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Energies of Cosmic-Ray Particles

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Cloud chamber photographs of cosmic-ray tracks in a magnetic field up to 17,000 gauss are shown. On the assumption that the particles producing the tracks are travelling downward through the chamber rather than upward, particles of positive charge appear as well as electrons. From the specific ionization along the track it is concluded that the positives are protons, and are not nuclei of charge greater than unity. No evidence is uncovered demanding the introduction of a neutron for cosmic-ray phenomena. Eight examples of associated tracks are shown. Energies range from below 10^6 electron-volts to values in a few cases of the order of 10^9 electron-volts. Energy values for 70 tracks are listed. The scattering of cosmic particles in traversing a 6.0 mm lead plate is measured.

An AUTOMATIC, vertical Wilson expansion chamber operating in a strong magnetic field up to 21,000 gauss was designed for a study of the high-energy corpuscles associated with cosmic rays. The expansion chamber itself is 15 cm in diameter and has a depth of 2 cm. The axis of the piston lies in a horizontal plane in order to effect the most favorable position for photographing the cosmic-ray tracks. The magnetic field was found by direct measurement to be homogeneous to within 10 percent throughout the volume of the chamber. Photographs are taken through a hole in the pole piece of the magnet along the lines of force, thus revealing a particle deflected by the magnetic field as an arc of a circle on the photographic film. A description of the apparatus will follow in a later publication.

A brief discussion of the results has been published jointly with Professor R. A. Millikan,[1] to whom the writer is indebted for suggesting the investigation and cooperating in planning it, and whose keen interest throughout the course of the work has been of the greatest value.

Of the 3000 photographs taken to date, 62 show cosmic-ray tracks of length sufficient for energy measurements, 19 of which are here reproduced with addition of 3 photographs taken for test purposes. The photographs are 7/10 full size. The dark back ground in several of the photographs is due to light scattered by the back wall of the expansion chamber.

[1] Millikan and Anderson, Phys. Rev. **40**, 325 (1932).

In the test photograph of Fig. 2 appear tracks in air of the secondary electrons ejected by gamma-rays from Ra. Figs. 3 and 4 show alpha-particle trajectories.

The remainder of the tracks shown, Figs. 5–23, are ascribed to cosmic rays because of their high energy. Cosmic-ray tracks are in all cases readily distinguishable from alpha-particle tracks due to the very much greater specific ionization of the latter.

Positively Charged Particles

A charged particle will be deviated by the magnetic field into an arc of a circle. The sense of rotation in the chamber as viewed in the photographs will be clockwise for a particle of negative charge, and counter-clockwise for one of positive charge. The sign of the charge can be ascertained only if the

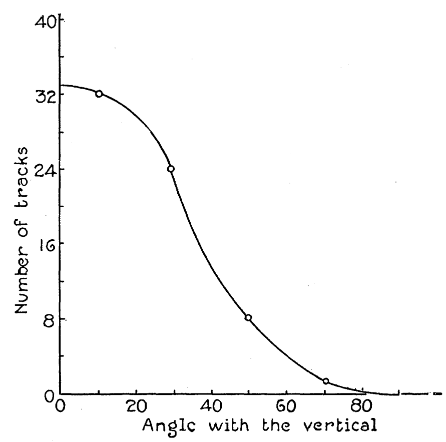


Fig. 1. The number of tracks per unit solid angle as a function of the angle with the vertical. Only those tracks are included whose curvature in the magnetic field is sufficiently small to allow a determination of the direction to be made. Therefore no electrons of energy less than 100×10^6 volts are included. This space-distribution in showing a large percentage of nearly vertical tracks differs from that reported by Skolbeltzyn.[2]

direction of motion of the particle is known. It is assumed here that the particles are traveling downward through the chamber. The small degree of scattering to be expected for high-energy particles, combined with the known fact that the rays come in from above, appears to justify this assumption. In Fig. 1 it is seen that the cosmic-ray tracks prefer the vertical direction over the horizontal indicating that backward or large angle scattering is infrequent.

In many instances on the above assumption as to the direction of motion, the tracks are deviated in a sense to indicate the presence of positively charged particles as well as electrons.

