy among the secondary particles.

In determining the attenuation-length, it is convenient to restrict observations to those made at atmospheric 'depths' large compared with the interaction-length (>100 g/cm² in air) of the primary protons; the great majority of the particles which produce showers will then be of secondary origin. Consider those of energy above E_0. The relative numbers, N/C, of showers produced by neutral and charged primaries is then

$$\frac{N}{C} = \frac{[\Sigma N_i (f_i)^\gamma \cdot g_i]_{\text{neutral}}}{[\Sigma N_i (f_i)^\gamma \cdot g_i]_{\text{charged}}}; \qquad S = \frac{\lambda_{att}}{\lambda_{int}} = \frac{1}{1 - \Sigma N_i (f_i)^\gamma g_i},$$

where N_i is the number of particles of type 'i' produced in the parent interactions; f_i is the average fraction of the primary energy which they each receive; g_i is the probability of survival before decay in one interaction length; and γ is the exponent (1·75) of the integral energy-spectrum.

As an example, assume that the secondaries of the parent interactions are pions and nucleons only; and that, on average, one secondary nucleon is thrown forward from the parent interaction, together with six pions of equal energy.

If attention is confined to showers produced by particles of energy >50 BeV, then $g_{\pi^0} = 0$; $g_{\pi^\pm} \sim 1$; and $g_n = g_p = 1$. Table 15–4 then shows how S and N/C vary with f_n, the fraction of the initial energy of the interaction taken by the emerging nucleon. If the value of N_π/N_n is increased, S does not change appreciably, whilst the values of N/C move towards unity.

At primary energies ~ 50 BeV, the value of N/C observed at mountain altitudes in work with emulsion is $0{\cdot}9 \pm 0{\cdot}2$—BROWN *et al.* 1949—whilst GREISEN and WALKER (1953) found $0{\cdot}77 \pm 0{\cdot}12$ by measurements with ionisation chambers. The 'attenuation length' of the shower producing radiation according to CAMERINI *et al.* is ~ 125 g/cm², corresponding to $S \sim 1{\cdot}25$, and $f_n \simeq 0{\cdot}3$. These results therefore suggest that in the parent interactions of energy <100 BeV, the nucleon commonly re-emerges with not more than 50% of its original energy.

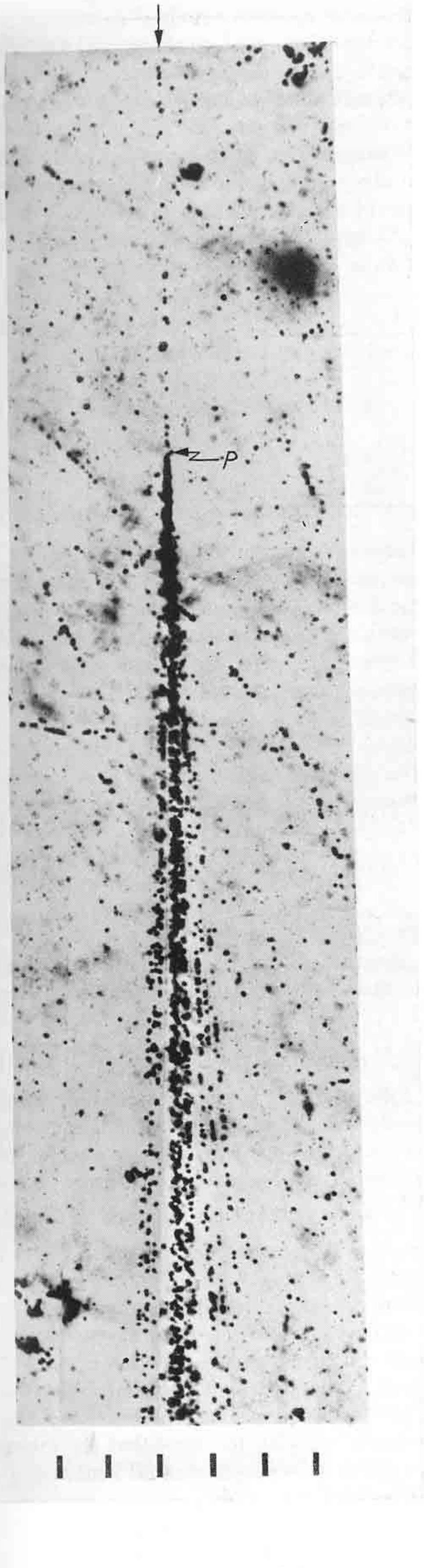
PLATE 15–11. 'Jets' of mesons produced by particles of energy ~ 3000 BeV and ~ 9000 BeV, respectively

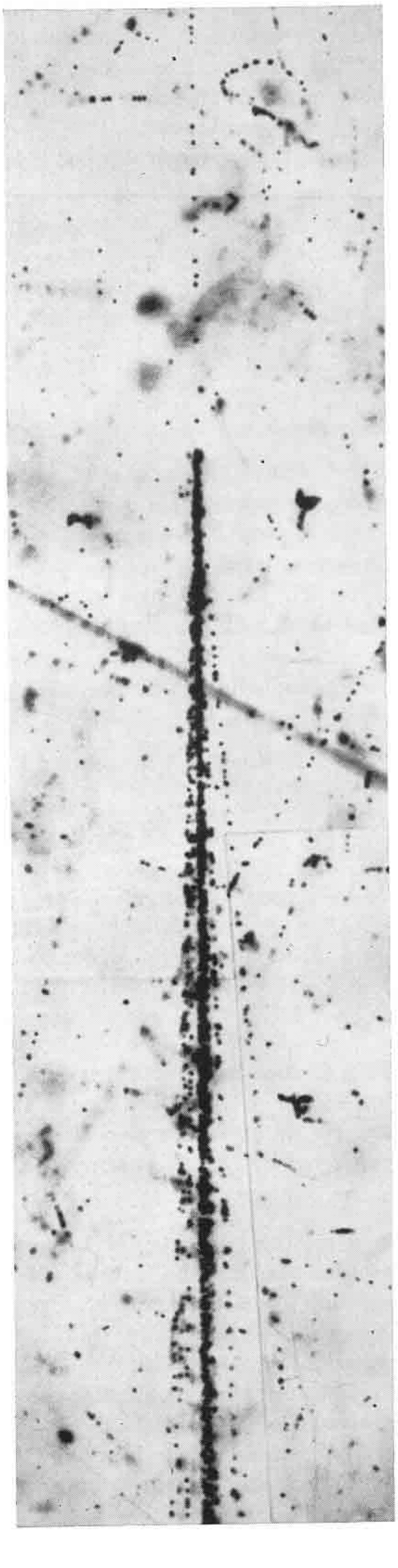
Ilford G 5 emulsion. DANIEL, DAVIES, MULVEY and PERKINS (1952).

In the left-hand event, of type $(0 + 28p)$, no heavily ionising particles are emitted, and it may be attributed, tentatively, to a proton-proton collision at the point P. The dense central 'core', photographed in a single setting of the microscope, can be distinguished, although only a few of the tracks within it are clearly resolved.

The right-hand photograph shows a jet of type $(0 + 32p)$, due to primary particle of energy about 9000 BeV. The angular distributions for the two events, transformed to the C-system, are shown in Fig. 15–18.

Plate 15–11. Jets of mesons of energy ~3000 BeV and ~9000 BeV





Nuclear interaction of a secondary particle from a 'jet'

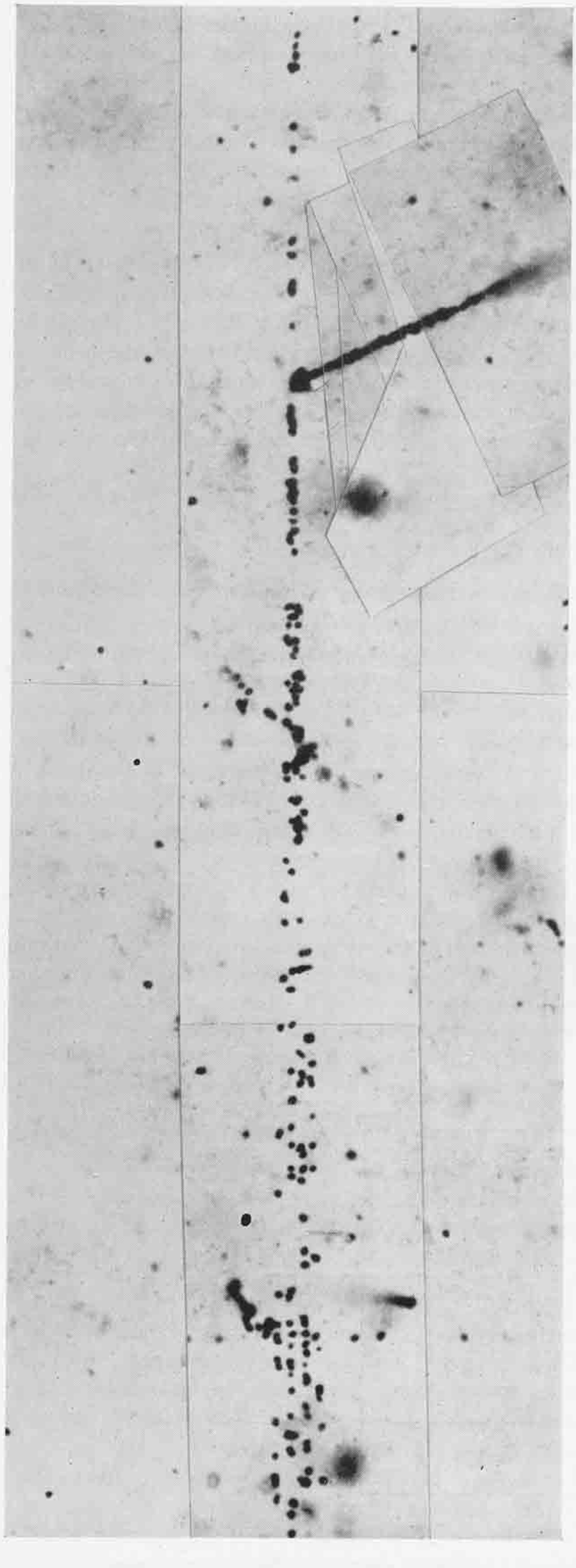


PLATE 15–12

This photograph shows a secondary interaction, of type $(1+5p)$ due to one of the shower particles of energy about 2000 BeV, originating in the event shown in Plate 15–8. Five such interactions of particles from this event were observed. Such studies of secondary interactions allow the mean 'interaction-length' of the shower particles to be determined. Many similar disintegrations must have occurred in the glass and were thus lost to observation. There are great advantages in making similar studies in stacks of stripped emulsions, especially if the stack has a length of the order of the interaction-length, i.e. ~ 33 cm, so that a large fraction of the secondary interactions are recorded.

The largest stack of emulsions employed hitherto appears to be one of 22·4 litres, exposed by balloon at great altitude in an experiment carried out in a collaboration between the Universities of Minnesota and Bristol.

Ilford G 5 emulsion.

Bristol (1952) unpublished.

Nuclear interaction of a proton of energy $\sim$40,000 BeV

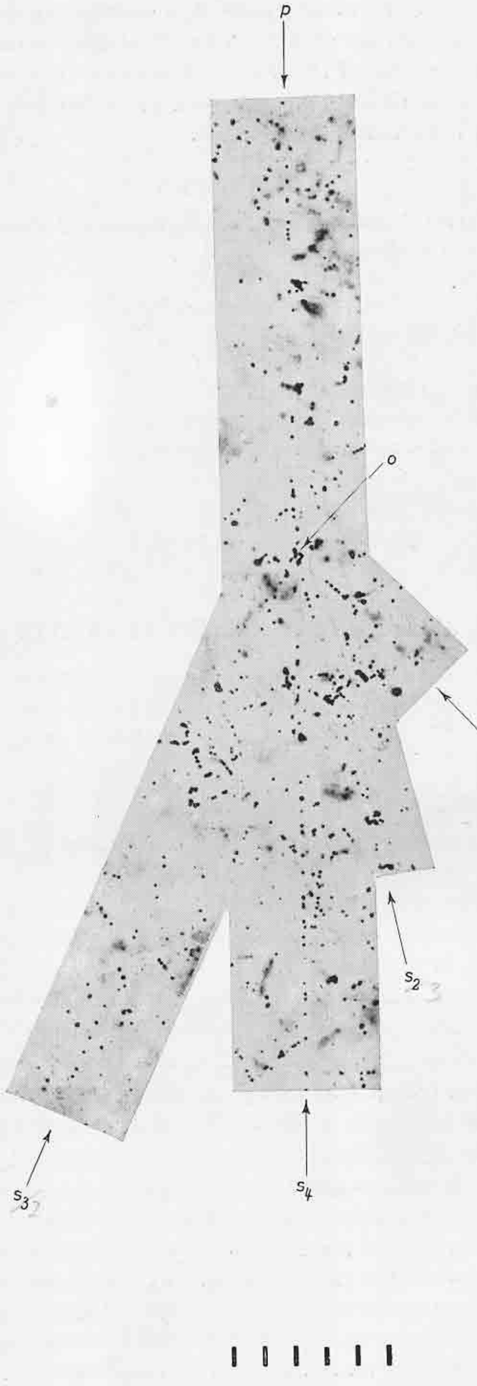
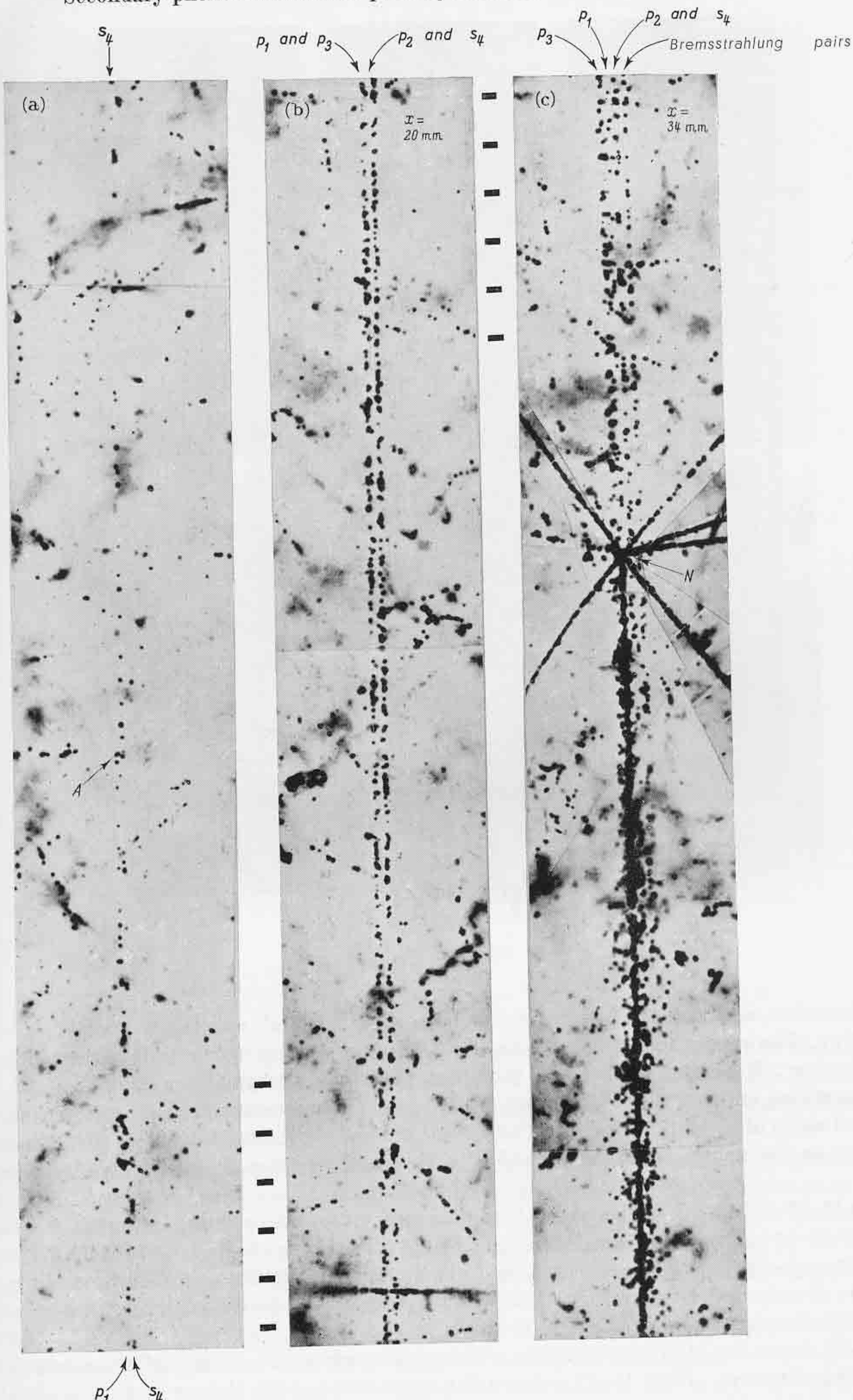


PLATE 15–13

Ilford G5 emulsion.

This event is analysed on pp. 560 *et seq.* It is remarkable for the small number of secondary particles and their angular distribution. The particle producing the track S_4 subsequently makes the disintegration shown in Plate 15–17, p. 565.

Secondary phenomena from a primary interaction at 40,000 BeV

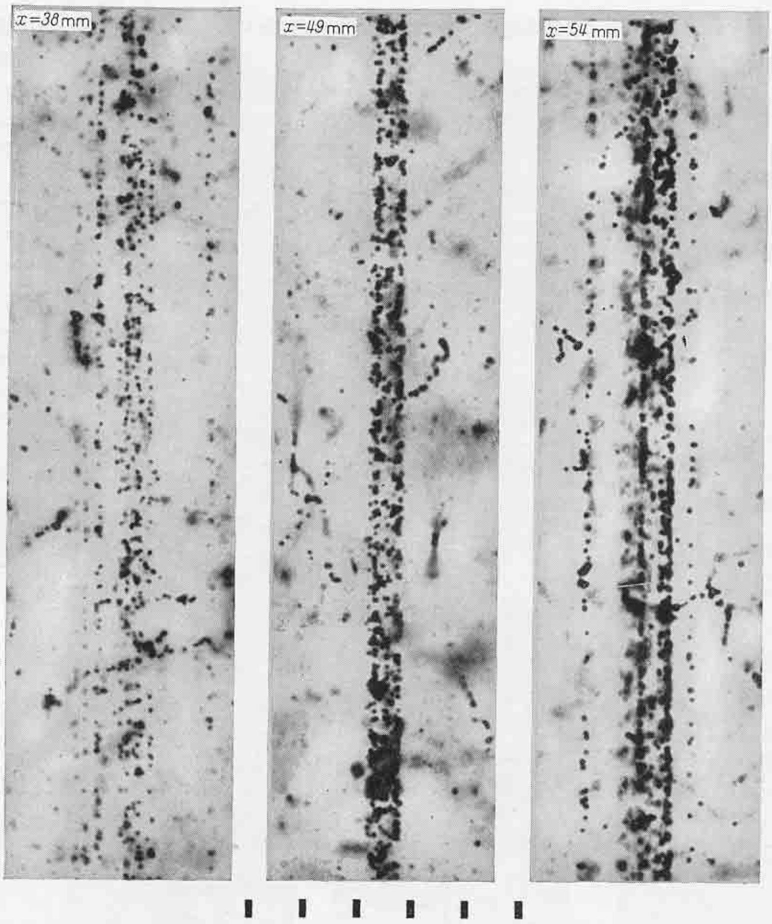


(a) (b) (c)

Ilford G 5 emulsion.

PLATE 15–14

(a) Single track, S_4, with origin of electron-pair near A.
(b) Pairs of electrons due to the conversion of γ-rays.
(c) Disintegration due to a neutral particle.



(a) (b) (c)

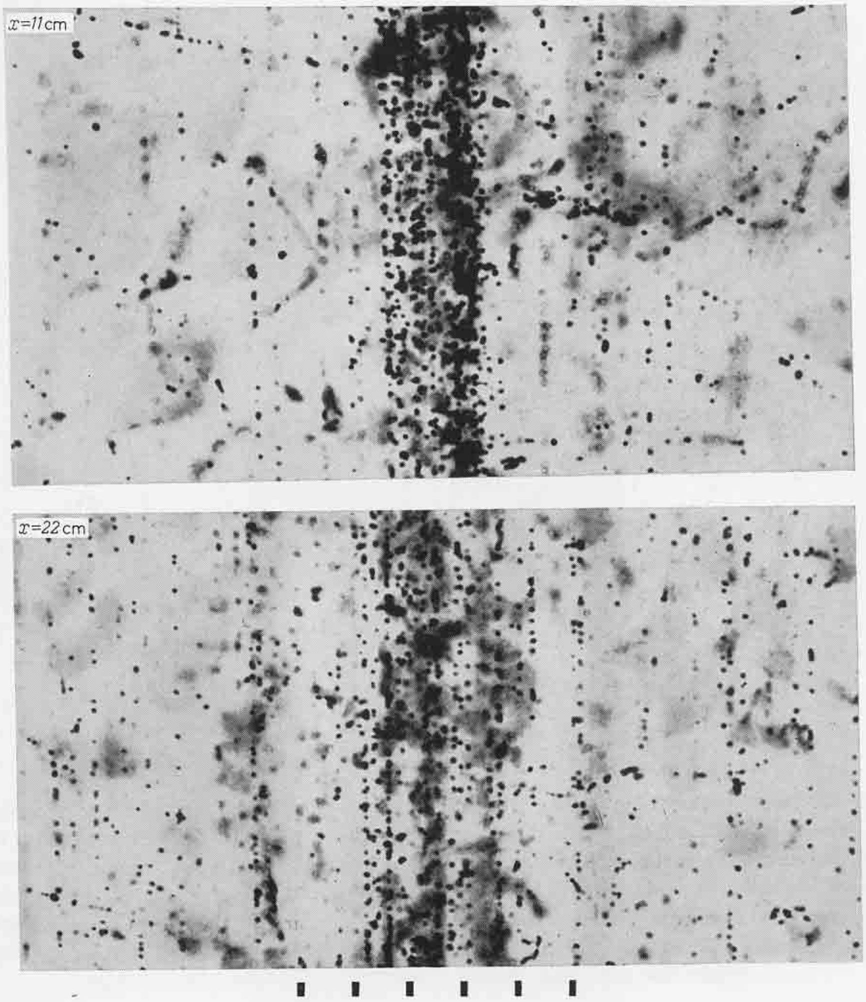
Ilford G 5. **PLATE 15–15**

primary interaction, and that the other three shower particles are all emitted at wide angles and are steeply dipping. The event therefore illustrates the dangers of missing some events of very high energy in 'area scanning'. P denotes the track of the primary particle, presumably a proton; S_1, S_2 and S_3 are shower particles, emitted at wide angles of 47°, 27° and 23°, respectively, to the primary direction. The projected angle of S_4 with the primary, on the other hand, is $< 0{\cdot}0015°$. It is difficult to measure the difference in the angles of dip of S_4 and P with great precision, but it is definitely less than $\sim 0{\cdot}01°$.

