

THE PHYSICAL REVIEW

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

VOL. 50, No. 4

AUGUST 15, 1936

SECOND SERIES

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

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(Received June 9, 1936)

Cloud chamber photographs at 4300 meters elevation show positive and negative electron tracks similar to those observed at sea-level, but positive-negative electron showers occur more frequently and, in general, consist of more numerous tracks. Showers of 2-4 tracks, 5-10 tracks, and 11-100 tracks occur respectively, 8.6, 21 and 29 times as frequently per unit time at 4300 meters as they do near sea-level. Further measurements on the energy loss in lead of electrons up to 400 MEV, are given. They show that in this range of energies the energy loss in lead is roughly proportional to the incident energy. About one

percent of the exposures on Pike's Peak reveal the presence of strongly ionizing particles which in most cases seem to be protons. The proportion of such tracks is considerably greater than at Pasadena. These heavy tracks in general bear only little relation in direction to that of the incoming beam, and usually arise from a type of nuclear disintegration not heretofore observed. The energies of these heavily ionizing particles may rise to values so high as 150 MEV, thus indicating that the source of the particle energies is in the cosmic rays.

THE magnet cloud chamber apparatus previously operated at Pasadena was used six weeks in the summer of 1935 to make about 10,000 counter-actuated exposures on the summit of Pike's Peak at an elevation of 4300 meters above sea-level.¹ A steady magnetic field of 7900 gauss was maintained with a solenoid current of 215 amperes at 110 volts obtained from a portable generator powered by an automobile engine.

Since the same apparatus was used both in Pasadena and on Pike's Peak, the screening material around the cloud chamber was sufficiently similar at both locations to permit reliable statistical comparisons on the occurrence of showers and heavy particles to be made.

I. FREQUENCY OF OCCURRENCE OF ELECTRON² SHOWERS AND THEIR DISTRIBUTION IN SIZE AT 4300 METERS AND NEAR SEA-LEVEL

Examples of electron showers photographed at 4300 meters are shown in Figs. 1-5. From a certain set of exposures made on Pike's Peak, counts were taken of the relative numbers of photographs showing respectively, a single track, two tracks, three tracks, etc. Throughout the set of exposures chosen for these statistics the chamber contained along its diameter a horizontal 0.35 cm lead plate; one Geiger counter was placed immediately above the chamber and one below. Similar counts were made on a number of photographs taken at Pasadena where the same lead plate was used, the counters were similarly

¹ C. D. Anderson, R. A. Millikan and S. H. Neddermeyer, *Phys. Rev.* **49**, 204, 415 (1936).

² The term "electron," when unmodified shall be taken to denote both positive and negative electrons.

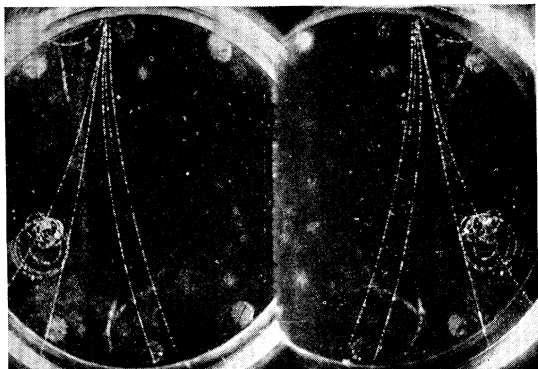


FIG. 1. Pike's Peak, 7900 gauss. An electron shower of three negatrons and three positrons of energies, respectively from left to right, 3.5, 55, 190, 78, 70, 90 MEV. The low energy electrons coincident in time with the shower represent the absorption of low energy photons accompanying the shower electrons. In all illustrations the *direct image is at the left*. The magnetic field is directed into the paper.

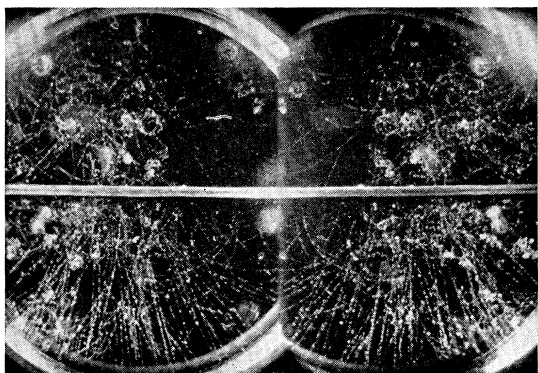


FIG. 2. Pike's Peak, 7900 gauss. A shower of numerous tracks showing several examples of low energy electrons resulting from photon absorption.

arranged, and the magnetic field strengths were comparable in the two instances, so that a comparison of the two sets of data may be made. It should be remembered that the counter-controlled cloud chamber, in responding to single particles selects only those within the small solid angle defined by the counters, whereas it records a relatively large proportion of the total number of showers which occur. The result is that the ratio of the number of photographs showing showers, to the number showing single tracks is enormously greater when counter control is used, than it is with the random method; the latter represents the showers in their true relation to the single particles. In a preceding publication³ the single tracks were shown to constitute about

³ C. D. Anderson, Phys. Rev. **44**, 415 (1933).

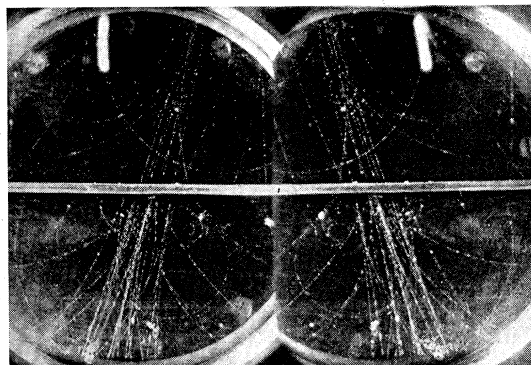


FIG. 3. Pike's Peak, 7900 gauss. A shower in which eight electrons (+ and -) strike the upper surface of the 0.35 cm lead plate. More than twenty-four electrons emerge from the lower face of the lead plate. This photograph is an example of the multiplication of shower tracks in a thin piece of absorbing material. Observation of many cases of this type shows that most of the additional tracks arise from the absorption of photons which accompany the electrons, but occasionally an electron itself may produce several positron-negatron secondaries.

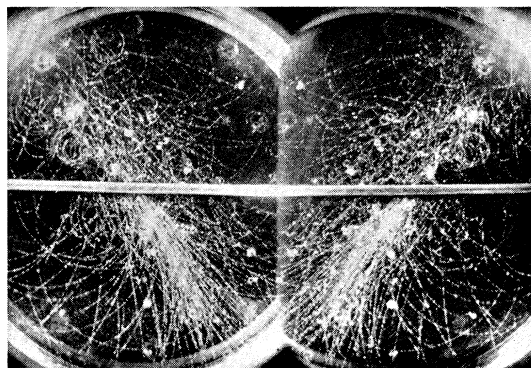


FIG. 4. Pike's Peak, 7900 gauss. A shower of more than 100 electrons. The summed energy represented by this shower probably exceeds 10,000 MEV. A shower such as this might result from one elementary process, but it is more likely due to a multiplication of tracks through photon intermediaries as in Fig. 3.

