Multiple Production of Mesons

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Cloud-chamber photographs and photographic emulsion events have been obtained which are interpreted in terms of multiple meson production. In some cases it can be shown by charge conservation and penetration of lead that a large number of the particles in hard showers are not nucleons or electrons. The results are compared with the predictions of Heisenberg and Leprince-Ringuet. By comparing the interactions in carbon and lead one is led to the conclusion that mesons are made at 55° geomagnetic latitude with an average multiplicity of about five by protons of average energy about 8 Bev.

THE generation of penetrating showers in lead was first observed by Fussel[1] and later reported by a number of other observers. In some cases it has been possible to show that one or more of the particles produced in such showers are mesons.[2,3] Recently photographic emulsion experiments[4,5*] have shown that, in energetic nuclear interactions, forward direction showers are produced and the particles in these showers are believed to be mesons. In one case,[5] the number of particles was great enough to make certain that at least several of the particles were either mesons or electrons. In cloud-chamber experiments, it is difficult to determine the number of mesons because the showers usually take place in lead and, consequently, the particles could all be nucleons (in the absence of mass determinations of individual particles). In the photographic emulsion, the difficulty of observing multiplication of electrons together with the uncertainty about the absorbing nucleus has made the results ambiguous.

An example of a shower containing penetrating particles is shown in Fig. 1. It was obtained in a balloon flight at a geomagnetic latitude of 55°. The residual pressure at which the cloud-chamber picture was taken was 1.7 cm of mercury. The top plate of the cloud chamber is $\frac{1}{4}$-in. carbon, the others are $\frac{1}{4}$-in. lead plates. The shower is associated with a star in the second (lead) plate and contains about 30 particles most of which penetrate the next lead plate. Two small electron showers originate in the plate below the one in which the interaction takes place. These showers seem to point to an origin in the gas between the plates and, although their energy and angle are consistent with neutral meson decay, turbulence in the cloud chamber makes this conclusion uncertain. The association of electrons with penetrating particles in nuclear interactions has been previously reported[6] and seems well established.

Figure 2 shows a photograph of a particle entering the carbon plate (top plate) and producing an interaction in which 13 charged particles come out. The ionization of the incident particle is estimated to be between 1.5 and 3 times minimum. It could not, therefore, be an incident α-particle. The charge of the incident particle plus the atomic number of carbon is seven, so at least six of the emerging particles must be

TABLE I. Multiplicity and average angle of hard showers.

Material	Average number of particles emerging	Average projected angle within which all of the particles are contained	Average projected angle within which half of the particles are contained
Carbon	6.8±2.0	56°	24°
Lucite	5.5±2.0	38°	15°
Lead	10.1±1.7	52°	16°

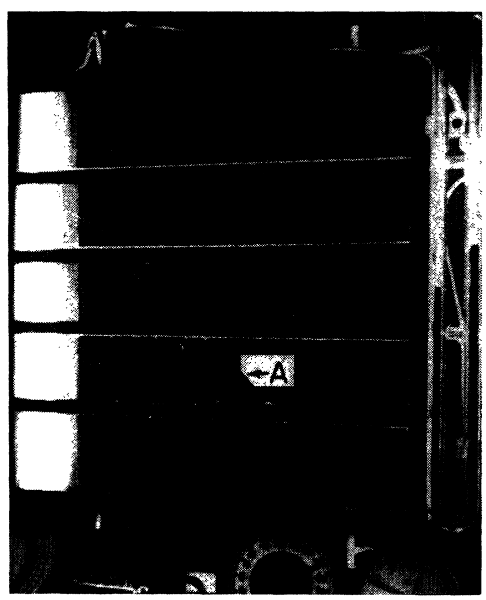

FIG. 1. A penetrating shower produced at a residual pressure of 1.7 cm mercury. This event has associated electrons and star particles. The ionization and scattering of particle *A* led us to believe that it is a meson.