[2] Skobeltzyn, C. R. **194**, 118 (1932).

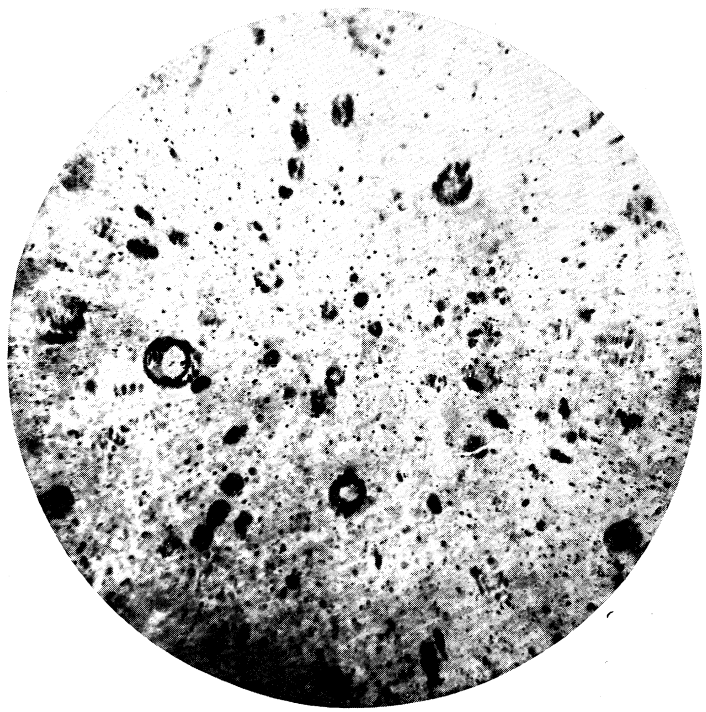


Fig. 2.

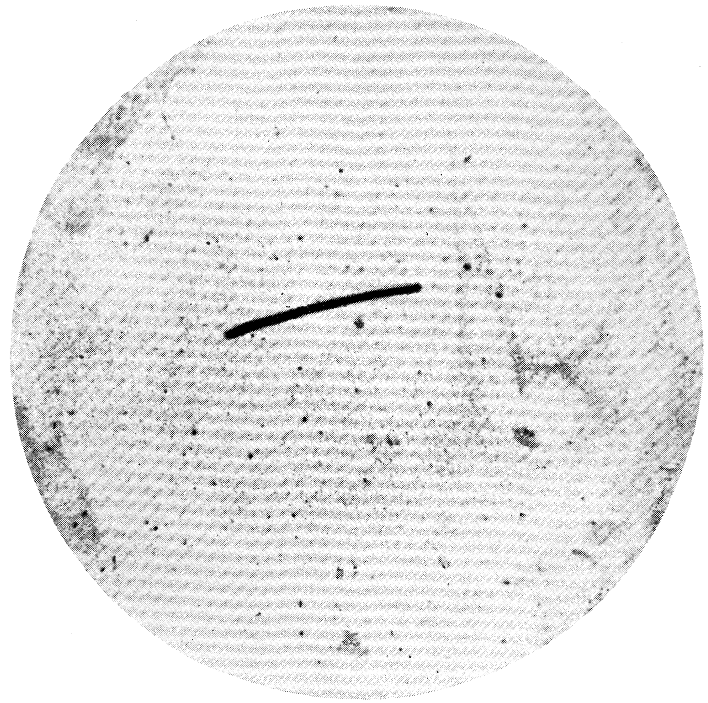


Fig. 3.

Fig. 2. 12,000 gauss. A test photograph showing tracks in air of secondary electrons ejected by gamma-rays from Ra, filtered through 2.5 cm of steel. The energies of the electrons range from 10^6 electron-volts down.

Fig. 3. 12,000 gauss. An α-particle trajectory of 3.85 cm range photographed in air.

Fig. 4.