88 percent of the successful exposures made at Pasadena by the random method. In Table I a summary of the new results is given. The examples of multiple tracks listed here include not only those cases where all the tracks seem to diverge from a single point, but all cases of "time associated" tracks. Tracks not coincident in time with those tripping the counters are omitted. With an increase in elevation the rate of occurrence of showers determined in this way increases more rapidly than does that of the single tracks.

The number of coincidences recorded per hour on Pike's Peak was approximately 92 as com-

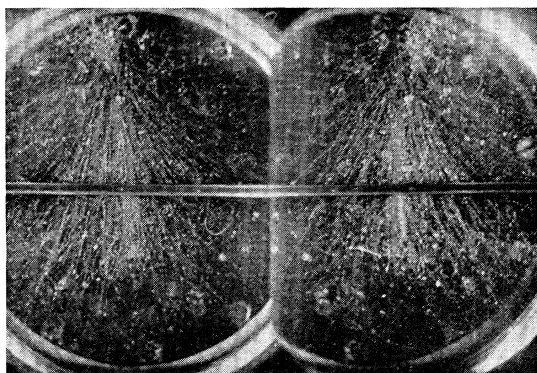


FIG. 5. Pike's Peak, 7900 gauss. A shower of a large number of electrons. The electrons in this shower were not counted, but estimates show that more than 300 are probably present. The summed energy probably exceeds 15,000 MEV.

pared with 33 at Pasadena for the same arrangement of the counters. Correcting for accidental coincidences, and for the resetting time of the cloud chamber (15 seconds) during which time the counters were inoperative, we find the true counting rates of 120 per hour on Pike's Peak and 34 per hour at Pasadena. This corresponds to a counting rate 3.5 times as fast on Pike's Peak as at Pasadena.

Using the data in Table I, which gives the relative frequency of occurrence of showers *per single track* at the two locations, we can compute the relative frequency of occurrence of showers *per unit time*, as a function of the number of rays which they contain, at the two locations. The results are given in the upper section of Table II.

To minimize the effects of statistical fluctuations we may collect the showers into three groups of respectively, 2-4 tracks, 5-10 tracks, and 11-100 tracks. The data so grouped are given in the lower section of Table II.

The numerical values here obtained are to be expected to depend to a considerable degree upon the distribution of matter about the cloud chamber and upon the position of the counters, thus making difficult a close comparison of these results with those of other observers who have used different experimental methods.

A rough comparison, however, can be made with those experiments in which counters arranged out of line are used to record showers, and with experiments in which electroscopes or ion-chambers are used to record bursts of ionization.

All the experiments⁴ with the exception of the counter experiments of Gilbert⁵ seem to agree that the numbers of showers and bursts increase with increasing altitude more rapidly than does the total ionization measured. For example Johnson⁶ and Woodward,⁷ who have made observations at an altitude comparable with that of

⁴ B. Rossi and S. de Benedetti, *Ricerca Scient.* **511**, 119 (1934); T. H. Johnson, *Phys. Rev.* **47**, 318 (1935); R. D. Bennett, G. S. Brown and H. A. Rahmel, *Phys. Rev.* **47**, 437 (1935); J. C. Street and R. T. Young, *Phys. Rev.* **46**, 823 (1934); **47**, 572 (1935); C. G. and D. D. Montgomery, *Phys. Rev.* **47**, 429 (1935); W. H. Pickering, *Phys. Rev.* **47**, 423 (1935).

⁵ C. W. Gilbert, *Proc. Roy. Soc.* **A144**, 559 (1934).

⁶ T. H. Johnson, *Phys. Rev.* **47**, 318 (1935). (Reference is made only to those experiments carried out at altitudes comparable with 4300 meters.)

⁷ R. H. Woodward, *Phys. Rev.* **49**, 638 (1936).

TABLE I. Summary of data.

n = Number of tracks appearing on photograph	1	2	3	4	5	6-10	11-20	21-100	>100
Total number of cases observed in group indicated:									
Pasadena	2301	168	95	31	16	41	14	18	0
Pike's Peak	1023	210	110	90	65	125	76	72	4
Frequency of occurrence of photographs, normalized to unit interval, that show n tracks per 1000 that show single tracks:									
N_1 Pasadena	1000	73	41.3	13.5	7.0	3.6	0.6	0.1	—
N_2 Pike's Peak	1000	205	108.0	88.0	64.0	24.4	7.4	0.9	—
N_2/N_1	1	2.8	2.6	6.5	9.1	6.8	12.3	9.0	—
n	1	2-4 tracks		5-10 tracks		11-100 tracks			
N_2/N_1	1	3.2		7.7		10.6			

TABLE II. Ratio of the frequency of occurrence per unit time of single tracks and showers of n electron tracks on Pike's Peak to the frequency at Pasadena.

n	single tracks	2	3	4	5	6-10	11-20	21-100
ratio	2.7	7.5	6.9	17	24	18	33	24
n	single tracks	2-4 tracks		5-10 tracks		11-100 tracks		
ratio	2.7	8.6		21		29		

the present experiments, find for particular arrangements of counters surmounted by a lead sheet, counting rates respectively 6.8 and 8.5 times greater at 4300 meters than near sea-level. Their values may be compared with the value found here, *viz.* 8.6 for showers of 2-4 tracks, although in their experiments the average number of rays in the recorded showers is somewhat uncertain.

Experiments have been made on the frequency of bursts of ionization at various altitudes, for example by Montgomery and Montgomery⁸ and by Young,⁹ who find an increase between near sea-level and 4300 meters by factors of 26.6 and 22 respectively, for the discharges corresponding to from 30 to 300 rays. These values may be compared with the ones given in Table II, *viz.*, 21 and 29, respectively, for the factor of increase in frequency of showers of 5-10 and 11-100 rays. Too much weight should not be attached to these rather close numerical agreements in view of the differences in experimental method, though the fact that the showers and bursts increase more rapidly with elevation than does the total radiation seems to be well established.

Experiments by Montgomery and Montgomery¹⁰ have furnished evidence that the smaller discharges recorded in their ion-chamber may be explained as showers of electrons. From the proof given by the cloud chamber results here reported that electron showers of so many as 300 particles do occur, it appears quite certain that their interpretation is correct. In the Montgomerys' ion-chamber a shower of 300 tracks should correspond to about 6×10^6 ion-pairs. It is

⁸ C. G. and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

⁹ R. T. Young, Phys. Rev. **49**, 638 (1936).

¹⁰ C. G. and D. D. Montgomery, Phys. Rev. **48**, 786 (1935). See also recent paper by H. Carmichael, Proc. Roy. Soc. **A154**, 223 (1936).

quite possible that the very large discharges from a hundred to a thousand times this value are produced by showers of many thousand electrons, but this has not yet been fully demonstrated.