In Plates 15–15 and 15–16, the corresponding distances, x, from the primary interaction O are shown in mm. Plate 15–14 c shows an interaction, N, at $x = 34$ mm of type $(8 + 33n)$, produced by a neutral particle, of energy $\sim$28,000 BeV as estimated from the angular distribution of its secondary shower particles. The direction of the secondary particles from N makes it certain that the neutral primary was associated with the event at P.

Plate 15–15 shows the striking variations which may occur in the density of the shower cores as the soft cascade develops. Plate 15–15 a shows the appearance of the shower at a point about 4 mm beyond Plate 15–14 c. The shower particles from the interaction N have now diverged, and about half the tracks seen in the photograph are electrons from pairs P_1, P_2 and P_3. In Plate 15–15 b, however, $x = 49$ mm, i.e. 15 mm from N, the core has become intense once again owing to cascade multiplication along the axes of all three pairs.

Plate 15–16 shows the appearance of the cascade at $x = 11$ cm, $x = 22$ cm. In this last photograph, the increasing diffuseness of the cascade is apparent.



Ilford G5. **PLATE 15–16**

A further interaction, B, of type $(5+7p)$, was observed at $x=220$ mm. From the relative positions of this interaction, and of the somewhat dispersed 'cores' due to pairs P_1, P_2 and P_3, it was concluded with some confidence that star B was produced by particle S_4. Its energy is estimated to have been 2200 BeV; see Plate 15–17.

At $x=35$ mm, i.e. 1 mm beyond N, a fourth electron pair materialised, P_4, of quite low energy, $\sim$30 BeV. Its direction clearly indicated that it originated from the primary interaction O, and not from event N. The absence of further high-energy 'cores' in the electro-magnetic cascade, suggests that, in the primary interaction, only two neutral pions were produced, at least in the inner 'core' of the primary interaction, leading to pairs 1–4 inclusive; and further, that no neutral pions of comparable energy were emitted from interaction N.

The total energy in event O must have been $\sim$40,000 BeV. Thus, if it is assumed that the particle producing the star N is collinear with the primary P, the angular distributions of the secondary particles S_1, S_2, S_3 and S_4, and of the two π^0-mesons can be determined; the result is shown in Fig. 15–16 and Fig. 15–12; E, F, G. This distribution is consistent with that expected in a nucleon-nucleon collision of primary energy $\sim$40,000 BeV. It is of special interest that the secondary particles are projected backwards and forwards in the C-system at extremely small angles, $\lesssim 1{\cdot}5°$. Assuming that the particle which produced star N was a neutron, it follows that only about 15–20% of the primary energy was radiated in the form of π-mesons in the first collision. This result is in agreement with the sum of the estimated energies of the pairs, 5500 BeV, and that of the particle, S_4, 2200 BeV.

Disintegration due to a secondary charged particle from a jet

PLATE 15–17

Ilford G 5 emulsion.

Disintegration of type $(5 + 7p)$, due to the secondary particle S_4 from the event shown in Plate 15–13. The angular distribution of the shower particles from this event is shown in Fig. 15–12, p. 550, and indicates an energy of $\sim$2200 BeV for the particle.

Cascades following from the nuclear interaction of an α-particle of energy 10^6 BeV

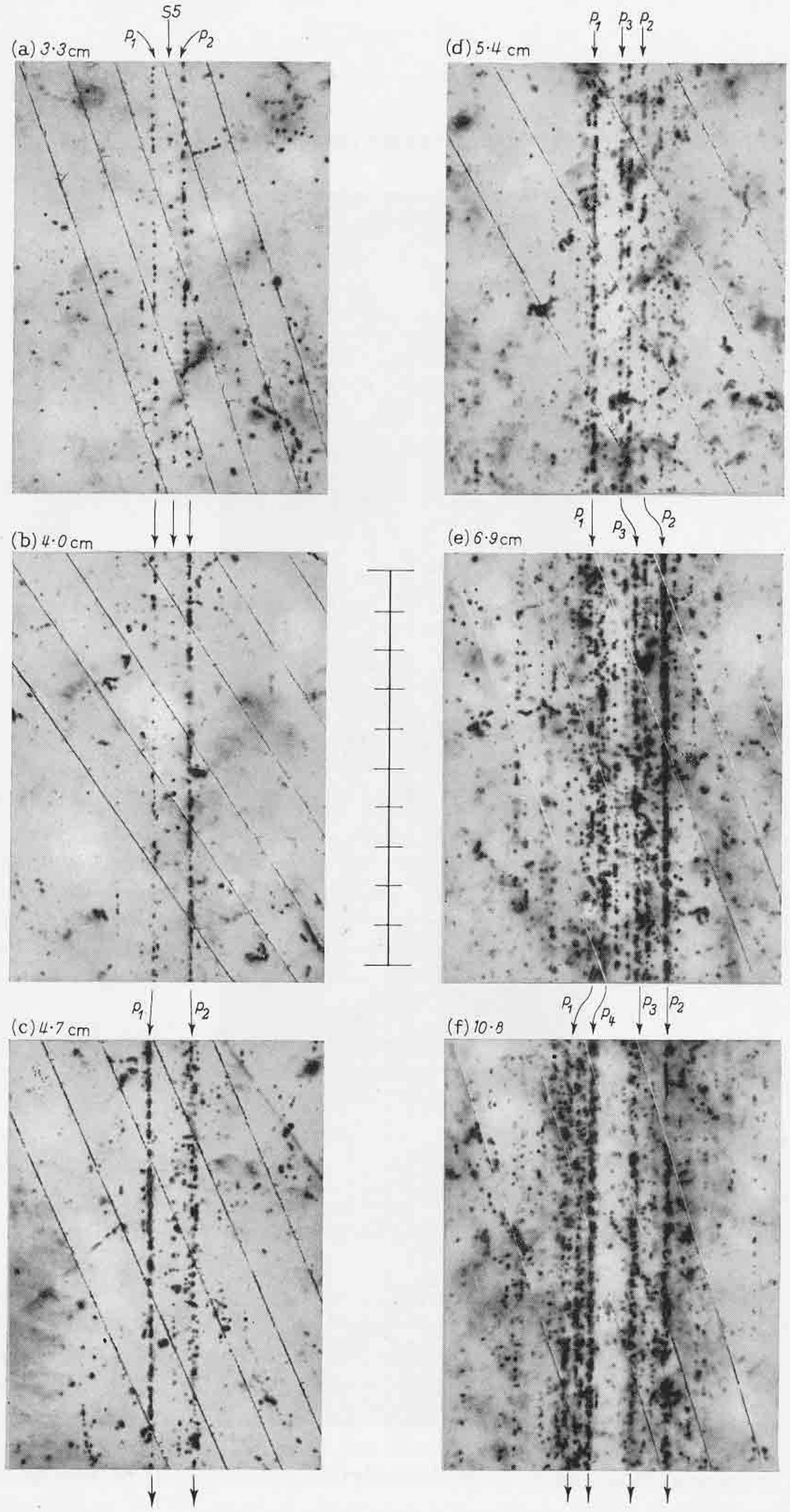


PLATE 15–18

Ilford G5 emulsion.

The cascades are developing in pure emulsion, the distance from the point of disintegration being shown for each photograph.

Cascades of electrons from the nuclear interaction of an α-particle of $\sim 10^6$ BeV

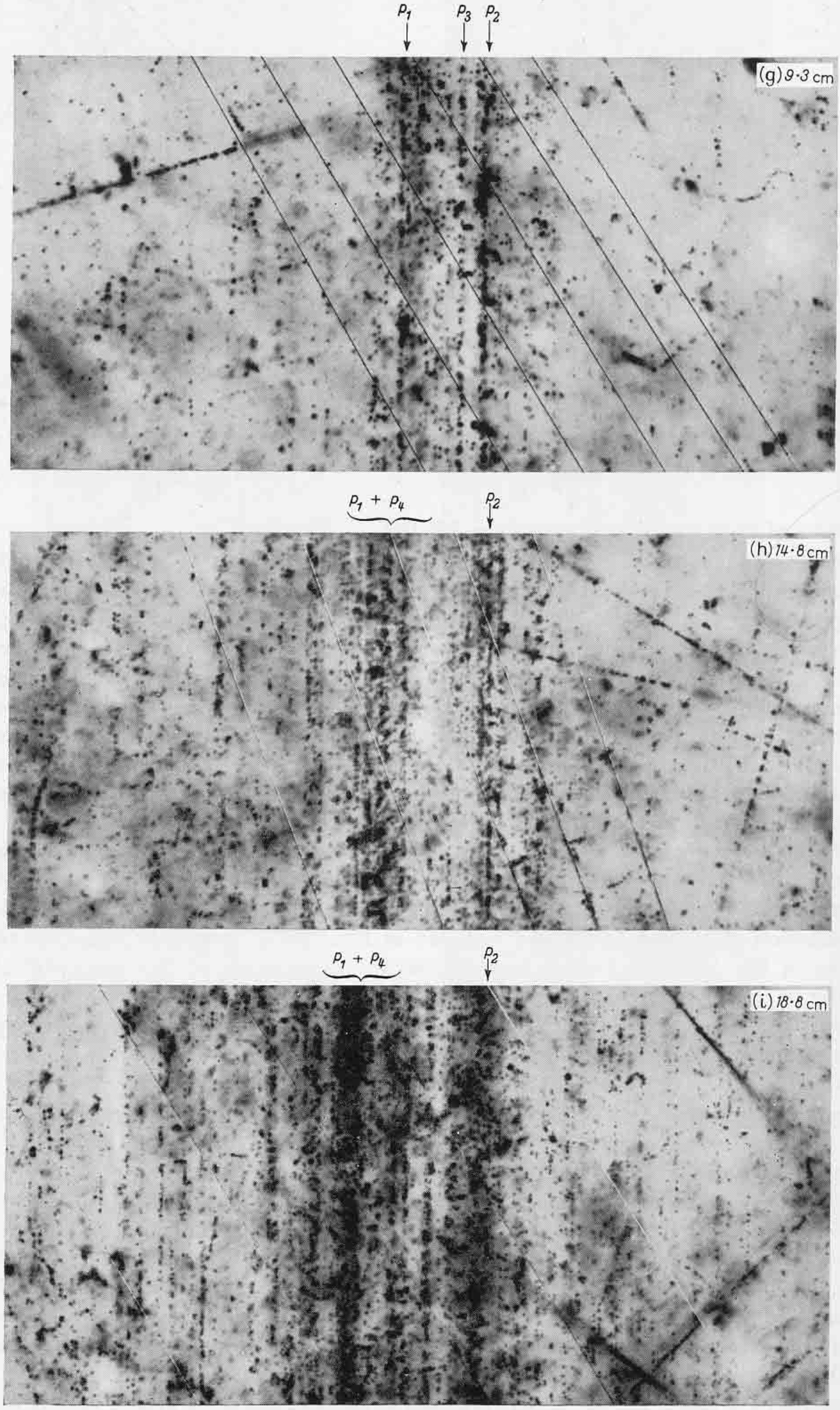


PLATE 15–19

Ilford G5.

Nuclear collision of secondary particle with energy $\sim 10^6$ BeV

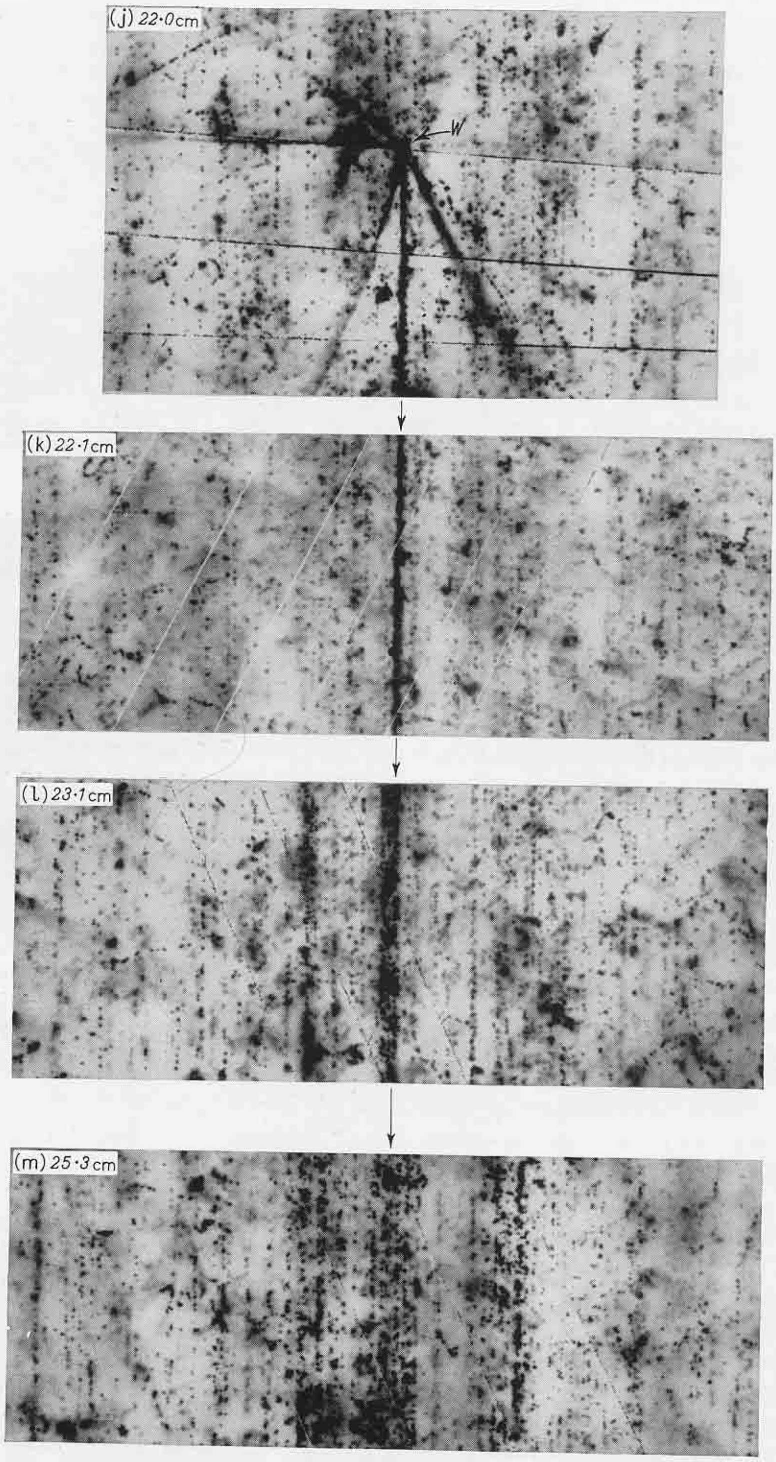


PLATE 15–20

Ilford G 5 emulsion.

The evidence that the apparent primary of the disintegration shown in (j) can be attributed to S_5 depends upon the fact that it is in the appropriate position with respect to the γ-ray cores, especially p_2 in (m), see Fig. 15–17. It must be remarked, however, that since the primary of the original event is an α-particle, and the multiplicity of the first disintegration is so small, the most reasonable assumption is that only one of the four nucleons of the primary α-particle was involved in the first interaction. If so, it would be most reasonable to assume that S_5 is one of the three remaining nucleons, the other two being neutrons. If indeed one only of the nucleons of the parent α-particle was involved in the original interaction, the tracks of the other three should have an angular divergence of $\sim 10^{-7}$ radians. Their paths at 22 cm from O would then be separated from one another by only $\sim 0{\cdot}02\,\mu$. It is therefore possible that the observed disintegration at W is due to any one of these

(Continued at top of page 572)

Development of cascades in a sandwich of lead and emulsion

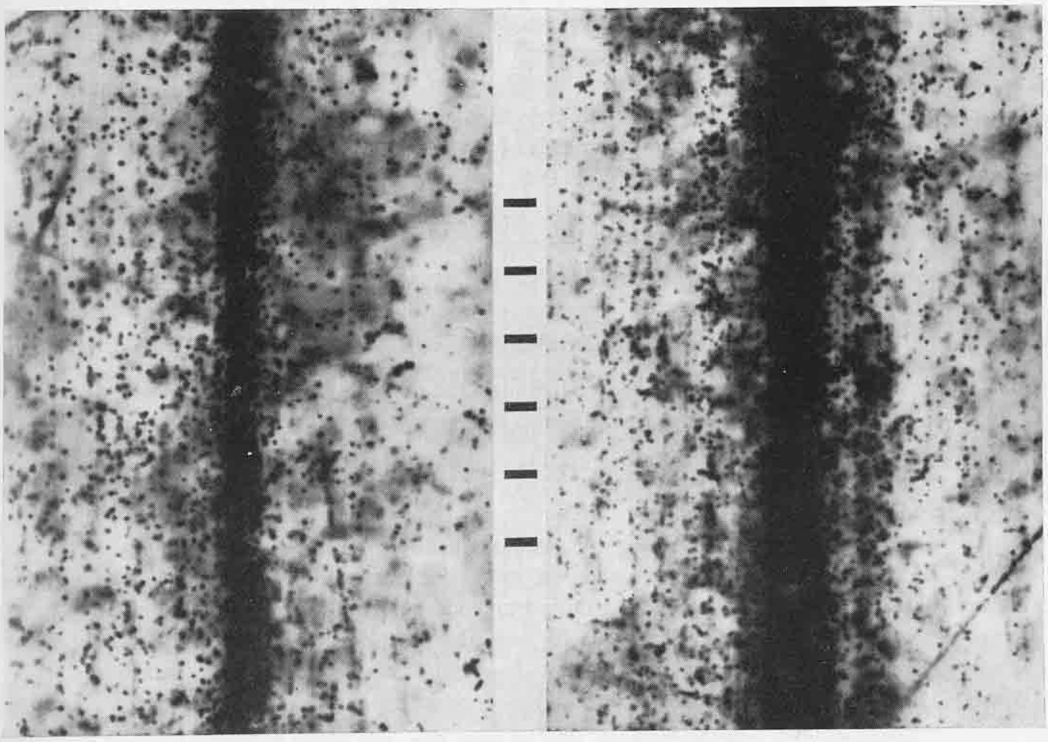


PLATE 15–21

Ilford G 5 emulsion.

Cascades of electrons from an event of energy about 40,000 BeV, observed in an assembly of lead and emulsion; see Fig. 15–10, a. The cascades are shown at 2 cm, and 5 cm from the original interaction, the effective cascade-length in the composite medium being ~ 1 cm. The photograph shows the great concentration of tracks brought about by reducing the radiation-length from 4 cm, the value characteristic of pure emulsion.

There would be some advantage in employing heavy elements with $Z > 82$, in place of lead for concentrating the 'soft-cascades'. Thus, uranium 238 has $Z = 92$ and a density of ~ 21; the corresponding radiation-length would be ~ 3 mm instead of 5 mm in lead. Among other objections to its use, however, is its residual γ-radiation which would fog the plates in long exposures. Gold would be preferable to lead because of its higher density, and it is readily rolled into thin sheets, but its great value, and the hazards of flights by balloon or by aircraft, prohibit its use. Tungsten with 2% nickel has a radiation-length of ~ 4 mm, and offers a valuable alternative.

Tracks of nuclei of the primary cosmic radiation moving at relativistic velocities

Ilford G5 emulsion. **PLATE 16–1** Dainton, Fowler and Kent (1952).

The tracks were identified by measurements of scattering and δ-ray density.