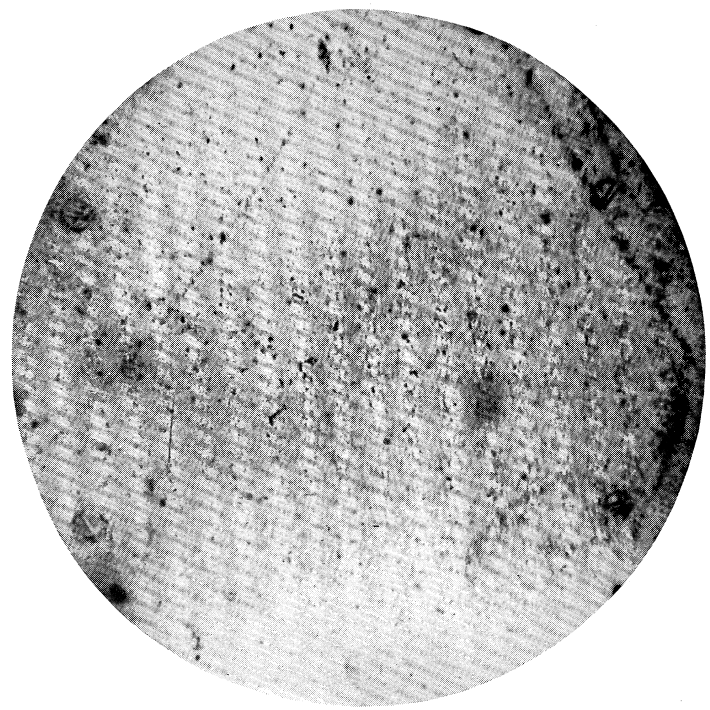


Fig. 5.

Fig. 4. 12,000 gauss. An α-particle trajectory photographed in helium, showing range of 10 cm.

Fig. 5. 17,000 gauss. A pair of associated tracks; at the left an electron of 120×10^6 volts energy, at the right a porton of 130×10^6 volts energy. Since protons and electrons, for a given velocity, have an equal specific ionization, then from the measurements of E. J. Williams and F. R. Terroux (Proc. Roy. Soc. **A126,** 300 (1929–30)) on the ionization by β-particles, the 120×10^6 volt-proton here is expected to ionize about $2\frac{1}{2}$ times as heavily as the electron.

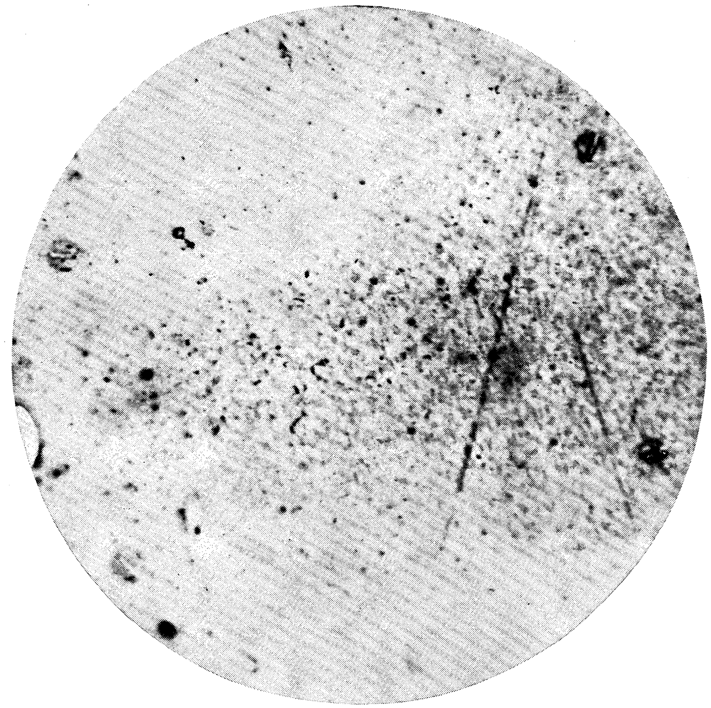


Fig. 6.


Fig. 7.

Fig. 6. 17,000 gauss. A group of three tracks; at the left an electron of 30×10^6 volts energy, at the right probably a proton of 400×10^6 volts energy. The center track, perhaps a proton of 150×10^6 volts energy, lies in a different plane from the other two, and because of its length there is a difficulty in associating it with the other two. The probability of its appearing here by chance is, however, very slight. A small scattering is noted in the center track.

