THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 59, No. 2 JANUARY 15, 1941 SECOND SERIES

Cloud Tracks of Cosmic Rays in the Substratosphere

G. HERZOG*
University of Chicago, Chicago, Illinois
(Received October 24, 1940)

A cloud chamber in a magnetic field of 708 oersteds was carried in an airplane to a height of 29,300 feet. The maximum measurable $H\rho$ was 5.6×10^5 which, for an electron, corresponds to an energy of 1.7×10^8 ev. Out of 155 pictures taken at altitudes greater than 15,000 feet, 51 slow mesotrons and 39 proton tracks were identified. The number of slow mesotron tracks at these altitudes is 9 percent of the number of electron and fast mesotron tracks. One photograph seems to show a slow mesotron shower. Some of the tracks with very high specific ionization may be due to the fragments of heavy nuclei.

It is of great importance to get direct evidence for the mass of the mesotron and to make a mass determination. This can be accomplished in a cloud chamber by measuring the number of ions formed in the gas, and by simultaneous determination of the curvature in a magnetic field which gives the momentum of the particle. Figure 1 shows the energy loss in air per g/cm^2 for single charged particles of mass one (electron), 100 and 300 (range of the mesotron mass) and 1840 (proton). For high momenta the ionization is practically independent of the rest mass of the particle. We can hope to get information concerning the rest mass only if the particle has a momentum low enough to put its energy loss caused by ionization on the increasing part of the curves in Fig. 1. The present experiment was performed to see whether such low momentum mesotrons can be observed in the substratosphere.

Mesotrons with a momentum below 100 mc ($H\rho=2\times10^5$) have losses greater than three times that of fast electrons, whereas for protons this value lies at 1000 mc ($H\rho=2\times10^6$). The great number of cosmic-ray pictures taken at sea level and on mountains, reveal only about 10 tracks with momenta small enough to show such increased ionization. We conclude that the percentage of slow mesotrons at low altitudes is extremely small.

Let us assume that mesotrons are produced as secondaries by γ-rays of the soft component in the atmosphere. According to the cascade theory the average energy of the γ-rays decreases rapidly with the amount of air traversed. On this theory

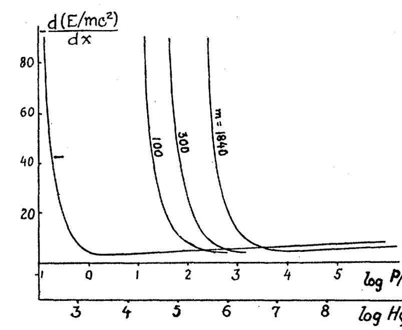

FIG. 1. Energy loss in air per g/cm^2 for single charged particles of various masses.

* Now at Texas Company, Houston, Texas.

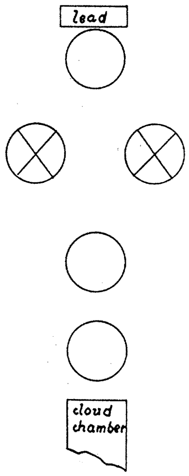

FIG. 2. Arrangement of the threefold counter telescope.

the number F of electrons with energies greater than E electron volts varies with the depth from the top of the atmosphere as

$$F(E, l) = 40(10^8/E)^{1.8}e^{-0.32(l-10)} \text{ min.}^{-1} \text{ cm}^{-2}.$$ [1]

l is measured in the units given in the cascade theory. Sea level corresponds to $l = 29$, 30,000 feet to $l = 10$. The number of γ-rays at a given height is about double that of the electrons. The minimum energy for a γ-ray to produce a mesotron of $\mu = 200$ is 10^8 ev. From the above formula one finds

$$2F(10^8, 29) = 0.18 \text{ min.}^{-1} \text{ cm}^{-2},$$
$$2F(10^8, 10) = 80 \text{ min.}^{-1} \text{ cm}^{-2},$$

i.e., the number of photons having enough energy to create the rest mass 200 of a mesotron increases by a factor of 440 from sea level to an altitude of 30,000 feet. Since other than cascade electrons appear at sea level, the actual ratio should be appreciably less than this factor of 440, but should, nevertheless, be large. This large increase suggests that finding slow mesotrons at high altitudes is probable.

