Cosmic Rays at 30,000 Feet

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A discussion is given of the data obtained in a recent series of flights of a B-29 airplane at altitudes up to 40,000 ft., in which a cloud chamber, actuated by Geiger counters, was operated in a magnetic field of 7500 gauss. The frequency of occurrence of single particles and electron showers at elevations of 800 ft., 14,100 ft., and 30,000 ft. is compared. Examples of heavily ionizing particles and of nuclear disintegrations are discussed. Direct measurements of the energies of cosmic-ray particles at 30,000 ft. are compared with similar measurements made at sea level. These measurements indicate that up to one-third of the particles which occur singly in the chamber, in the momentum range up to 10^7 gauss-cm, may consist of protons and the remainder of mesotrons, in contrast to sea level observations which show that protons are there present in only negligible numbers.

I. INTRODUCTION

A MAGNET cloud-chamber previously operated at Pasadena (800-ft. elevation) and on Pikes Peak (14,100-ft. elevation) has been operated in a B-29 airplane flying at altitudes between 30,000 and 40,000 ft. above sea level. Of a total of 35 flights made within a range of 40 to 46 degrees north magnetic latitude, 28 flights of five hours duration each were made at 30,000 ft., while the remaining flights were made at higher altitudes. Approximately 9000 exposures have been taken with the cloud chamber actuated by Geiger counters. The chamber was immersed in a steady magnetic field of 5500 gauss for the first 2000 photographs and of 7500 gauss for the remaining 7000 photographs.

II. THE APPARATUS

The apparatus consists of an electromagnet and cloud chamber, originally built in 1930,[1] together with auxiliary apparatus which has been added for operation in the pressurized cabin of the airplane. The gross weight of the equipment is about 4000 pounds.

The chamber is 17 cm in diameter and has a useful depth of 2 cm. Cloud tracks are produced with ethyl alcohol vapor in argon gas at a total pressure of about 1.7 atmospheres. Rapid expansion of the gas is attained through motion of a magnesium piston which constitutes the rear wall of the chamber. The piston is held in the compression position by a solenoid-operated latch. When a high voltage condenser discharge triggers the latch, the piston is driven backward by a pressure differential of 1.2 atmospheres between its two surfaces. The piston motion is arrested at the end of the stroke by an air dashpot.

The expansion is completed in only 4 milliseconds following the time of passage of an ionizing particle through the Geiger counters. The resulting tracks are quite sharp because appreciable ion diffusion cannot take place before the droplets form. Separation of the positive and negative ions is minimized by electronic cut-off of the electric clearing field by the counter pulse. The use of slow expansions between counter-actuated expansions is not necessary for clearing the chamber of old droplets.

The chamber is photographed through the hollow core of the magnet. Two aluminized plane mirrors placed parallel to the core axis provide for stereoscopy. The exposure is timed by a high intensity, short duration flash which is produced in a xenon-filled lamp by a condenser discharge initiated about 70 milliseconds after the completion of the expansion stroke. A lens stop of f:5.6 is used. Sharply defined, high contrast photographs are obtained on 35-mm Eastman Linagraph Ortho film.

The iron-cored electromagnet produces a

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[1] C. D. Anderson, Phys. Rev. 44, 406 (1933).

steady magnetic field of 7500 gauss, uniform to within ten percent over the volume of the expansion chamber. The field current of 750 amperes at 27 volts is supplied by special high altitude generators on the engines of the airplane. Selenium-rectifier units connected across the magnet coils minimize the voltage surges which occur when the magnet circuit is opened. The coils of the magnet consist of copper tubing wound in single-layered spirals. The Joule heat is removed by circulating water through the tubing to an air-cooled radiator. Mounted in the bombbay, the radiator receives air from a scoop on the underside of the fuselage. Remotely operated shutters control the air flow, and hence the cooling of the circulating water.

A control panel both measures and provides adjustments for the following: the expansion ratio of the cloud chamber, the current and voltage of the magnet circuit, the temperature of the cooling water, the illumination time-delay, and the voltages of various of the electronic components. Measurements are given without provision for direct adjustment of the following: the temperatures of the body of the cloud chamber, of the magnet frame, and of various other components of the equipment; the outside air temperature; the outside air pressure; the cabin air pressure; and the air speed. Except for visual inspection of the tracks at about hourly intervals, it is ordinarily unnecessary for the operator to leave his station at the control panel.

The most important source of error in cloud track measurements arises through distortions of the tracks by mass motion of the gas within the cloud chamber. This motion stems primarily from two sources: the turbulence set up by the resetting of the chamber after each expansion and the convection currents set up by temperature inequalities in the chamber.

The turbulence and temperature gradients produced by resetting the chamber are permitted to die out during a 45-sec. waiting period between expansions.

Particular effort has been exerted to hold uniform the temperature of the chamber and its surroundings during flight. The temperature of the chamber proper is determined primarily by the mass of iron and copper at the center of the magnet. Because the magnet temperature follows the temperature of its surroundings only very slowly, temperature equilibrium must be established prior to flight by refrigeration or heating of the cabin. For the same reason the effect of the cabin air temperature, which varies between 15° and 25°C during flight, is only of secondary importance. In operation the magnet takes on the temperature of the cooling water, which is controlled so that the chamber temperature remains constant to ± 1°C throughout the flight.

As a result, the track distortion has been found to be not significantly greater than that occurring when the chamber is operated in the laboratory.

TABLE I. Summary of data, giving the number of photographs of each type.

Altitude	Number of tracks appearing on each photograph: 1	2–4	5–10	11–100	>100	Total number of photographs
800 ft.	2301	294	57	32	0	2684]
14,100 ft.	1023	410	190	148	4	1775
30,000 ft.	485	397	181	106	3	1172

III. ELECTRON SHOWERS AND HEAVILY IONIZING PARTICLES

The relative frequency of occurrence of single tracks and of electron showers of various sizes has been determined from a set of 1172 cloud photographs taken at 30,000-ft. elevation. Similar counts on photographs taken with the same cloud chamber at 800 ft. and 14,100 ft. above sea level already have been reported.[2] A direct comparison of the data at the three elevations may be made because the distribution of dense material around the cloud chamber, the strength of the magnetic field, and the size and arrangement of the Geiger counters are essentially identical in all three cases.

TABLE II. Summary of data, giving the percentage of photographs of each type.

Altitude	Number of tracks appearing on each photograph: 1	2–4	5–10	11–100	>100
800 ft.	85.7	11.0	2.12	1.2	0
14,100 ft.	57.6	23.0	10.7	8.3	0.22
30,000 ft.	41.3	33.9	15.4	9.0	0.26

[2] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. 50, 263 (1936).

TABLE III. Frequency of occurrence *per unit time* of single particles and showers relative to the frequency of their occurrence at 800-ft. elevation.

Altitude	Number of tracks appearing on each photograph 1	2–4	5–10	11–100
800 ft.	1	1	1	1
14,100 ft.	2.7	8.4	20	28
30,000 ft.	13.5	87	203	210

In practically all cases the showers observed originate in the large amount of heavy material which surrounds the chamber. Although more than 80 percent of the solid angle formed by the Geiger counters is free of all dense material except that represented by the cloud chamber itself and, in the case of the 30,000-ft. data, by the thin aluminum skin of the airplane, the mass of copper and iron lying outside this solid angle is quite effective in producing showers which can actuate the counters. At the two lower elevations the cloud chamber contained a lead plate of 3.5-mm thickness, which was absent at the 30,000-ft. elevation, for those photographs which were analyzed with respect to the electron showers. The presence of the lead plate does not seriously affect the statistics because only a small proportion of the showers were observed to originate in the plate.

Table I gives, for each elevation, the number of counter-actuated photographs showing, respectively, a single track, a group of 2 to 4 tracks, a group of 5 to 10 tracks, and a group of 11 to 100 tracks. Only groups of electrons resulting from cascade showers are included and not groups of particles which result from nuclear disintegrations. In Table II the percentage distribution of each class of photographs is given for each of the three elevations.

The relative frequency of occurrence *per unit time* of single tracks and showers is given in Table III. These values can be computed from Table II since it is known that, for this experimental arrangement, the ratio of the counting rates at 14,100 ft. and at sea level is 4.0, while between 30,000 ft. and sea level the ratio is 28.

In agreement with the data previously reported for 14,100 ft., the new data show that the rate of increase of the electron showers with altitude is much more rapid than is the rate of increase of the single particles, and that the increase with altitude is greater for the large showers than for the small ones.

The data gathered at 30,000 ft. show further that the character of the radiation with respect to the relative numbers of showers observed changes less in the range from 14,100 ft. to 30,000 ft. than it does in the range from sea level to 14,100 ft. This can be seen (Table II) from the fact that the *percentage* of the photographs which show large showers is comparable at the two higher elevations, but is much lower in the case of the photographs made near sea level.

Many experiments have previously been carried out in which the intensity of the cosmic radiation has been measured as a function of altitude. The results of these experiments vary markedly, depending upon the relative sensitivity of the measuring equipment to the various components of the radiation. Thus, a comparison between the new data here reported and those obtained by other observers, using different experimental arrangements, cannot be expected to yield more than qualitative agreement. However, a rough comparison will be made.

Counter telescope experiments show a factor of 6 in the relative intensities at 30,000 ft. and at sea level of the cosmic-ray component which is capable of penetrating 4 to 18 cm of lead.[3] This value may be compared with the factor of 13.5 found in the relative intensities of the singly occurring particles at the two elevations (cf. Table III). The intensity factors may be expected to differ because the two experimental methods are widely different and because of experimental uncertainties. In addition, the group of single particles found in the cloud-chamber experiments can be expected to include, in addition to penetrating particles, a small number of individual electrons originating in atmospheric showers and a large number of protons which will not penetrate 4 cm of lead (cf. Section V of this paper).

In recent experiments by Bridge, Rossi, and Williams[4] the number of "bursts" in an ionization chamber under six inches of lead has been

[3] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).