Fig. 7. 12,000 gauss. A proton of 20×10^6 volts energy and an electron of about 400,000 volts energy.

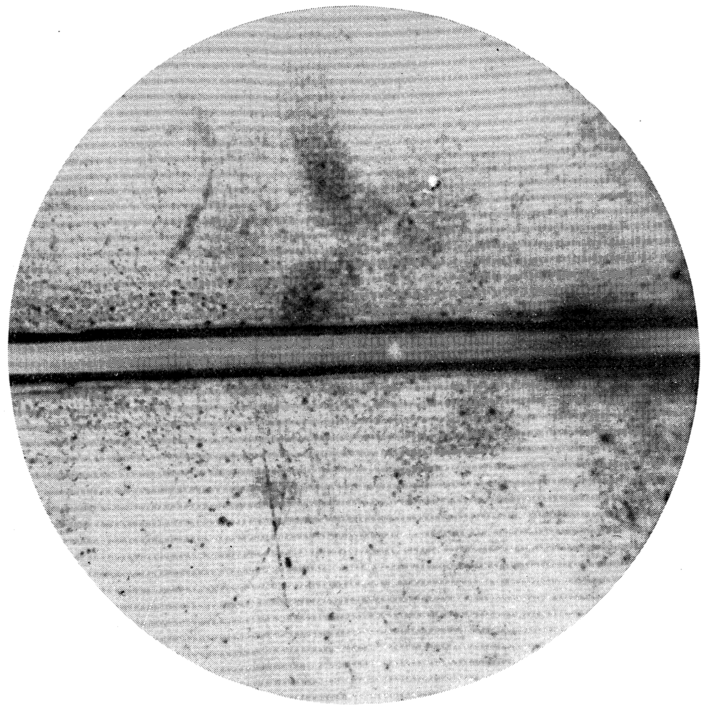


Fig. 8.

Fig. 9.

Fig. 8. 12,000 gauss. A plate of lead 6.0 mm thick extends horizontally across the chamber. Below the lead appear two tracks, one apparently a proton of about 100×10^6 volts energy, the other an electron of 11.4×10^6 volts energy which passes out through the 0.5 cm glass wall. Above the lead another electron enters through the glass wall, or perhaps the same electron after having been deflected into the chamber again by the magnetic field. It suffers a deflection of 80° upon striking the lead surface. Its energy is 8.2×10^6 volts. The assumption that the same electron re-entered the chamber above the lead is borne out by the fact that an energy loss of 3.0×10^6 volts is to be expected for an electron traversing the 0.5 cm glass wall twice as shown in the figure. The angle of divergence of the two associated tracks below the lead is 25°. (The track above the lead appears double due to a double reflection of the light before entering the camera.)

Fig. 9. 12,000 gauss. Two electrons of energy about 180×10^6 volts and 2×10^6 volts respectively.

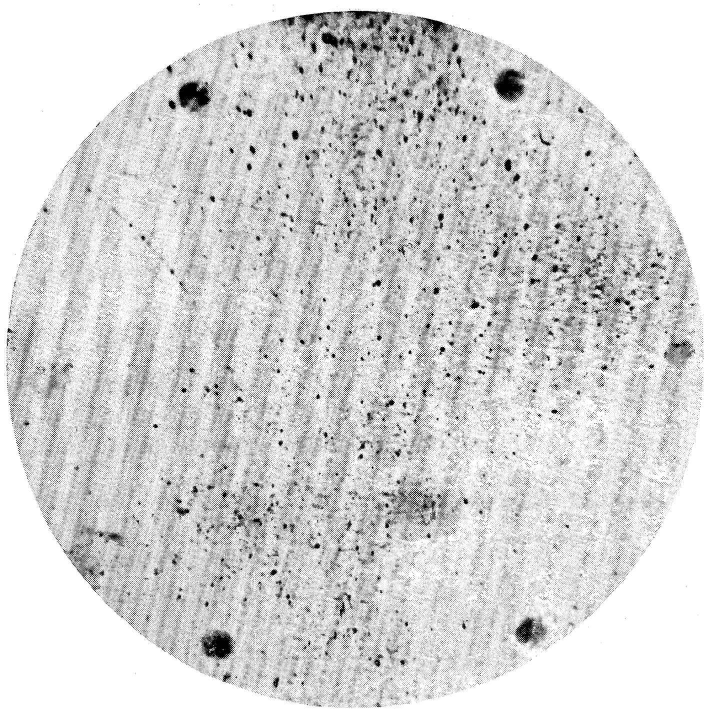


Fig. 11.