Also the experiments of Schein and Wilson[2] and of Jesse, Schein and Wollan[3] have proved the creation of mesotrons in altitudes attainable in an airplane. Although the arrangement of the lead filters in their experiments prevented the detection of mesotrons below 2×10^8 ev (kinetic energy), there is good reason to believe that together with these particles slow mesotrons are also created.

It is worth mentioning that the slow mesotrons have kinetic energies that are near the lower limit for cosmic-ray particles. For a momentum of 100 mc the velocity is $0.45c$ and the kinetic energy 12 Mev. The range is 0.75 cm of lead, or 4.8 g/cm^2 of air, which corresponds to 37 m at sea level and 110 m at 30,000 feet. This short range is the reason that mesotrons which have been created with low momenta higher in the atmosphere cannot reach sea level. This is quite aside from the possible decay of the mesotron.

THE APPARATUS

The 6-inch diameter cloud chamber has a 1-inch depth of illumination, a rubber piston, and is filled with argon at $\frac{1}{3}$ atmos. overpressure. The expansion is accomplished by tripping a magnet which releases a valve in the back chamber. Special precautions were taken to adjust to the varying outside pressure in the course of a flight. The illumination is accomplished by four photofloodlight lamps which are flashed when the expansion starts. They draw 16 amp. at 150 volts out of 96 No. 6 $1\frac{1}{2}$-volt dry cells. A "Sept" movie camera is used with an $f : 1.9$ lens and is equipped with an attachment so that all photographs are taken stereoscopically. The timing control of the expansion, illumination

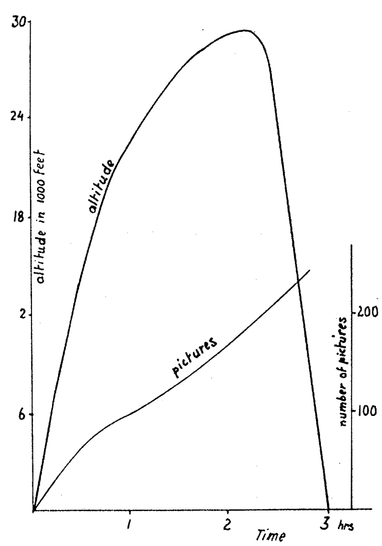

FIG. 3. Record of altitudes reached and number of pictures taken.

[1] W. Heisenberg and H. Euler, Ergeb. d. exact. Naturwiss. **17** (1938).
[2] M. Schein and V. C. Wilson, Rev. Mod. Phys. **11**, 292 (1939).
[3] Schein, Jesse and Wollan, Phys. Rev. **57**, 847 (1940).