[1] Reported by H. Euler and W. Heisenberg, Ergeb. d. exak. Naturwiss. **17**, 1 (1938).
[2] Rochester, Butler, and Runcorn, Nature **159**, 227 (1947).
[3] W. M. Powell, Phys. Rev. **69**, 385 (1946).
[4] J. Hornbostel and E. O. Salant, Phys. Rev. **76**, 859 (1949).
[5] Leprince-Ringuet, Bousser, Tchang-Fong, Jauneau, and Morellet, Comptes Rendus **229**, 163 (1949).
* It has just come to our attention that Kaplon, Peters, and Bradt have also obtained photographic emulsion data bearing on this question.
[6] W. B. Fretter, Phys. Rev. **73**, 41 (1948).

mesons or electrons. Although all of the particles cannot be followed through the next lead plate, of the nine that can be followed, none produce electron showers. The conclusion can be drawn that at least three and probably more than six of the particles emerging are mesons. It is interesting to note that the particles come out in groups which may be the result of several nucleon-nucleon interactions. The fact that the ionization of the incident particle is above minimum is believed to be due to the relativistic increase of energy loss at very high energies. Two carbon and two Lucite

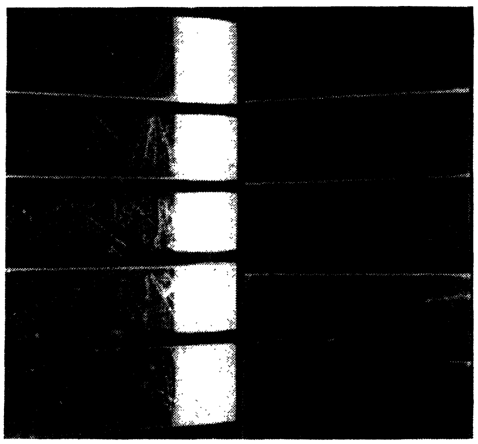

FIG. 2. Right and left stereophotographs of a carbon interaction in which a particle enters the carbon plate and 13 charged particles come out of the interaction. The electron shower which crosses in front at an angle of about 45° is unrelated to the event.

interactions have been observed giving rise to at least 13, 11, 7, and 10 particles, respectively. No cascade multiplication was observed in any of these cases. The Lucite interactions took place in the top of the cloud chamber which is constructed of plastic.

Because the carbon interactions demonstrate that mesons can be made in groups, the cloud-chamber interactions in which narrow groups of particles come out were compared in lead, Lucite, and carbon. Table I shows the results, based on six carbon, four Lucite, and 32 lead interactions.

Because of the difficulty of deciding which events to include and because of the rather poor statistics, these figures should be considered tentative.

Leprince-Ringuet[7] and Heisenberg[8] have considered the dynamics of meson production. Leprince-Ringuet considers the case in which the mesons are all emitted with the same energy in the center-of-mass system of the nucleons, and Heisenberg has assumed an energy spectrum of emitted mesons in the center-of-mass system of the form

$$dI = a\,dK_0/K_0, \tag{1}$$

where dI is the number of mesons emitted with energies

[7] Peyrou, d'Espagnat, and Leprince-Ringuet, Comptes Rendus **228**, 1777 (1949).
[8] W. Heisenberg, Nature **164**, 67 (1949).

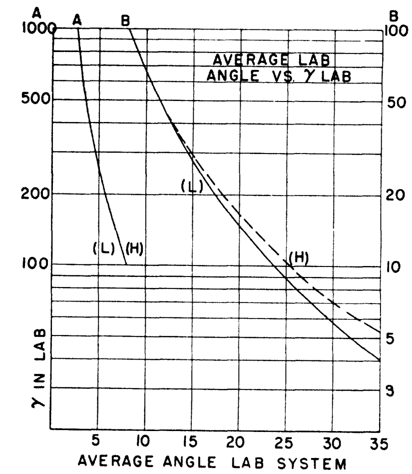

FIG. 3. The average proton γ_L for production of mesons with the indicated average angle.

between K_0 and K_0+dK_0. Both theories assume that the mesons are emitted symmetrically in the center-of-mass system of the nucleons. We will use the following notation to present their theory for comparison with experiment. We will also assume that the mesons produced are π-mesons.

ψ = angle in the lab system of a given meson with respect to the direction of the incident nucleon.
$\psi_{\max}$ = maximum value of ψ.
$\bar{\psi}$ = angle within which half the mesons are contained.
β_1 = average v/c of the meson in the center-of-mass system.
n = total number of mesons produced.
$1/k$ = fraction of kinetic energy in the center-of-mass system used in making mesons.
$\beta = v/c$ of nucleon in the center-of-mass system.
$\gamma = (1-\beta^2)^{-\frac{1}{2}}$.
$\gamma_1 = (1-\beta_1{}^2)^{-\frac{1}{2}}$.
$\gamma_L = \gamma$ of the nucleon in the lab system.
r = ratio of rest mass energy of meson to rest mass energy of proton.