The experiments discussed above show that the shower phenomena are more frequently associated with the soft component of the cosmic rays than with the penetrating components.

II. FURTHER DATA ON THE ABSORPTION OF ELECTRONS

Until the absorption laws of high energy electrons and photons are known the above effects cannot be understood in detail nor can the soft component of the primary cosmic rays be definitely identified. Our direct measurements on the energy loss of electrons passing through fairly thick lead plates (0.6-1.0 cm) have shown the occurrence of nuclear radiative impacts in which a considerable fraction of the total energy of the electron is sometimes removed, the measured values of the energy loss being much greater than that due only to ionization along the path and to the production of electron secondaries.¹¹ These data, however, as stated at the time, were not adequate to give a reliable value of the average specific energy loss of fast electrons in lead.

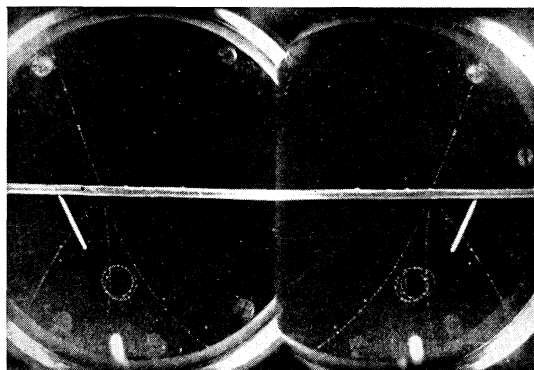


FIG. 6. Pike's Peak, 7900 gauss. An example of an electron losing a large amount of energy in a lead plate. In this case, a positron of ~ 480 MEV energy strikes a 0.35 cm lead plate. Below the plate three electrons appear of energies respectively: positron, 45 MEV; negatron 45 MEV; and positron 31 MEV. One of the tracks below the plate presumably represents the incident positron after passage through the plate, and the other two tracks a pair generated by the absorption of a photon produced in the plate. The energy lost in the plate by the incident positron is at least 435 MEV, which corresponds to a specific energy loss of ~ 1150 MEV/cm of lead since the distance traversed is 0.38 cm. The short heavy track may represent an alpha-particle arising from contamination in the plate.

¹¹ C. D. Anderson and S. H. Neddermeyer, Int. Conf. on Physics, London, 171 (1934).

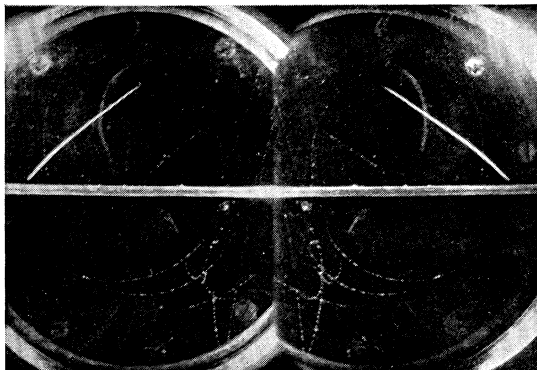


FIG. 7. Pike's Peak, 7900 gauss. A dense track whose range exceeds 6.3 cm measured in the chamber, which contained argon at 1.8 atmospheres pressure. This corresponds to a range greater than 11.5 cm in standard air. This track, coincident in time with the electron shower which also appears on the photograph, is probably due to a proton of low energy which resulted from a nuclear disintegration in the material of the cloud chamber. The scattering which this track exhibits makes impossible a reliable determination of its curvature.

Further measurements of energy loss in a plate of more suitable thickness (0.35 cm) showed the specific energy loss to increase with the energy of the incident electron.¹² Recently we have extended these data to include measurements on tracks corresponding to electron energies up to about 300 MEV. To avoid any selective action of the counters controlling the chamber, in this group are included only those photographs where a particle, other than the one measured, appeared, which could have set off the lower counter. These data, given separately in Table III, include two groups of measurements, one taken in a field of 4500 gauss and the other in 7900 gauss. The average initial energy of the electrons (+ and -) in each group is designated by \bar{E}_1 and the average energy loss by $\overline{\Delta E/d}$, obs., where d is the thickness of material traversed, and ΔE the difference between the initial and final energy. The total average specific energy loss ($\overline{\Delta E/d}$, theor.) to be expected from radiative and ionizing collisions in a lead plate of the particular thickness used (0.35 cm), calculated from the theory of Bethe and Heitler¹³ is given also in Table III.

Within the accuracy of the measurements the experimental energy losses and those calculated from the theory are in agreement up to electron energies of ~ 300 MEV. The total number of

¹² S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **48**, 486 (1935).

¹³ H. Bethe and W. Heitler, Proc. Roy. Soc. **A146**, 83 (1934).

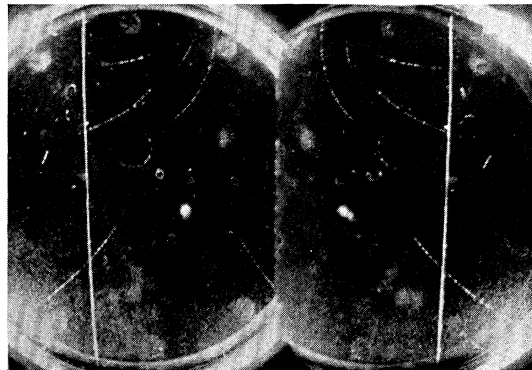


FIG. 8. Pike's Peak, 7900 gauss. A strongly ionizing particle traversing nearly vertically the full diameter of the chamber. It is probably coincident in time with the electron shower which also appears. If traveling downward it has a positive charge and an $H\rho = 1.8 \times 10^6$ gauss cm. If it is assumed to be a proton its energy is 150 MEV and its velocity 0.5 c. The density of ionization exhibited by this track is therefore not inconsistent with the view that it represents a proton. Only a very few examples of strongly ionizing particles traversing the chamber vertically are observed.

positron-negatron pairs produced in the plate (13 pairs) by the passage of the 227 electrons is approximately the number to be expected if they are produced by the absorption in the plate of the photons originating in the radiative impacts. No reliable average values of energy loss for higher energy electrons (> 300 MEV) have been obtained; however, the several individual particles that have been measured, some of which showed energy losses greater than 1000 MEV/cm of lead, do not so far indicate a breakdown of the theoretical formula at somewhat higher energies (see Fig. 6). A more complete discussion of the energy loss of electrons with special reference to the distribution of the observed losses, including also measurements on absorption in substances other than lead will be given later.

The direct energy loss measurements on electrons, so far, furnish no evidence that the theory

TABLE III. Energy loss of electrons in Pb. (MEV/cm).