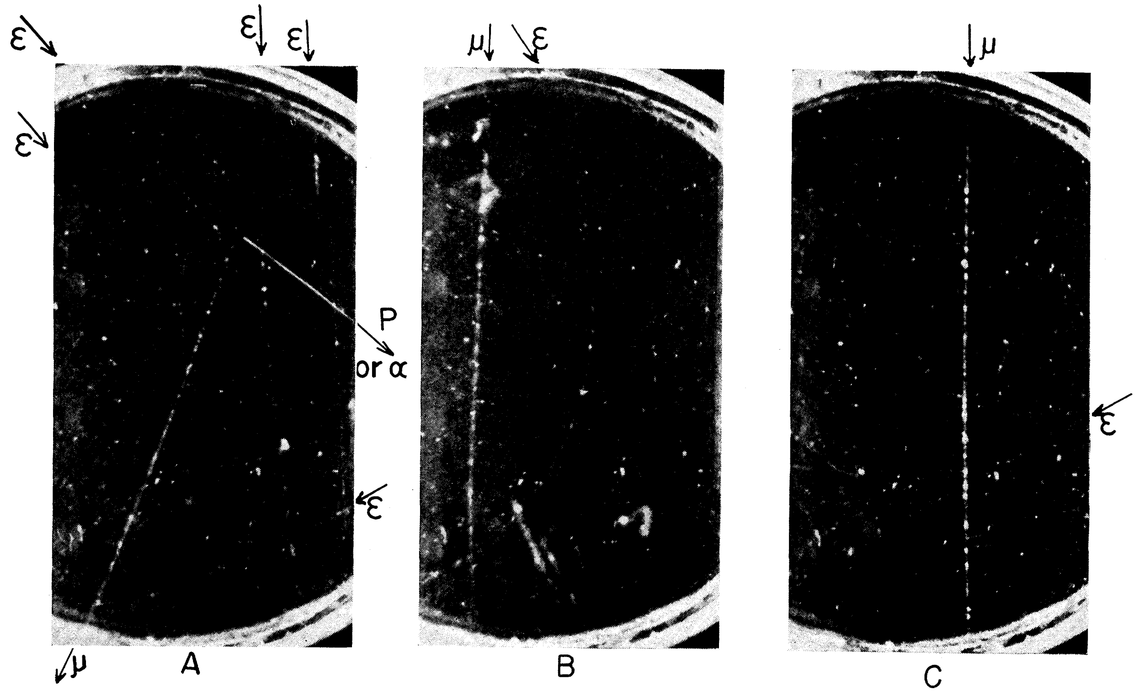

FIG. 4. Cloud-chamber photographs. *A*, negative mesotron ($H\rho=1.4\times10^5$) with an electron shower and α-particle or proton. *B*, mesotron with some scattering after first three-quarters of its path. The sign is positive and initial $H\rho$ is about 5.5×10^5. The electron has an energy of 1.7×10^6 ev. *C*, positive mesotron of $H\rho=1.4\times10^5$.

and exposure is performed by an R C-controlled vacuum-tube circuit. This circuit can work for random expansions with a cycle of 20 seconds between successive expansions, or the cycle can be initiated by the discharge of a G-M counter arrangement.

The magnetic field is provided by a U-shaped permanent magnet weighing 400 pounds. The pole pieces have a square cross section of 4.5 inches on the side. The gap of the magnet is 8 inches. The back part of the cloud chamber (soft iron) forms one pole piece. This reduces the actual gap to 6 inches. The field inside the cloud chamber is 708 oersteds, and it has a homogeneity of 98 percent over the surface of the chamber. The largest radius of curvature which can be measured is about 800 cm (length of tracks 14 cm, deviation from a straight line in center 0.3 mm). This corresponds to a value $H\rho=5.6\times10^5$. For an electron this would be an energy of 1.7×10^8 ev.

The apparatus was installed in a Douglas DC3 transport plane, whose closed cabin was maintained at nearly constant temperature.

The G-M counter arrangement

Figure 2 shows the arrangement of a threefold counter telescope. Placing all counters above the cloud chamber provides for the possibility of catching tracks which end inside the cloud chamber. A lead sheet 2 cm thick in which new mesotrons may be created lies on top of the counters. This lead also would act as an optimum source for shower production. The number of showers tripping the chamber is reduced by the arrangement of two anticounters. They respond to shower electrons at an average of 20 degrees with the vertical. The threefold telescope and the anticounters are connected to an anticoincidence amplifier[4] which controls the expansion. Hence, expansions are made only when a particle crossing the telescope is not accompanied by shower electrons penetrating the anticounters.

The counting rate of this arrangement is 0.125 per minute in the laboratory at sea level, and increased to 2 per minute at an altitude of 26,500 feet. This increase by a factor of 16 may be com-

[4] G. Herzog, Rev. Sci. Inst. **11**, 84 (1940).