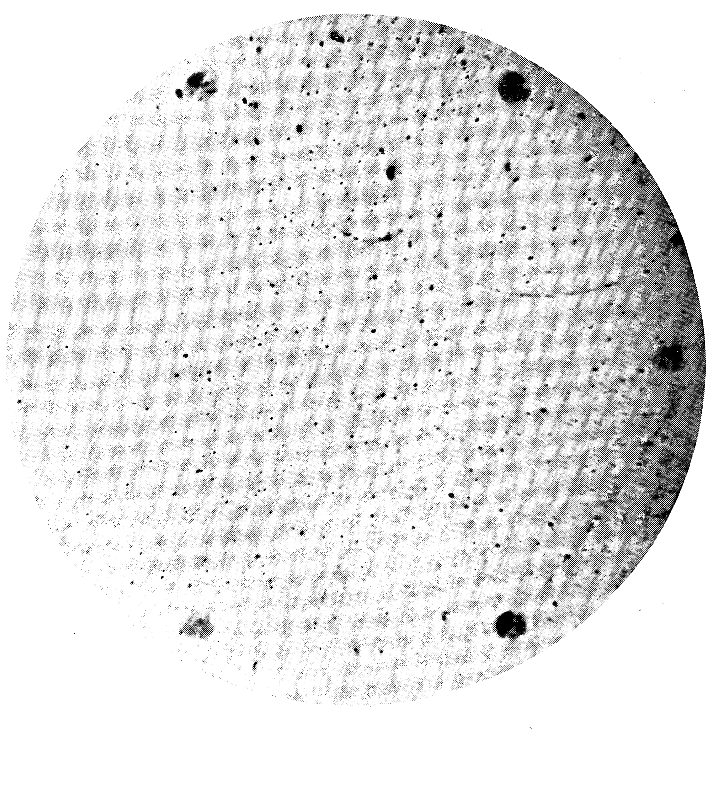


Fig. 10.

Fig. 10. 12,000 gauss. Two associated electrons moving upward through the chamber, of energy 170×10^6 volts and 11×10^6 volts respectively. A large angle scattering from the glass wall is noted.

Fig. 11. 12,000 gauss. An electron of 27×10^6 volts energy and probably a proton of 450×10^6 volts energy though the curvature here is small. A slight scattering is apparent.

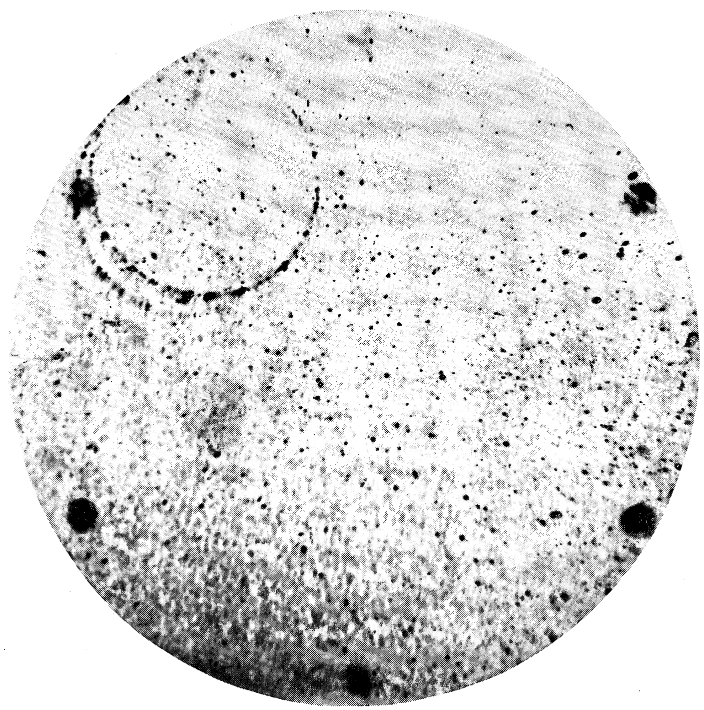


Fig. 12.