The two theories will be identified by (L) and (H).

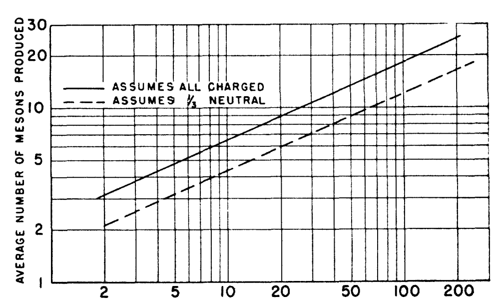

FIG. 4. The average number of mesons produced in a nucleon-nucleon encounter according to Heisenberg.

THE ANGULAR DISTRIBUTION OF MESONS

$$\text{(L)} \quad \tan\bar{\psi} = \beta_1/\beta\gamma \tag{2a}$$

$$\text{(L)} \quad \sin\psi_{\max} = \beta_1\gamma_1/\beta\gamma \tag{2b}$$

$$\text{(H)} \quad \langle\cos\psi\rangle_{\text{Av}} = 1 - 0.87/\gamma^2. \tag{2c}$$

For high energies of the primary nucleon and the emitted mesons, Eq. (2a) reduces to $\tan\bar{\psi} = 1/\gamma$ and $\gamma_L \cong 2\gamma^2$. Hence, one should compare the following equations in the lab system.

$$\text{(H)} \quad \langle\cos\psi\rangle_{\text{Av}} = 1 - 1.74/\gamma_L \tag{3a}$$