	7900 gauss					0.35 cm Pb plate (Pike's Peak)				
Energy interval in MEV	<50	50-100	100-150	150-200	200-400	<50	50-100	100-150	150-200	200-400
No. of tracks	29	65	18	13	21	22	28	15	16	20
\bar{E}_1	31	75	123	177	272	26	71	117	170	207
$\overline{\Delta E/d}$ obs.	42	82	178	191	358	37	84	124	207	240
$\overline{\Delta E/d}$ theo.	50	110	175	248	378	43	105	167	240	240

	4500 gauss					0.35 cm Pb plate (Pasadena)				
Energy interval in MEV	<50	50-100	100-150	150-200	200-400	<50	50-100	100-150	150-200	200-400
No. of tracks	22	28	15	16	20	22	28	15	16	20
\bar{E}_1	26	71	117	170	207	26	71	117	170	207
$\overline{\Delta E/d}$ obs.	37	84	124	207	240	37	84	124	207	240
$\overline{\Delta E/d}$ theo.	43	105	167	240	240	43	105	167	240	240

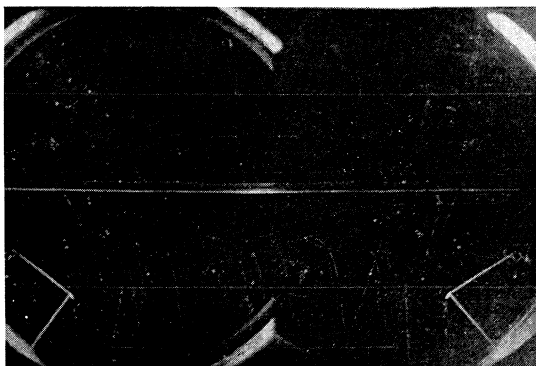


FIG. 9. Pike's Peak, 7900 gauss. A disintegration occurring in the gas (argon) of the chamber. An electron shower occurring apparently simultaneously with this disintegration is only barely visible due to the poor development of the negative on the mountain in a too cool solution. The three heavy particles all diverge within a hemisphere, so that it is impossible for the three particles among themselves to conserve momentum. Momentum might have been supplied by an incoming neutron producing the disintegration. It is possible also that in the disintegration one or more neutrons were ejected. These neutrons would produce no tracks, but can be called upon to conserve momentum in the disintegration. Stereoscopic examination shows that neither of the two longer tracks ends in the gas. It is not possible definitely to identify the particles; the two longer ones may be either protons or alpha-particles and the shorter one the remainder of the argon nucleus.

of absorption through radiative losses is not valid at high energies. Nevertheless our observations of many thousand traversals of high energy particles through lead plates (detailed data have been given on 2400 of these¹¹) show an observed number of electron secondaries fewer in order of magnitude than that to be expected theoretically through the production of secondary photons and their absorption in the plate itself, provided that these particles are all electrons. The experiments of Rossi,¹⁴ Street, Woodward and Stevenson¹⁵ also have shown the presence of particles too penetrating to permit identifying them with electrons if the Bethe-Heitler theory is assumed to be even approximately valid at high energies. It is obvious that either the theory of absorption breaks down for energies greater than about 1000 MEV, or else that these high energy particles are not electrons.

If one assumes that these penetrating particles are not electrons and that the theory of absorp-

¹⁴ B. Rossi, *Zeits. f. Physik* **82**, 151 (1933), and *Int. Conf. on Physics*, London (1934).

¹⁵ J. C. Street, R. H. Woodward and E. C. Stevenson, *Phys. Rev.* **47**, 891 (1935). See also two recent papers by P. Ehrenfest and P. Auger and L. Leprince-Ringuet, *J. de phys. et rad.* **7**, 65 and 67 (1936).

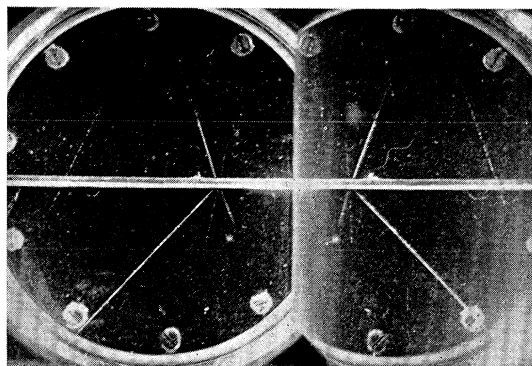


FIG. 10. Pasadena, 4500 gauss. Five shower particles appear, diverging from a region above the chamber. One of these shower particles, probably an electron, in passing through the 0.35 cm lead plate produces a disintegration which results in the ejection of two strongly ionizing particles, one downward to the left and another upward to the left; a third particle which produces a short track in the chamber (downward to the right), shows a lower specific ionization than the others and may be either an electron or a fast proton. The two particles which show a specific ionization too great to be electrons are probably protons. The one ejected downward is positively charged and has an energy of 40 MEV ($H\rho=9\times 10^8$ gauss cm) if it is a proton. The sign of charge of the one ejected upward is not determined; its energy if it is a proton is greater than 20 MEV ($H\rho>6.5\times 10^8$ gauss cm). Stereoscopic examination shows these tracks to intersect very accurately in the plate at a point on the path of the shower particle.

tion of photons and electrons remains approximately valid up to very high energies some well known cosmic-ray phenomena, e.g., the production of large electron showers; the transition effects; the variation in counting rate of tube-counters arranged out of line to record showers, as a function of the kind and thickness of material above them, etc., find a qualitative explanation in terms of the production of photons through radiative impacts, and their absorption through pair-production. On the other hand, their interpretation presents some difficulty if one assumes that the theory of absorption of electrons breaks down at high energies to an extent such that the penetrating particles referred to above, can be interpreted as electrons. In particular, the rapid increase in the number of showers with increasing altitude indicates that the photons and electrons producing the showers are highly absorbable and have a high probability of secondary electron production. This large absorbability of electrons and photons is difficult to reconcile with the highly penetrating character of a large fraction of the sea-level particles on the view that the latter are electrons.¹⁶

¹⁶ Reference 11. Footnote p. 182.

It is therefore important to identify the penetrating particles. Some difficulties with identifying a large fraction of them with protons have already been discussed by Bowen, Millikan and Neher,¹⁷ and by ourselves.¹¹ Furthermore, experiments that we have carried out at Pasadena, designed to bring into evidence high energy primary particles of protonic mass, should they exist in appreciable numbers, have so far given negative results. Since the energy loss by ionizing collisions to be expected of a proton traversing the earth's atmosphere vertically to sea-level is only about 2000 MEV, and since the earth's magnetic field will not permit the entry at this latitude of protons of energy less than 5000 MEV, the chance is especially small of observing a primary proton sufficiently near the end of its range so that it can be readily distinguished from an electron when counters are used to select only the nearly vertical tracks as is normally done. Therefore, photographs were taken with a 0.35 cm lead plate placed across the chamber at 45° with the vertical, and with the two counters placed above and to one side of the chamber so as to permit the entry of particles up to 70° with the vertical, which particles could have traversed up to three times the vertical thickness of the atmosphere; and other photographs in which a meter of lead was placed above the counters for the particles to traverse before entering the chamber. Although the total number of exposures (1500) taken under these conditions is not large, they have so far revealed no tracks which could be ascribed to primary protons near the ends of their ranges. These experiments are being continued.