[4] H. Bridge, B. Rossi, and R. Williams, Phys. Rev. **72**, 257 (1947).

measured at sea level and at 30,000 ft. These investigators have found it possible to distinguish between bursts resulting from electron showers and those resulting from heavily ionizing particles by a study of the shape of the pulse from the ionization chamber. They find that the *total* number of bursts which represent an ionization greater than that corresponding to contamination alpha-particles and greater than that corresponding to 35 shower particles, increases by a factor of about 260 between sea level and 30,000 ft. The corresponding increase in the fraction of the bursts which they ascribe to shower particles alone is about 200. This value may be compared with the increase in the number of showers observed in the present experiments, *viz.*, 87, 203, and 210 for showers of 2 to 4, 5 to 10, and 11 to 100 particles, respectively. In making a comparison between the two experiments, one must make allowance for the fact that the cloud chamber, which has an effective size only one-fifth that of the ionization chamber, will record a smaller number of particles of a given size shower than will the ionization chamber. Thus the cloud-chamber data corresponding to a certain number of particles should be compared with the burst data corresponding to many more particles. Under this consideration, the results may be considered to be in qualitative agreement.

The photographs at 30,000 ft. show numerous cases of heavy tracks (Fig. 1) quite similar to those previously observed at 14,100 ft.[2] On a set of 3914 photographs, a count of single heavily ionizing particles shows a total of 378 which either have a range too long to represent alpha-particles arising from contamination, or which are definitely identified either as protons or mesotrons.

Because of their heavy ionization these particles are all of relatively low energy: less than about 100 Mev if they are protons and less than about 10 Mev if they are mesotrons. In the majority of cases where identification is possible the particles are found to be protons, and in all cases where it is possible to ascertain the direction in which the proton is traveling, its charge is found to be positive. Only a few tracks are observed which can definitely be identified as due to mesotrons. This is to be expected since mesotrons do not begin to ionize heavily until they have reached a much lower energy and have a much smaller residual range than do protons.

The distribution in direction of the single heavily ionizing particles is almost isotropic, thus indicating that in most cases they originate in nuclear disintegrations.

A preliminary study of the photographs indicates that only 3 percent of the single heavy tracks are definitely associated in time with the tracks of electron showers. In most cases the heavily ionizing particles do not directly actuate the Geiger counters. The data have not yet received sufficient study to permit a determination of the frequency of occurrence of heavily ionizing particles as a function of altitude.

In this same set of 3914 photographs there were present 72 cases in which two or more particles emanated from a common point, usually in the material surrounding the chamber, or in a plate placed across the chamber, thus indicating their origin in nuclear disintegrations. Examples are shown in Figs. 2, 3, and 4. Where identification is possible these particles are nearly always found to be protons, although a few cases of mesotrons and alpha-particles are observed. The disintegrations are sometimes produced by nonionizing particles, presumably neutrons, and sometimes by high energy, lightly ionizing particles, presumably either protons or mesotrons. In the case of a disintegration produced by an ionizing particle (e.g., Fig. 2), the secondary particles of high energy are ejected almost in the direction of the incoming particle, as one would expect from momentum considerations, while the particles of low energy (10 to 50 Mev) are often ejected at large angles to that direction. An example of the low energy electrons (1 Mev or less) which are sometimes observed is shown in Fig. 4. These presumably arise from the absorption of photons produced in the disintegration. The largest number of particles observed emanating from a single disintegration is seventeen, although because this disintegration occurred in a wall of the chamber, it may be assumed that a considerably larger number were actually produced.

IV. EXAMPLES OF MESOTRON TRACKS

The classification of cloud-chamber particles as electrons, mesotrons, or protons requires care-

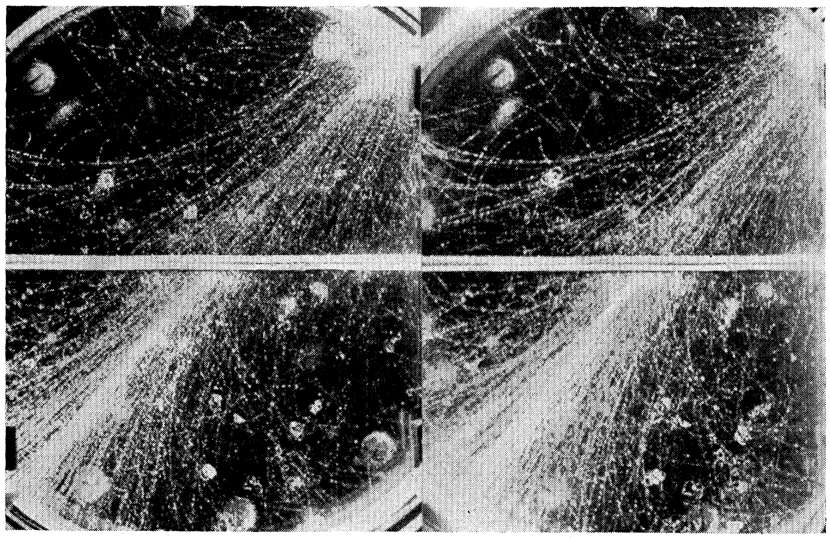


FIG. 1. This is the largest electron shower photographed during the high altitude flights. The shower has a well defined core and undergoes multiplication in traversing the 3.5-mm lead plate placed across the center of the chamber. By actual count, the lower limit on the number of tracks above the plate is 250. The energy per particle is of the order of 125 Mev. giving a total energy of the order of 30 Bev. This is probably a very low estimate of the total energy of the visible shower particles. (The photographs of Figs. 1 to 11 have been reproduced in such a manner that the reader may view them stereoscopically, with the aid of simple magnifying lenses. Some persons find it possible to obtain the three-dimensional effect with the unaided eye.)

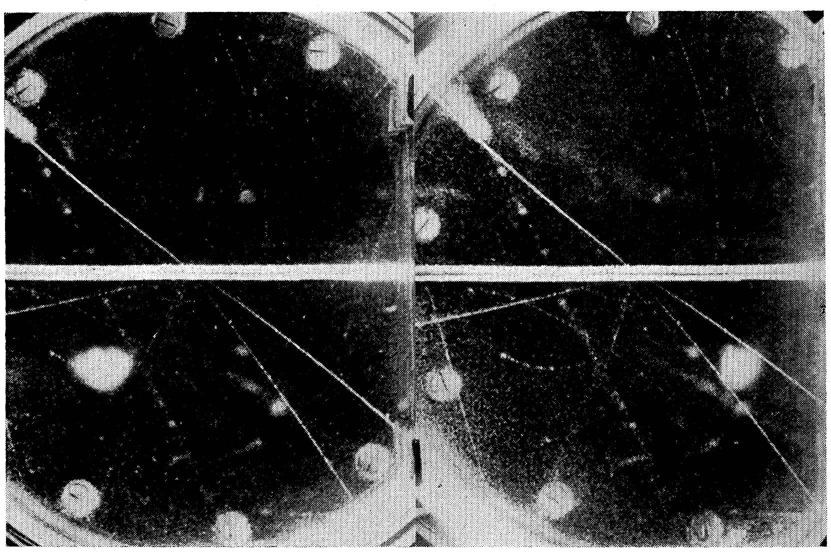


FIG. 2. A lightly ionizing particle produces a nuclear disintegration in a 3.5-mm lead plate giving rise to three lightly ionizing particles and four heavily ionizing particles. The lightly ionizing particles, which may be either mesotrons or protons of high energy, are all ejected in a direction closely parallel to that of the incoming particle. The four heavily ionizing particles are ejected almost at right angles to that direction. Three of the heavily ionizing particles are positively charged and have momenta in the range (4 to 8) $\times 10^5$ gauss-cm and can be identified definitely as protons. The fourth heavily ionizing particle, its track too short for accurate measurement, is also positive and has a momentum of the order of 10^6 gauss-cm.

ful interpretation of the data in order that the classification may have meaning. The particle type is usually determined by a combination of two of the following: the range, the ionization, and the magnetic curvature. If the data are not subject to uncertainties, such as that resulting from multiple scattering of the particle in the gas of the cloud chamber,[5] an accurate mass determination is possible. In the usual cloud-chamber photographs where special arrangements for mass determination are not employed,[6] it is a rare photograph that permits an accurate mass determination to be made. In fact, photographs from which one can conclude unambiguously that a given particle is a mesotron are almost equally as rare.

When scattering errors are high, such as in cases in which magnetic fields of intensities of the order of 1000 gauss or less are used or in

[5] H. A. Bethe, Phys. Rev. **70**, 821 (1946).

[6] For an example of a special experimental arrangement suitable for making mesotron mass measurements, see that of W. B. Fretter, Phys. Rev. **70**, 625 (1946).

cases in which the observed particles are near the ends of their ranges, it is not only impossible to obtain an accurate mass determination, but it is impossible even to determine whether the particles are protons or mesotrons.

Two examples of tracks among the 30,000-ft. data which can be identified definitely as mesotrons will be discussed in some detail. These photographs, which are shown in Figs. 5 and 6, do not provide accurate mass measurements, but it is possible to set lower and upper limits to the masses, which clearly eliminate the possibility that either of the particles is an electron or a proton. In addition, it seems unlikely that either of the particles has a mass as low as 100-electron masses. A third example, Fig. 8, shows a heavily ionizing particle which comes to rest in the gas of the chamber and which shows evidence of considerable scattering. Its ionization, curvature, and range do not permit one to distinguish whether it is a mesotron or proton (cf. the disintegration particles, presumably protons, in

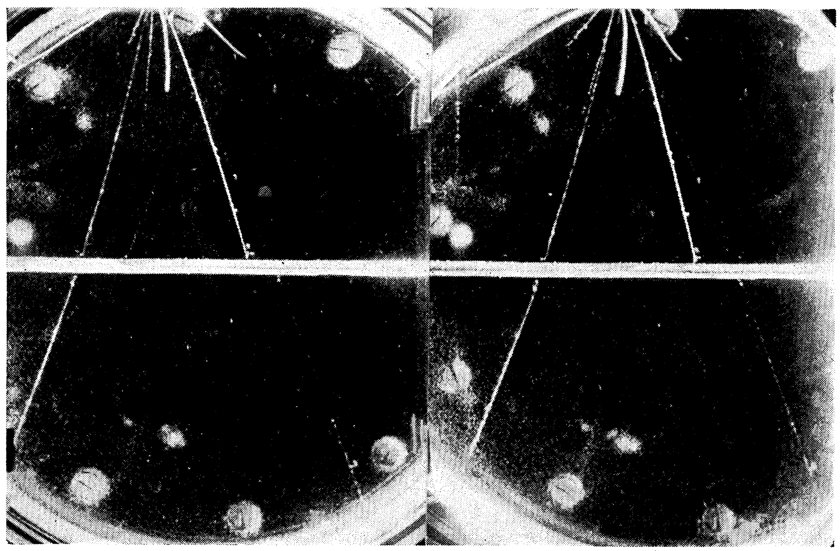


FIG. 3. A nine-particle disintegration occurs in the chamber wall. Two of the particles penetrate the 3.5-mm lead plate while a third stops in the plate. The identifiable particles are all protons. The large scattering of the two protons which are near the ends of their ranges should be noted.