$$\text{(L)} \quad \tan\bar{\psi} = 1.41/\gamma_L^{\frac{1}{2}}. \tag{3b}$$

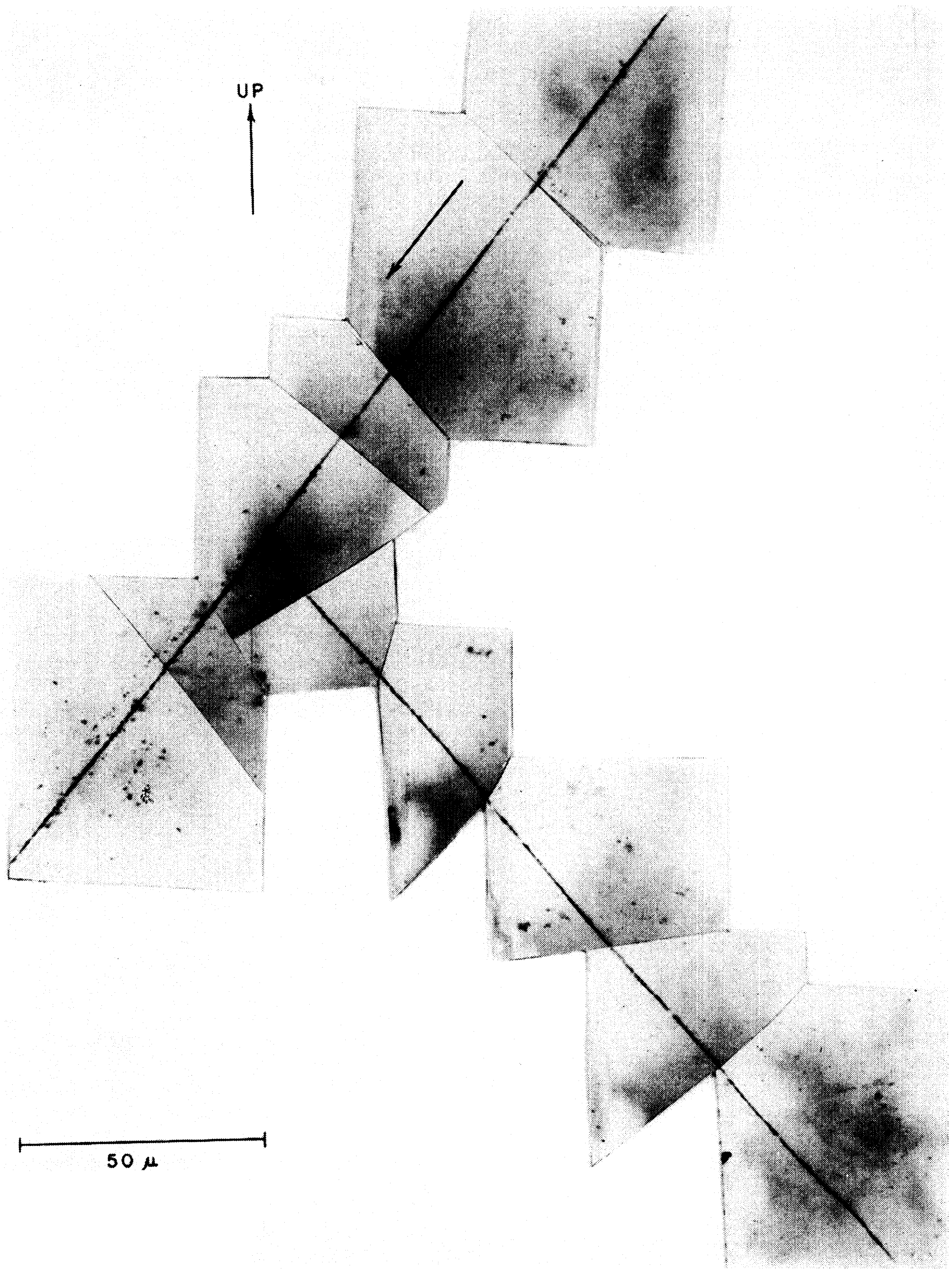

FIG. 5. Photo-micrograph of an event in which an incident carbon nucleus collides with an emulsion proton making mesons.

A graph of these functions is shown in Fig. 3 in which $\langle\cos\psi\rangle_{\text{Av}}$ is approximated by $\cos(\bar{\psi}/\sqrt{2})$. In spite of the quite different energy assumptions of (L) and (H), the angular distribution as a function of γ in both theories is essentially the same. It is probable then that the angular distribution depends to a first approximation only on the fact that the mesons are made, provided they are emitted with spherical symmetry in the center-of-mass system. The angles given in Table I vary considerably, but the average angles are not appreciably different in lead and carbon. This leads one to believe that the same fundamental process is going on with protons of essentially the same average energy in lead as in carbon. Using the data from Table I, we conclude that the average angle in the meson showers corresponding to the measured projected half-angles is about 25°. From Fig. 3 the average γ_L corresponding to this angle is 9. This is rather large since the cut-off γ at our latitude of 55° is 2.5. This result could be explained if only the higher energy events were included in our selection, if only higher energy protons make large groups of mesons, or if the mesons were emitted preferentially in the direction of the colliding nucleons in the rest system.

THE MULTIPLICITY OF MESON PRODUCTION

Heisenberg's theory predicts that the average number of mesons as a function of the energy is given by

$$\text{(H)} \quad n=[2(\gamma-1)/r]/\ln[2(\gamma-1)/r] \qquad \text{(4a)}$$

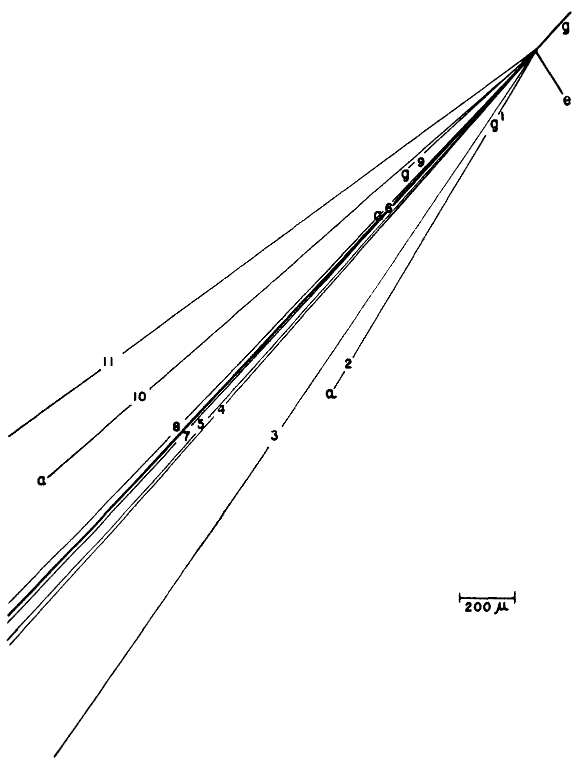

FIG. 6. Drawing of the event of Fig. 5. Angles are projected angles in the plane of the emulsion. The letters g, a, and e refer to the particles which leave the glass or air surface of the emulsion or end in the emulsion.