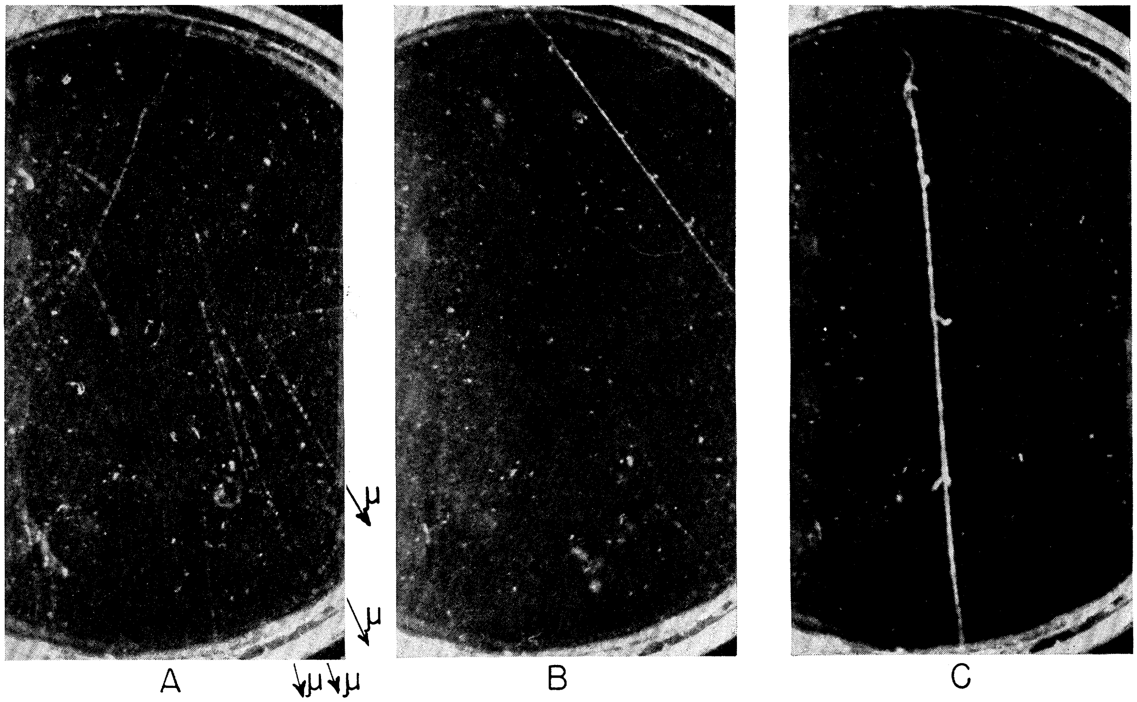

FIG. 5. Cloud-chamber photographs. *A*, shower of slow mesotrons. *B* and *C* show particles heavier than mesotrons with several delta-rays.

pared with the value of 15 for the total vertical counting rate as measured without lead by Pfotzer.[5]

As the airplane left the ground, the random expansion arrangement was used. When the counting rate reached a value of about two per minute the arrangement was switched over to counter-controlled expansions.

THE RESULTS

Figure 3 shows a record of the altitudes reached and the number of pictures taken. Altogether, 230 pictures were taken in a total flying time of three hours.

The pictures show three distinct groups of tracks. Those in the first group have specific ionization similar to that of electrons in the test experiments in the laboratory. These tracks correspond to electrons or heavier particles with speeds approaching that of light. The second group has a definitely higher specific ionization. It can be estimated to be about 3 to 5 times that of the electron tracks, and probably corresponds to slow mesotrons. Both of these groups show clusters of drops and gaps along the tracks, whereas in the third group the ionization is so dense that the tracks are uninterrupted lines. These latter tracks are created by protons and heavier particles.

For the present purpose the most interesting tracks are those of the second group. For a qualitative test the number of clusters per cm path, caused presumably by secondary electrons, was counted for the electrons and mesotrons. The tracks selected by appearance as being of the second group, were found to have two to four times as many clusters as the average electron track. These figures have, however, no

TABLE I. *Number of different tracks.*

ALT. IN 1000 FEET	ELECTRONS TOTAL	ELECTRONS $l>5$	MESOTRONS TOTAL	MESOTRONS $l>5$	PROTONS AND α'S TOTAL	PROTONS AND α'S $l>5$	NO. OF PICTURES
0 to 5	8	2	—	—	1	—	14
5 to 10	30	9	—	—	9	1	32
10 to 15	33	13	—	—	3	—	29
15 to 20	51	17	2	1	2	—	28
20 to 25	111	38	6	4	5	2	38
above 25	425	137	43	16	32	6	89

[5] G. Pfotzer, Zeits. f. Physik **102**, 34 (1936).

exact numerical significance. In an electron track with its low average ionization, small clusters can be detected which would be obscured in the denser mesotron tracks. The $H\rho$ values for the 14 mesotron tracks which were long enough for measurement lie between 3×10^4 and 5×10^5. Figure 1 shows that this is the region where a large ionization is to be expected for mesotrons It seems quite impossible to explain these tracks as being produced either by electrons or by protons, even if one allows for large errors in the estimate of the ionization and in the curvature determination (see Fig. 1).