III. OCCURRENCE OF STRONGLY IONIZING PARTICLES AT 4300 METERS AND NEAR SEA-LEVEL, AND THE DISINTEGRATIONS GIVING RISE TO THEM

Out of a set of 9188 exposures taken on Pike's Peak 113 showed 123 strongly ionizing particles associated with the cosmic radiation,¹⁸ most of which seem to be protons. Such particles occur very rarely at sea-level, only a few scattered ob-

¹⁷ I. S. Bowen, R. A. Millikan and H. V. Neher, Int. Conf. on Physics, London (1934), p. 206.

¹⁸ F. Rieder and V. F. Hess, Nature **134**, 772 (1935) report the observation of several heavily ionizing particles at 2300 meters. G. Herzog and P. Scherrer, J. de phys. et rad. **6**, 489 (1936) report one heavily ionizing track at 3500 m.

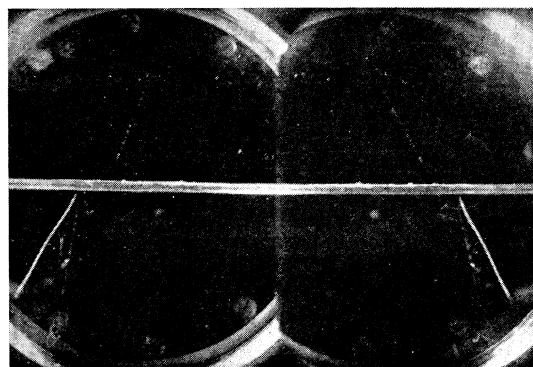


FIG. 11. Pike's Peak, 7900 gauss. A proton and an electron ejected from a point in the lead plate by a non-ionizing ray. One of our early photographs at Pasadena indicated that such a process could occur and was so interpreted at that time.¹⁹ The distortion of the low energy proton track due to scattering in the argon and to a motion of the gas, which seems to have occurred in this case, does not permit a measurement of its curvature; the electron's energy exceeds 240 MEV ($H_p > 8 \times 10^5$ gauss cm). The nonionizing particle producing the disintegration may be either a photon or a neutron, but the fact that the electron receives most of the energy tends to favor the photon.

servations having been previously published.²⁰ The particles reported here are clearly differentiated from alpha-particles arising from radioactive contamination, since, first, their range is in some cases much greater than that of the alpha-particles from any radioactive substance (see Figs. 7, 8) and, second, in other cases they arise from disintegrations which occur in the gas of the chamber itself, or in a plate placed across its center (see Figs. 9, 10, 11, 12, 14).

TABLE IV. *Space distribution of the dense tracks occurring on Pike's Peak.*

Angle with vertical (degrees)	0-30	31-60	61-90
Number	55	41	27

The spatial distribution of the dense tracks occurring on these exposures is shown in Table IV, in which is given the number of heavy particles occurring in 30° intervals of the angle with

¹⁹ C. D. Anderson and R. A. Millikan, Phys. Rev. **40**, 325 (1932); C. D. Anderson, Phys. Rev. **41**, 408 (1932), Fig. 5.

²⁰ C. D. Anderson, Phys. Rev. **41**, 405 (1932); **44**, 406 (1933); C. D. Anderson and S. H. Neddermeyer, London Conf. (1934); P. M. S. Blackett and G. P. Occhialini, Proc. Roy. Soc. **A139**, 699 (1933); J. C. Street, E. G. Schneider and E. C. Stevenson, Phys. Rev. **48**, 463 (1935). G. L. Locher, Phys. Rev. **44**, 779 (1933), has interpreted short diffuse heavy tracks as representing cosmic-ray effects, but many of these tracks are doubtless due to alpha-particles arising from contamination in the chamber.

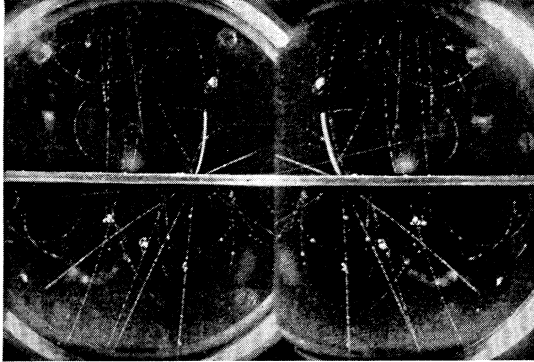


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^6$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to estimate to what extent scattering may have modified the curvature in this case. The particle is therefore tentatively interpreted as a proton. The other particle ejected upward to the right may be either an electron or a fast proton. The four particles ejected downward are positively charged and do not ionize sufficiently strongly to represent protons of the curvatures shown. If they are positrons their energies are respectively 105, 250, ~ 500 and 60 MEV. The summed energies of the six particles produced in this disintegration must exceed 1000 MEV. Since an electron shower, coming in from above the chamber, occurs on this exposure coincident in time with the disintegration in the plate, the latter probably resulted from an encounter by a photon or neutron which was produced along with the electrons in the shower. The fact that light particles receive so much energy would tend to favor the photon view. This disintegration in which all the ejected particles are probably positively charged represents a process fundamentally different from the usual electron shower; *it shows that charge has been removed from the nucleus and made to appear in the form of light particles.*

the vertical as measured in the plane of the chamber. Whereas the high energy electrons favor the vertical direction very strongly, a large percentage of the heavy particles are nearly horizontal, and in several instances they are clearly seen to be projected upward (see Figs. 9, 10, 12), indicating that in general they represent secondaries resulting from nuclear disintegration.

Wherever the direction of the particles is definitely known (as for particles produced by a disintegration occurring inside the chamber), the sense of curvature in the magnetic field is such as to indicate particles of positive charge. In the cases where the direction of travel is not known,

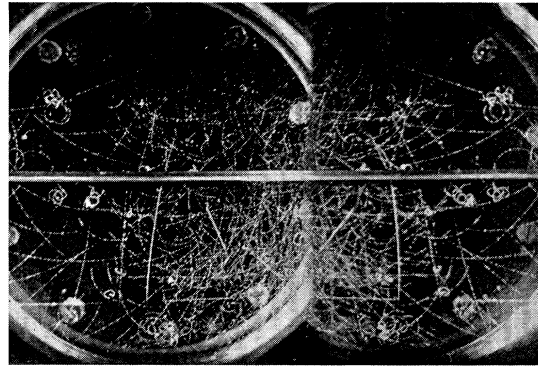


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^6 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

but the assumption made that the particle travels downward, there occur 33 tracks representing positively charged particles, and 5 representing negative particles; the latter 5 tracks, however, may well represent positive particles thrown backward.