or as a function of the angle by

$$\text{(H)} \quad \langle\cos\psi\rangle_{\text{Av}}=1-8/n^2, \quad n>4. \qquad \text{(4b)}$$

According to (L), the number of mesons is directly related to the angle only when ψ is very large. For this case

$$\text{(L)} \quad \sin\psi_{\max}=2/nkr. \qquad \text{(4c)}$$

Because k may be as small as 1 and $r\cong 1/7$, Eq. (4c) is of little use unless many mesons (greater than 14) are made in a single act. Figure 4 is a graph of Eq. (4a) in terms of γ_L instead of γ. The dotted line is the number of observed mesons if one-third of those produced are neutral, the solid line is the number of observed mesons if all are charged. From the γ estimated on the basis of the angular distribution, one can see that between four and six mesons should be observed in a nucleon-nucleon interaction. In the carbon interactions the average multiplicity is seven. The average of 10 mesons observed in lead with essentially the same angular distribution as those in carbon indicates that in heavy elements the larger number of mesons is the result of several interactions within the same nucleus. In order to check up on this point we are now flying cloud chambers with many lead, aluminum, and carbon plates.

Figures 5 and 6 show an event in the emulsion in which a heavy particle comes in, is associated with 11 minimum ionization particles in a narrow cone and one slow proton, and goes on undeflected. The heavy particle ionizes less after the collision, the δ-ray count decreasing by a factor of 1.5 ± 0.3. If the 11 minimum ionization tracks were protons, the incoming heavy particle would necessarily have lost about 10 Bev to give these protons the required energy. This is inconsistent with the decreased ionization of the heavy particle unless this particle is on the high energy side of minimum ionization. The incoming heavy particle does not change its charge by more than one, and, therefore, does not contribute more than one minimum ionization particle. The only nuclei in the emulsion that could contribute 11 charged particles are Ag and Br, and no stars definitely identified as resulting from Ag or Br have been observed to have only one slow particle. The possibility that there are 11 protons is, therefore, very small. The 11 minimum ionization particles are followed in this one emulsion for a total distance of 4 cm or 16 g/cm^2 without any multiplication. Although this is only about two-thirds of a radiation length in emulsion, the cloud-chamber pictures seem to rule out the possibility that such particles as these are electrons. Because the heavy particle travels almost parallel to the emulsion, the angles between the heavy particle and the minimum ionization particles could be carefully measured. The angles are given in Table II.

Using the angle in which all the mesons are contained, the angle in which half the mesons are contained, and the number of mesons formed, and assuming that in the center-of-mass system monoenergetic π-mesons are produced with angular symmetry, one can determine

TABLE II. Angles between the heavy particle and the minimum ionization particles.

1. 12° 20′	5. 55′	9. 4° 50′
2. 12° 15′	6. 8°	10. 8° 50′
3. 8° 10′	7. 20′	11. 13° 25′
4. 1° 10′	8. 20′	

the velocity of the emitted mesons, the velocity of the incoming particle, and the fraction of the kinetic energy which is used in the meson production. Such an analysis leads to the following tentative interpretation of this event.

A relativistic carbon nucleus with 60 Bev/nucleon in the lab system enters at an angle of 39° from the vertical. Its ionization is 1.3 times that of carbon at minimum ionization. One proton in the carbon collides with a hydrogen nucleus in the emulsion and they rebound after collision 180° apart in the center-of-mass system. The incoming proton of the carbon is the 5.2-Mev proton ejected after collision at 102° 30′ in the lab system. The knock-on proton is computed to be at 6′ from the heavy particle. Particle No. 8 is in the right plane but makes an angle of 20′ with the heavy particle. Ten charged mesons are produced in the collision. The remainder of the carbon nucleus goes on as $B_5{}^{11}$ and can be followed for 6 g/cm^2 after the collision. If 10 mesons are produced in this one collision, the incoming proton loses one-third of its energy measured in the center-of-mass system.