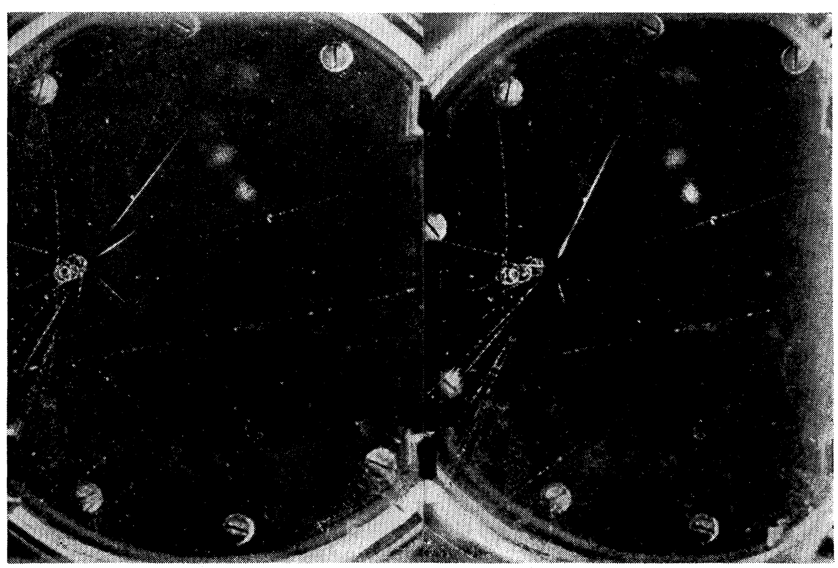


FIG. 4. A seventeen-particle disintegration, which occurs in the back wall of the chamber, shows both heavily and lightly ionizing particles. The track which can be seen spiraling out from the center of the disintegration is a positron of about 200-kilovolts energy and probably results from a photon. Several other disintegrations have been found also to contain very low energy electrons. All of the remaining tracks except the two heaviest ones may represent either protons or mesotrons. The two heaviest tracks, since they show no appreciable curvature in the magnetic field, are probably to be ascribed to alpha-particles.

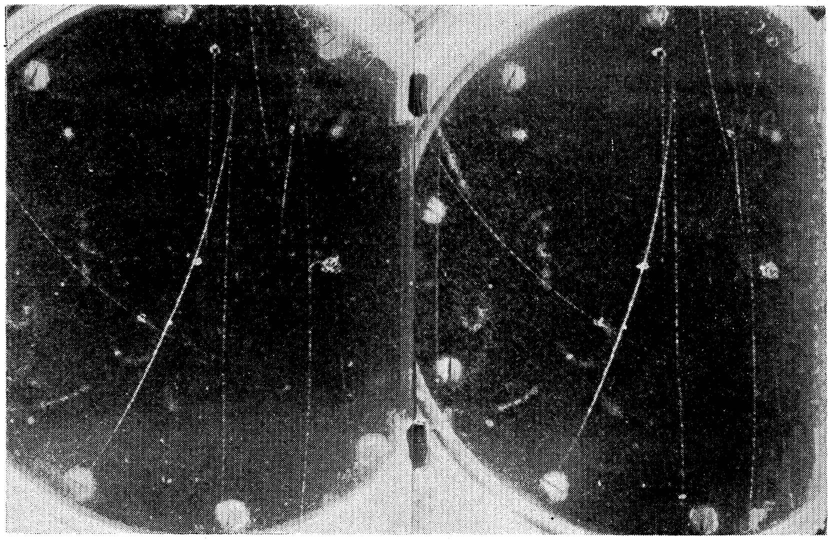


FIG. 5. This photograph shows the track of a heavily ionizing particle, which can be unambiguously identified as a mesotron. The other particles are of minimum ionization. (This photograph is more fully discussed in Section IV.)

Fig. 3), but the photograph is of particular interest because the heavily ionizing particle appears to disintegrate into an electron.

The mesotron shown in Fig. 5 has an $H\rho = 1.7 \times 10^5$ gauss-cm, a measurement which is not subject to scattering error. Its charge is positive if it is traveling downward. Its specific ionization is clearly above the minimum value, as may be seen by comparing this track with the other tracks which appear in the same photograph, all of which represent particles whose specific ionization is near the minimum value for fast particles of unit charge. In particular, the vertical track near the center of the chamber is in a region of comparable illumination and is therefore favorably located for such a comparison. (Stereoscopic examination of the photograph will make this evident.) Although a quantitative determination of the specific ionization of the mesotron is not possible here, the evidence presented by the photograph does enable one to draw some conclusions with respect to the mass. A mesotron of this magnetic curvature and of a mass equal to 200-electron masses should have a specific ionization which is 3.5 times the minimum, a value which is quite consistent with the

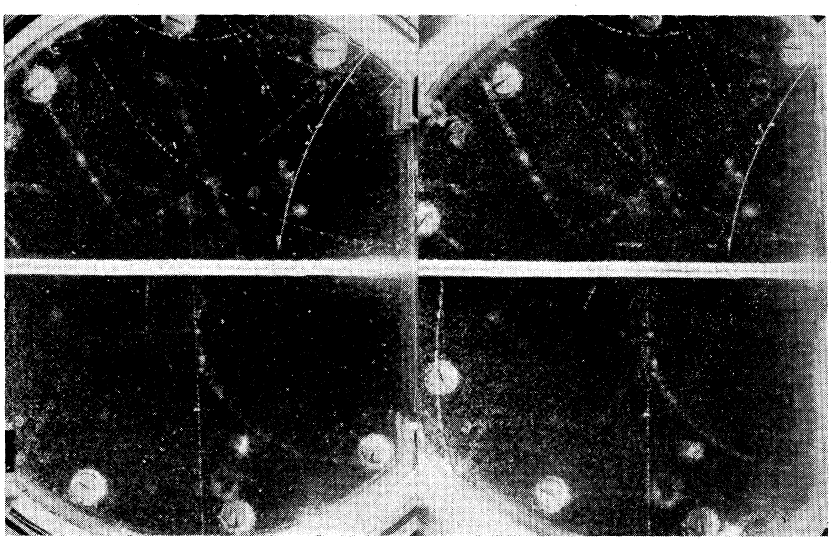


FIG. 6. The heavily ionizing particle, which stops in the 3.5-mm lead plate, can be definitely identified as a mesotron. Its mass cannot be greater than 500-electron masses. It is unlikely that its mass is as low as 100-electron masses. (A more detailed discussion is given in Section IV.)

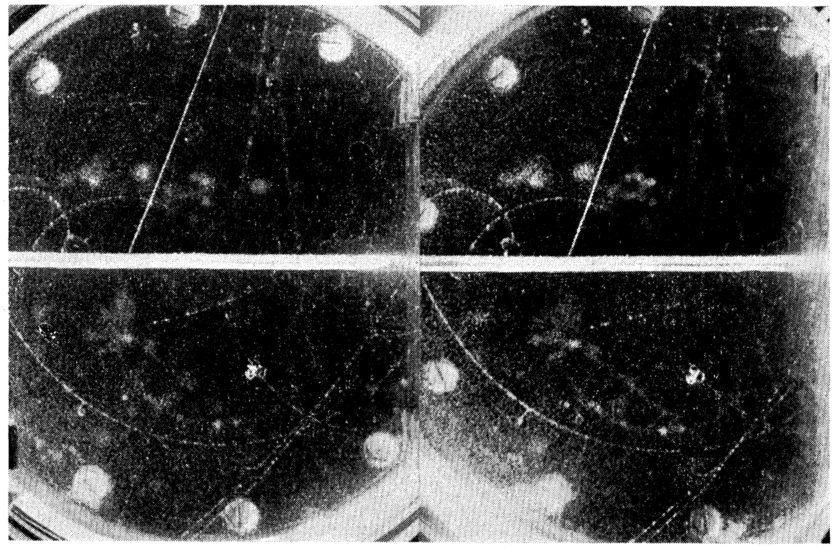


FIG. 7. This is an example of a proton which comes to rest in a 3.5-mm lead plate. It is shown for comparison with the mesotron track of Fig. 6. Figures 2, 3, 9, and 10 show other examples of proton tracks.

appearance of the mesotron track in the photograph. It appears unlikely that the mesotron can have a mass as low as 100 electron masses for then the specific ionization would be only 1.4 times the minimum, a value which is too low to be consistent with the appearance of the track. Assigning a close *upper* limit to the mass of a particle in a case such as this is difficult because the appearance of a track does not change markedly after the ionization has increased to the point where the track loses its "beaded" appearance and becomes continuous. Under the conditions of our experiment it is estimated that this occurs for a specific ionization of about five times the minimum. In this instance, then, the possibility that the mass can be as high as 300 electron masses, which would correspond to an ionization six times the minimum, cannot be ruled out. On the other hand, the particle cannot be a proton because a proton of this magnetic curvature would have an ionization 100 times the minimum and a range of only 2.2 cm, both of which values are inconsistent with the photograph. In addition, the particle does not exhibit

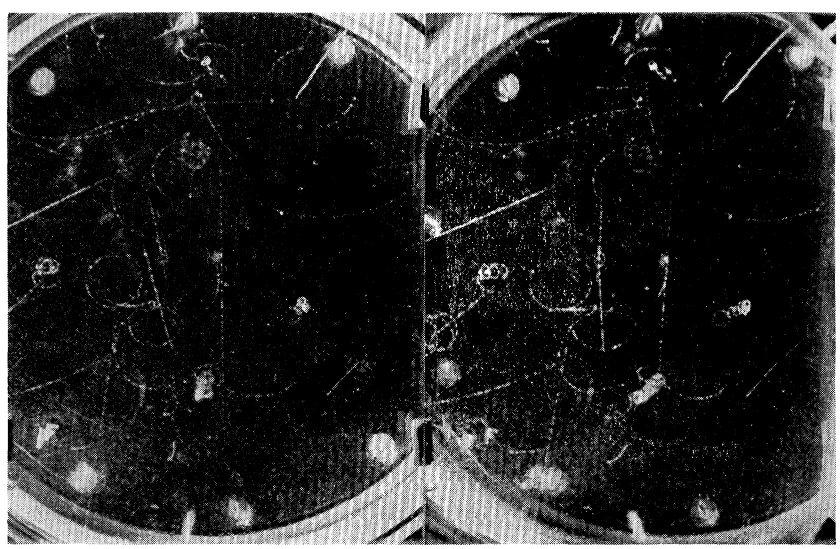


FIG. 8. Entering the chamber in the upper right-hand region, a heavily ionizing particle appears to give rise to a 25-Mev disintegration electron which can be seen passing horizontally across the chamber from a point near the terminus of the heavy track. The space association can be verified by stereoscopic examination of the photograph. An electron shower and at least one other heavily ionizing particle appear in the same picture. Further discussion is given in Section IV. (The direction of the magnetic field in this photograph is opposite to that of the other photographs.)