For comparison with the Pike's Peak data a set of 10,543 exposures made at Pasadena under

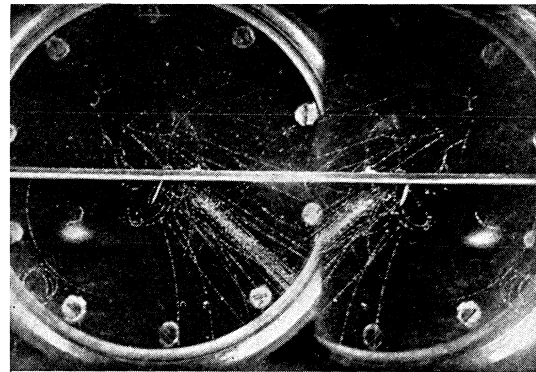


FIG. 14. Pasadena, 4500 gauss. A short dense track shows the ejection of a strongly ionizing particle from the lead plate, apparently coincident in time with the electron shower. This particle may be a proton although it is not possible to determine its energy.

similar conditions was studied, 11 of which showed unambiguous cases of strongly ionizing cosmic-ray particles. Dense tracks are found, therefore, 11.8 times as frequently per exposure on Pike's Peak as at Pasadena. The frequency of occurrence *per exposure* of the larger electron showers with 11–100 tracks increases between the two locations by a factor 8.4, which agrees within a probable fluctuation, with the factor for heavy tracks. This observation, together with the fact that of the 113 Pike's Peak photographs showing heavily ionizing particles, 30 also show time-associated electron showers, suggests that the strongly ionizing particles in most instances result from disintegrations produced by photons and electrons, and in some instances by neutrons which arise in the electron showers. The number of strongly ionizing particles given here represents a lower limit to the true number occurring, as all cases of dense tracks which could possibly arise from radioactive contamination are excluded. It is probable that a certain number of these excluded cases result from cosmic ray effects.

The photographs reveal distinctly new types of nuclear disintegrations, heretofore unreported. Our earlier photographs have shown the presence in the cosmic rays of photons of energies ranging from below 10 MEV up to above 3000 MEV. Many of these photons—those of smaller energy—clearly arise as secondaries in the electron showers.²¹ The new photographs present evidence of disintegration of a heavy element, *viz.* lead, by photons (Figs. 11 and 12). The probability of this type of nuclear photo-absorption, although apparently much smaller than the probability of producing the positive-negative electron pairs and showers, seems to be large enough to account for many of the strongly ionizing particles observed. Evidence is here found for the first time that electrons also can occasionally disintegrate nuclei and eject from them massive particles. In Fig. 10 an electron apparently disintegrates a lead nucleus, ejecting protons from it. Some evidence is found of disintegrations which seem to be produced by neutrons occurring as second-

aries in the cosmic rays (Fig. 9). Figs. 7–14 all show examples of heavily ionizing particles and the types of disintegrations giving rise to them. Descriptions of the individual photographs are given in the captions.

The foregoing data show that (1) the majority of the heavy tracks seem to represent protons. (2) They appear to be ejected in all directions and to have little relation to the direction of the incoming beam. (3) In several cases electrons and protons originate in the same center. (4) The proton tracks appear as the result of disintegrations produced by both ionizing and nonionizing rays. (5) Practically all the heavy particles can be interpreted only as secondaries produced within the atmosphere or material surrounding the cloud chamber. (6) Certain types of disintegrations, heretofore unobserved, in which the summed energies of the ejected particles exceeds 1000 MEV show that at these high energies the ejection of several particles is common. In these high energy disintegrations the particles ejected show a greater divergence from the direction of the incoming ray than do the electrons produced in the usual high energy electron showers. (7) Whereas many of the disintegrations produced by nonionizing rays seem to result from photon encounters, certain types of disintegrations heretofore unobserved, seem to indicate the presence of neutrons.

We wish to express our sincere gratitude to Professor R. A. Millikan for his unfailing support and interest in the work, and for his continual assistance in the planning of it, and the analysis of the results. Our thanks are due also to Dr. John Strong for aluminizing the mirrors used for the stereoscopic photography, and to Messrs. Lewis Browder and Thomas Harper for their able assistance in preparing the apparatus for use on Pike's Peak, and in gathering data from the photographs. It is a pleasure to thank Mr. E. E. Ewing and Mr. B. Stewart for their courtesies extended to us on Pike's Peak. We are also much indebted to the Union Oil Company of California for their kind gift of the fuel used to operate the power plant on the summit, and to the Carnegie Corporation of New York and the Carnegie Institution of Washington for allotting to Professor Millikan the major part of the funds which have made these researches possible.

²¹ C. D. Anderson and S. H. Neddermeyer, *Phys. Rev.* **45**, 295 (1934); C. D. Anderson, R. A. Millikan, S. H. Neddermeyer and W. H. Pickering, *Phys. Rev.* **45**, 352 (1934).

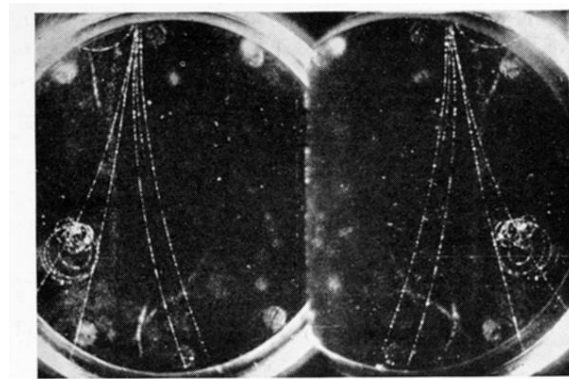


FIG. 1. Pike's Peak, 7900 gauss. An electron shower of three negatrons and three positrons of energies, respectively from left to right, 3.5, 55, 190, 78, 70, 90 MEV. The low energy electrons coincident in time with the shower represent the absorption of low energy photons accompanying the shower electrons. In all illustrations *the direct image is at the left*. The magnetic field is directed into the paper.

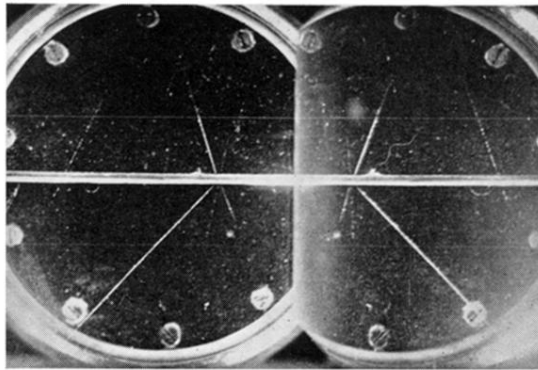


FIG. 10. Pasadena, 4500 gauss. Five shower particles appear, diverging from a region above the chamber. One of these shower particles, probably an electron, in passing through the 0.35 cm lead plate produces a disintegration which results in the ejection of two strongly ionizing particles, one downward to the left and another upward to the left; a third particle which produces a short track in the chamber (downward to the right), shows a lower specific ionization than the others and may be either an electron or a fast proton. The two particles which show a specific ionization too great to be electrons are probably protons. The one ejected downward is positively charged and has an energy of 40 MEV ($H_p=9\times 10^5$ gauss cm) if it is a proton. The sign of charge of the one ejected upward is not determined; its energy if it is a proton is greater than 20 MEV ($H_p>6.5\times 10^5$ gauss cm). Stereoscopic examination shows these tracks to intersect very accurately in the plate at a point on the path of the shower particle.