Out of these 14 tracks, 8 correspond to positive and 6 to negative particles.

In addition, 37 tracks were photographed whose appearance shows very clearly that they belong in this group of the mesotron tracks, although their curvature could not be measured. Either the length of the track is not sufficient, i.e., the track does not lie in the plane of the cloud chamber, or the radius of curvature is too great for an exact measurement. None of these tracks could have been produced by electrons, because electrons of this ionization would show a very small radius of curvature, which could have been easily measured. The general appearance also makes it very unlikely that they are protons. These tracks, therefore, have been counted as mesotrons.

In Table I the frequency distribution of the different groups with altitude is listed. In each group the total number of tracks is given and then out of those the number of tracks showing a length over 5 cm. The first group headed as electrons also contains all fast particles whose ionization is practically the same as for electrons. The second group contains only the slow mesotrons, the third the protons and heavier particles.

TABLE II. *Number of tracks per expansion.*

Alt. in 1000 feet	Electrons		Mesotrons		Protons and α's	
	Total	$l>5$	Total	$l>5$	Total	$l>5$
0 to 5	0.57	0.14	—	—	0.07	—
5 to 10	0.94	0.28	—	—	0.28	0.03
10 to 15	1.14	0.45	—	—	0.10	—
15 to 20	1.92	0.61	0.07	0.04	0.07	—
20 to 25	2.82	1.00	0.16	0.10	0.13	0.05
above 25	4.77	1.54	0.48	0.18	0.36	0.07

The next column gives the number of pictures taken at the respective altitudes.

In a similar way, the frequency occurrence per expansion is listed in Table II. Table III gives the number of slow mesotrons divided by the number of tracks with electronic appearance.

These figures show that very few slow mesotrons are found below 20,000 feet, and that at 25,000 feet their number becomes 10 percent that of the particles which ionize like electrons. This

TABLE III. *Number of mesotrons per electron track.*

Alt. in 1000 feet	Total	$l>5$	Alt. in 1000 feet	Total	$l>5$
0 to 5	—	—	15 to 20	0.04	0.02
5 to 10	—	—	20 to 25	0.05	0.04
10 to 15	—	—	above 25	0.10	0.04

figure seems very high, and further experiments will be needed to check it. The occurrence of slow mesotrons at these altitudes agrees, however, with the results by Schein and Wilson. They found that in 2 cm lead at 25,000 feet, about as many mesotrons are created as are coming through the atmosphere. If the observed slow mesotrons are the ends of energetic mesotrons produced high in the atmosphere, it can hardly be understood why these ends should be so much more abundant at 25,000 feet than at sea level. It seems much more probable that the slow mesotrons are created in the neighborhood of the cloud chamber, in the lead, the iron of the magnet and in the air.

In Fig. 4*A* a negative mesotron of $H\rho=1.4\times10^5$ occurs simultaneously with an electron shower and α-particle or proton. In Fig. 4*B* the mesotron has some scattering after the first three-quarters of its path. From the upper, undistorted part one finds $H\rho$ about 5.5×10^5 and the sign to be positive. The electron on the same picture has an energy of 1.7×10^6 ev. Figure 4*C* shows a positive mesotron of $H\rho=1.4\times10^5$, and on the same expansion an electron whose ionization is much smaller.

Several expansions have more than one mesotron. There are 6 pictures with two mesotrons, 2 pictures with 3 and 2 pictures with four mesotron tracks. Figure 5*A* seems to be a shower of slow mesotrons. Figures 5*B* and *C* show particles, heavier than mesotrons, with several delta-rays similar to those observed with alpha-particles.

Summary

This flight shows that slow mesotrons occur in appreciable numbers above 20,000 feet altitude. There seem to be also some heavy nuclei present. These could be the result of nuclear reactions created by neutrons. It is planned to make further flights to get better numerical information.

Acknowledgment

I wish to thank Mr. W. H. Bostick who assisted in the flight and who was very helpful in computing the results. Mr. Leonard Miller was kind enough to help in the construction of the timing set. I have, further, to thank the United Air Lines and their engineer, Mr. W. Davies, for valuable help and cooperation. My special gratitude belongs to Dr. A. H. Compton, who was always ready to give helpful advice and encouragement.