Tracks of heavy nuclei of the cosmic radiation

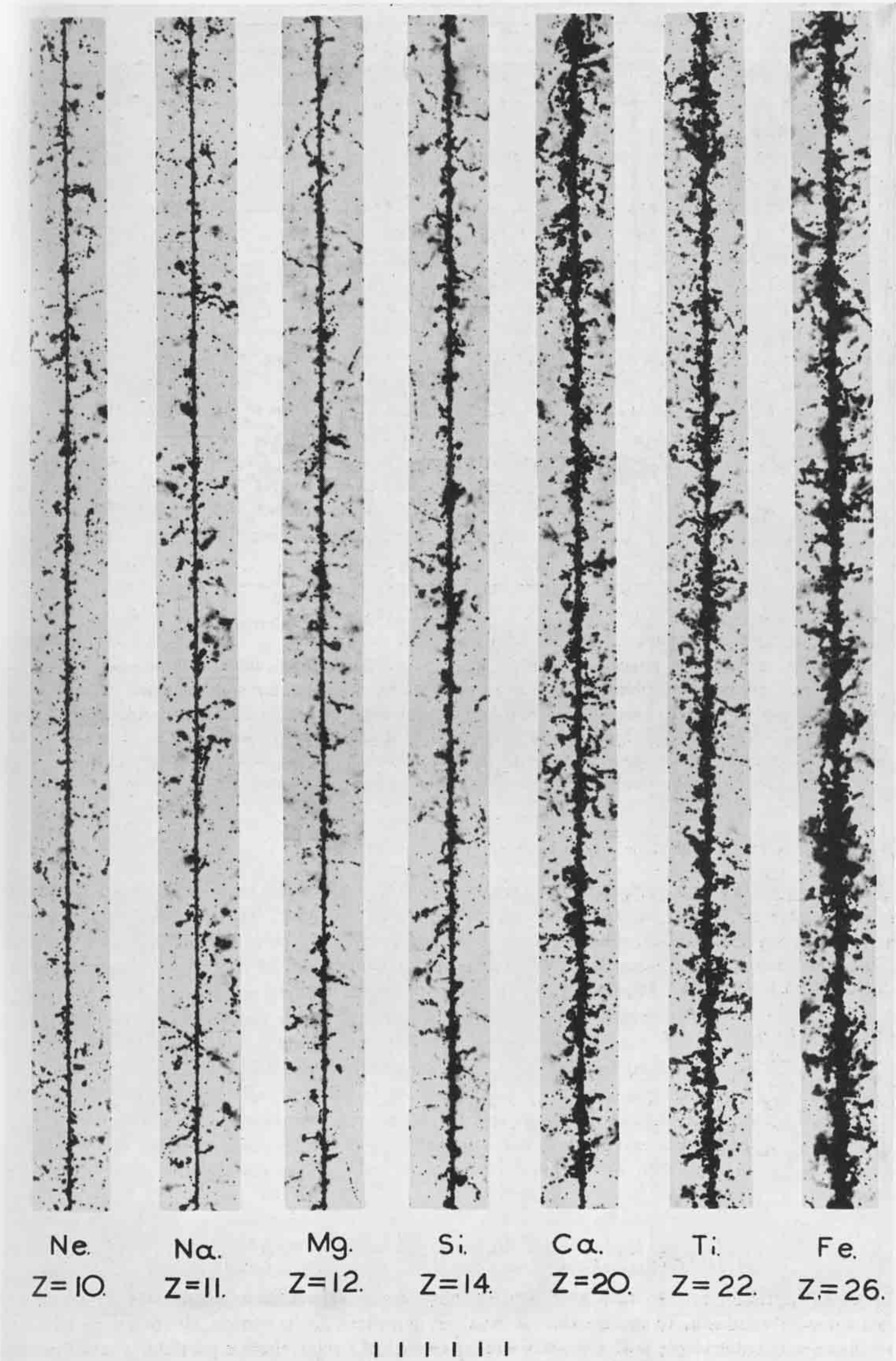


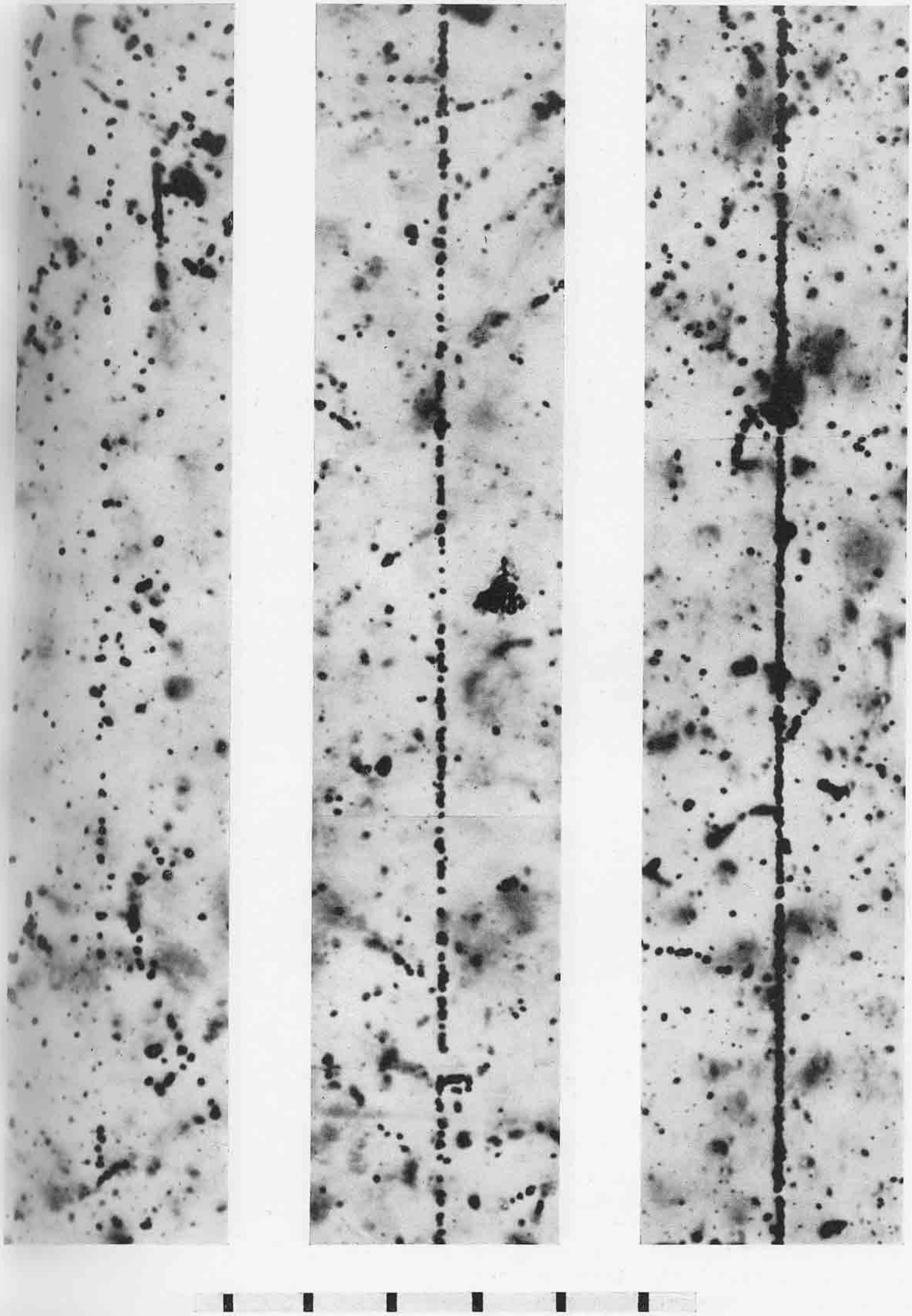
PLATE 16–2

Ilford G5 emulsion. DAINTON, FOWLER and KENT (1952).

The tracks were identified by measurements of scattering ($\bar{\alpha}$), and δ-ray density (N_δ).

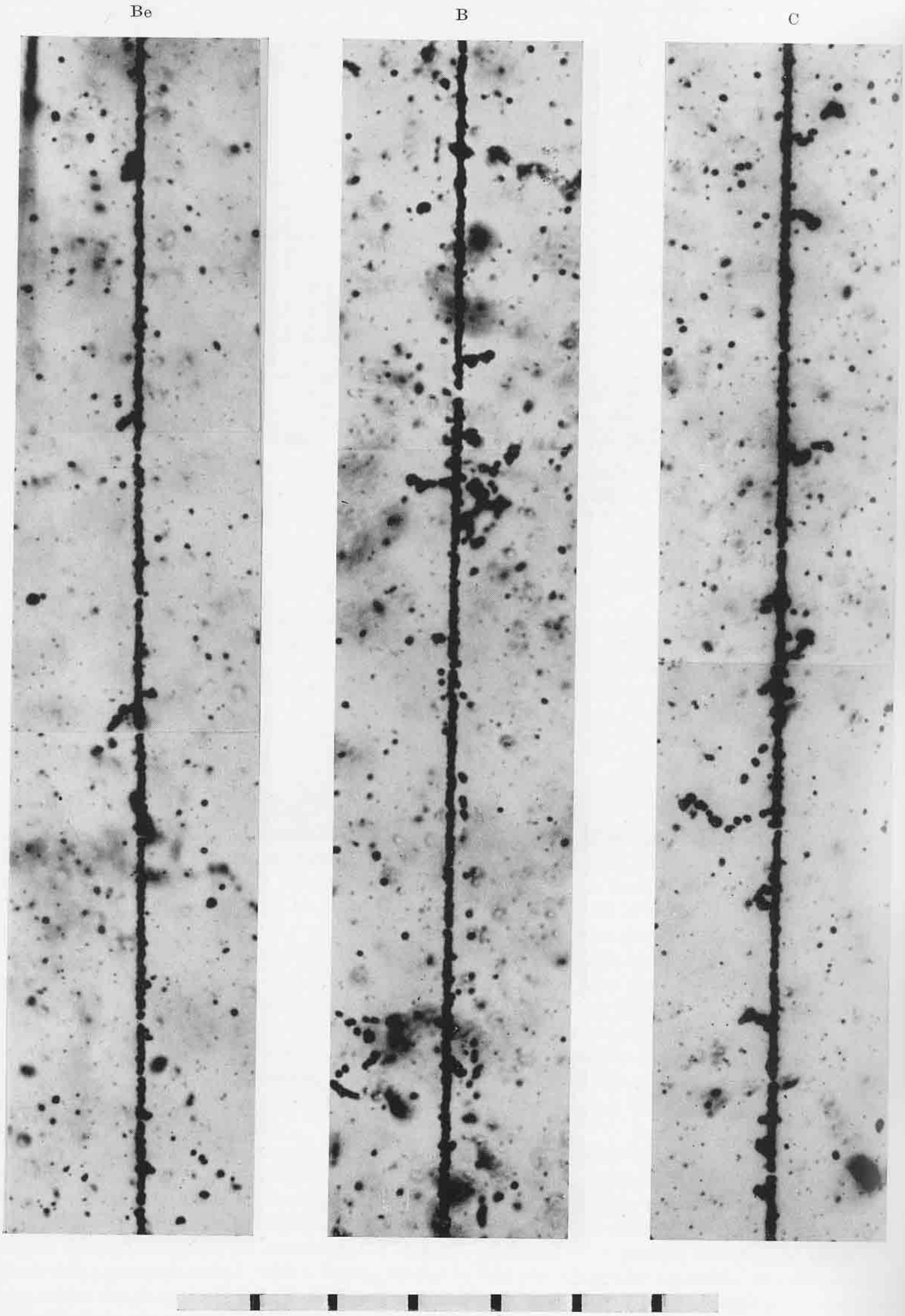
Tracks of hydrogen, helium and lithium nuclei of the primary cosmic radiation moving at relativistic velocities

H He Li



Ilford G5 emulsion. **PLATE 16—3** DAINTON, FOWLER and KENT (1952).

Tracks of beryllium, boron and carbon nuclei of the primary cosmic radiation moving at relativistic velocities

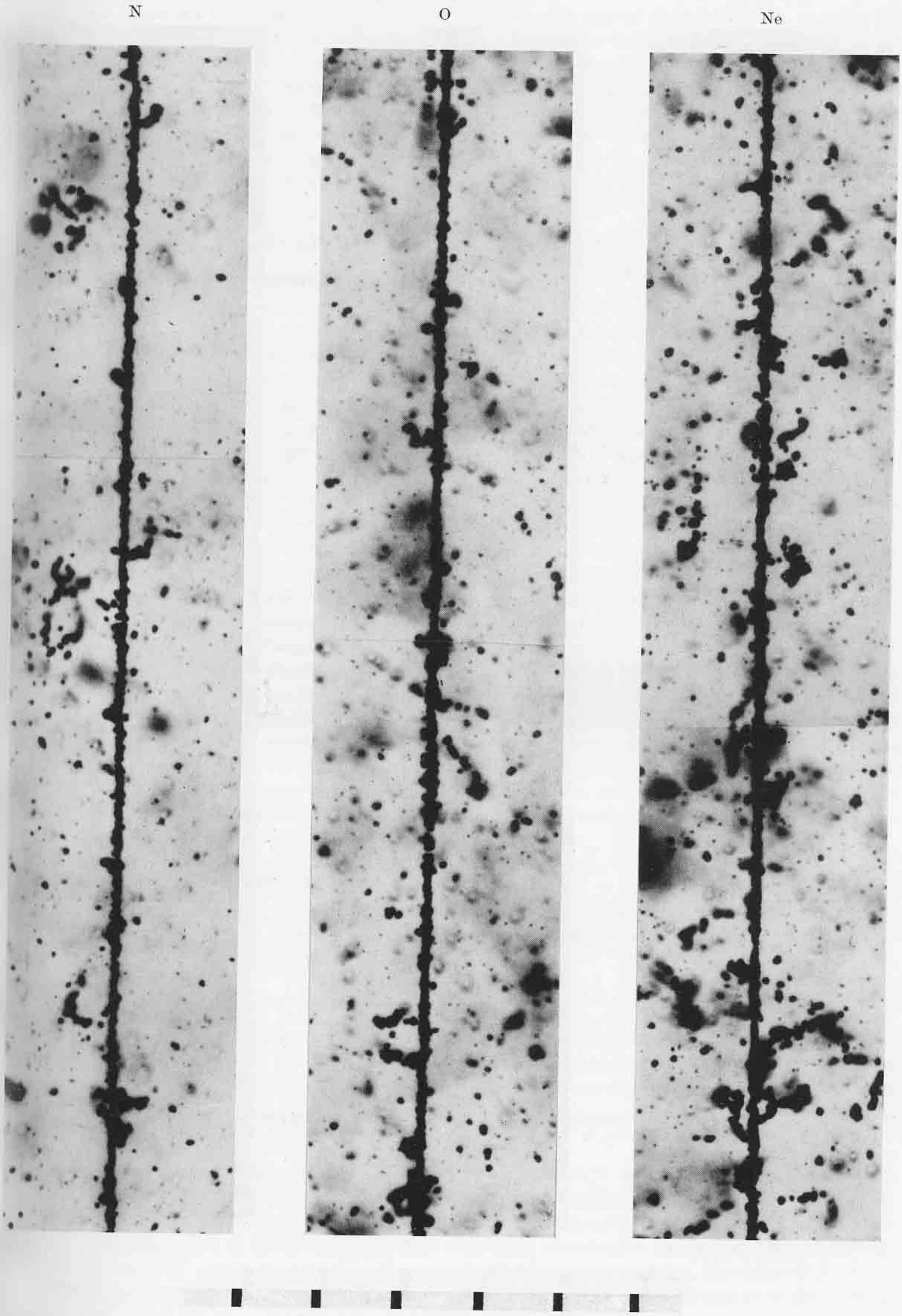


Ilford G 5 emulsion.

PLATE 16–4

DAINTON, FOWLER and KENT (1952).

Tracks of nitrogen, oxygen and neon nuclei of the primary cosmic radiation moving at relativistic velocities



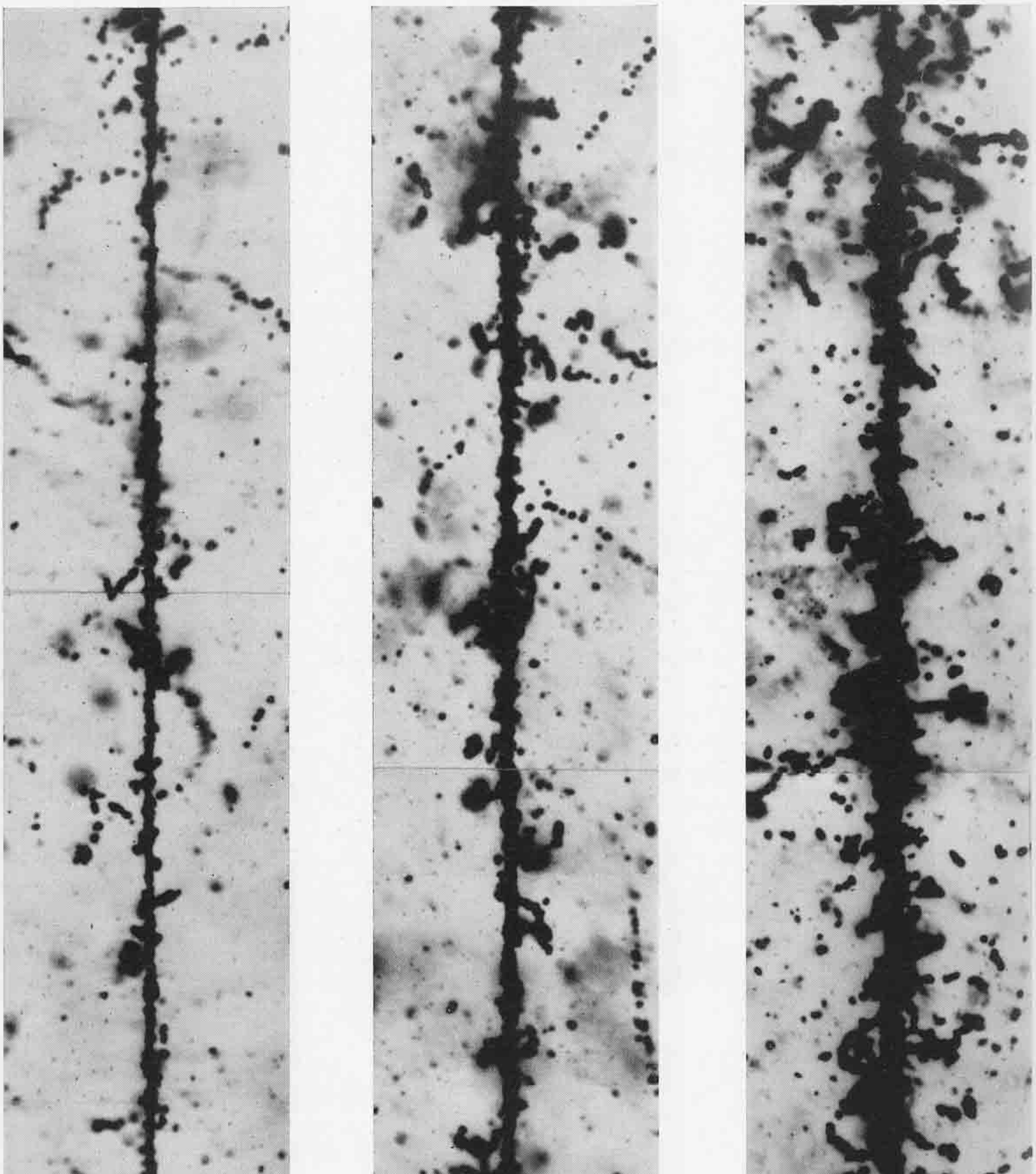
Ilford G 5 emulsion.

PLATE 16–5

DAINTON, FOWLER and KENT (1952).

Tracks of heavy nuclei of the cosmic radiation moving at relativistic velocities

$Z = 12 \pm 1$ $Z = 14 \pm 1$ $Z = 20 \pm 1$



Ilford G5 emulsion. **PLATE 16–6** DAINTON, FOWLER and KENT (1952).

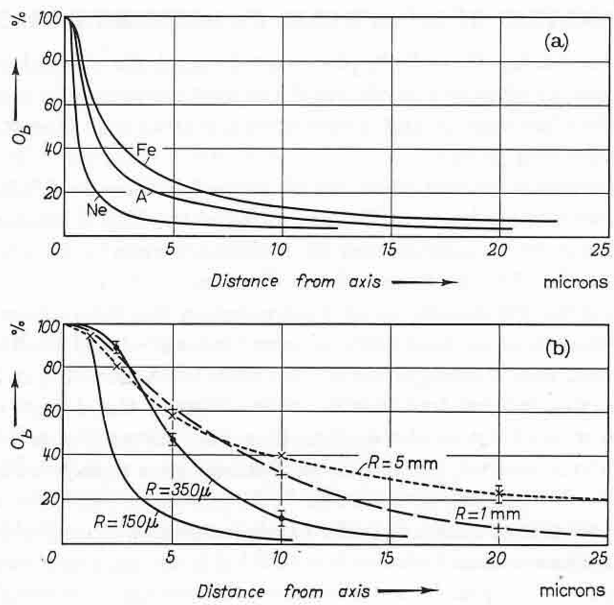


Fig. 16–5. Distribution of the obscuration produced by the tracks of heavy nuclei, at different distances from the trajectory. The measurements were made using a slit of equivalent width 1 μ in the focal plane of the objective, the values being normalised to 100 for observations on the axis of each track. (a) Measurements for the tracks produced by nuclei of Ne, A and Fe moving at relativistic velocities. (b) Similar measurements for an Fe nucleus at regions near the end of the range.

With the above simplifying assumptions, consider the obscuration produced by a track parallel to the plane of the emulsion and scanned by a narrow slit which moves across the track but always parallel to it. Ignoring both statistical fluctuations and the contraction of the emulsion after processing, the grains may be assumed to be distributed with circular symmetry in any plane normal to the track. Suppose the density of grains at a distance r from the axis of the track is equal to $S(r)$. The fractional reduction of intensity due to grains between r and $r+\delta r$, when the microscope is focussed on the axis of the track, is then given by the relation: $\delta I/I = -k \,.\, S(r) \,.\, \delta r$, where k is a constant which depends upon the mean size of the developed grains. It follows that $I = I_0\, e^{-k\int S(r)\cdot dr}$. In effect, for this particular setting of the microscope, the obscuration produced by the track is closely similar to that which would occur if all the silver in the track were projected on a plane parallel to the surface at the depth of the track. For other settings of the microscope, when it is focussed at points displaced from the axis of the track, the same conclusion is valid if the aperture of the objective is

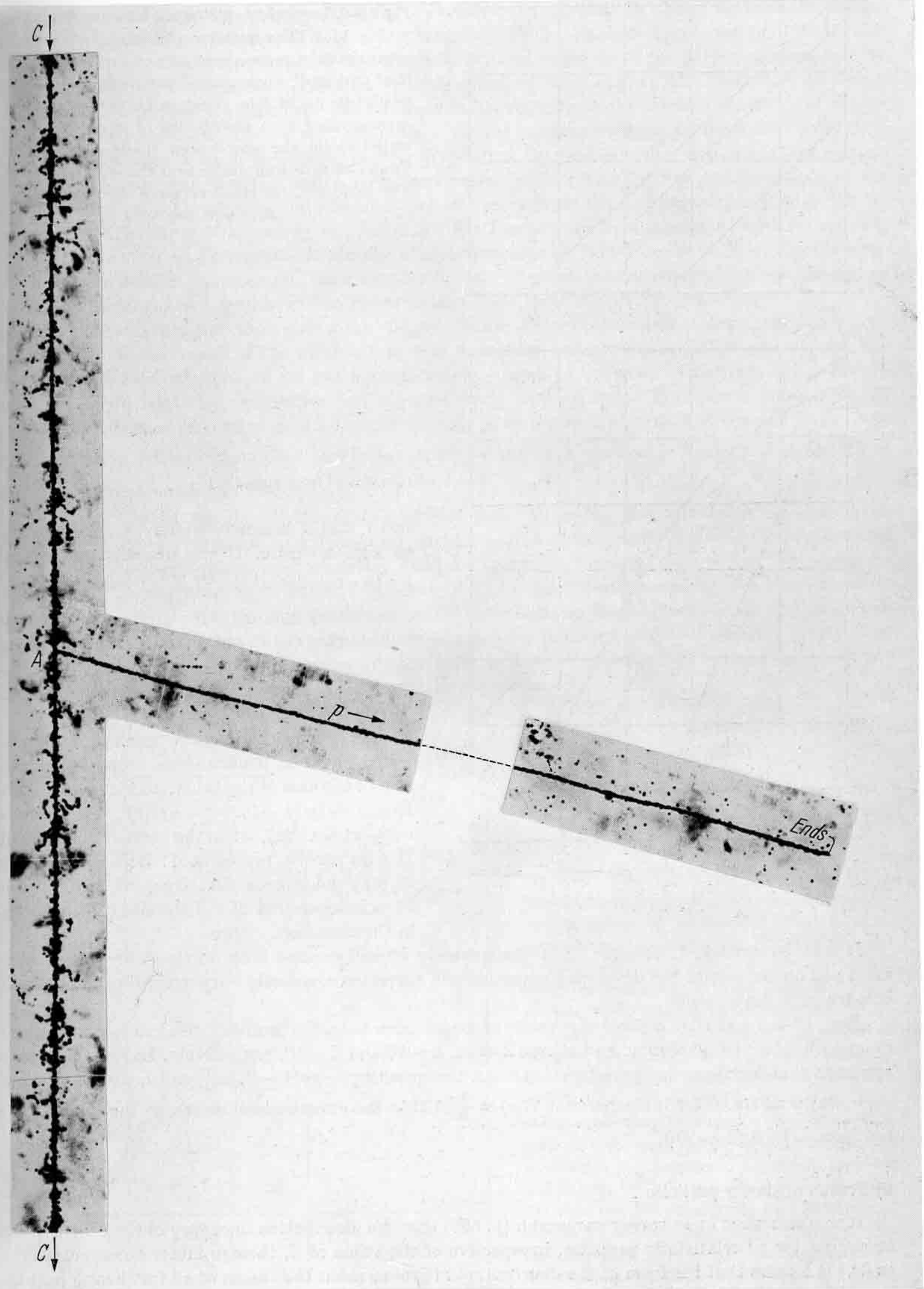
(Continued on page 594)

PLATE 16–7. Collision of a carbon nucleus with a free proton ▸

A slow carbon nucleus—compare the track with that of similar particles in Plates 16–4 and 16–8—collides elastically with a hydrogen nucleus in the emulsion. The interpretation is based on the observed range of the recoiling proton, and on the change in direction of the carbon nucleus of known momentum. The detailed study of the collisions of nuclei with individual protons is of great interest because of its bearing on the problem of the origin of the cosmic radiation.