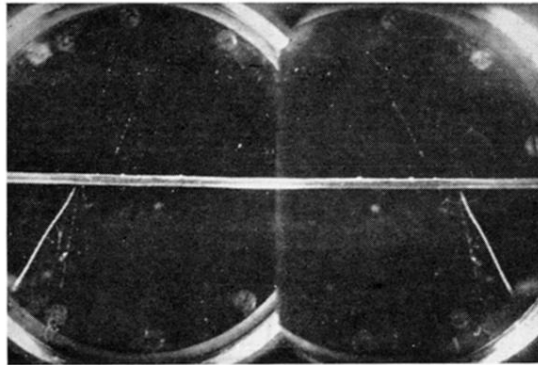


FIG. 11. Pike's Peak, 7900 gauss. A proton and an electron ejected from a point in the lead plate by a nonionizing ray. One of our early photographs at Pasadena indicated that such a process could occur and was so interpreted at that time.¹⁹ The distortion of the low energy proton track due to scattering in the argon and to a motion of the gas, which seems to have occurred in this case, does not permit a measurement of its curvature; the electron's energy exceeds 240 MEV ($H_p > 8 \times 10^5$ gauss cm). The nonionizing particle producing the disintegration may be either a photon or a neutron, but the fact that the electron receives most of the energy tends to favor the photon.

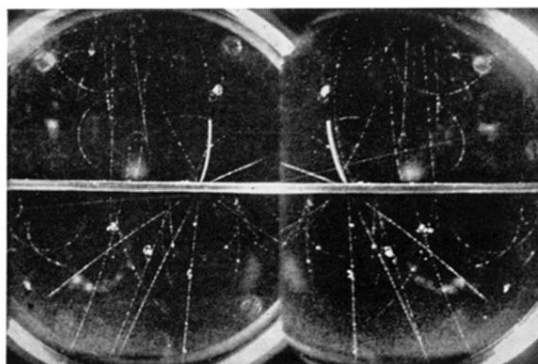


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to estimate to what extent scattering may have modified the curvature in this case. The particle is therefore tentatively interpreted as a proton. The other particle ejected upward to the right may be either an electron or a fast proton. The four particles ejected downward are positively charged and do not ionize sufficiently strongly to represent protons of the curvatures shown. If they are positrons their energies are respectively 105, 250, ~ 500 and 60 MEV. The summed energies of the six particles produced in this disintegration must exceed 1000 MEV. Since an electron shower, coming in from above the chamber, occurs on this exposure coincident in time with the disintegration in the plate, the latter probably resulted from an encounter by a photon or neutron which was produced along with the electrons in the shower. The fact that light particles receive so much energy would tend to favor the photon view. This disintegration in which all the ejected particles are probably positively charged represents a process fundamentally different from the usual electron shower; *it shows that charge has been removed from the nucleus and made to appear in the form of light particles.*

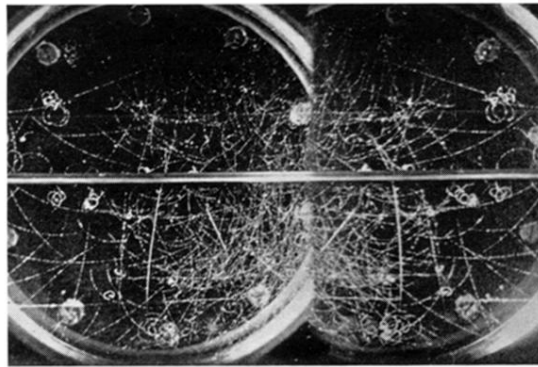


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its H_p is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

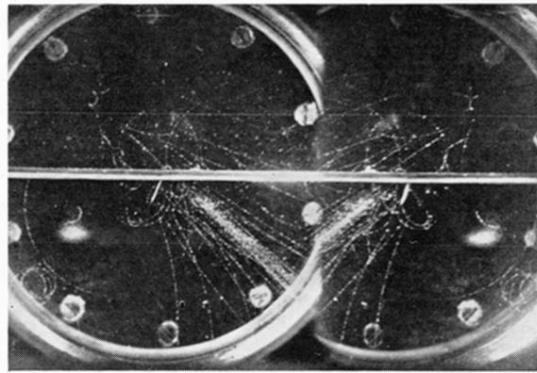


FIG. 14. Pasadena, 4500 gauss. A short dense track shows the ejection of a strongly ionizing particle from the lead plate, apparently coincident in time with the electron shower. This particle may be a proton although it is not possible to determine its energy.

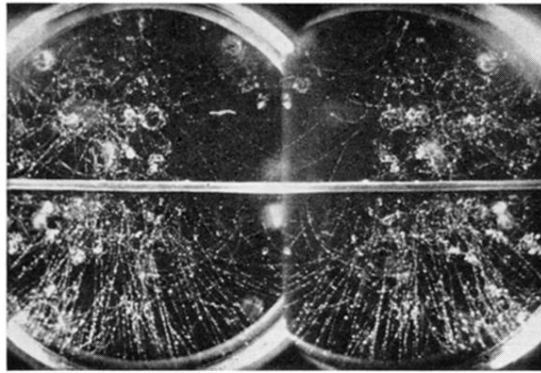


FIG. 2. Pike's Peak, 7900 gauss. A shower of numerous tracks showing several examples of low energy electrons resulting from photon absorption.

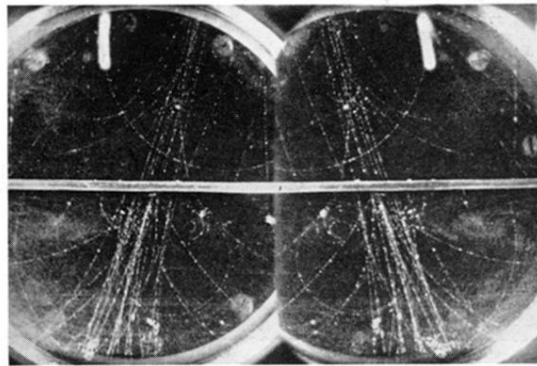


FIG. 3. Pike's Peak, 7900 gauss. A shower in which eight electrons (+ and -) strike the upper surface of the 0.35 cm lead plate. More than twenty-four electrons emerge from the lower face of the lead plate. This photograph is an example of the multiplication of shower tracks in a thin piece of absorbing material. Observation of many cases of this type shows that most of the additional tracks arise from the absorption of photons which accompany the electrons, but occasionally an electron itself may produce several positron-negatron secondaries.