JANUARY 15, 1941 PHYSICAL REVIEW VOLUME 59

Cloud-Chamber Pictures of Cosmic Rays at 29,000 Feet Altitude

G. Herzog* and W. H. Bostick
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
(Received November 9, 1940)

Cloud-chamber pictures (115 in number) of cosmic rays were taken during an airplane flight. The range of slow mesotrons was investigated by inserting a copper plate across the middle of the chamber. The slow mesotron rate above 15,000 feet is 9.6 percent of the occurrence rate of electrons and fast mesotrons. The formation of a pair of positive and negative slow mesotrons was photographed. Statistical evidence is given that mesotrons do not always disintegrate when stopped. One proton was photographed.

RECENTLY one of us[1] reported photographs of cosmic rays made with a cloud chamber at altitudes up to 29,300 feet. The apparatus was installed in a Douglas DC3 airplane, and consisted of a cloud chamber 6 inches in diameter mounted in the gap of a permanent magnet which gives a homogeneous field of 708 oersteds. The results of this first flight indicated that there is a good chance to photograph slow mesotrons at higher altitudes. This conclusion was drawn from an evaluation of the ion density of the tracks combined with a measurement of the momentum of the particle (curvature in the magnetic field).

On April 30th we used the same equipment for a second flight.[2] With a total flying time of four hours and 10 minutes we stayed for three hours above 20,000 feet and reached a top altitude of 29,000 feet. Figure 1 shows the altitude-time record of this flight.

About half of the expansions were made at random, the other half were controlled by the same anticoincidence arrangement of G–M counters as previously described. Because of difficulty with the temperature control in the airplane cabin, convection currents in the cloud chamber caused occasional distortions in the tracks.

In order to obtain additional information two changes were made in the cloud chamber. The first was to mount a horizontal copper plate across the center of the chamber. Careful investigations in the laboratory proved that the plate does not appreciably distort the tracks. The purpose of the plate was to slow down or stop some of the slow mesotrons. For the range of a track which is stopped in the plate, one can give an upper limit. This range determination, together with the curvature measurement, gives

* Now with the Texas Company in Houston, Texas.
[1] G. Herzog, Phys. Rev. **59**, 117 (1940) preceding paper, referred to as I.
[2] We wish to thank the United Air Lines for their support in carrying out this flight and Mr. W. Davies, research engineer of this company, for his valuable help.