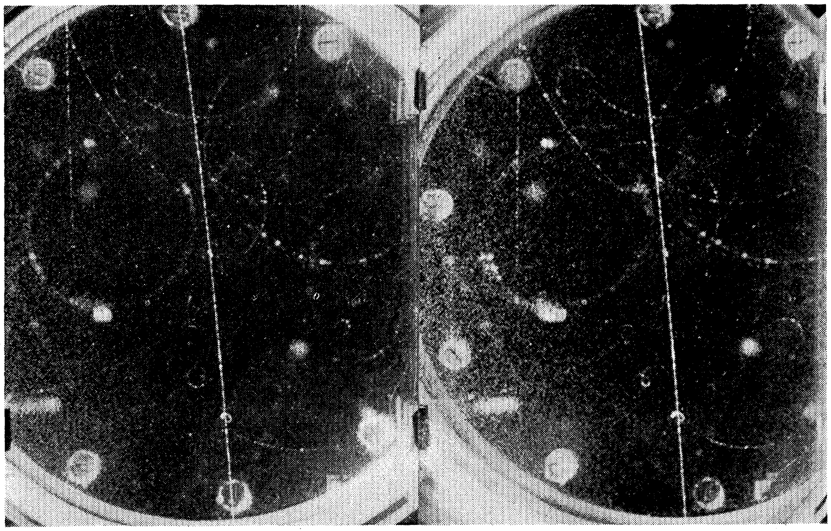


FIG. 9. This is an example of one of the protons occurring among the tracks used in determining the energy spectrum of single particles. The proton has a magnetic curvature, $H\rho$, of 1.6×10^{6} gauss-cm and is positive if it is traveling downward. A proton of this momentum has an energy of 110 Mev. an ionization of 3.2 times the minimum, and a range of 11 g/cm² (in air). All these values are consistent with the photograph. (There also appears an electron shower which probably is not time coincident with the proton.)

the relatively large scattering that one would expect of a proton of this momentum.

The mesotron shown in Fig. 6 has an $H\rho$ of 8×10^{4} gauss-cm. It is definitely not a proton; in fact, its mass cannot exceed 500 electron masses for that is the greatest mass a particle of this momentum can have and still have a residual range as great as the 7 cm of track actually observable. Assumed values of the mass equal to 300, 200, and 100 electron masses would correspond to values of the specific ionization of 19, 10, and 3.7 times the minimum, respectively. Since this mesotron track has the appearance of being completely continuous, with the droplets wholly unresolved, the higher values of mass, 300 and 200, are both consistent with the photograph, while a mass of 100 electron masses should be excluded because a specific ionization of 3.7 times the minimum seems to be too low to reconcile with the photograph.

It is not possible here to determine the direction in which the mesotron is traveling. If it is traveling downward its sign of charge is negative, and it definitely stops in the 3.5-mm lead plate. A calculation of the residual range of the mesotron shows that it should be absorbed in the

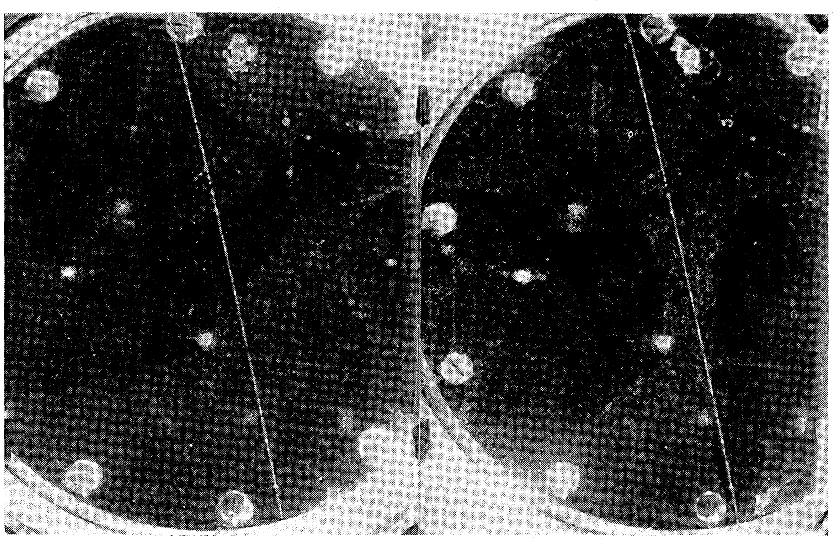


FIG. 10. This is another example of a proton found among the energy spectrum photographs. It has an $H\rho$ of 1.3×10^{6} gauss-cm and is positive if traveling downward. A proton of this momentum has an energy of 75 Mev, an ionization of 4.4 times the minimum, and a range of 5.5 g/cm². The values are all consistent with the photograph. This particle has slightly more than the minimum momentum required of protons for penetration of the lower chamber wall to reach the lower Geiger counter. (There also appears a small electron shower which is probably not time coincident with the proton.)

TABLE IV. Momentum distributions for all tracks (random and counter-controlled).

Magnetic curvature ($H\rho$ in 10^6 gauss-cm)	Number of particles in interval all particles	positives	negatives
0.0 - 0.49	40	22 (1)*	18
0.25- 0.74	27	17 (1)	10
0.50- 0.99	18	12 (2)	6
0.75- 1.24	23	17 (4)	6
1.00- 1.49	20	12 (5)	8
1.25- 1.74	27	21 (6)	6
1.50- 1.9	30	25 (3)	5
1.75- 2.24	23	18	5
2.0 - 2.4	12	10	2
2.5 - 3.4	22	14	8
3.0 - 3.9	21	15	6
3.5 - 4.5	16	10	6
4.0 - 6.0	26	16	10
5.0 - 7.0	18	12	6
6.0 - 8.0	13	11	2
7.0 - 9.0	9	7	2
8.0 -12.0	11	8	3

* Numbers of protons in each energy interval are shown in parentheses.

TABLE V. Momentum distributions for counter-controlled tracks.

Magnetic curvature ($H\rho$ in 10^6 gauss-cm)	Number of particles in interval all particles	positives	negatives
0.0 - 0.49	24	13	11
0.25- 0.74	21	12	9
0.50- 0.99	15	9	6
0.75- 1.24	18	12	6
1.00- 1.49	16	8	8
1.25- 1.74	25	19	6
1.50- 1.9	28	24 (2)*	4
1.75- 2.24	20	16	4
2.0 - 2.4	12	10	2
2.5 - 3.4	21	14	7
3.0 - 3.9	21	15	6
3.5 - 4.5	15	9	6
4.0 - 6.0	25	15	10
5.0 - 7.0	18	12	6
6.0 - 8.0	12	10	2
7.0 - 9.0	9	7	2
8.0 -12.0	11	8	3

* Numbers of protons in each energy interval are shown in parentheses.

plate if its mass is greater than about 65 electron masses. A negative mesotron would be expected to enter a nucleus in the lead plate and produce a disintegration, but it is quite probable that any protons or alpha-particles produced would not have sufficient energy to emerge from the plate.

For comparison with the tracks of mesotrons, an example of a proton track of $H\rho=7\times10^5$ gauss-cm is shown in Fig. 7. The specific ionization exhibited in this track exceeds the minimum value by a factor of more than four since the droplets are unresolved and the track appears continuous. A particle of this magnetic curvature whose specific ionization exceeds the minimum value by at least a factor of four would have a mass equal to at least 900 electron masses. The specific ionization of a proton of this magnetic curvature is 12 times the minimum, a value completely consistent with the photograph. Thus, the possibility that the track represents a mesotron is ruled out completely, and the particle must be a proton.

The photograph shown in Fig. 8 may repre-

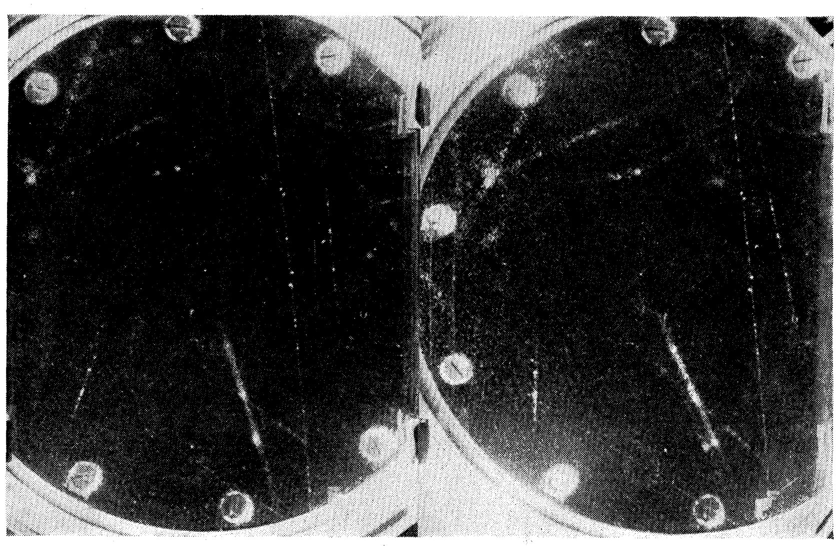


FIG. 11. This is a track representing minimum ionization, which is shown for comparison with the proton tracks of Figs. 9 and 10. It has about the same momentum ($H\rho=1.6\times10^6$ gauss-cm) as the protons and so cannot itself be a proton. It may be either a mesotron or an electron insofar as its ionization and magnetic curvature are concerned. A mesotron of this momentum would have an energy of 380 Mev, an ionization equal to the minimum, and a range of 200 g/cm² (in air). (The three photographs, Figs. 9, 10, and 11, were obtained on the same flight; in fact, the photographs of Figs. 10 and 11 were obtained in two consecutive expansions.)