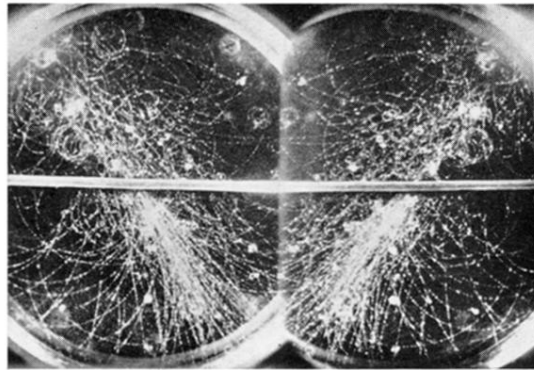


FIG. 4. Pike's Peak, 7900 gauss. A shower of more than 100 electrons. The summed energy represented by this shower probably exceeds 10,000 MEV. A shower such as this might result from one elementary process, but it is more likely due to a multiplication of tracks through photon intermediaries as in Fig. 3.

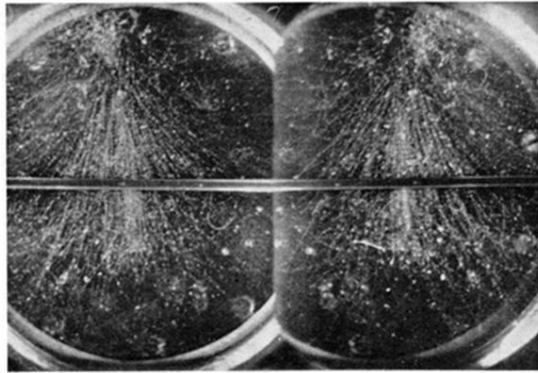


FIG. 5. Pike's Peak, 7900 gauss. A shower of a large number of electrons. The electrons in this shower were not counted, but estimates show that more than 300 are probably present. The summed energy probably exceeds 15,000 MEV.

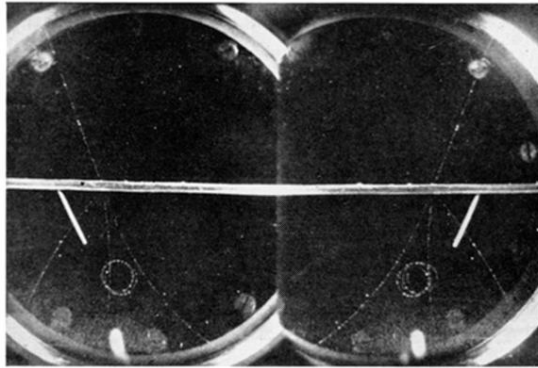


FIG. 6. Pike's Peak, 7900 gauss. An example of an electron losing a large amount of energy in a lead plate. In this case, a positron of ~ 480 MEV energy strikes a 0.35 cm lead plate. Below the plate three electrons appear of energies respectively: positron, 45 MEV; negatron 45 MEV; and positron 31 MEV. One of the tracks below the plate presumably represents the incident positron after passage through the plate, and the other two tracks a pair generated by the absorption of a photon produced in the plate. The energy lost in the plate by the incident positron is at least 435 MEV, which corresponds to a specific energy loss of ~ 1150 MEV/cm of lead since the distance traversed is 0.38 cm. The short heavy track may represent an alpha-particle arising from contamination in the plate.

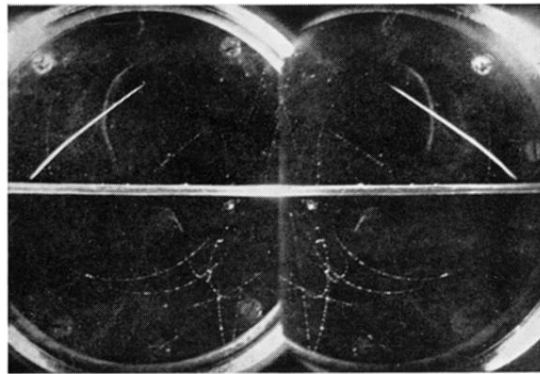


FIG. 7. Pike's Peak, 7900 gauss. A dense track whose range exceeds 6.3 cm measured in the chamber, which contained argon at 1.8 atmospheres pressure. This corresponds to a range greater than 11.5 cm in standard air. This track, coincident in time with the electron shower which also appears on the photograph, is probably due to a proton of low energy which resulted from a nuclear disintegration in the material of the cloud chamber. The scattering which this track exhibits makes impossible a reliable determination of its curvature.

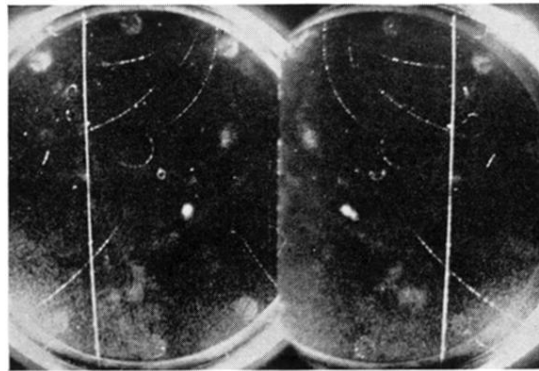


FIG. 8. Pike's Peak, 7900 gauss. A strongly ionizing particle traversing nearly vertically the full diameter of the chamber. It is probably coincident in time with the electron shower which also appears. If traveling downward it has a positive charge and an $H\rho = 1.8 \times 10^6$ gauss cm. If it is assumed to be a proton its energy is 150 MEV and its velocity 0.5 c. The density of ionization exhibited by this track is therefore not inconsistent with the view that it represents a proton. Only a very few examples of strongly ionizing particles traversing the chamber vertically are observed.

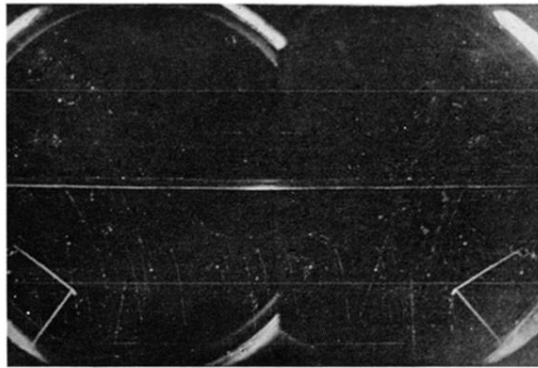


FIG. 9. Pike's Peak, 7900 gauss. A disintegration occurring in the gas (argon) of the chamber. An electron shower occurring apparently simultaneously with this disintegration is only barely visible due to the poor development of the negative on the mountain in a too cool solution. The three heavy particles all diverge within a hemisphere, so that it is impossible for the three particles among themselves to conserve momentum. Momentum might have been supplied by an incoming neutron producing the disintegration. It is possible also that in the disintegration one or more neutrons were ejected. These neutrons would produce no tracks, but can be called upon to conserve momentum in the disintegration. Stereoscopic examination shows that neither of the two longer tracks ends in the gas. It is not possible definitely to identify the particles; the two longer ones may be either protons or alpha-particles and the shorter one the remainder of the argon nucleus.