Such collisions with interstellar hydrogen will sometimes cause the fragmentation of the nuclei. They will therefore change the form of the 'mass spectrum' of the particles reaching the upper atmosphere. The modifications will be more profound the greater the distance of the source from the earth. Any satisfactory theory must allow for such effects in accounting for the observed mass spectrum of the incoming particles; see p. 638.

Collision of a carbon nucleus with a free proton



Ilford G 5 emulsion.

50μ

DAINTON, FOWLER and KENT (1951).

PLATE 16–7

c) Empirical expression for the obscuration produced by a track

The results described in previous paragraphs allow an expression to be deduced for the obscuration produced by the track of a relativistic particle as a function of its charge, Z. Thus, from Sect. 3, p. 101, it follows that if $1/g$ is the mean size of the gap which may exist between developed grains, the number of gaps per unit length in the core of the track is equal to $\sim g e^{-gu}$, where u is the mean diameter of the developed grains. The total length of the gaps, per unit length of core, is therefore e^{-gu}, so that the fraction of the core obscured by grains is $\sim 1 - e^{-gu}$. The value of g varies approximately as Z^2 (see, however, p. 104), so that putting $u = 0{\cdot}75\,\mu$, and assuming the value of g for a singly charged relativistic particle to be $0{\cdot}25\,(\mu^{-1})$, the obscuration due to the core is given by the relation $O_b(\text{core}) = 0{\cdot}75\,(1 - e^{-0{\cdot}18 Z^2})$. This value of the obscuration may be assumed to apply to a region extending to $\sim 0{\cdot}4\,\mu$ on both sides of the trajectory of the parent particle.

Consider now the effect of the δ-rays on the obscuration in the region between $0{\cdot}4$ and $2{\cdot}5\,\mu$ from the trajectory. The obscuration for this region is given by $2\int_{0\cdot4}^{2\cdot5}(1 - e^{-kZ^2/x})\,dx$. To a first approximation this equals

$$2\int_{0\cdot4}^{2\cdot5} \frac{kZ^2}{x}\,.\,\delta x = 2kZ^2 \ln \frac{25}{4}. \qquad \text{Eq. (16–iii)}$$

In a typical result in G5 emulsion, the obscuration due to the track of an iron nucleus, in a region $1\,\mu$ from the trajectory, is $\sim 70\%$. Substitution then shows that $k \sim (^1/_{26})^2$. It follows that the contribution due to δ-rays, in the case of a slit $5\,\mu$ wide centred on the track in the focal plane, is given by $(5{\cdot}4 \times 10^{-3})\,Z^2$. The total obscuration due to both core and δ-rays is therefore given by

$$O_b \sim a(1 - e^{-bZ^2}) + cZ^2, \qquad \text{Eq. (16–iv)}$$

where $a = 0{\cdot}75$, $b = 0{\cdot}18$ and $c = 5{\cdot}4 \times 10^{-3}$. The corresponding variation of the obscuration with Z^2 is shown in Fig. 16–7, for this and other slit widths, and displays the poor resolution for values of Z between 4 and 10.

d) Determination of charge *Z* by photometry

In the above treatment, it has been tacitly assumed, (a), that the grains absorb light incident upon them without scattering; and (b), that there are no other scattering centres in the emulsion, neither developed grains nor 'fog'. In such conditions, and in the absence of diffraction, grains in sharp focus would appear black, irrespective of their depth in the emulsion. In practice, it is a matter of common observation that the contrast in the image becomes progressively less at increasing depth. This is mainly due to the scattering of light by the medium above the grains. As we have seen, p. 108,

(Continued on page 598)

PLATE 16–8. Nuclear collisions of carbon nuclei

In the event at A, a carbon nucleus, identified by measurements of N_δ and $\bar{\alpha}$, was moving with a velocity close to that of light. As a result of the collision, it decomposed into three α-particles. The latter, which were identified by measuring the scattering and grain-density of their tracks, emerged with nearly equal velocities. This observation, and the absence of tracks associated with the evaporation of a struck nucleus, makes it reasonable to attribute the event to a collision with a proton. The latter recoiled and produced the track diverging to the left. If this interpretation is correct, the collision is closely similar, as seen by an observer moving with the centre of mass of the interacting particles, to the well known reaction in which carbon is disintegrated into three α-particles under proton bombardment. The possibility that the observation represents a glancing collision with a heavier nucleus, while less probable, cannot however, be excluded.

In the right-hand photograph, the incident carbon nucleus, and the hydrogen, helium and lithium nuclei into which it decomposes at B, all produce tracks sufficiently long to allow the particles to be identified. The nature of the other secondary particles is uncertain, but it is probable that they are π-mesons produced in the interaction.

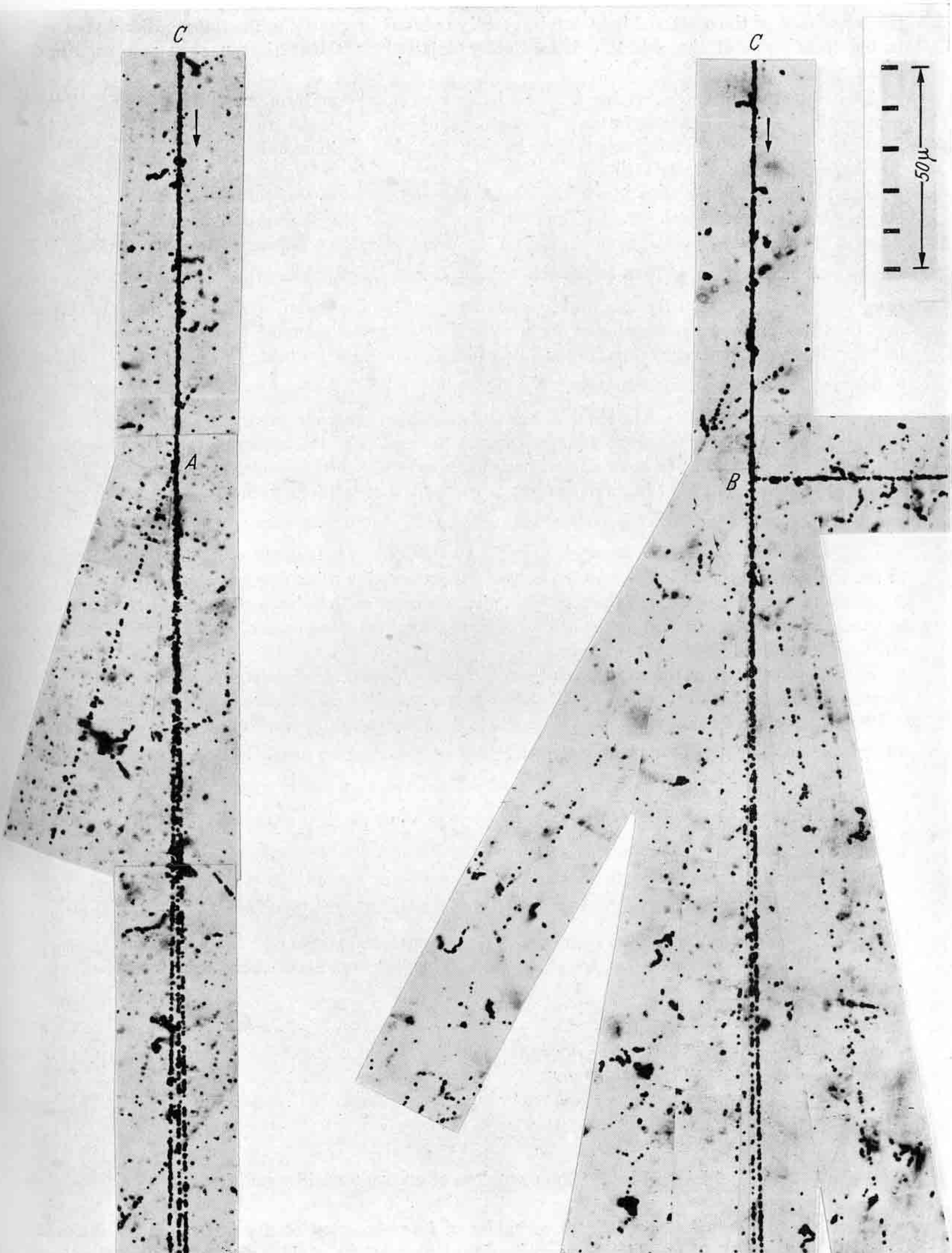


PLATE 16–8

Ilford G 5 emulsion.

the magnitude of the scattered light can be greatly reduced by confining the illumination to the region in the focal plane of the objective immediately adjacent to the track, but even so a considerable effect remains.

The scattering in the overlying medium leads to a nearly uniform diminution in the degree of contrast in the image of grains in the immediate neighbourhood of the track, for most of the scattered light comes from centres relatively remote from it. Grains in the core and those a few microns from it are therefore nearly equally affected.

The above difficulties complicate the problem of determining the value of Z from the apparent obscuration produced by the track: Thus, we have seen that the obscuration, measured by a narrow slit at a standard distance, x, from the axis of the track should be approximately proportional to Z^2. In ideal conditions it would then be possible to measure Z by determining the quantity $\frac{I_\infty - I_x}{I_\infty}$, where I_x is the transmitted intensity at x, and I_∞ a similar quantity at a distance sufficiently remote to ensure that the track produced no significant obscuration, but not so far removed that effects due to a change in the general translucency in moving across a plate might be important.

In practice, however, the quantity $\frac{I_\infty - I_x}{I_\infty}$ for a given track is found to change as a result of variations in contrast of emulsions in the same stack, and with changes in depth within a single emulsion. It is therefore necessary to adopt some method of 'normalising' the observations. For this purpose, it would be an advantage to have a completely opaque object in the emulsion, such as a wire, and to measure the amount of light in its image. In practice, it is convenient to measure the intensity in the image of the core of the track, I_c, corresponding to $x=0$, and to determine the quantity $\frac{I_\infty - I_x}{I_\infty - I_c} = x$; x is found to be almost independent of the optical conditions and it can therefore be taken as a measure of the charge Z, but the precise relation between them remains to be determined.

From the point of view of determining Z, the weakness of the above method is that I_c does not, in general, correspond to the complete obscuration of light by the core of the track, and allowance must be made for this fact.

As a demonstration of the transparency of the core of the lighter nuclei, events are sometimes observed in which one of the heaviest nuclei disintegrates in the emulsion, a secondary nucleus with charge $Z \sim 8$ being produced; the latter may be identified by δ-ray counting or other methods. Such an event allows the quantity $\frac{I_\infty - I_c}{I_\infty}$ to be determined for both of two nuclei in nearly identical conditions. Similar observations of nearly equal value may be made on tracks of unrelated nuclei which, by chance, pass near one another. Such observations give an average value for $\frac{I_\infty - I_c}{I_\infty} \sim 0{\cdot}45$ for oxygen nuclei in G5 emulsion, and $\sim 0{\cdot}75$ for the heaviest nuclei recorded. A charge spectrum based on measurements of this type for 156 tracks of particles with $Z \gtreqless 8$ is shown in Fig. 16–19, p. 638.

The average values shown in Fig. 16–19 for the quantity $\frac{I_\infty - I_c}{I_\infty}$ allow the degree of obscuration in the core of the lighter nuclei to be estimated, if it is assumed that the core of any one of the heaviest nuclei is completely opaque. Thus, for oxygen, the average obscuration of the core is estimated to be $\sim 0{\cdot}45/0{\cdot}75 \sim 0{\cdot}60$.

PLATE 16–9. Fragmentation of carbon nuclei by collision

The three photographs show the three modes of fragmentation of the carbon nuclei, illustrated in Plates 16–7 and 16–8, at a higher magnification. Observations of this type sometimes allow an independent determination of the charge of the incident particle, the most reliable examples being those in which no relativistic singly charged particles emerge, so that uncertainties associated with meson production are absent.

Fragmentation of carbon nuclei by collision

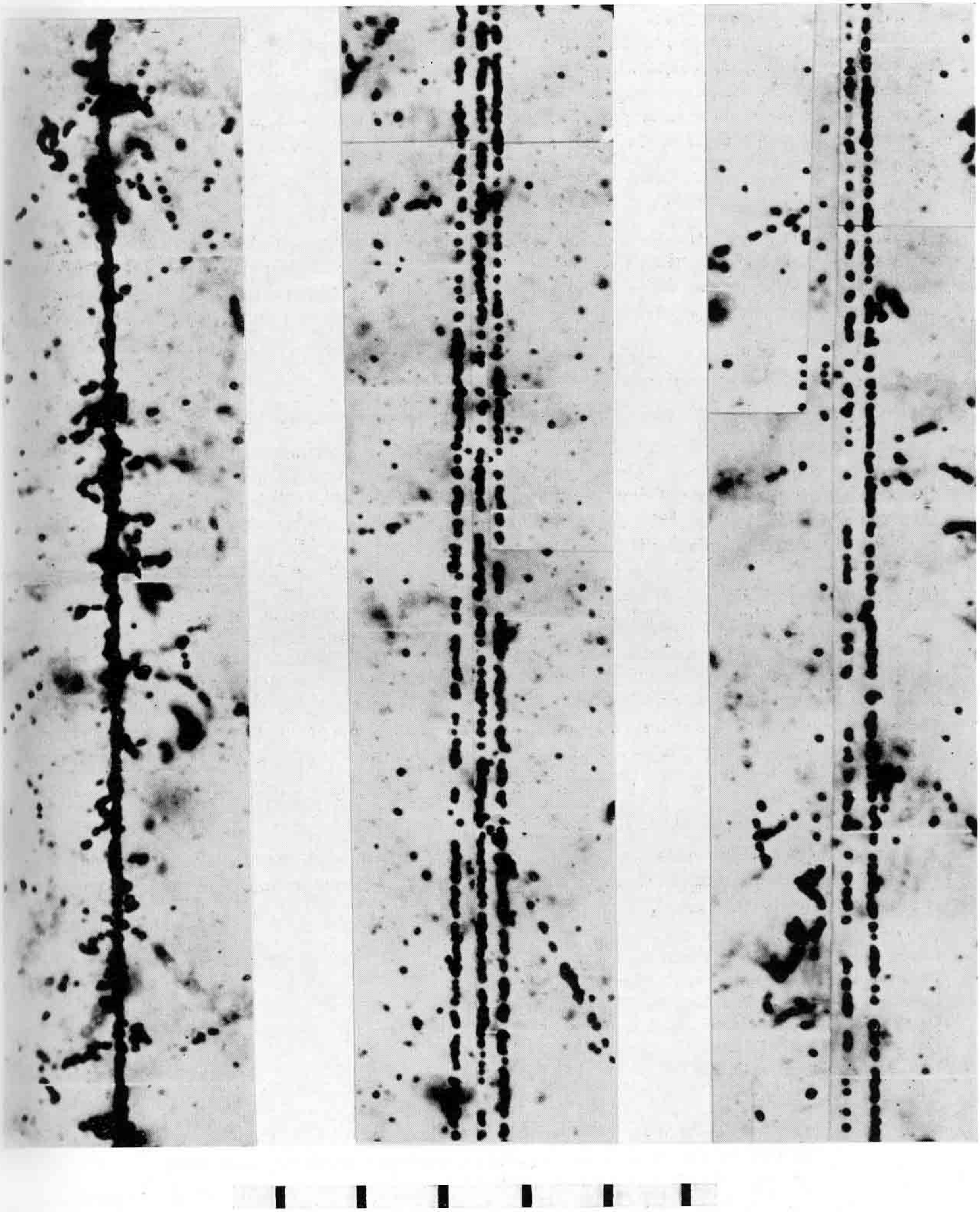


PLATE 16–9

Ilford G 5 emulsion.

Dainton, Fowler and Kent (1952).

5. DETERMINATION OF THE VELOCITY OF HEAVY NUCLEI

Since the δ-ray density in a track is given by the relation $N_\delta \propto Z^2 . f(v)$, the velocity of a particle as well as its ionisation must be measured in order to determine the charge. For this purpose a number of methods may be employed:

Given suitable measurements of ionisation and velocity, the charge carried by an individual nucleus can be determined. Because of its important bearing on the problem of the origin of the cosmic radiation, many experiments have been made to determine the charge 'spectrum' of the primary particles. Typical results based on a variety of methods are shown in Figs. 16–15 to 16–21, and the subject is discussed in pp. 633 *et seq.* Conclusions about the velocity of heavy nuclei can be based on the following observations:

(i) *Measurement of range*

In exposures at high latitudes, a considerable fraction of the primary heavy nuclei are of low energy so that they may be brought to rest in a stack and their ranges measured. Assuming $A = 2Z$, the observation of N_δ at a given value of the residual range allows the determination of Z by a procedure analogous to that used in applying the (g, R) method in measurements on the tracks of particles of unit charge; see p. 154.

(ii) *Measurement of scattering*

For a particle of charge Z, mass M, the scattering parameter is given by the relation: $\bar{\alpha} = \frac{KZ\sqrt{1-\beta^2}}{Mv^2}$. If again it is assumed that $A = 2Z$, $M = A . m_p = 2Z . m_p$, then scattering measurements give a measure of the velocity of the particle. This method can be applied only to tracks with small angles of dip—to about 10% of the tracks in the type of exposure commonly employed. This method was first used by DAINTON *et al.* (1951); it is particularly appropriate in high magnetic latitudes, where the proportion of slower heavy nuclei entering the atmosphere is large.

(iii) *Use of geo-magnetic cut-off*

At low geo-magnetic latitudes ($\lambda < 40°$), the magnetic field of the earth prevents the entry into the atmosphere of heavy primaries with energy less than 1 BeV/nucleon. At high altitudes in these latitudes therefore, practically all the heavy nuclei are moving at relativistic velocities. A measure of N_δ, or of ionisation, then permits the determination of charge; see BRADT and PETERS (1950). For values of $\beta > 0{\cdot}75$, the grain-density or the δ-ray density of a track is practically independent of velocity see Fig. 16–8. In applying this method, it is important to remark that relatively slow fragments may sometimes enter the stack during the period of the ascent.

(iv) *Study of nuclear interaction*

If a primary particle makes a nuclear collision in its path through the emulsion, its velocity may sometimes be inferred from the characteristics of the resulting disintegration. The methods employed are discussed in pp. 606 *et seq.*

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CECCARELLI and ZORN; Phil. Mag. **43**, 356 (1952).
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KAYAS and MORELLET; J. de Phys. **14**, 253 (1952).
NEY; Mexico Conference (1955).

PLATE 16–10. Fragmentation of a magnesium nucleus into α-particles

The incident nucleus, magnesium ($Z = 12$), or aluminium ($Z = 13$), was identified by observations of N_δ and $\bar{\alpha}$. It fragments into six α-particles as a result of a collision with a nucleus in the emulsion. As shown by the grain-densities in their tracks, the helium nuclei emerge with nearly equal velocities. The seventh track, of similar grain-density to the central six tracks, is due to a deuteron of low energy.