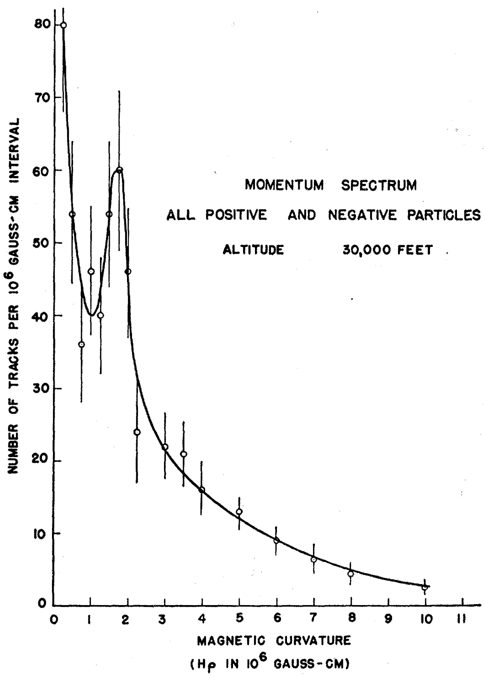


FIG. 12.

sent an additional case[7] of the disintegration of a mesotron in which the energy of the resulting electron is measurable. The track of a heavily ionizing particle appears in the upper right-hand region of the chamber. The track of a lightly ionizing particle originates very close to the terminus of the heavy track and extends almost horizontally across the chamber to the left. If these two tracks represent, respectively, the mesotron and its disintegration positron, then the disintegration occurs just outside the illuminated region of the cloud chamber. If the two tracks are each considered to be extended, then stereoscopic observation shows that they actually seem to converge to a single point or very nearly so. (A unique extension of the heavily ionizing track is difficult because of the large degree of scattering in the gas which it exhibits at its lower end, a behavior which is characteristic of mesotrons near the end of their range.) It is difficult to evaluate the chance that two independent tracks should pass so close to one another in space, although the possibility for such a coincidence is felt to be rather small, even after allowance is made for the fact that many other electron tracks also appear on the same photograph.

Positive identification of the heavily ionizing track is not possible on the basis of its curvature and range. It has an apparent $H\rho=6\times10^4$ gauss-cm, which value is subject to a large error because of the high probability of scattering of the particle in the gas. The mass of the particle computed from its magnetic curvature and its range is 450 electron masses, with a 6 percent chance that it is 100 electron masses or less and a 13 percent chance that it is 1840 electron masses or more.[5]

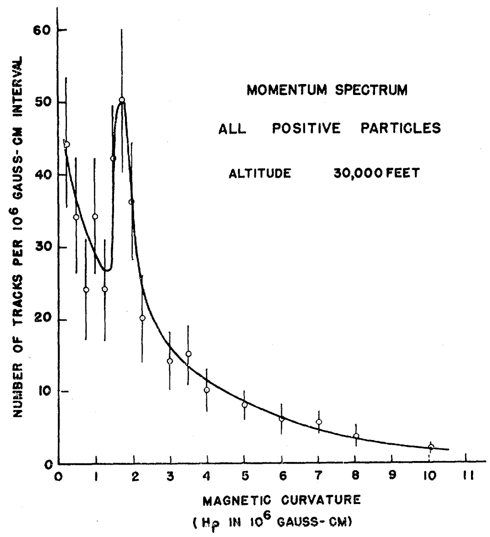


FIG. 13.

The positron track has an $H\rho=8.4\times10^4$ gauss-cm corresponding to an energy of 25 Mev, a value which within experimental uncertainty is the same as the value of 24 Mev previously reported[7] for the energy of a positron resulting from the disintegration of a mesotron. Out of the total of 9000 photographs these two cases represent the only ones involving sharp tracks which could possibly be taken to represent the disintegration of a mesotron and the production of an electron.

V. ENERGY SPECTRUM OF MESOTRONS AND PROTONS

Magnetic curvature measurements on a selected group of 246 cloud tracks of cosmic-ray

[7] C. D. Anderson, R. V. Adams, P. E. Lloyd, and R. R. Rau, Phys. Rev. **72**, 724 (1947).

particles obtained at an altitude of 30,000 ft. have been made. These photographs were taken in a magnetic field of 7500 gauss, with the cloud chamber operated by the coincidence of pulses from two Geiger counters, one placed above and one below the chamber.

Tracks for energy measurement were taken in a series of flights carried out specifically to obtain energy data. No plates were used inside the chamber, so that tracks could be as long as possible and so that turbulence within the chamber could be held to a minimum. Because temperature conditions in the immediate vicinity of the chamber were quite uniform during these flights, the accuracy of the curvature measurements approaches the limitations of accuracy of a cloud chamber of this size and magnetic field strength.

All tracks occurring singly and of at least 8-cm length were measured. The curvatures of all

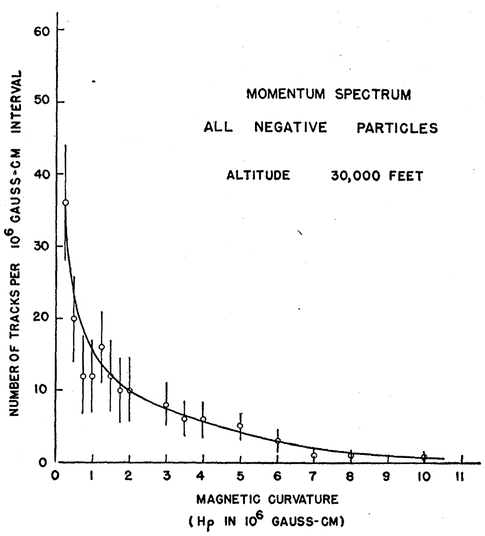


Fig. 14.

tracks of radii less than 140 cm were measured by direct comparison of the projected tracks with a family of circular arcs. For all other tracks, measurements were made on the original negatives by means of a comparator, coordinates of points along the tracks being plotted on graph paper. When plotted with a magnified scale for abscissas, a circular track forms a parabola to the first approximation. Deviations from a parabola show the extent of distortion of the tracks, and hence give an excellent indication of the validity of the measurements on very high energy tracks. The degree of curvature in the parabola together with the scale used in plotting abscissas gives the radius of curvature of the track.

For low momentum tracks the accuracy of the measurements is limited by the homogeneity of the magnetic field, while for high momentum tracks the accuracy of measurement is limited by distortions produced by mass motion of the gas within the cloud chamber. Since the magnetic field is homogeneous to about 10 percent, the accuracy of measurements of momenta up to 2×10^6 gauss-cm is about 10 percent. Above this momentum the accuracy of measurements decreases. The measurements of 5×10^6 gauss-cm are accurate to ± 20 percent; of 7×10^6 gauss-cm, $+40$ percent, -30 percent; of 11×10^6 gauss-cm, $+100$ percent, -40 percent. For higher momentum tracks uncertainties in the curvature measurements permit only the placing of a lower limit of 1.5×10^7 gauss-cm on the momenta.

Of the 246 tracks, 206 are classified as counter-controlled tracks and 40 as random tracks. "Random" particles are those which cannot have tripped the chamber either because the positions of their tracks in the chamber preclude the possi-

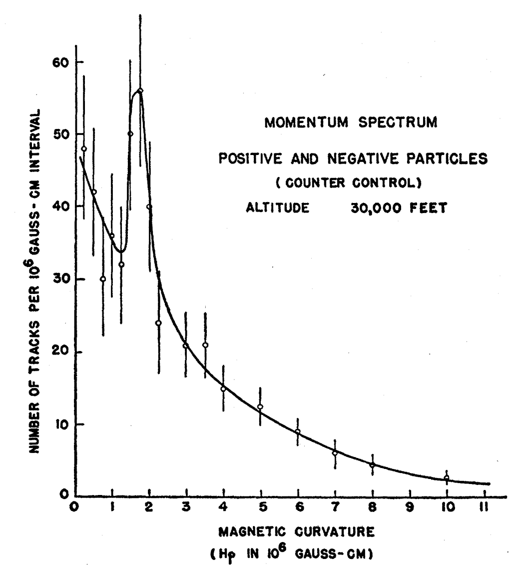


Fig. 15.

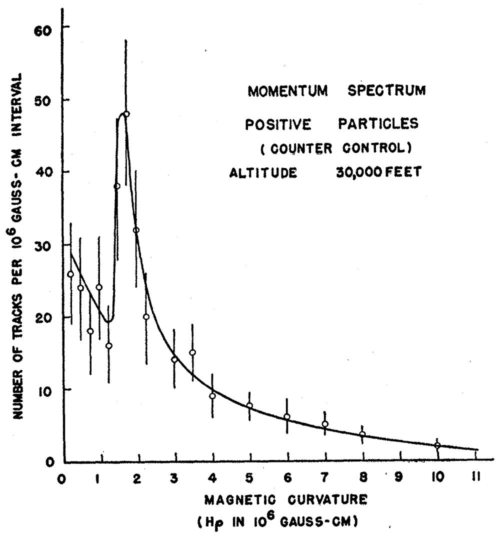


FIG. 16.

bility of their passing through both counters or because their extreme sharpness shows that they have passed through the chamber after the expansion has taken place. (Tracks occurring prior to counter-actuation are not included because they lack the sharpness necessary for accurate measurement.) All other tracks are called "counter-controlled" tracks. Among the latter are probably a few tracks which entered the chamber before or after the expansion, but whose sharpness is not noticeably different from that of counter-controlled tracks. It is presumed that the number of such tracks is too small to affect the energy distribution appreciably.

All tracks of measurable curvature are classified according to sign of electric charge. The sign of the charge of a cosmic-ray particle is uniquely determined by its direction of curvature in a magnetic field, provided that the direction of travel of the particle is known. For the tracks here reported the direction of the magnetic field is such that positive tracks curve clockwise while negative tracks curve counter-clockwise. Because it is impossible to tell the direction of travel of the particles, but since it is known that most cosmic rays are traveling downward, it is assumed for purposes of classification that *all* the particles are moving downward. Data for eight random tracks which were nearly horizontal are not included here. All particles are taken to be singly charged.