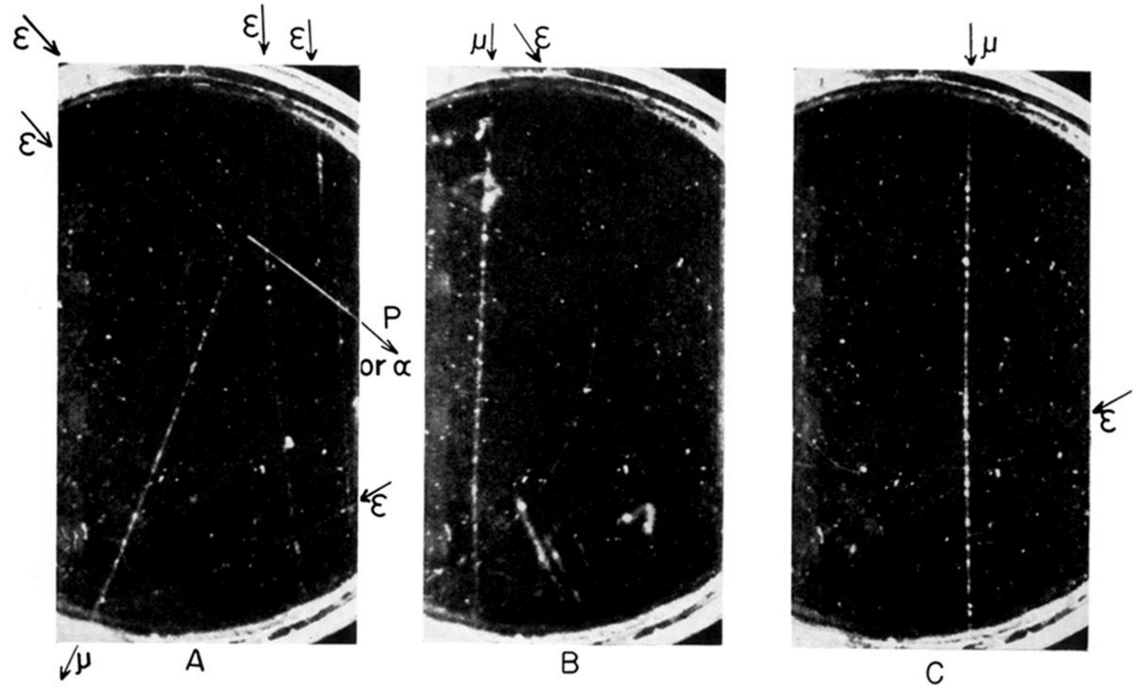

FIG. 4. Cloud-chamber photographs. *A*, negative mesotron ($H\rho = 1.4\times10^5$) with an electron shower and α-particle or proton. *B*, mesotron with some scattering after first three-quarters of its path. The sign is positive and initial $H\rho$ is about 5.5×10^5. The electron has an energy of 1.7×10^6 ev. *C*, positive mesotron of $H\rho = 1.4\times10^5$.

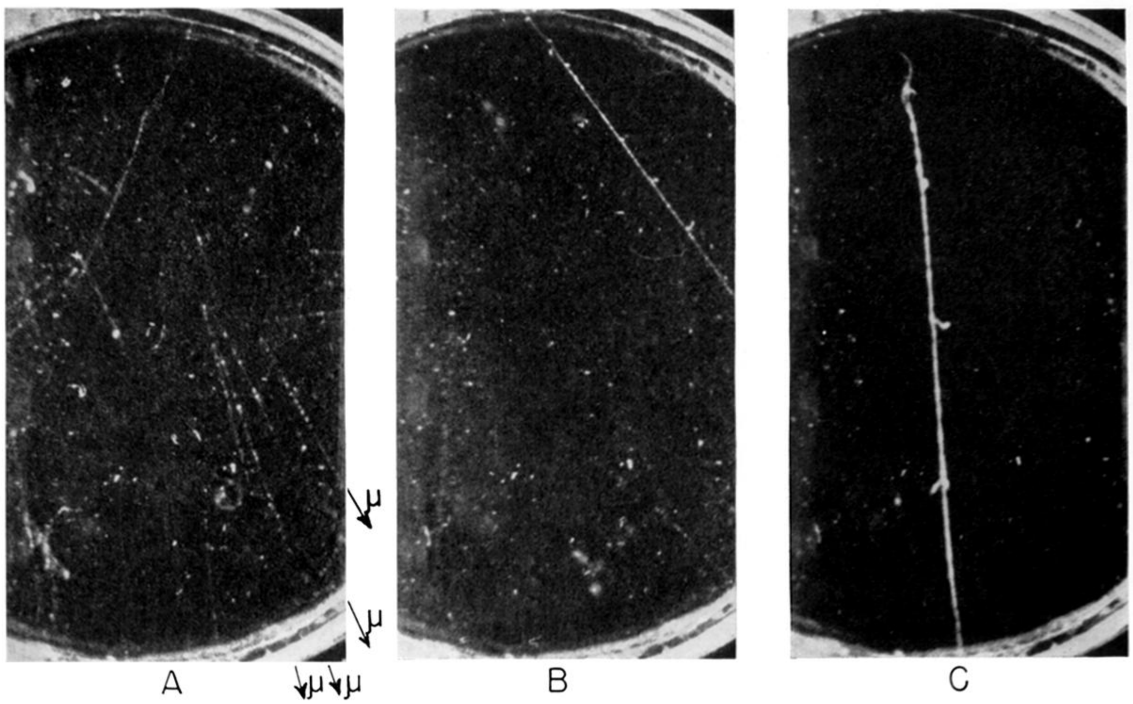

FIG. 5. Cloud-chamber photographs. *A*, shower of slow mesotrons. *B* and *C* show particles heavier than mesotrons with several delta-rays.