Fragmentation of a magnesium nucleus into α-particles

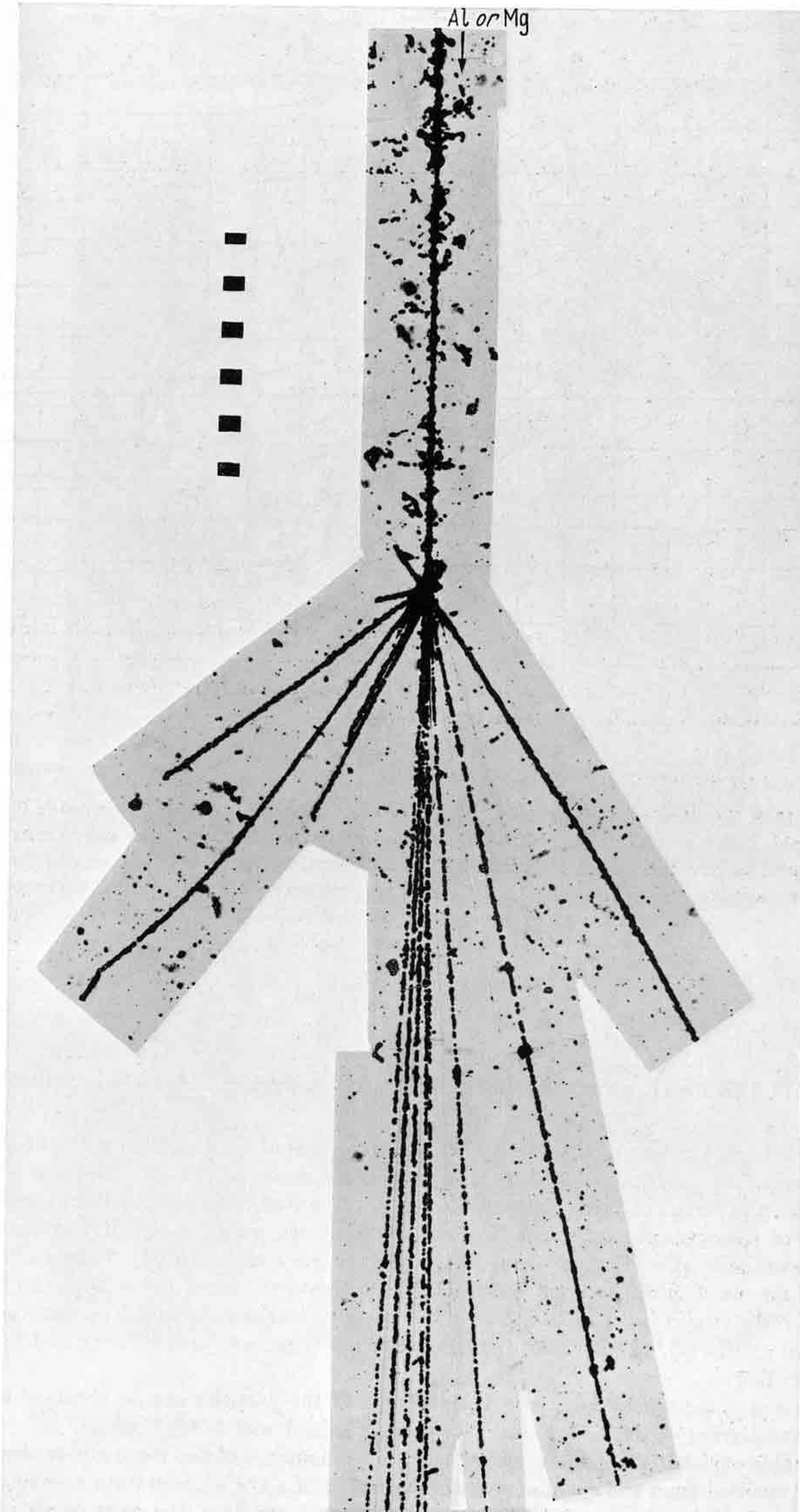


PLATE 16–10

Ilford G 5 emulsion.

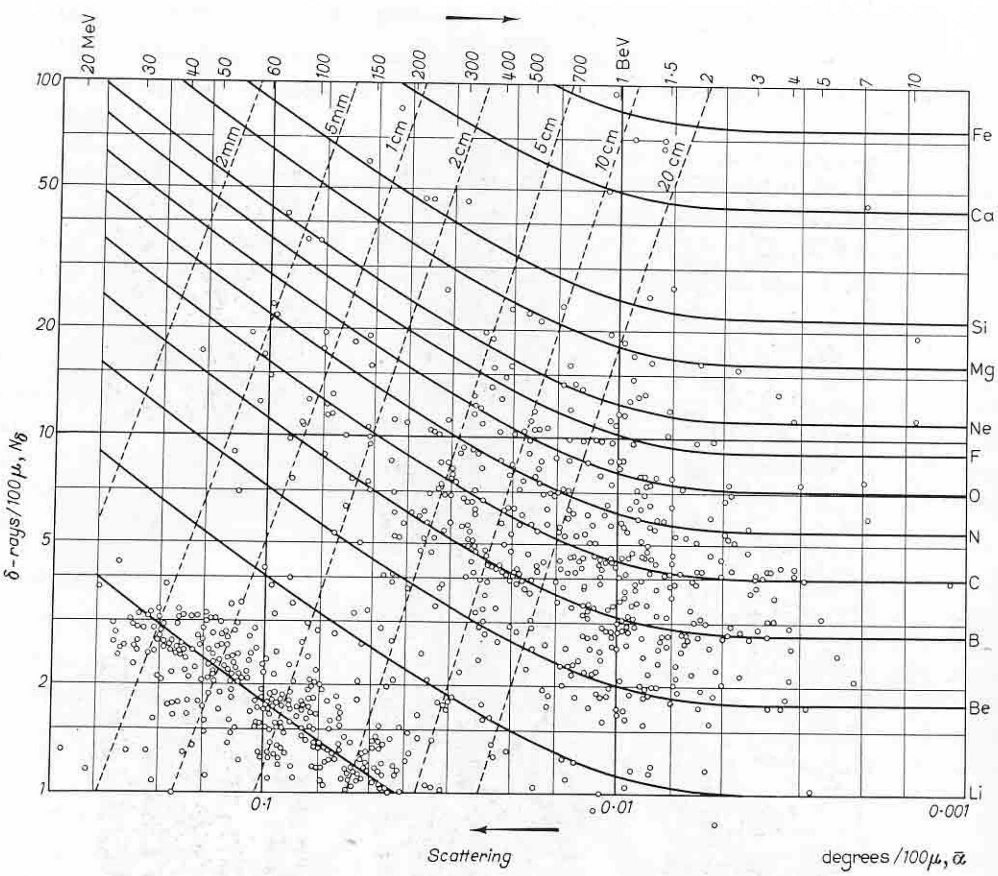


Fig.16–8. Results of measurements of $\bar{\alpha}$ and N_δ on the tracks of heavy nuclei recorded in photographic plates exposed at high altitudes at geomagnetic latitude 55° N. The dotted lines correspond to constant values of the residual range for particles of different charge, and the full lines show the expected variation of N_δ with $\bar{\alpha}$ for particles of different charge. Values of the kinetic energy per nucleon are indicated at the top of the figure.
(After Dainton *et al.* 1952.)

PLATE 16–11. Nuclear collision of magnesium nucleus with meson production ▸

A relativistic magnesium nucleus interacts with a nucleus of the emulsion with the production of about 20 charged mesons. Four α-particles emerge from the encounter. In (b), at a point 500 μ from the disintegration, the tracks of three of the α's are still unresolved from one another, showing the very small value of their relative transverse momenta. The three particles together produce a track of density intermediate between that of relativistic Li and Be nuclei. In (c), 8 mm from the disintegration, the three tracks can be resolved, the fourth being to the right and outside the field of view. By chance in (d), 15 mm from the disintegration, the three tracks re-approach one another as a result of scattering; and in (e), 19 mm from the disintegration they have crossed over and finally diverge from one another.

In this event, a satisfactory measure of the energy of the particles can be obtained by measuring the relative scattering of the α-particles. The value obtained was 2 BeV/nucleon.

A reasonable explanation of the very low transverse momenta of the three α-particles, ~8 MeV/c, is that they resulted from the spontaneous disintegration of a C^{12} nucleus from an excited state just above the threshold for the reaction $C^{12} \rightarrow 3\alpha$; compare, for example, the pairs of α's resulting from evaporation of Be^8 in the ground state from silver or bromine nuclei; see Plate 13–13, p. 469.

Nuclear collision of magnesium nucleus with meson production

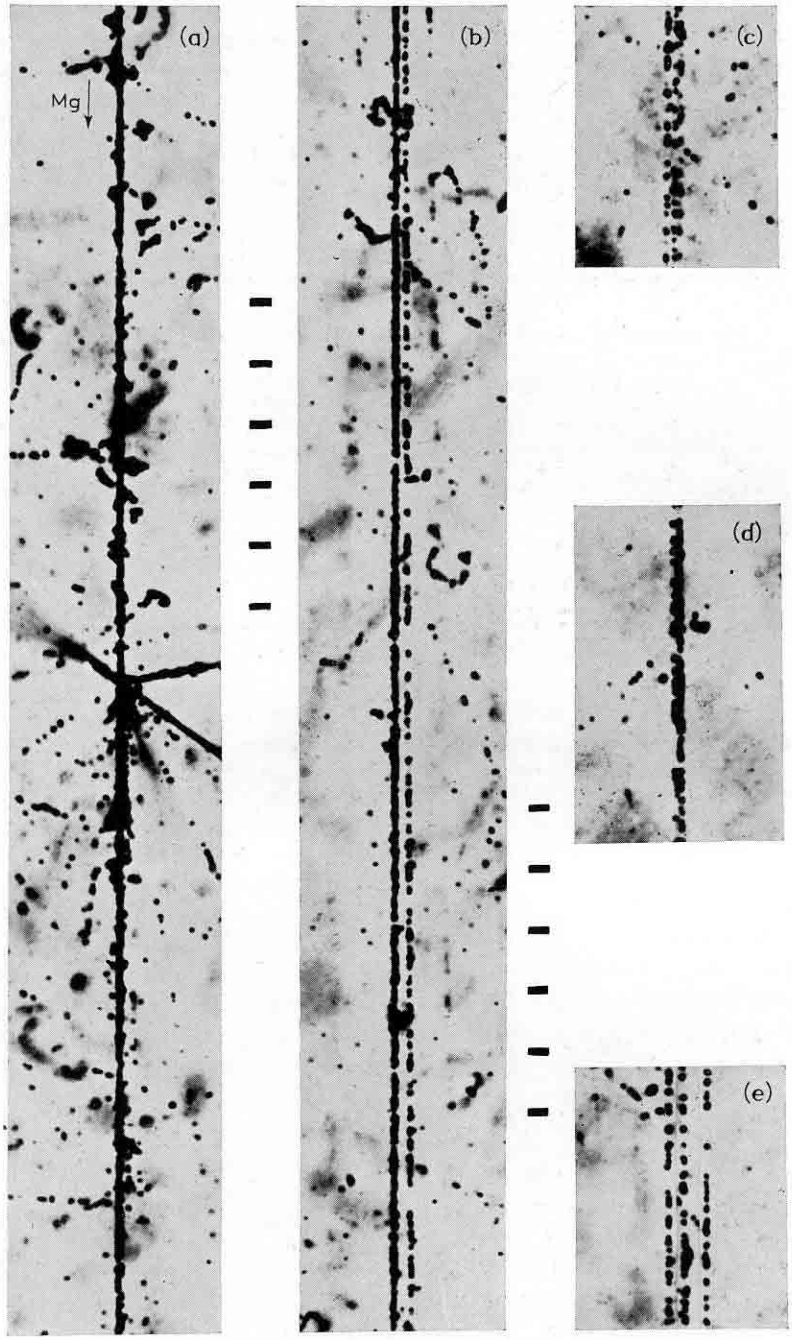


PLATE 16–11

Ilford G 5 emulsion.

Collision of nitrogen nucleus with meson production

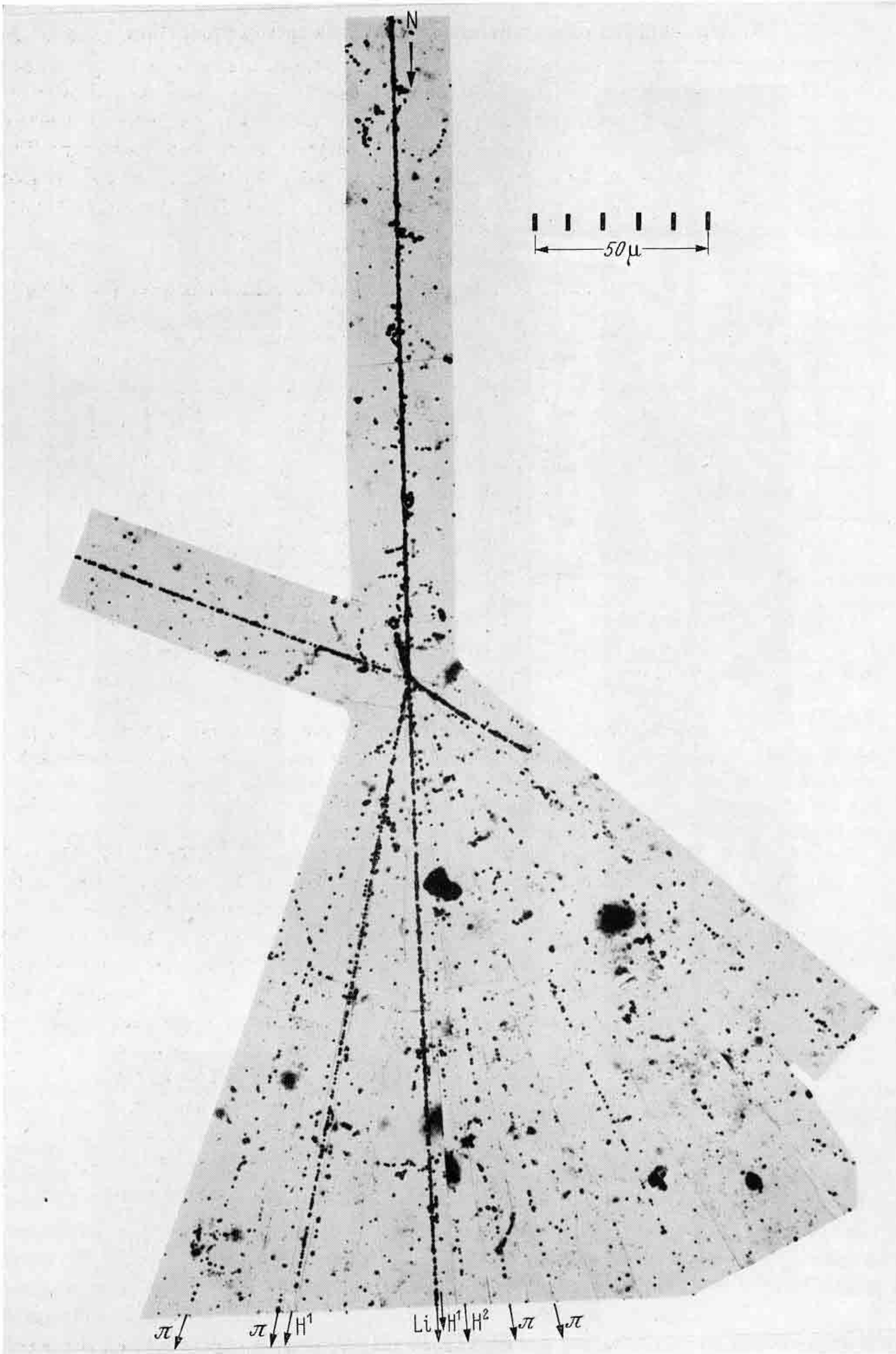


PLATE 16–12

Ilford G5 emulsion.

DAINTON and FOWLER (unpublished).

6. DISINTEGRATIONS OF FAST HEAVY NUCLEI

a) The interaction length

By following the tracks of heavy primary nuclei from their points of entry into a stack until they either escape from it or interact with nuclei, the value of the 'interaction length' may be determined. Although the statistical weight of the early observations was not great, and the charge of the particles, Z, subject to some uncertainty, there was general agreement between the results from different laboratories. They indicated that the interaction length does not vary significantly with the energy. Table 16–1 summarises the results of experiments by KAPLON *et al.* (1954); RAJOPADHYE and WADDINGTON (1958). CESTER *et al.* (1958), FOWLER *et al.* (1956) and ENGLER *et al.* (1959). These authors also studied the characteristics of the disintegrations produced by the energetic nuclei.

Table 16–1. Interaction length in emulsion in cm, of heavy nuclei of different types as determined by different authors (G5 emulsion: $\varrho = 3{\cdot}82\ g/cm^3$)

Charge group Z	KAPLON *et al.* (1954)	RAJOPADHYE and WADDINGTON (1958)	CESTER *et al.* (1958)	FOWLER *et al.* (1956)	ENGLER *et al.* (1959)	Calculated
3–5 inc.	$16{\cdot}1 \pm 5{\cdot}1$		$15{\cdot}7 \pm 1{\cdot}5$	$13{\cdot}5 \pm 1{\cdot}6$	$13{\cdot}3 \pm 2{\cdot}8$	15·2
6–9 inc.	$15{\cdot}6 \pm 1{\cdot}6$*		$13{\cdot}5 \pm 0{\cdot}9$	$13{\cdot}6 \pm 1{\cdot}0$	$13{\cdot}2 \pm 1{\cdot}9$	13·4
10–19 inc.		$10{\cdot}4 \pm 1{\cdot}4$		$9{\cdot}9 \pm 1{\cdot}3$		10·2
>20		$7{\cdot}0 \pm 1{\cdot}4$		$9{\cdot}2 \pm 1{\cdot}8$		7·6
>10	$9{\cdot}6 \pm 1{\cdot}3$	$9{\cdot}4 \pm 1{\cdot}1$	$11{\cdot}5 \pm 1{\cdot}1$	$9{\cdot}65 \pm 1{\cdot}1$	$10{\cdot}9 \pm 2{\cdot}9$	9·7

The calculated values are those deduced from Eq. (16–v). * Corresponds to $Z = 6$—10, inclusive.

The interaction cross-section for an incident nucleus of radius R_i, colliding with a target nucleus of radius R_t, may be expressed in terms of an empirical relation introduced by BRADT and PETERS (1950):

$$\sigma = \pi (R_t + R_i - R)^2, \qquad \text{Eq. (16–v)}$$

where $R_{t,i} = R_o A_{t,i}^{\frac{1}{3}}$. Assuming $R_o = 1{\cdot}45 \times 10^{-13}$ cm, R may then be deduced by comparing the experimental results with those computed. With $R = 1{\cdot}17 R_o$, Eq. (16–v) is found to be valid, within an error of $\pm \sim 15\%$, for all particles, provided that *either* the incident or target nucleus, or both, have atomic numbers, $A > 12$. In particular, the calculated interaction lengths in emulsion, for nuclei ranging from helium to iron, deduced from it, are in good agreement with those found experimentally. It is therefore reasonable to use Eq. (16–v) to estimate the relative frequency with which primary nuclei of various masses interact with the different atomic components of the emulsion. The results calculated for normal Ilford G5 emulsion are included in Table 16–2. It may be seen that, apart from the increased frequency of collisions with hydrogen, the relative proportions of the primary nuclei which interact with light and heavy elements change little in passing from $Z = 3$ to $Z = 30$. Cross-sections for the interactions of protons of different energy with a variety of nuclei have been determined by experiments with beams of particles from the accelerators; the corresponding values for the collisions of these nuclei with hydrogen, for the same relative velocity of approach, are therefore well established.

◄ **PLATE 16–12. Collision of a nitrogen nucleus with meson production**

A nitrogen nucleus makes a collision in which several π-mesons are produced. The event is remarkable because of the large proportion of the associated tracks which are long enough to permit the corresponding particles to be identified. The parent nucleus fragments into a lithium nucleus, a deuteron and several protons. As indicated in the Plate, four of the secondary particles can be identified as π-mesons. The three fast particles of charge e, which produce tracks diverging to the right, are also probably π-mesons. The energy of the parent nucleus was about 2 BeV per nucleon.

Table 16–2. Relative frequencies of collisions of nuclei with different constituents of the emulsion as deduced from equation (16–v). The corresponding interaction lengths in emulsions are included together with analogous results for air

Target nuclei \ Incident nuclei	Normal G 5					
	H^1	He^4	Be^9	N^{14}	Si^{28}	Fe^{56}
H	4	8	11	14	17	20
CNO(S)	24	28	29	30	31	31
AgBr(I)	72	64	60	56	52	49
Interaction length in cm	28	20	15	13	9·7	7·1
	x 2 gel (G 5)					
H	6	12	16	20	23	27
CNO(S)	38	40	41	42	41	40
AgBr(I)	56	48	43	38	36	33
Interaction length in emulsion; cm	33	22	16	14	9·8	7·0
Interaction length in g/cm² for air	72	45	33	28	20	14

b) Features of the disintegrations produced by heavy nuclei

A very striking feature of the collisions involving primary heavy nuclei is the frequency with which a fast secondary heavy nucleus, or a number of α-particles, emerge from the encounter. Nuclei with $Z \gtreqless 2$ are never emitted at relativistic velocities from disintegrations due to fast protons. It is therefore reasonable to assume that any fast heavy secondary particles formed a part of the incoming nucleus, and that they are fragments of it; that they are produced in peripheral collisions between two nuclei, only a few of the nucleons of the primary fast particle, or of the target nucleus, being involved in the impact. In such a collision, it may happen that the main groups of nucleons of the interacting nuclei are not sufficiently disturbed to be disrupted, a heavy nuclear fragment emerging from the encounter with a velocity little different from that of the incoming particle; whilst a fragment of the struck nucleus is given little velocity and remains intact in the emulsion.

In the 'head-on' collisions between two nuclei, however, both of them may be completely dispersed into their component nucleons (see Plates 16–14, 16–19). In such events, and when the primary particle is moving with great energy, the number of secondary products of the impact—mesons and other particles—may be very great because of the large number of nucleon-nucleon collisions involved. It

(Continued on page 608)

PLATE 16–13. Fragmentation of an energetic iron nucleus ▸

A relativistic iron nucleus of the primary cosmic radiation makes a nuclear interaction at *A*, producing a number of mesons. The relativistic nuclear fragments of the primary are seen well resolved in (b), 3 mm away from the point of disintegration; they are due to lithium, oxygen and helium nuclei, respectively. The event is unusual in that two fragments with charge $Z \gtreqless 3$ are produced.

The single heavily ionising particle from the struck nucleus is a proton of short range. The target nucleus cannot have been a free proton because the singly charged particle, track *p*, moved backwards with respect to the line of motion of the primary; it must therefore have been 'evaporated' from the struck nucleus. It may be remarked, *a priori*, there is an equal probability that the slow proton might have been ejected in the forward direction. If so, the event might then have been wrongly attributed to a collision with a free hydrogen nucleus. The event therefore serves to emphasise the need for caution in attributing events to collisions with free protons when a single proton appears to recoil from the interaction with a primary particle.