All tracks are classified as to whether their specific ionization is equal to or greater than the minimum ionization for a singly-charged particle. Inasmuch as these tracks are quite

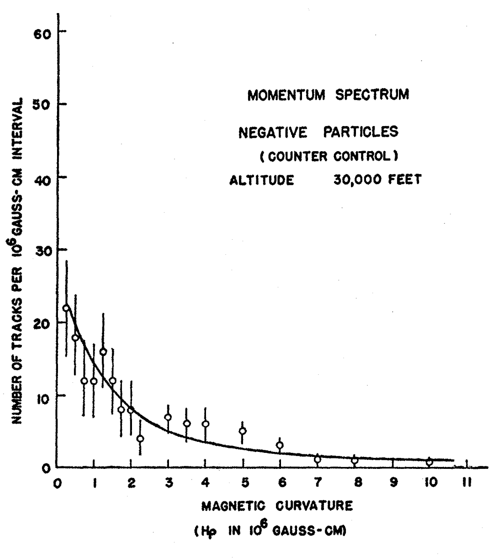


FIG. 17.

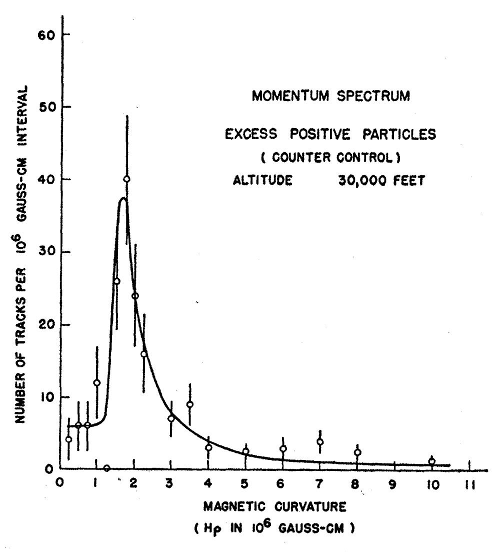


FIG. 18.

FIGS. 12–18. In Figs. 12 to 18 are shown the differential momentum distributions for single particles in each of several classifications. The small circles are the experimental points, while the vertical lines give an indication of the statistical uncertainties of the points. Smooth curves have been drawn through the experimental points.

sharp, the single ions along the tracks are not resolved, and an accurate ion count is impossible. Since the eye is unable to distinguish the density of a sharp track which has less than 3 to 4 times the minimum ionization from the density of a track of minimum ionization, the classification "greater than minimum ionization" implies an ionization greater than 3 to 4 times the minimum. The classification "minimum ionization" may imply an ionization almost as great as 3 to 4 times the minimum. Figures 9, 10, and 11 show three representative tracks of the same momentum, two of which have "greater than minimum ionization" while the other is of "minimum ionization."

Because the magnetic curvature measures the momentum rather than the energy of a particle, the "energy" distributions are given in terms of the magnetic curvature, $H\rho$, in gauss-cm. Tables IV and V give the numbers of particles in overlapping momentum intervals. Figure 12 shows graphically the momentum distributions for all tracks (regardless of sign). Figures 13 and 14 show the distributions for positive tracks and for negative tracks, respectively. These include both counter-controlled tracks and random tracks. Figures 15, 16, and 17 show similar curves for counter-controlled tracks only. Figure 18 shows the excess of positive over negative tracks for the counter-controlled group.

The momentum distribution includes in the main the following particles: mesotrons (positive and negative), protons, and a few single electrons, the latter probably occurring principally at the low momentum end of the distribution. Because these data include only particles which occur singly, it is assumed that only very few of them are shower electrons. The fact that no negative particle is found to have an ionization and momentum consistent with the e/m of a proton can be taken as evidence, first, that the assumption that nearly all particles are traveling downward is valid, since a *positive* proton traveling upward would appear to be negatively charged, and second, that negative protons do not occur (in thus far detectable numbers) at 30,000-ft. altitude.

The following experimental results are evident from the data: (1) positive tracks are much more numerous than negative tracks;[8] (2) the positive and negative spectra are quite dissimilar; and (3) a number of tracks (11 ± 3 percent of the total) have momenta greater than 1.5×10^7 gauss-cm and cannot be classified as to sign of charge.

In the momentum range $(2 \text{ to } 10)\times10^6$ gauss-cm both positive and negative particles decrease in numbers in much the same fashion. Although it cannot be said (because of statistical uncertainties) that the numbers decrease according to any mathematical law, the experimental data are consistent with an energy power law, $E^{-\gamma}$ with $\gamma=1.5$. A much more rapid decrease ($\gamma=2.8$) is usually predicted for the particles of higher energies ($E<7$ Bev).

The presence of the large excess of positive particles at 30,000 ft. shows a change in the characteristics of the radiation between this altitude and sea level where, it will be recalled, the penetrating component consists principally of positive and negative mesotrons, which have similar energy spectra and which occur in nearly equal numbers, the excess of positives being about ten percent of the total number of particles.[1, 9] Existing cloud-chamber energy data are insufficient to determine with certainty whether the positive excess at 14,100 ft. is as great as that at 30,000 ft.; however, a small group consisting of 48 measured tracks[10] shows a positive-to-negative particle ratio of 1.8 at Pikes Peak, indicating that the change in the characteristics of the penetrating component with altitude may be much smaller between 14,100 ft. and 30,000 ft. than between sea level and 14,100 ft.

The dissimilarities in the positive and negative spectra at 30,000 ft. show that there exists among the positive particles a component which

[8] A second set of photographs for energy measurements has been taken with the direction of the magnetic field reversed. Although a detailed analysis of these has not yet been made, the large excess of positive particles at 30,000 ft. is confirmed.

[9] E.g., P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937); D. J. Hughes, Phys. Rev. **57**, 592 (1940).

[10] Unpublished Pikes Peak data of Anderson and Neddermeyer.

has no symmetric counterpart of negative charge. If one assumes that positive and negative mesotrons exhibit the same symmetry at 30,000 ft. as at sea level, the negative spectrum of Fig. 17, which probably consists principally of mesotrons, can be taken to represent also the spectrum of *positive* mesotrons. The positive excess of Fig. 18 may then represent another type of particle.

The data are consistent with the interpretation that the positive excess consists principally of protons. Supporting this hypothesis are the following: first, identifiable protons constitute 30 percent of the positive particles in the momentum range $(0.4 \text{ to } 1.6)\times 10^6$ gauss-cm, a range in which protons are distinguishable from other particles; second, the positive excess spectrum shows a relatively sharp cut-off at about 1.2×10^6 gauss-cm, which is the minimum momentum which a proton must have to penetrate the material between the chamber and the lower Geiger counter to produce a coincidence. (The greater portion of the identifiable protons are not among the counter-controlled tracks because the proton cut-off occurs in the region of momenta where protons have about 2 to 4 times the minimum ionization.)

An abundance of low energy protons already has been found in photographic emulsion experiments.[11] These protons are produced in nuclear disintegrations and by knock-on collisions of neutrons with nuclei. Such protons are most abundant in the energy range 5 to 30 Mev, with only a few having energies up to 80 Mev.[12] The present data give the first direct indication that *higher* energy protons exist in relative abundance at high altitudes. The high energy protons probably are of secondary origin also; if the primary radiation does contain a large percentage of protons, few of them would be expected to survive, unchanged, in passing through the three meters of water equivalent to the 30,000-ft. level.

The multiple creation of mesotrons in nuclear impacts by high energy protons has been postulated to account for the rapid production of the penetrating secondary radiation in the top of the atmosphere.[13] It will be of interest to look for cloud-chamber examples of this process at high altitudes and in particular to determine whether the process occurs with the frequency which has been postulated. We now have an indication that sufficient high energy protons are present at 30,000-ft. altitude to give a reasonable probability of observing multiple mesotron production. It will be recalled that about ten percent of the single particles have energies greater than 2.5 Bev. If the 2:1 ratio of positive-to-negative particles extends into this energy region (as it does to the highest measurable energies), then 1/30 of all the single particles may well be protons of energies greater than 2.5 Bev. If one assumes a cross section for the multiple process of 2.5×10^{-25} cm^2,[14] then multiple mesotron production can be expected to occur on an average of once in 1500 traversals of a 1-cm carbon plate. In these 30,000-ft. flights, approximately 1000 traversals of a 7.5-mm carbon plate have so far been observed without the occurrence of multiple mesotron production, there being only examples of knock-on electrons and an occasional electron-pair production.

Although these data are consistent with the view that the positive excess may represent protons, it is, of course, equally possible that in the momentum range where it is not possible to differentiate protons from mesotrons by the specific ionization ($H\rho > 1.6\times 10^6$ gauss-cm), the positive excess may consist largely of mesotrons. In fact, one would expect a positive excess in the mesotron component, of about the observed magnitude, if these mesotrons are produced as secondaries of primary protons, and if each primary proton on the average gives rise to about three or four mesotron secondaries. A larger multiplicity for mesotron production would produce a smaller positive excess than that observed.

VI. ACKNOWLEDGMENT

The greater part of this work was carried out under Contract N6onr-102, Task Order No. III, with the Office of Naval Research. We wish to

[11] M. Blau and H. Wambacher, Nature **140**, 585 (1937).
[12] A. Widhalm, Zeits. f. Physik **115**, 481 (1940).
[13] L. W. Nordheim, Phys. Rev. **56**, 502 (1939); M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 930 (1941).
[14] I. Bloch, Phys. Rev. **69**, 575 (1946).

acknowledge also our indebtedness to the U. S. Air Forces for the use of a B-29 airplane and to the U. S. Naval Bureau of Ordnance for the use of laboratory and ground facilities at the Naval Ordnance Test Station at Inyokern, California. In particular, we take pleasure in expressing our personal thanks to the many officers and men connected with the above organizations for the very willing cooperation which has made this work possible. We wish to thank Mr. A. J. Seriff for his help in making many of these measurements.