Figure 7 shows a cloud-chamber picture in which 11 particles arise in a carbon interaction. It can be seen that this case of a proton colliding with a carbon nucleus is very similar to the angular distribution of the emitted particles to the emulsion example of an *incident carbon* nucleus colliding with a proton. In the emulsion case, of course, the residual nucleus continues in the forward direction.

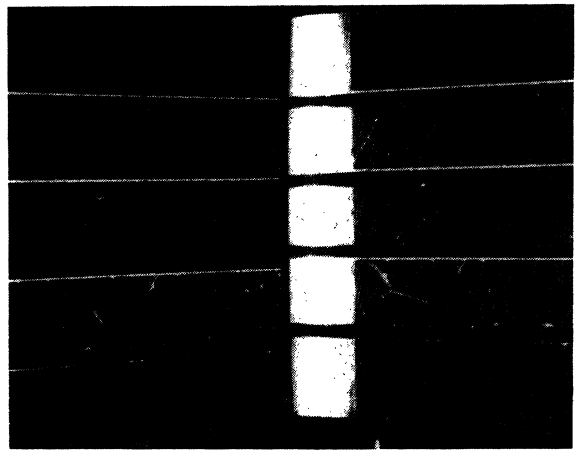

FIG. 7. Right and left stereos of a cloud-chamber photograph very similar to the emulsion event of Fig. 5 except that the carbon nucleus at rest is struck by an incident proton. The angular distribution of the mesons is quite similar to that in Figs. 5 and 6.

CONCLUSIONS

Evidence is presented which indicates that at 55° geomagnetic latitude and 1 cm residual pressure the average multiplicity of meson production in nucleon-nucleon encounters is about five. In single nucleon-nucleon interactions as many as 10 mesons can be produced. Because hard showers produced in lead have a higher multiplicity but essentially the same angular distribution as in carbon, the larger average number of particles produced in heavy nuclei should probably be interpreted as caused by successive interactions in the same nucleus. At present the data are not detailed enough to decide about the energy distribution and angular distribution in the rest system of the mesons produced.

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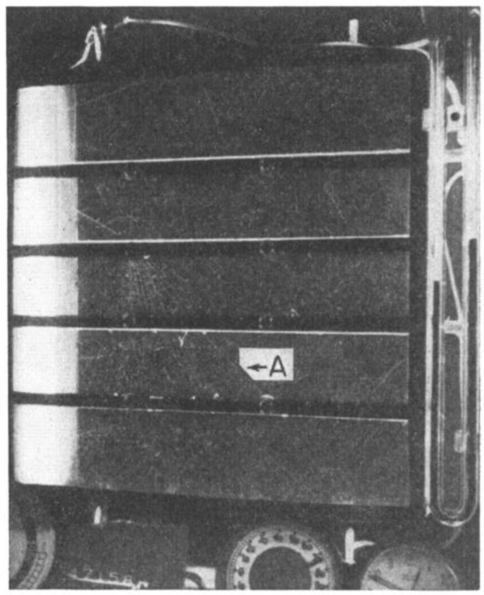

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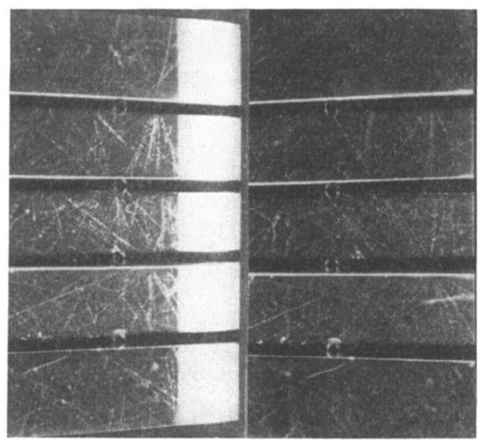