Fragmentation of an iron nucleus of great energy

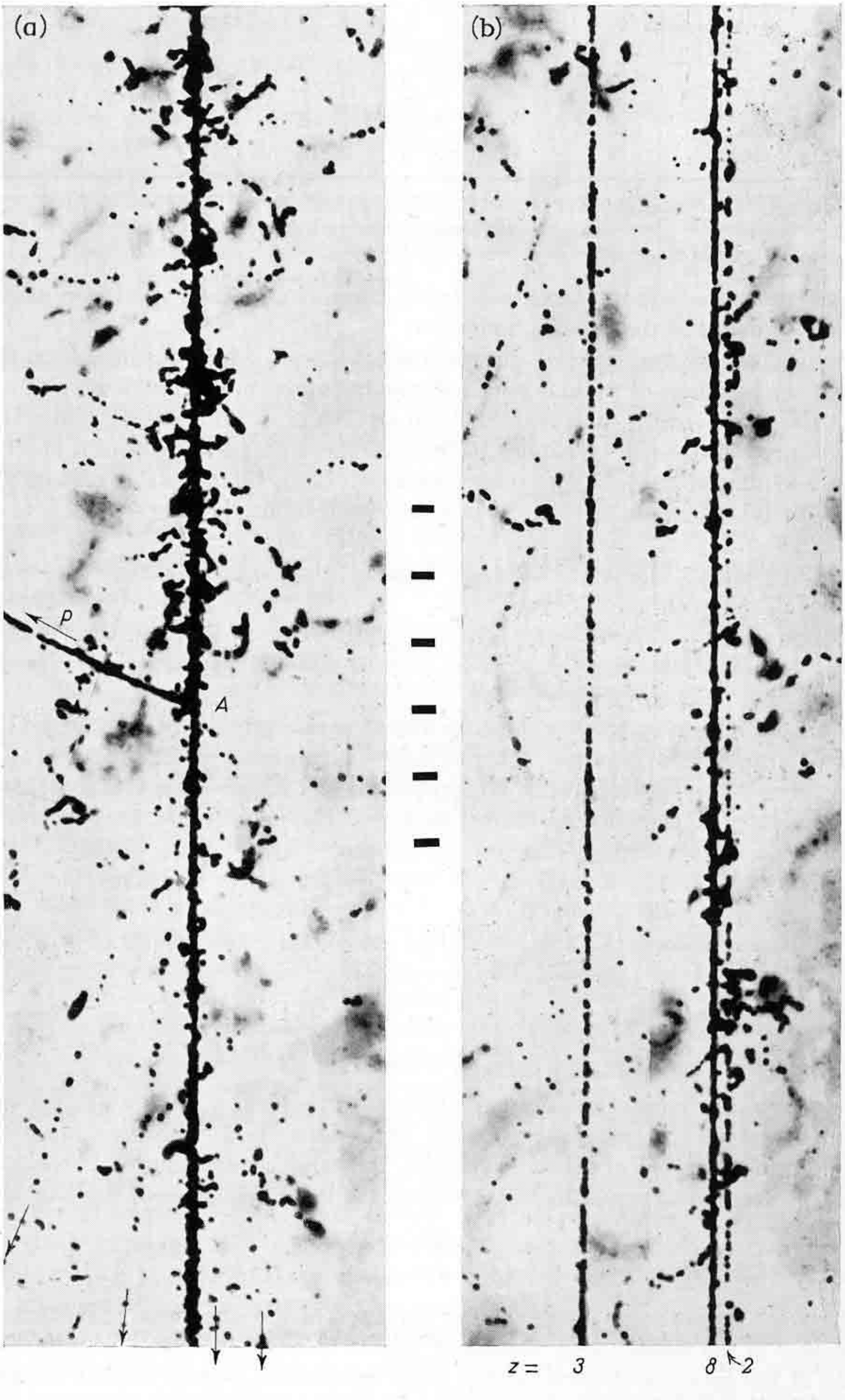


PLATE 16–13

Ilford G 5 emulsion.

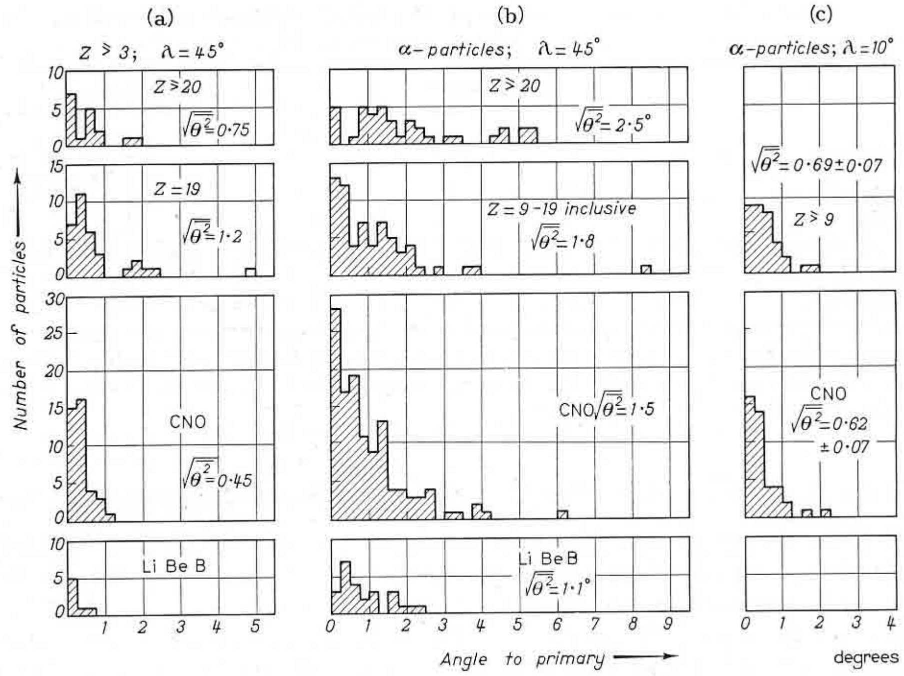


Fig. 16–9. Angular distribution of α-particles and heavier fragments arising from the fragmentation of nuclei with different values of Z. (a) and (b) are from measurements in plates exposed in N. Italy ($\lambda = 45°$), where the measured 'cut-off' is 1·5 BeV/nucleon; and (c) from plates exposed over Guam ($\lambda = 10°$). θ gives the true inclination of a secondary particle to that of the primary, not its projection. In (a), '$Z = 19$' should read '$Z = 9$–19'.

The angular distribution for the heavy fragments is much narrower than that for α-particles; and the α-particles from the Guam exposure are more confined than those from N. Italy, corresponding to the greater average energy of the particles in an exposure near the magnetic equator.

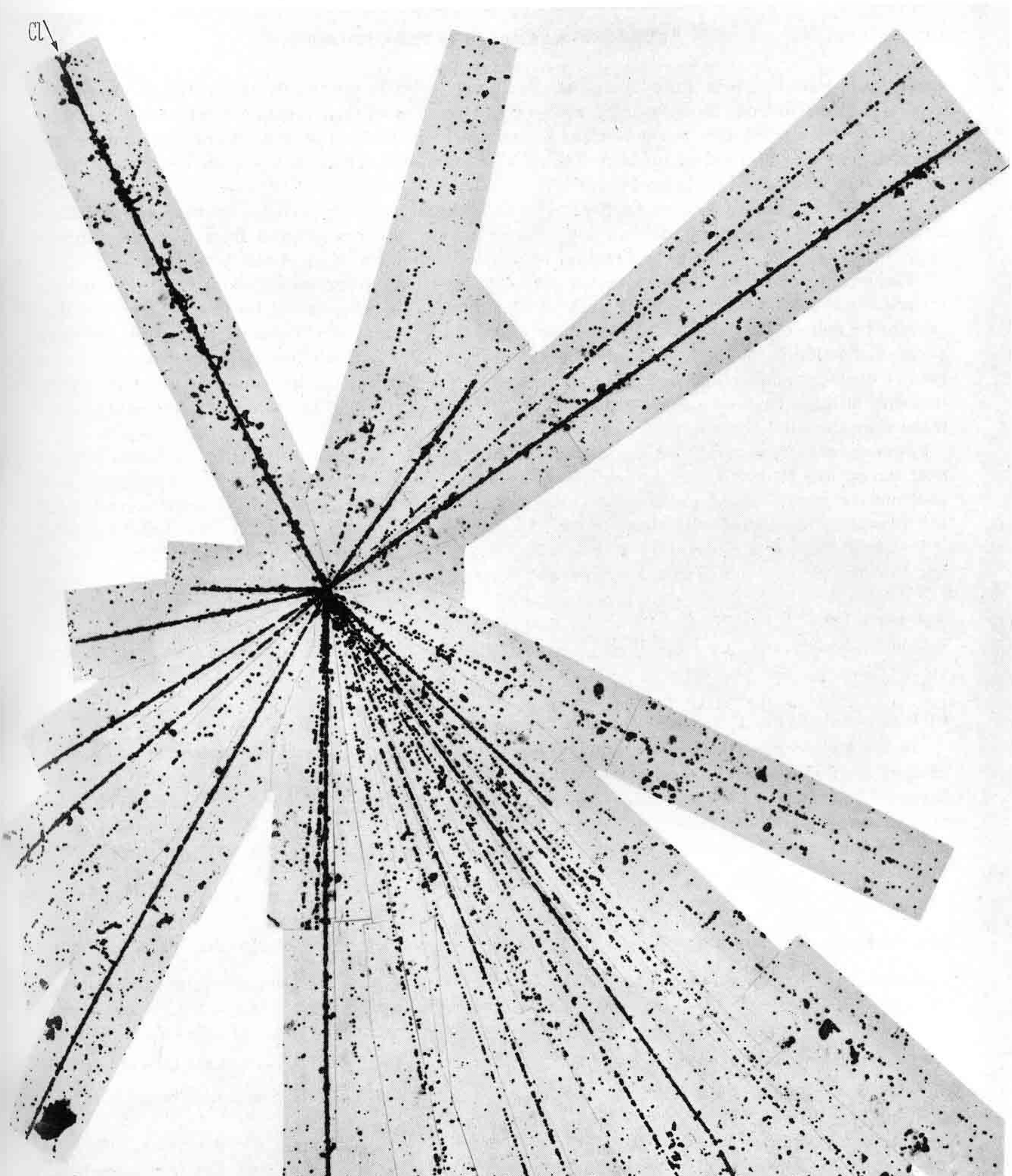
for only a small part of the increased divergence of the secondary α-particles from the heavier nuclei.

The energy spectrum and the geomagnetic 'cut-off' were determined for the exposure which provided the results in Fig. 16–9 so that the effective value of p in Eq. (16–vi), p_{eff}, is known for each charge group, assuming the velocity spectrum at the top of the atmosphere to be identical for all values of $Z \geqq 3$. The mean energy, E_α, of the secondary α-particles in the L-system of the cosmic ray primary can therefore be computed, and the corresponding values for each charge group are included in Table 16–4. The results show that the energies are of the same order of magnitude as those of α-particles emitted from disintegrations resulting from the collision of protons with nuclei of the emulsion. The tendency for α-particles of higher average energy to result from the collisions of the heavier nuclei may be attributed to the greater Coulomb repulsion to which they are subject.

If four or more α-particles emerge from the fragmentation of a heavy primary particle, their angular divergence usually allows an approximate estimate of the energy of the primary, using Eq. (16–vi)

PLATE 16–14. Head-on collision of a magnesium nucleus with one of bromine ▸

A nucleus of charge 12 ± 2 makes a nuclear collision and fragments. The incident particle is almost completely dispersed into its parent nucleons, and the struck nucleus is also shattered. As a result, this event provides a rare example in which the struck nucleus can be identified with considerable confidence. The total charge carried by all the fragments of both nuclei is $\sim 47e$. Since the energy of the primary is only ~ 700 MeV/nucleon, the production of many mesons is improbable; since the charge on the primary is $\sim 12e$, that of the struck nucleus must have been $\sim 35e$; it was bromine. Note that the incoming particle is wrongly labelled Cl.



Ilford G5 emulsion.

50μ

Dainton and Kent (1950).

Sometimes, however, this procedure gives a gross overestimate of the primary energy, because some α-particles emerge from the encounter with very low values of transverse momentum. This is most likely to happen when the parent nucleus is completely evaporated into single nucleons and α-particles, there being no residual nucleus. The effect of Coulomb repulsion upon the emission of α-particles is thus greatly reduced; see Plate 16–11, p. 603.

Estimates of primary energy for events from which only three α-particles emerge, are subject to large statistical fluctuations, for an α-particle produced by evaporation from a struck nucleus may, by chance, be ejected in a direction only little inclined to that of the parent particle.

The angular distribution of fragments with $Z \gtreqless 3$ resulting from the collisions of heavy nuclei is included in Fig. 16–9. Corresponding to the smaller velocities of these particles in the C-system, they tend to be more closely confined to the direction of the primary. For these particles also, the mean square deflection is found to be greater for the heavier nuclei. This effect may be attributed to the greater average number and energy of the evaporation particles; the increased resultant transverse momentum more than compensates for the greater average mass of the secondary fragments evaporated from the excited nucleus.

Similar measurements of the angular spread of α-particles have been made in emulsions exposed near the equator (GUAM, $\lambda = 10°$) where a large fraction of the primary particles of lowest energy are not present. The results of the measurements are included in Fig. 16–9. The smaller angular deviations of the α-particles, compared with those in higher latitudes, are apparent. If it is assumed that the mean value of the transverse momentum of the α-particles in the C-system is unaltered at this higher energy, and that the primary momentum spectrum above 'cut-off' is also unchanged, an estimate can be made of the geomagnetic 'cut-off' at Guam, compared with that in N. Italy; the measured value of the latter is 3·2 BeV/c. The effective 'cut-off' at Guam, is thus found to be $9 \pm 0{\cdot}7$ BeV/c, a result in good agreement both with geomagnetic theory, and with the measured flux of α-particles and heavy primaries described on pp. 628 and 630.

d) Disintegrations due to electro-magnetic interaction

In the collisions between nuclei, in addition to effects due to the specific nuclear forces, disintegrations may also result from electro-magnetic interactions between the particles, a virtual photon from either incident or target nucleus being absorbed by the other. Using the Williams-Weizsäcker method, the equivalent photon spectrum for an incident nucleus of charge Z_1, mass number A_1, if α is the fine-structure constant, is found to be given approximately by the relation:

$$N(k)\,.\,dk = \frac{2}{\pi}\,.\,Z_1^2\,\alpha\left(\ln\frac{B\hbar c}{k\,b} - 0{\cdot}4\right).\frac{dk}{k}, \qquad \text{Eq. (16–vii)}$$

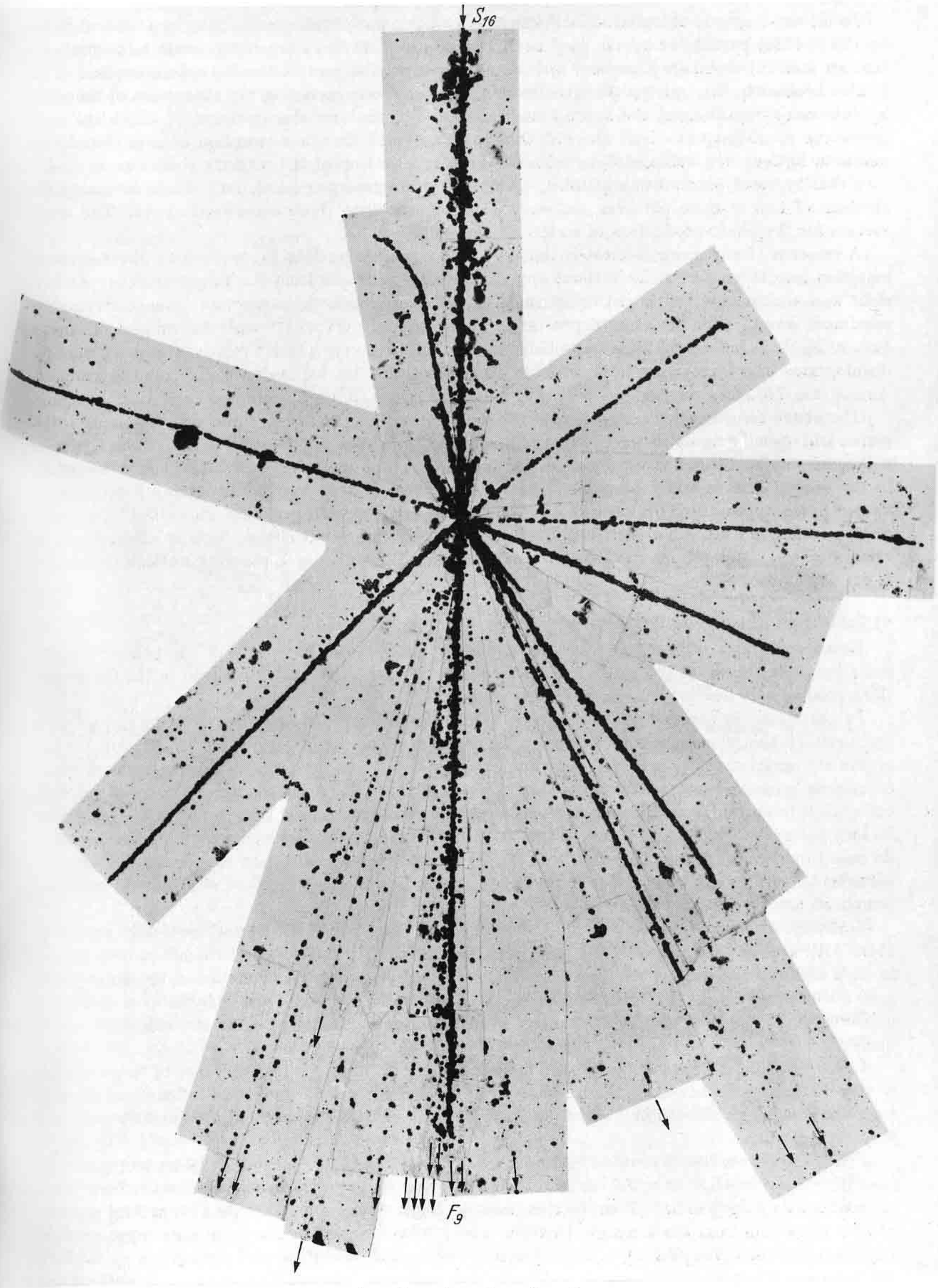
where k is the photon momentum; $B = \frac{1}{\sqrt{1-\beta^2}}$, βc being the velocity of the incident particle; b is the minimum impact parameter, the sum of the radii of the interacting nuclei, smaller values being classed as nuclear interactions. This approximate expression falls to zero when $B/(kb) \simeq 0{\cdot}5$. A more exact expression (see HEITLER 1954) gives a rapid fall in the spectrum when $B/kb \to 1$. This means that the virtual photon spectrum extends up to $k \sim \frac{B\hbar c}{b}$, which is ~150 MeV for $B = 3$ in the case of two light nuclei. The intensity of the spectrum varies as Z^2, and depends only logarithmically on B, for low energy γ-rays.

For photons of energy $\lesssim 40$ MeV, the major processes are (γ, p) and (γ, n) reactions. They are most probable for γ-rays of energy ~20 MeV, for interactions with all nuclei. The total area under the peak in the curve showing the variation of cross-section with energy is about 150 mb×MeV for the (γ, p) reaction at ~20 MeV; see STRAUCH (1953).

PLATE 16–15. Meson production by a sulphur nucleus ▸

A sulphur nucleus, moving with a velocity in the relativistic region, suffers a nuclear collision and leads to the production of a 'jet' of about 25 mesons. Several of the tracks in the main jet are not individually resolved in the photograph. A fluorine nucleus, $Z = 9$, appears as one of the fragments of the parent particle.

Collision of a sulphur nucleus with meson production



Ilford G5 emulsion.

PLATE 16–15

POWELL (1950).

Disintegration due to relativistic lithium nucleus

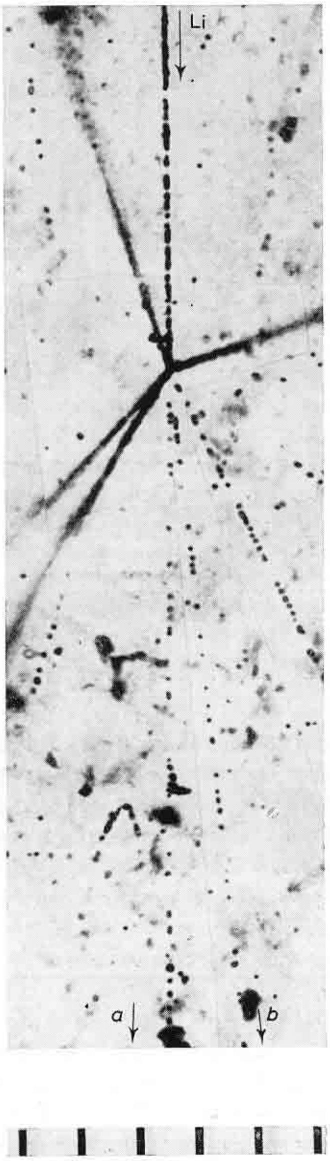


PLATE 16–16

Ilford G 5 emulsion. Bristol (unpublished).

The plate shows a disintegration produced by a relativistic Li nucleus from which only two shower particles emerge. The primary particle is definitely a lithium nucleus and not a slow α-particle, for the two tracks a and b are both produced by relativistic particles. Further, the exposure was made at a geomagnetic latitude where the cut-off was determined as 1·5 BeV per nucleon.

The event provides a clear example of an interaction from which the relativistic secondary particles emerging carry a total charge less than that of the primary; see Fig. 16–12, p. 622, the value of ΔZ being -1. It thus emphasises the need for caution in assuming without reservation that the charge carried by the relativistic secondaries is equal to, or greater than, that of the primary.