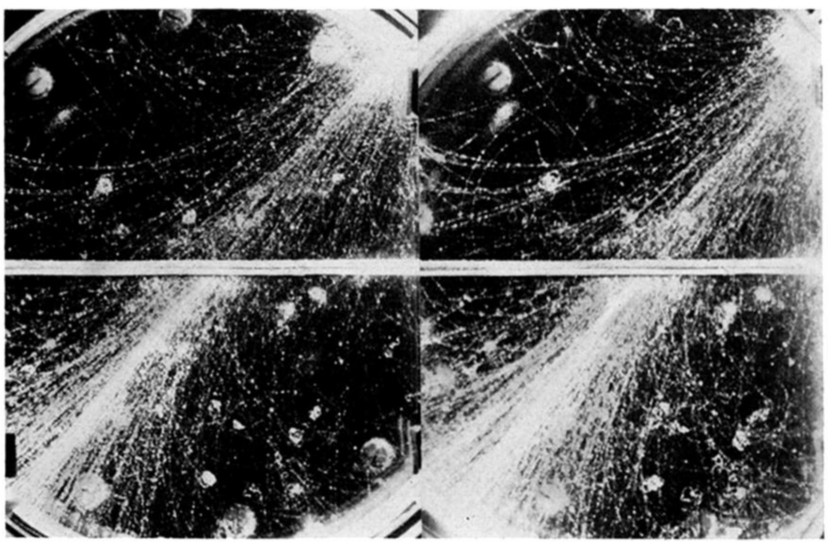


FIG. 1. This is the largest electron shower photographed during the high altitude flights. The shower has a well defined core and undergoes multiplication in traversing the 3.5-mm lead plate placed across the center of the chamber. By actual count, the lower limit on the number of tracks above the plate is 250. The energy per particle is of the order of 125 Mev. giving a total energy of the order of 30 Bev. This is probably a very low estimate of the total energy of the visible shower particles. (The photographs of Figs. 1 to 11 have been reproduced in such a manner that the reader may view them stereoscopically, with the aid of simple magnifying lenses. Some persons find it possible to obtain the three-dimensional effect with the unaided eye.)

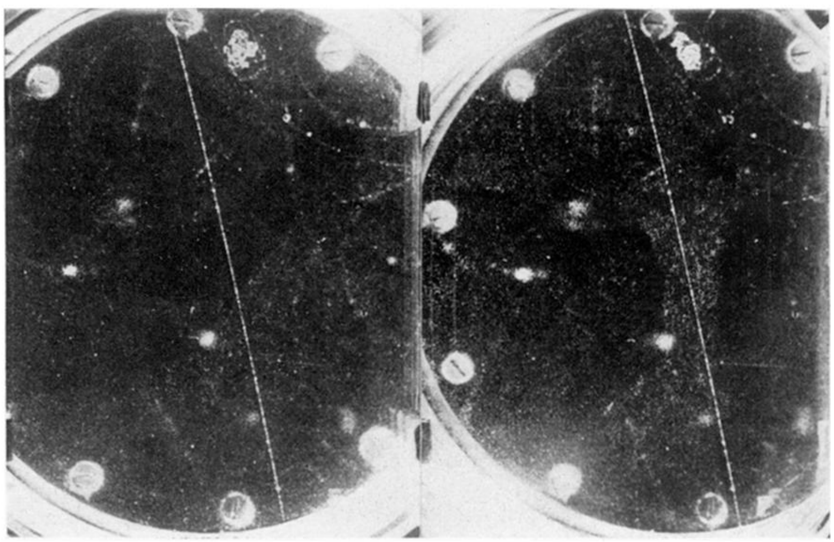
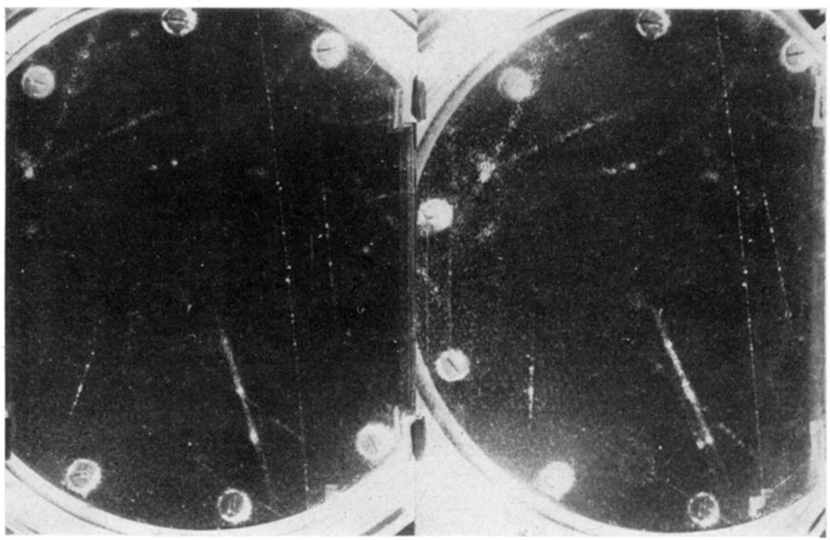


FIG. 10. This is another example of a proton found among the energy spectrum photographs. It has an $H\rho$ of 1.3×10^6 gauss-cm and is positive if traveling downward. A proton of this momentum has an energy of 75 Mev, an ionization of 4.4 times the minimum, and a range of 5.5 g/cm². The values are all consistent with the photograph. This particle has slightly more than the minimum momentum required of protons for penetration of the lower chamber wall to reach the lower Geiger counter. (There also appears a small electron shower which is probably not time coincident with the proton.)

FIG. 11. This is a track representing minimum ionization, which is shown for comparison with the proton tracks of Figs. 9 and 10. It has about the same momentum ($H\rho = 1.6 \times 10^6$ gauss-cm) as the protons and so cannot itself be a proton. It may be either a mesotron or an electron insofar as its ionization and magnetic curvature are concerned. A mesotron of this momentum would have an energy of 380 Mev, an ionization equal to the minimum, and a range of 200 g/cm^2 (in air). (The three photographs, Figs. 9, 10, and 11, were obtained on the same flight; in fact, the photographs of Figs. 10 and 11 were obtained in two consecutive expansions.)



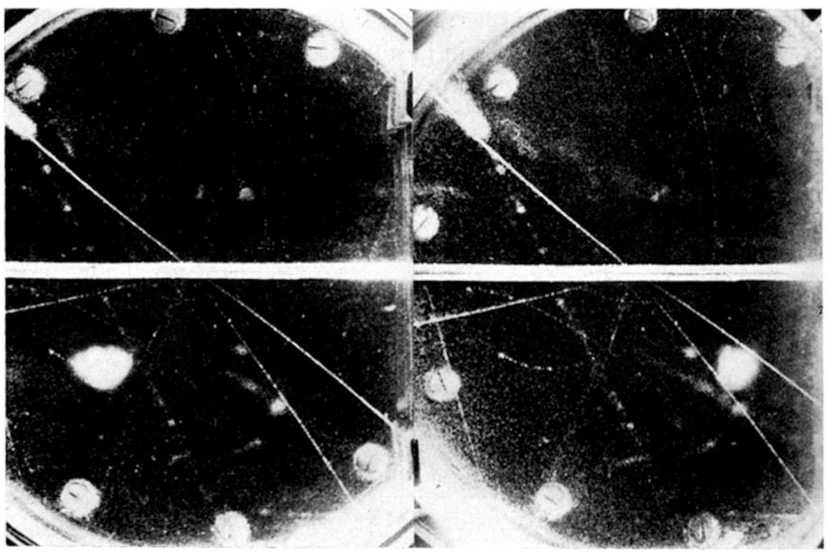


FIG. 2. A lightly ionizing particle produces a nuclear disintegration in a 3.5-mm lead plate giving rise to three lightly ionizing particles and four heavily ionizing particles. The lightly ionizing particles, which may be either mesotrons or protons of high energy, are all ejected in a direction closely parallel to that of the incoming particle. The four heavily ionizing particles are ejected almost at right angles to that direction. Three of the heavily ionizing particles are positively charged and have momenta in the range (4 to 8) $\times 10^5$ gauss-cm and can be identified definitely as protons. The fourth heavily ionizing particle, its track too short for accurate measurement, is also positive and has a momentum of the order of 10^6 gauss-cm.

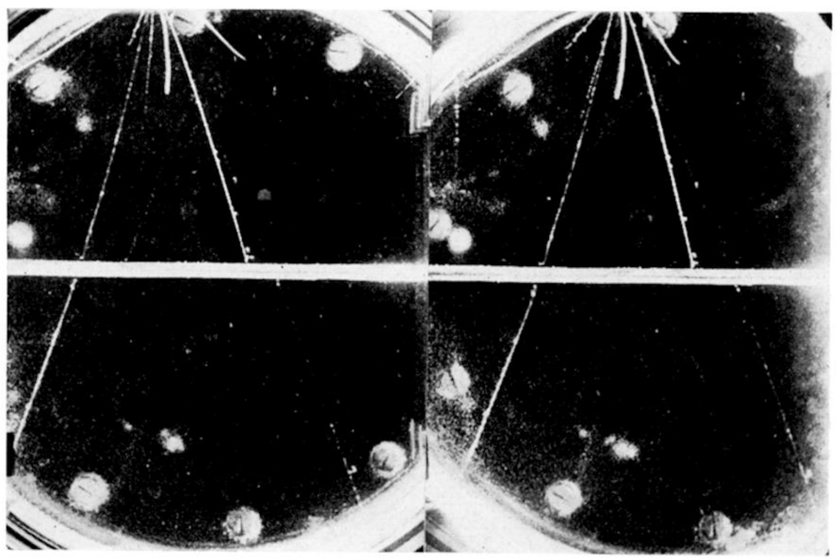


FIG. 3. A nine-particle disintegration occurs in the chamber wall. Two of the particles penetrate the 3.5-mm lead plate while a third stops in the plate. The identifiable particles are all protons. The large scattering of the two protons which are near the ends of their ranges should be noted.