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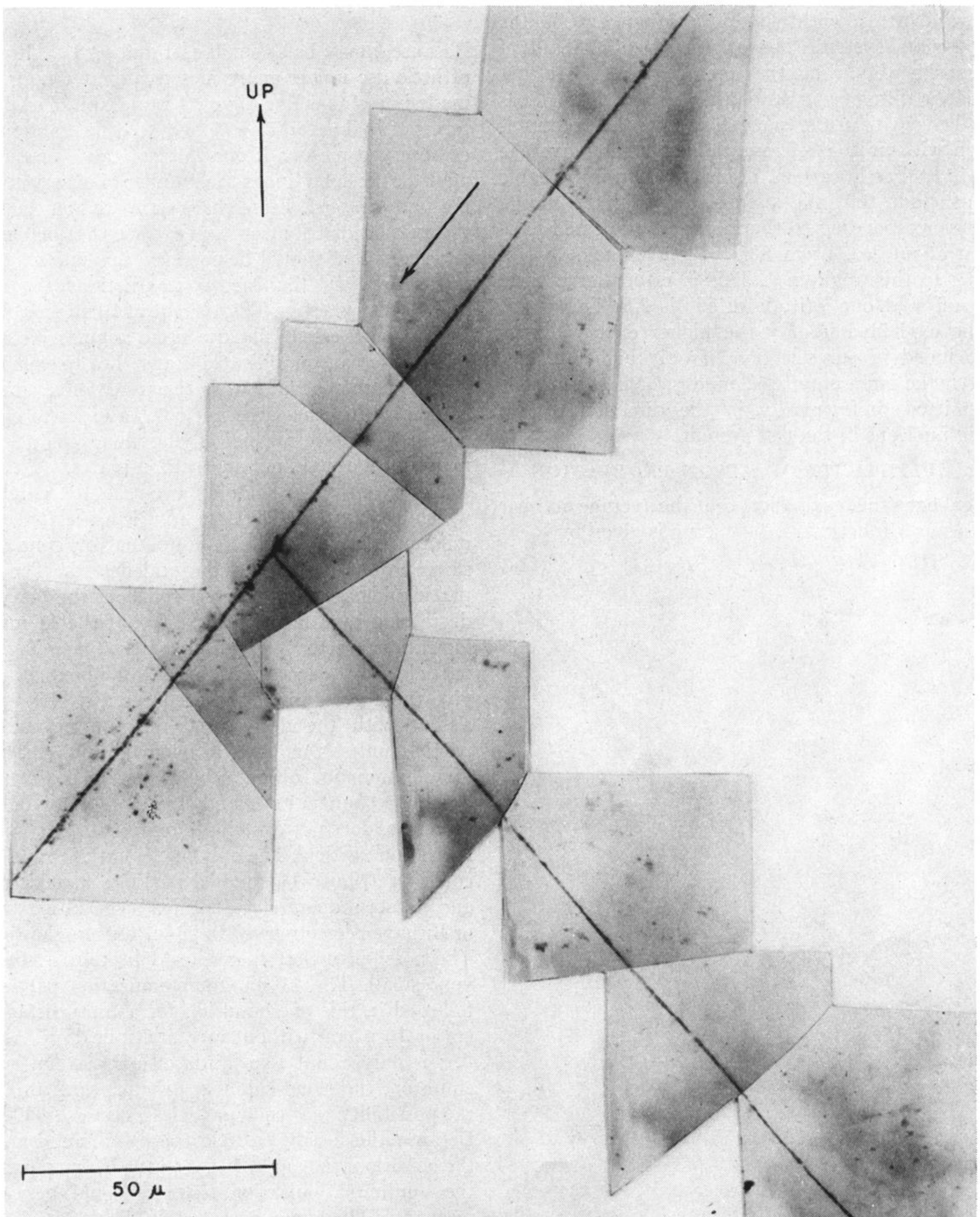

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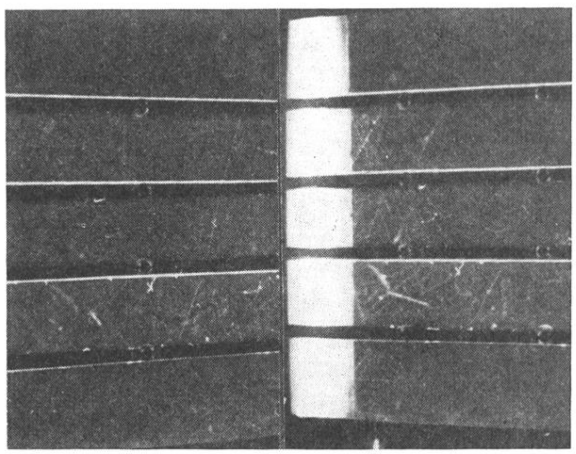

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