High energy interactions involving a single nucleon of a complex nucleus

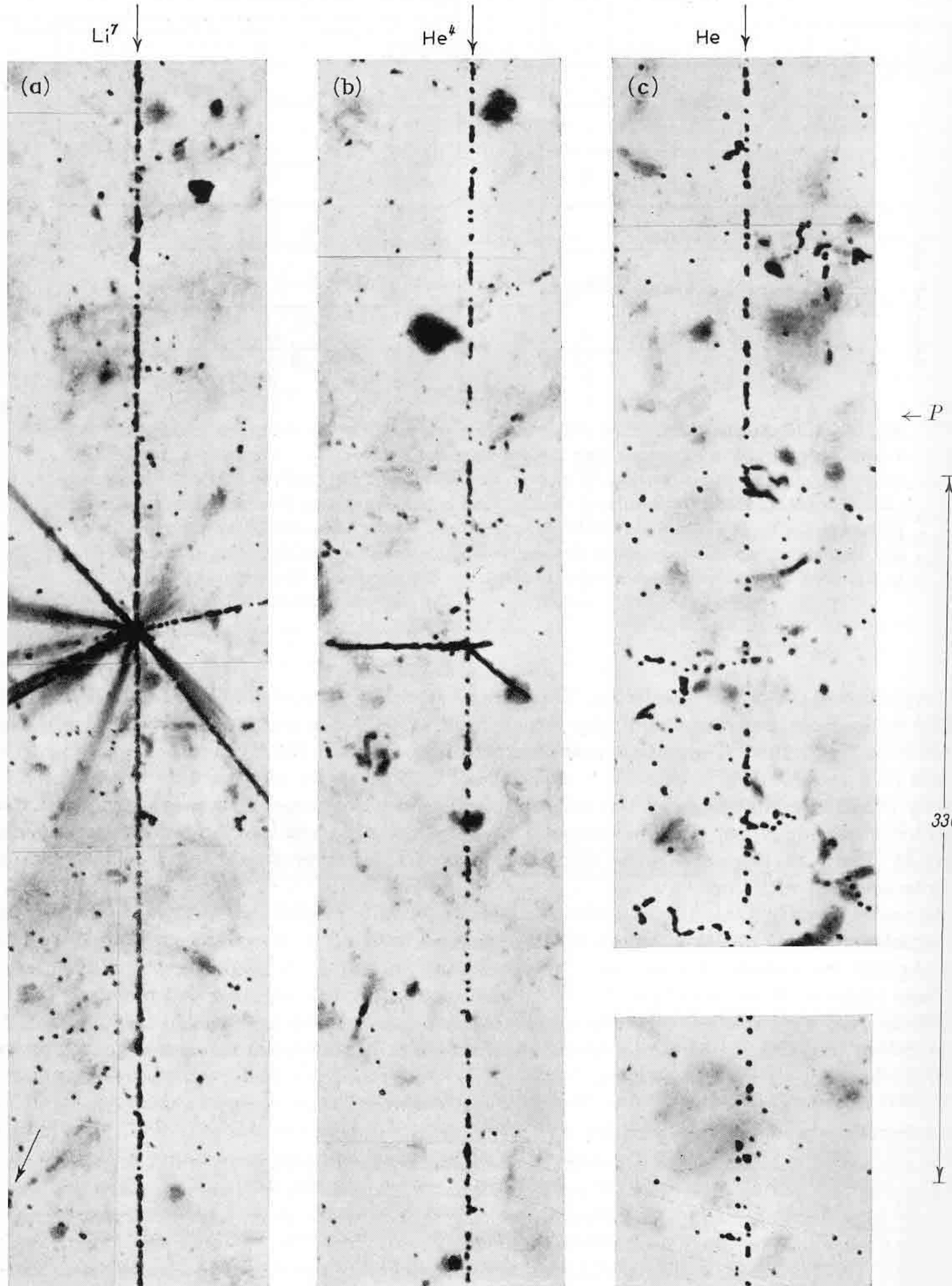


PLATE 16–17

Ilford G 5 emulsion. (Unpublished).

In 5% of the 'stars' produced by α-particles, a fast He nucleus emerges from the collision: Plate 16–17, b shows an example of such a disintegration. The proportion of such secondary nuclei due to He^3 has not been established, but it is reasonable to suppose that in an appreciable fraction of such events, a single neutron of the parent particle interacts with the target nucleus, the remaining three nucleons proceeding intact. Similar results for heavier primary nuclei have been obtained by WADDINGTON (1957); see Fig. 16–11, b.

Checks on the methods for determining the charge of nuclei moving at relativistic velocities can sometimes be obtained from a study of those of their nuclear collisions from which no relativistic *singly* charged particles emerge. It is then certain that charged meson production has not taken place; the charge of the primary is then usually equal to the sum of the charges of all the relativistic particles into which it decomposes. As an indication of the frequency of such events, among a sample of 765 interactions involving heavy nuclei, there were only 21 in which α-particles or heavier nuclei were sheared off the primary, and from which no singly charged relativistic particles were emitted.

h) Meson production by heavy nuclei

Typical disintegrations with which secondary tracks of fast singly charged particles are associated are commonly of little value in such an analysis, because tracks are contributed by positive and negative mesons. This conclusion is illustrated in Fig. 16–12, where the frequency of events for which the quantity $\Sigma Z_s - Z_p = \Delta Z$ assumes different values is plotted for a sample of disintegrations due to heavy nuclei. ΣZ_s represents the arithmetic sum of the charges of the relativistic secondary particles from a given event, taken without regard to sign.

◂ **PLATE 16–17. High energy interactions involving a single nucleon of a complex nucleus**

(a) A primary Li nucleus, with energy ~2·5 BeV/nucleon as determined by scattering measurements, disintegrates a target nucleus of silver and bromine into ~11 slow fragments. In addition, two shower particles are emitted, of which one track is indicated by an arrow; the second was steeply inclined to the plane of the emulsion and its track cannot be seen in the photograph. The main mass of the lithium nucleus was deflected by only ~0·02° in the collision, and emerged with its charge unchanged. The most probable explanation of the event is that the interaction involved one of the neutrons of a nucleus Li^7, the main mass, Li^6, proceeding without being dissociated. If so, it follows that a nucleon of energy ~2·5 BeV, on making a peripheral collision with a nucleus of silver or bromine, may sometimes cause a dispersal of the nucleons of the struck nucleus.

(b) A disintegration produced by a relativistic α-particle which appears to emerge from the encounter. There are four secondary particles of low energy from the struck nucleus, the tracks of two of which are superimposed. The most probable interpretation is that the target nucleus was of oxygen, which was decomposed into four slow α-particles. The primary α-particle suffers a deflection of about 1° in the interaction. The disintegration may be attributed either to an electro-magnetic interaction or to one only of the neutrons of the primary α-particle which emerges as He^3.

(c) Disintegration of fast α-particle. In this event, an α-particle is decomposed by a nuclear interaction, but there is no evidence for the disintegration of the struck nucleus. Two tracks, almost certainly due to protons or heavier hydrogen nuclei, emerge from the point P, where there is a sudden reduction in grain-density. Such events in which no 'star' results from a collision are not infrequent and account for ~3% of the interaction cross-section in emulsion. A small proportion may be attributed to the disintegration of the α-particle in the Coulomb field of silver or bromine nuclei, but most are due to nuclear interaction in which the products of the struck nucleus were neutrons only. It is probable that one only of the neutrons of the primary α-particle was involved in the collision, the two protons and a neutron proceeding forward with little change in velocity.

were found to be unreliable (SIMPSON *et al.* 1956, WADDINGTON 1956, and FOWLER *et al.* 1956, 1957, a and 1957, b), the expected values at geomagnetic latitudes between 40–55° N sometimes differing from those observed by a factor of two. It was therefore necessary to re-examine the conclusions drawn from the early work on the energy spectrum, and direct measurements become important.

In using the photographic method for determining α-particle fluxes, the energy of the slowest particles can be deduced from their observed range. At higher energies, if the particles are moving with non-relativistic velocities, measurements can best be made from the track-density, g^*, multiple scattering measurements being made only to ensure that the particle is of charge $Z = 2$. For energies greater than ~500 MeV per nucleon, the density of the track is almost independent of energy, and the determination must then be based on scattering measurements alone.

Using these methods, and others based on counters, the differential energy-spectrum of the α-particles at high altitude has been determined for the interval between 130 and 500 MeV per nucleon, at a number of places in N. America, including several at high geomagnetic latitudes. Typical results are shown in Fig. 16–13, where the results are given for four values of λ. At the left side of the figure, the distribution in the values of track-density of the α-particles is shown; and at the right, the corresponding differential energy-spectrum, the lower limits on the energy due to the absorption of the overlying air being indicated. It may be seen that the number of low energy α-particles increases in passing from $\lambda = 41°$ N to $\lambda = 61°$ N. The forms of the energy distribution are closely similar, however, for values of $\lambda = 54$ and 61° over North America. It follows that geomagnetic effects are not the cause of the plateau in the distribution at energies < 500 MeV/nucleon, and that in this respect, the

(Continued on page 628)

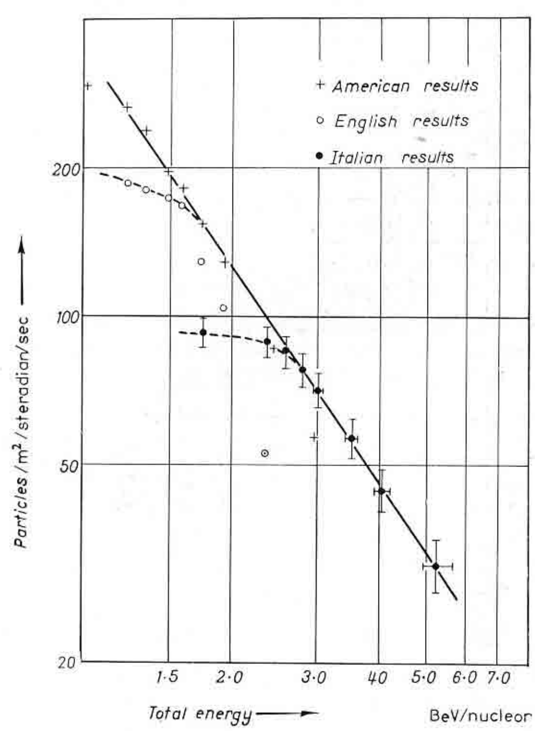


Fig. 16–14. Integral energy spectrum of α-particles as determined at different geomagnetic latitudes, by observations with emulsions: +, results at 55° N over North America; ○, at 55° N over Southern England; ● at 45° N over Northern Italy. The full line corresponds to a distribution represented by the equation: $N_\alpha(E) = 370/(E + 0{\cdot}94)^{1{\cdot}5}$, where E represents the kinetic energy per nucleon, measured in BeV. Note that the abscissa shows the total energy, including the energy corresponding to the rest-mass, 0·94 BeV.

Observations on six jets produced by α-particles, one of which is shown in Plate 16–18, opposite, and of which the energies were estimated to be >800 BeV per nucleon, allow an approximate value for the integral flux at the top of the atmosphere to be determined. The result thus obtained is $1{\cdot}7 \times 10^{-2}$ α-particles/m²/sterad/sec. This value lies on the continuation of the full line in the figure. Assuming that the values both of energy and of flux in the above estimate are in error by a factor of two, the corresponding index of the exponent of the integral spectrum is thereby changed by only $\pm 0{\cdot}15$.

(FOWLER and WADDINGTON 1956.)

PLATE 16–18. Nuclear disintegration due to an α-particle with energy ~3000 BeV ▸

A nuclear disintegration of great energy produced by an α-particle. The star is of type $15 + 136\alpha$; that is, 15 star particles, with tracks of grain density $> 1{\cdot}5$ g, and 136 shower particles emerge from the disintegration; it follows that about 200 charged and neutral pions were created. The energy of the primary, as deduced from the angular distribution of the shower particles is ~800 BeV/nucleon.

Nuclear disintegration due to an α-particle with energy $\sim$3000 BeV

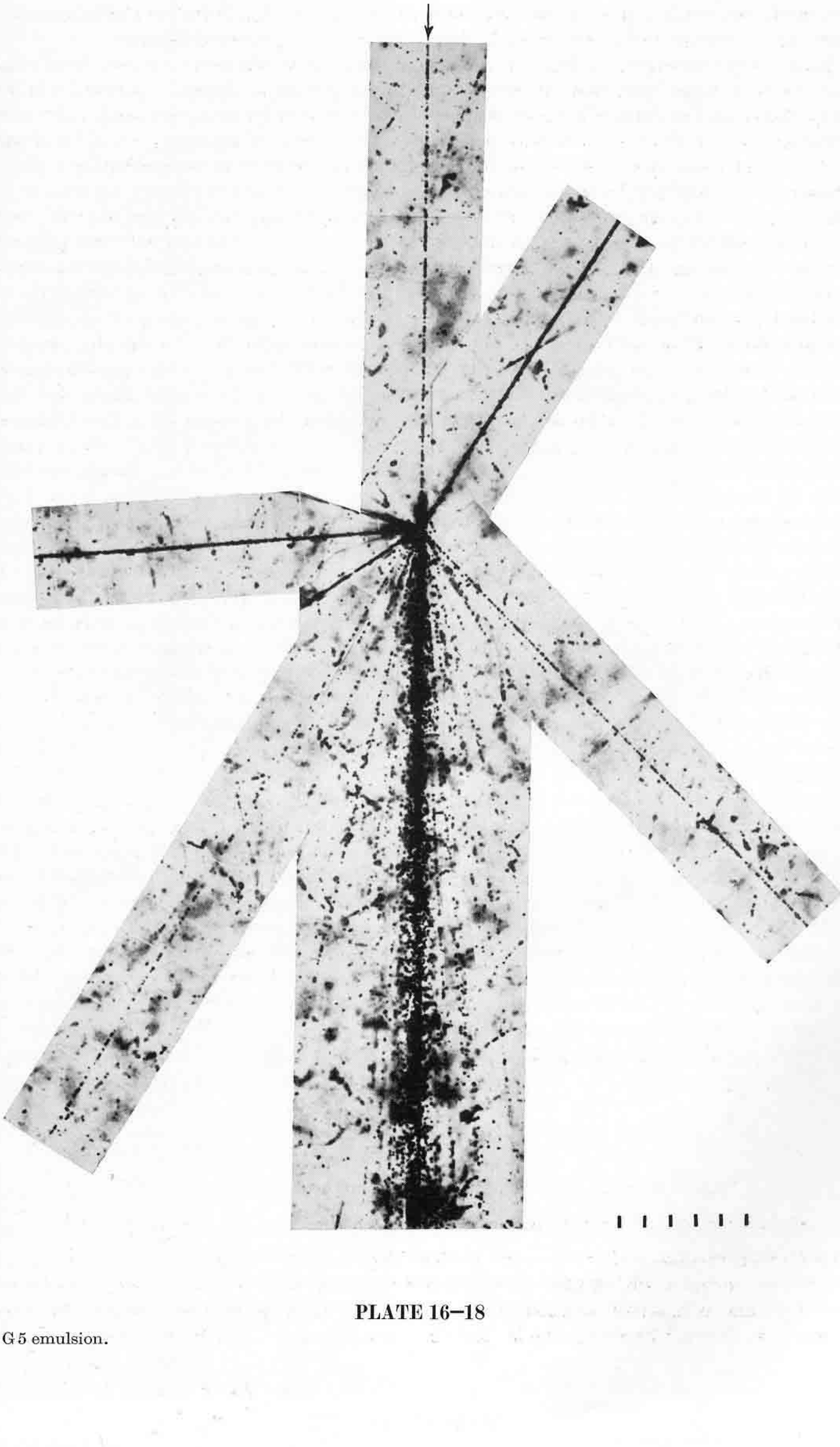


PLATE 16–18

Ilford G5 emulsion.

observed spectrum is characteristic of that outside the range of influence of the earth's magnetic field. Had the spectrum continued to rise at lower energies, the particles would have been recorded and detected in increasing numbers down to a limit set by ionisation loss in the air above the apparatus. The observed broad peak is characteristic of the primary spectrum and is not due to a failure to detect tracks. Briefly, the differential spectrum of the α-particles far from the earth does not continue to rise indefinitely as lower energies are approached. It reaches a broad maximum at between 200 and 500 MeV per nucleon, and there is a fall in intensity for both lower and higher energies. The results shown in Fig. 16–13 illustrate the great sensitiveness of the spectrum of the α-particles to changes in the value of λ for values of the geomagnetic latitude in the neighbourhood of $\lambda = 50°$. The changes here are so rapid that the low-energy end of the spectrum of primary α-particles at high altitude is sensitive to changes in the locality of a flight of about 30 miles; the 'cut-off' 'rigidity' for the vertical direction varies approximately as $\cos^4 \lambda$. The results also illustrate the nature of the departures from simple geomagnetic theory. Thus for the flight over N. Missouri ($\lambda = 50{\cdot}5°$ N), the theoretical cut-off is ~700 MeV/nucleon, whereas it may be seen that 30% of the particles have energies less than this limit, the distribution showing evidence of a 'cut-off' at ~350 MeV/nucleon—a value which would have been expected for $\lambda = 55°$ N according to the geomagnetic theory. The results of a similar analysis from flights over N. Iowa ($\lambda = 54°$ N), where the predicted cut-off is at ~450 MeV/nucleon, show that the spectrum extends down to 200 MeV per nucleon; the 'cut-off' is obscured because ionisation in the overlying air prevented the slowest particles from reaching the stack.

The above results refer to the North American continent; those for North-West Europe are strikingly different. In illustration, Fig. 16–14 shows the *integral* energy-spectrum for α-particles, (a), at $\lambda = 55°$ N over North America; (b), at $\lambda = 55°$ N over Southern England; and (c), at $\lambda = 45°$ N over Northern Italy. Note that in this figure the results are plotted against the total energy per nucleon, a quantity which includes the energy equivalent to the rest-mass of a nucleon, 0·94 BeV. It may be seen that whereas there is no clearly distinguished 'cut-off' over North America at $\lambda = 55°$, and it is certainly less than 200 MeV/nucleon, for the same geomagnetic latitude over Southern England there is an apparent 'cut-off' at about 600 BeV per nucleon. The prediction for $\lambda = 55°$ is 350 MeV/nucleon; whereas the American values are much too low in this respect, those over Southern England are too high. Similarly, for Northern Italy, $\lambda = 45°$ N, the integral energy-spectrum suggests a 'cut-off' at about 1·5 BeV per nucleon, whereas the expected value is near 1 BeV/nucleon. These discrepancies cannot be explained in terms of the fact that the equivalent dipole of the earth's geomagnetic field is not centrally placed.

These results, and observations by SIMPSON *et al.* (1956) on the minimum vertical flux of neutrons at aeroplane altitudes, which determine the effective cosmic-ray equator, can be brought in to approximate accord if the geomagnetic pole is shifted by about 400 miles from the commonly accepted position at 68° W, $78\frac{1}{2}°$ N, towards the American continent. This is approximately equivalent to taking the magnetic latitude, as determined from the regional angle of dip, instead of the geomagnetic latitude, in estimating the 'cut-off'. These effects appear to be a consequence of the influence on the 'cut-off' of the detailed local features of the magnetic intensity near the top of the atmosphere.

For energies greater than 4 BeV/nucleon, scattering measurements are generally unreliable. The flux of α-particles observed at the geomagnetic equator gives a measure, however, of the number with energy greater than about 6–7 BeV/nucleon, although the precise value is not yet known. In emulsions exposed over Guam, a rough estimate of the cut-off energy for *heavy primaries* has been deduced from observations on the angular distribution of the α-particles which result from the fragmentation of the heavy nuclei. The value obtained is $7{\cdot}2 \pm 1{\cdot}0$ BeV/nucleon. It is reasonable to assume that this value is also

PLATE 16–19. Collision of carbon nucleus with energy ~20,000 BeV ▸

A carbon nucleus makes a nuclear collision as a result of which more than 100 charged mesons are created, about half of which are in the central 'jet' of secondary particles. The velocity of the incident nucleus has been determined from the semi-vertical angle of the cone which embraces half the secondary particles. The incoming particle was dispersed into its component nucleons as a result of the collision.

Collision of carbon nucleus of energy $\sim$ 20,000 BeV

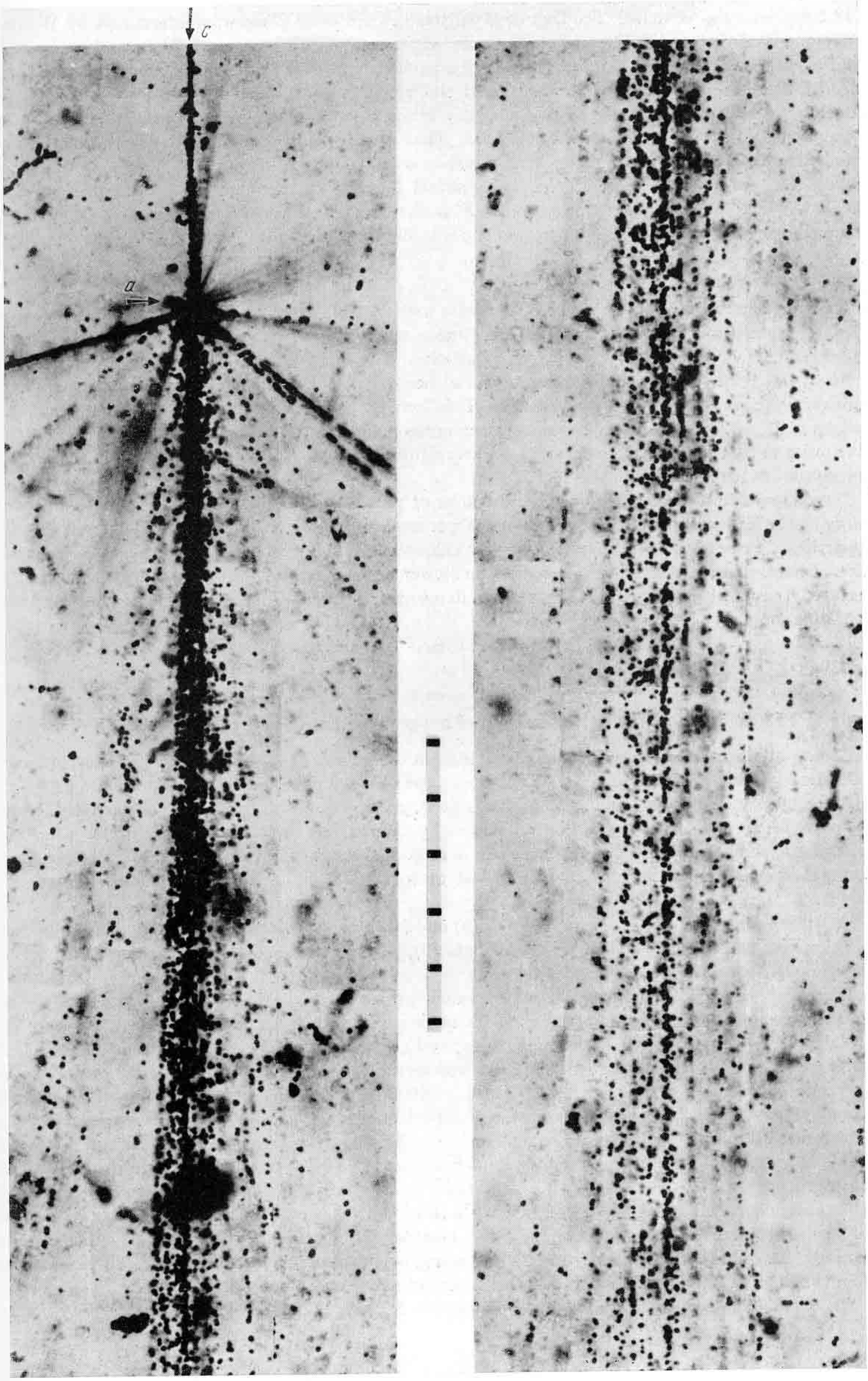


PLATE 16–19

Ilford G 5 emulsion.