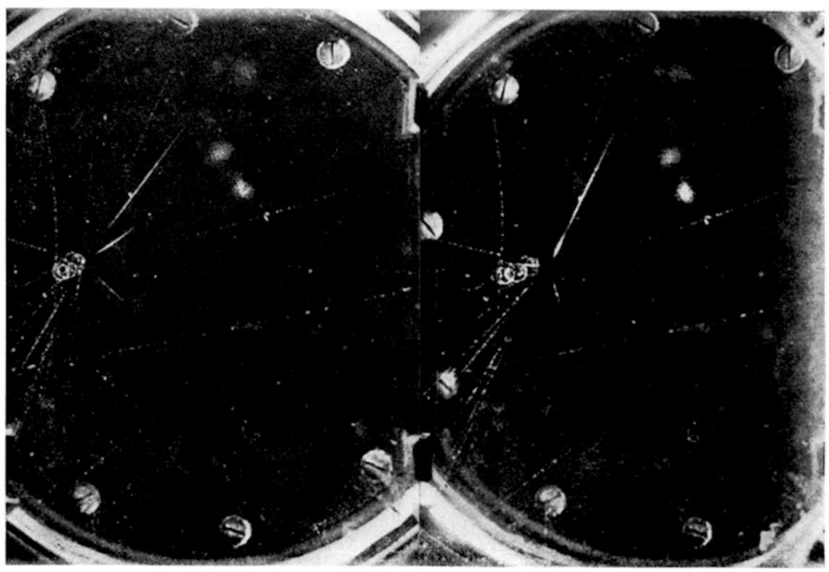


FIG. 4. A seventeen-particle disintegration, which occurs in the back wall of the chamber, shows both heavily and lightly ionizing particles. The track which can be seen spiraling out from the center of the disintegration is a positron of about 200-kilovolts energy and probably results from a photon. Several other disintegrations have been found also to contain very low energy electrons. All of the remaining tracks except the two heaviest ones may represent either protons or mesotrons. The two heaviest tracks, since they show no appreciable curvature in the magnetic field, are probably to be ascribed to alpha-particles.

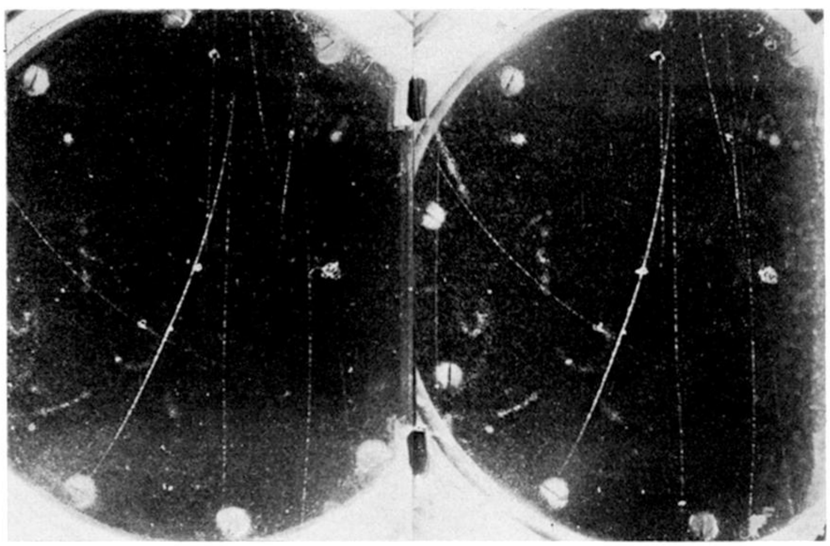


FIG. 5. This photograph shows the track of a heavily ionizing particle, which can be unambiguously identified as a mesotron. The other particles are of minimum ionization. (This photograph is more fully discussed in Section IV.)

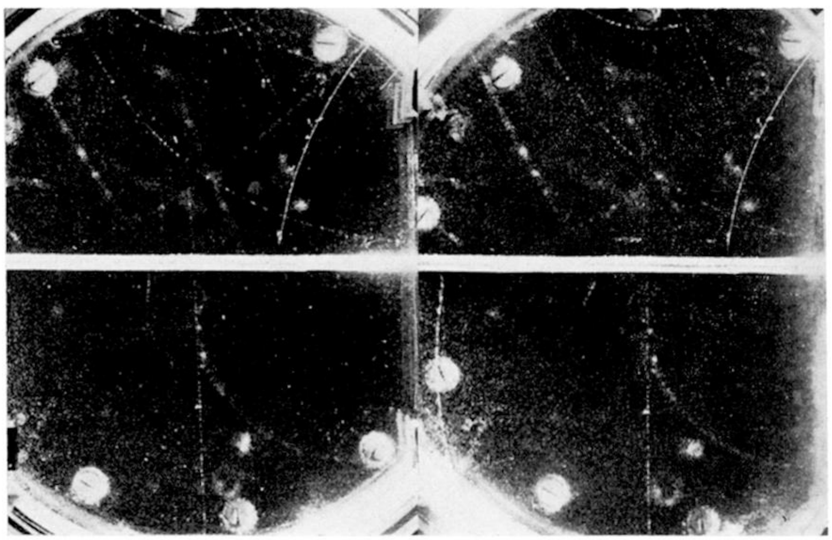


FIG. 6. The heavily ionizing particle, which stops in the 3.5-mm lead plate, can be definitely identified as a mesotron. Its mass cannot be greater than 500-electron masses. It is unlikely that its mass is as low as 100-electron masses. (A more detailed discussion is given in Section IV.)

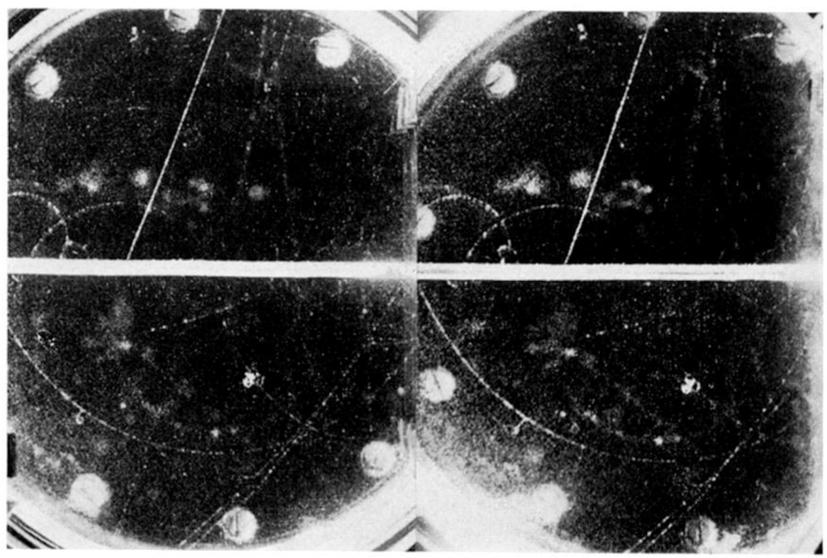


FIG. 7. This is an example of a proton which comes to rest in a 3.5-mm lead plate. It is shown for comparison with the mesotron track of Fig. 6. Figures 2, 3, 9, and 10 show other examples of proton tracks.

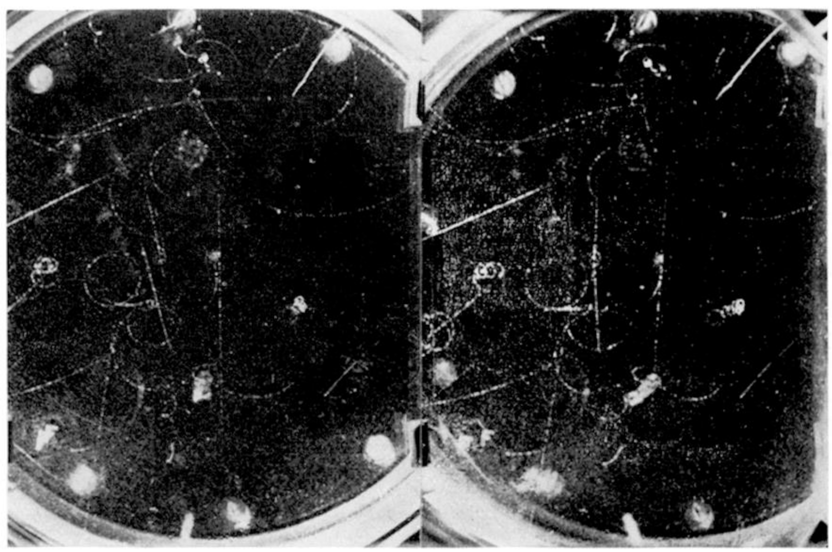


FIG. 8. Entering the chamber in the upper right-hand region, a heavily ionizing particle appears to give rise to a 25-Mev disintegration electron which can be seen passing horizontally across the chamber from a point near the terminus of the heavy track. The space association can be verified by stereoscopic examination of the photograph. An electron shower and at least one other heavily ionizing particle appear in the same picture. Further discussion is given in Section IV. (The direction of the magnetic field in this photograph is opposite to that of the other photographs.)

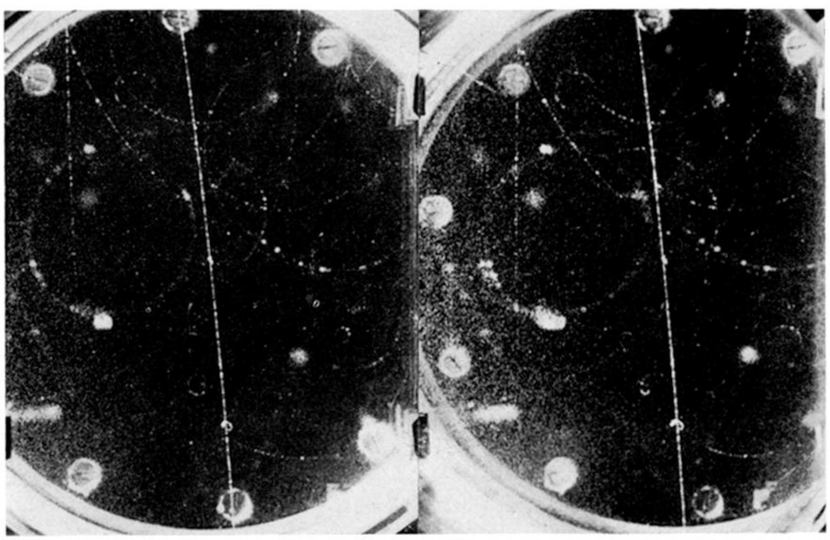


FIG. 9. This is an example of one of the protons occurring among the tracks used in determining the energy spectrum of single particles. The proton has a magnetic curvature, $H\rho$, of 1.6×10^6 gauss-cm and is positive if it is traveling downward. A proton of this momentum has an energy of 110 Mev. an ionization of 3.2 times the minimum, and a range of 11 g/cm^2 (in air). All these values are consistent with the photograph. (There also appears an electron shower which probably is not time coincident with the proton.)