DANIEL and PERKINS (unpublished).

valid for primary α-particles. The flux of α-particles at the same place was determined by WEBBER (1957) and McDONALD (1957), who both made experiments with counters and found values of 14 and 16 α-particles per m²/sec/sterad. The flux of α-particles at Galapagos has been measured with emulsions by SHAPIRO *et al.* (1957); they obtained the value 22 ± 2 α-particles per m²/sec/sterad. The cut-off at Galapagos is expected to be somewhat lower than at Guam, viz. ~ 6 BeV/nucleon, owing to the displacement of the Earth's dipole field. That a cut-off of 6 BeV/nucleon is a reasonable estimate is borne out by the neutron survey of SIMPSON *et al.* (1956). These equatorial values of intensity straddle the curve corresponding to the empirical formula for the energy spectrum: $N_\alpha(>E) = 370/(E + 0{\cdot}94)^{1{\cdot}5}$ particles/m²/ster/sec, where E is the kinetic energy measured in BeV per nucleon. This relation, for low energies, is shown by the full line in Fig. 16–14.

d) Energy spectrum of particles $Z \gtreqless 3$

Knowledge of the energy spectrum of particles with $Z \gtreqless 3$ is much less precise than that for α-particles. It is probable, however, that the distribution of the primary flux of these particles, in energy per nucleon, is closely similar to that for α-particles. The following evidence supports such a view.

First, the relative numbers of α-particles and heavier nuclei observed at high altitudes show no significant variation with changes of latitude. It follows that the constitution of the primary radiation changes little with variations in the energy per nucleon for values between 0·4 and 6 BeV, and that it is similar to that for the higher energies, for any significant changes would be reflected in the average composition at different latitudes.

Direct scattering measurements on the tracks of particles with different values of Z, and with energy in the interval between 300 and 700 MeV per nucleon, by DAINTON *et al.* (1952) showed that the proportion of these particles with relatively low velocity is similar to the corresponding ratio for α-particles. Direct evidence for the presence of even slower heavy particles was obtained by YAGODA who measured the number of tracks of short range due to heavy nuclei, in experiments at great altitudes over Minnesota.

PLATE 16–20. Nuclear interaction of oxygen nucleus of energy about 40,000 BeV ▸

Events of this type are important in providing a direct demonstration of the presence of heavy nuclei amongst the particles of greatest energy in the primary cosmic radiation.

An oxygen nucleus interacts in the emulsion at O, giving rise to fifty-four shower particles. Three slow particles are ejected from the target nucleus; by chance they are all in the 'backward' direction. Eight of the shower particles are contained in a cone of semi-vertical angle $\sim 3 \times 10^{-3}$ degrees. It is certain that most of these 'inner-core' particles are protons from the decomposition of the primary nucleus.

In (a), the central core is quite unresolved. (b) and (c) show the form of the jet at points ~ 5 and ~ 12 mm from the origin O, respectively. In Plate (b), pairs of tracks, due to electrons created in the conversion of two γ-rays, can be seen.

The energy of the primary particle can be estimated in two ways: (a) from observations of the relative scattering of the secondary particles of the inner core over a track-length of 17 cm; (b) from the angular divergence of the fragmentation protons; and (c), from the angular distribution of the other shower particles, most of which are mesons. The first method gives a value of 2500 ± 1000 BeV/nucleon; the second ~ 2000 BeV/nucleon; and the third, ~ 4000 BeV/nucleon. Such independent checks are of great value. The event provided a homogeneous jet of protons, accompanied by a similar stream of neutrons, all with the same energy per nucleon within narrow limits. In general, such streams provide a very valuable random sample of nuclear disintegrations in emulsion, due to nucleons of the same energy. In the 20 cm of emulsion traversed by the particles from this particular event, only one interaction occurred; it was produced by a fast neutral particle, which made a star of type $15 + 45n$. Its energy as determined from the angular distribution of the secondary mesons was 5000 BeV. Many of the mesons from the primary event interacted in the stack. Three of them, not in the inner core, gave disintegrations with an estimated energy of ~ 1000 BeV.

The event was observed in the G-stack exposed in N. Italy in 1953.

Nuclear interaction of oxygen nucleus of energy 40,000 BeV

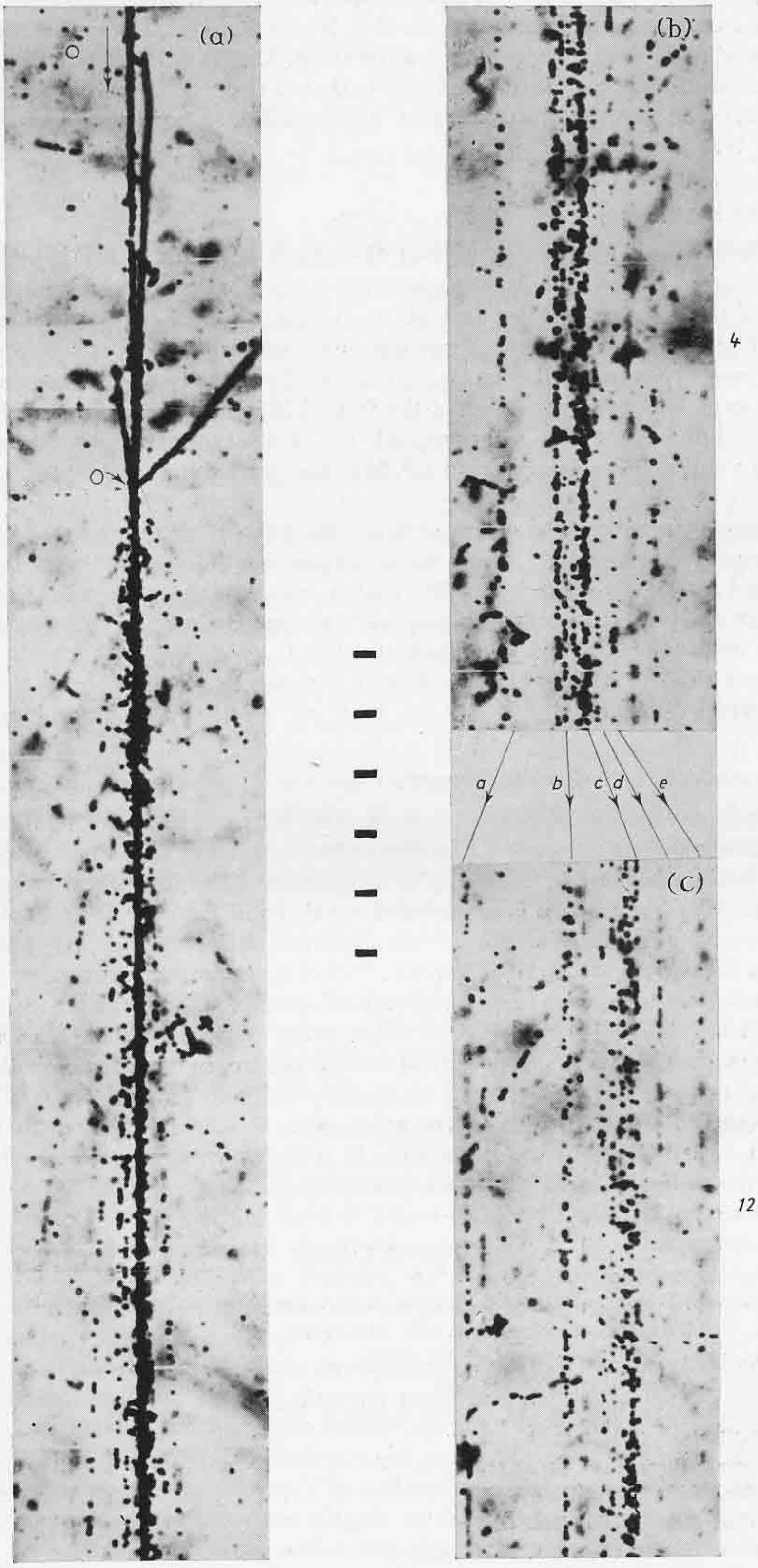


PLATE 16–20

Ilford G 5 emulsion. Unpublished.

Examples of a form of distortion in emulsion known as 'chopping'

A B

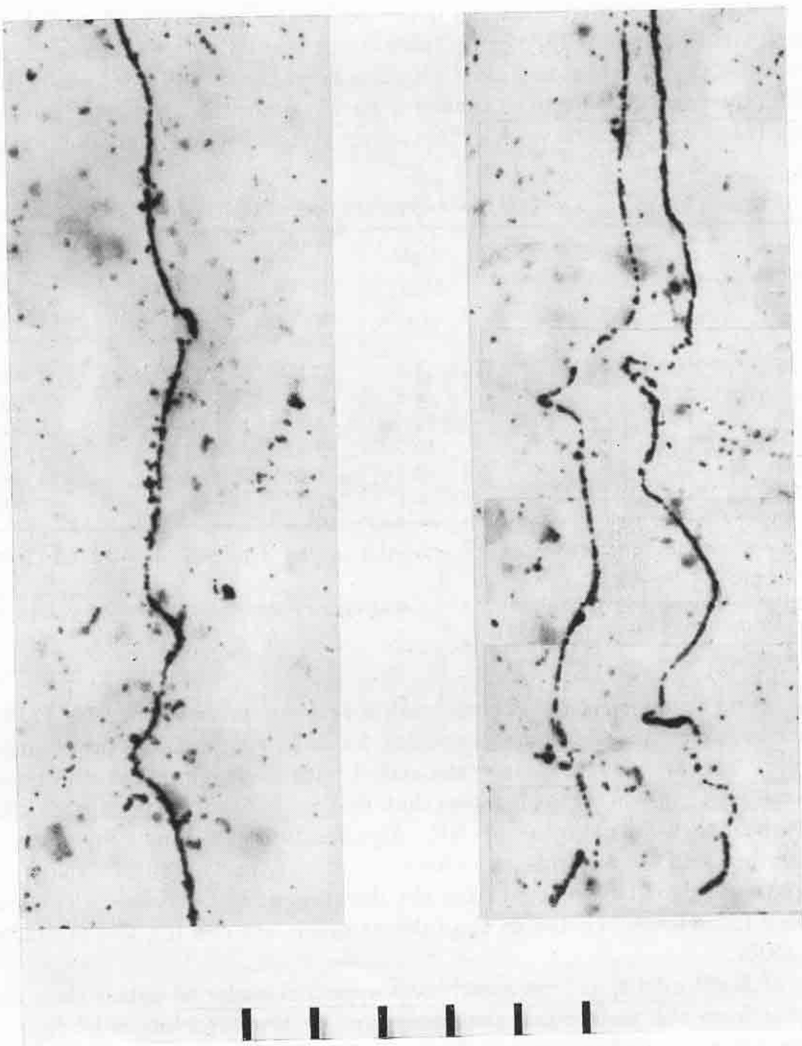


PLATE I

Ilford G 5 emulsion. (Bristol, 1951; unpublished).

Plate A shows the track of a relativistic carbon nucleus whose track dipped at only 2° in the unprocessed emulsion. Plate B shows two tracks from a nuclear disintegration, with an angle of dip of about 30°. The two photographs are from neighbouring regions of the same glass-backed emulsion, and illustrate severe examples of a form of distortion known as 'chopping'.

APPENDIX 3

SCANNING BY UNAIDED EYE

It has already been mentioned on p. 524 that the number and density of electron tracks at about 7 radiation lengths in electromagnetic cascades in emulsion of energy about 1500 BeV is sufficiently great for the cascade to be rendered visible to the unaided eye, as a faint diffuse line. At still higher energies, the electromagnetic cascades become readily visible over an appreciable number of radiation lengths. It is also possible to detect the tracks of individual heavy primary nuclei, if of $Z > 16$; these give rise to sharp rather than diffuse lines. The amount of light obscured by relativistic heavy primary tracks has been given in Fig. 16–7, p. 595. The visibility, and hence the threshold for detection, depends on the length per emulsion sheet of the cascade or track, as well as on the transparency of the emulsion, and the number and form of any silver deposits or scratches on the surfaces. Scanning by eye, either unaided, or possibly assisted by a low power lens, is an efficient and useful way of quickly detecting high energy cascades. In the two 'Comet' stacks described below, some 600 cascades were detected in this manner.

As an illustration of the possibilities of such scanning, Plates II and III show seven contact prints of various emulsion sheets. Care has been taken in each of the seven prints to reproduce as nearly as possible the degree of contrast and general appearance of the original emulsions; in each case the print shows part of an emulsion sheet at its natural size. It may be seen that Plate III, B shows much more surface deposit on the emulsion than the other plates. In this plate, the severe markings happen to be on the glass-emulsion interface, and so are difficult to remove. They were due partly to the use of 6 μ terylene foil as a spacer between the lead and emulsion sheets, and the consequent electrification produced in unwrapping the emulsions; and partly to the fact that the emulsions of the stack were packed under considerable pressure for a prolonged period.

Plate II, A is a contact print (natural size) of part of an emulsion sheet, 600 μ thick, flown on a balloon over Minnesota for 8 hours at an atmospheric depth of ~ 6 g/cm^2. This emulsion sheet formed part of a stack of pure emulsion of total volume 22 litres, shared between the Universities of Bristol and Minnesota. The particular emulsion shown contained an exceptionally flat cascade, extending right across the plate. At its maximum density, this cascade, when examined by a photometer, using a slit of width 10 μ, is found to obscure 20% of the incident light. The primary nuclear disintegration responsible for this cascade occurred in a metal counterweight just beyond the bottom corner of the stack. The stack was turned over shortly after the balloon reached ceiling; the cascade occurred before this inversion took place, and thus, in the plates, comes upwards from the lower left-hand side.

In the same photograph, the tracks of many individual heavy primary nuclei can be distinguished. A few of the more prominent have been indicated by crosses at their extremities. The contrast between the diffuseness of the later stages of the line due to the cascade, and the sharpness of the lines due

PLATE II. Contact prints of emulsion sheets exposed at high altitude by balloons ▶

Plate II, A shows a contact print of part of an emulsion exposed at high altitude over Minnesota. The very flat cascade is prominent; some shorter tracks due to heavy primary nuclei are indicated by crosses at their extremities. Unfortunately most of the black marks are due to scratches and silver deposit on the emulsion surfaces.

Plates II, B, C and D are contact prints of adjacent portions of three emulsions exposed at high altitude over Northern Italy. An energetic and well developed electromagnetic cascade crosses all three emulsions. One of the X-ray lines used for registration of the stack is visible on the left-hand side of each print.

The prints illustrate the different appearance of lines in the emulsions due to heavy primaries, which are sharp, and those due to well developed electromagnetic cascades, which are relatively diffuse.

Contact prints of emulsion sheets exposed at high altitude by balloons

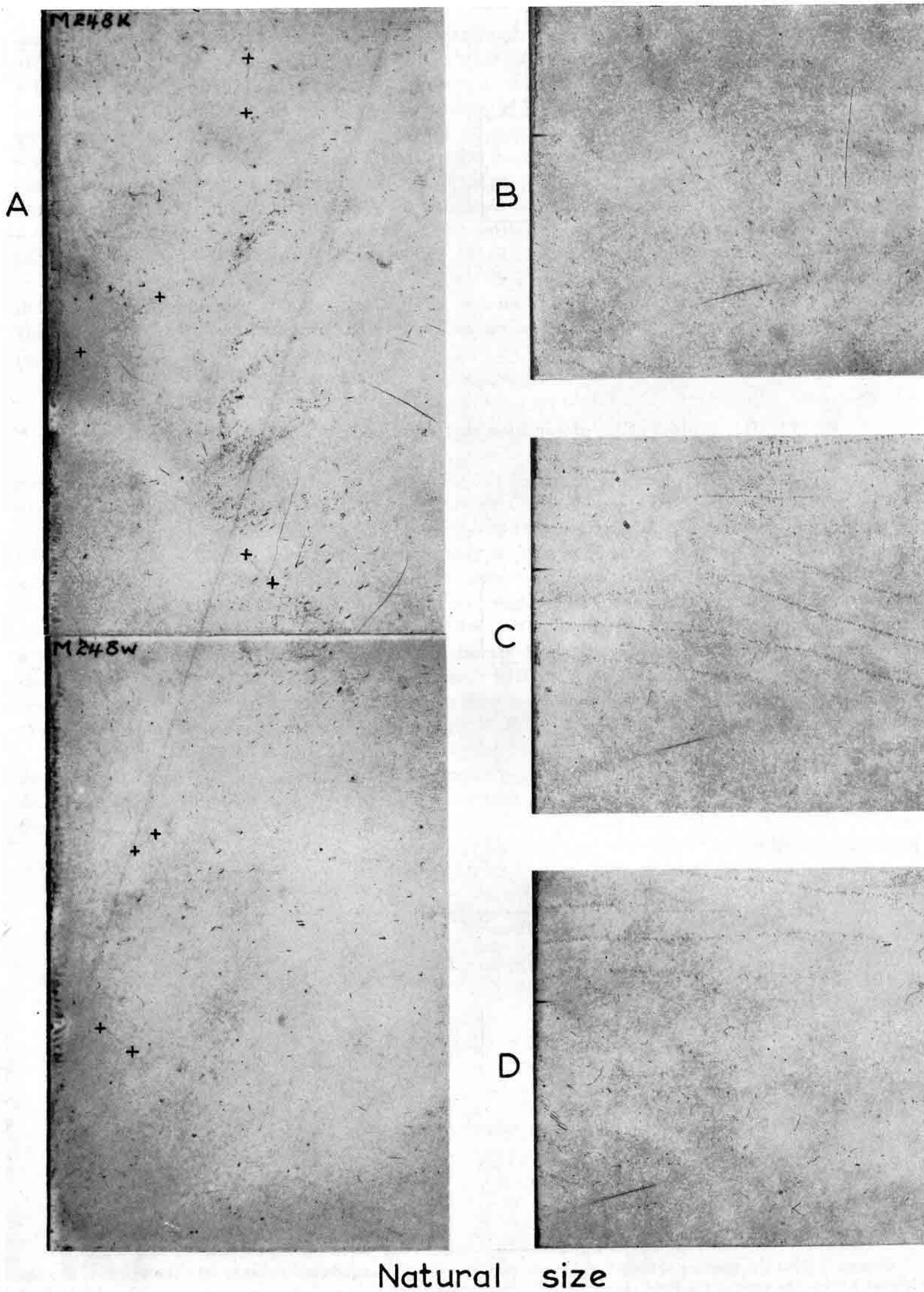
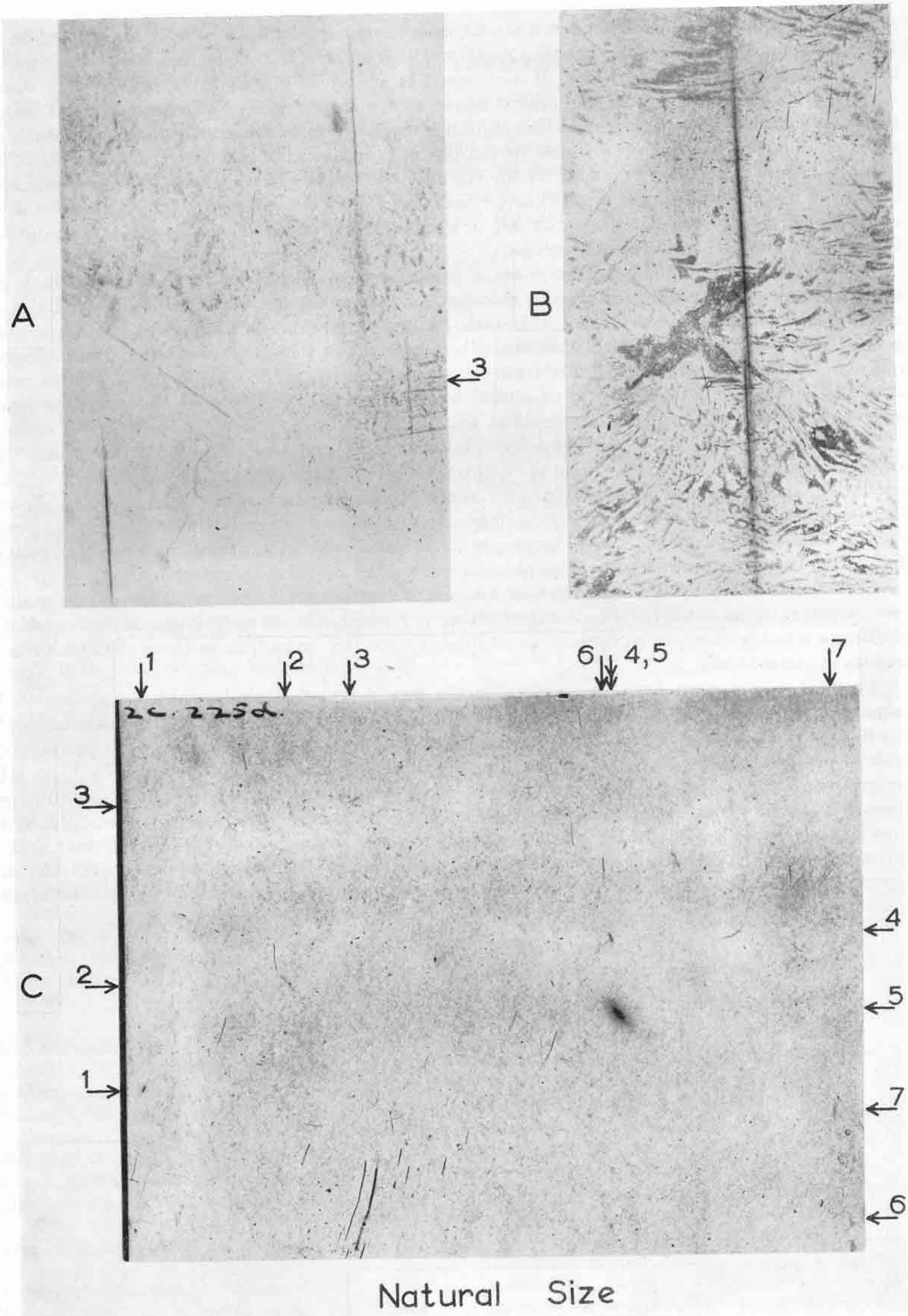


PLATE II

Ilford G 5 emulsion.

(Bristol, 1956; unpublished).

Contact prints of emulsion sheets exposed on a BOAC Comet aircraft



Ilford G 5 emulsion.

PLATE III

(Bristol, 1958; unpublished).