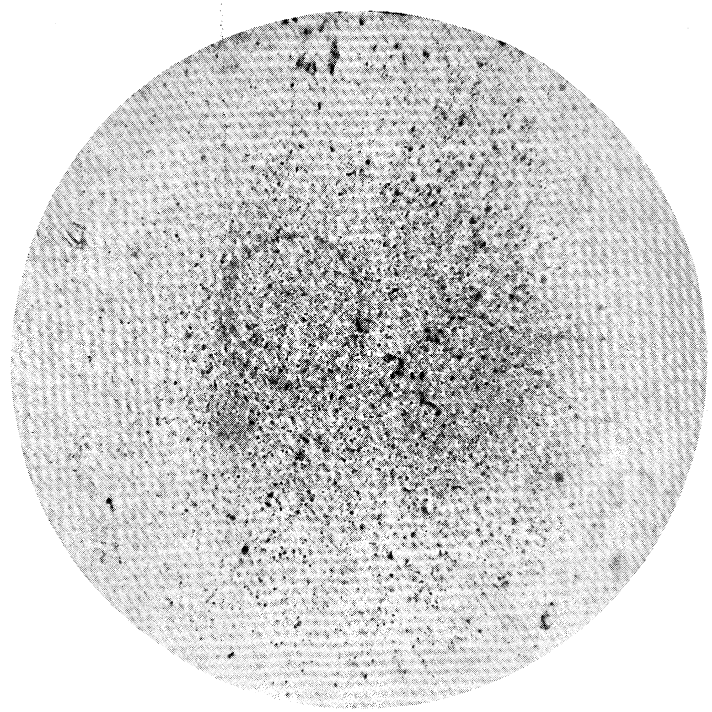


Fig. 13.

Fig. 12. 12,000 gauss. An electron of 8×10^6 volts energy. It is seen to make over $1\frac{1}{2}$ complete revolutions in the chamber. The displacement of the track from left to right is quantitatively explained by the fact that the magnetic field is 10 percent stronger at the center than at the edge of the chamber.

Fig. 13. 17,000 gauss. An electron of 7×10^6 volts energy.

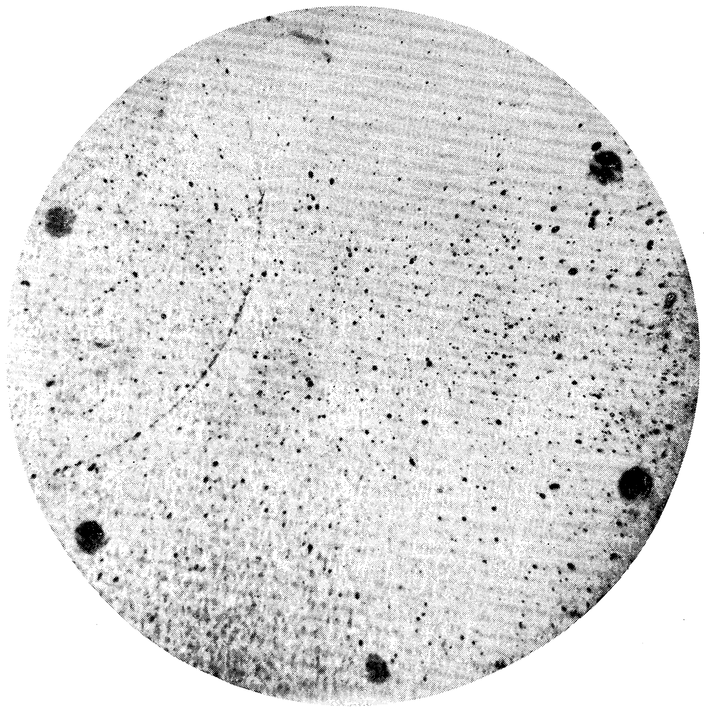


Fig. 14.

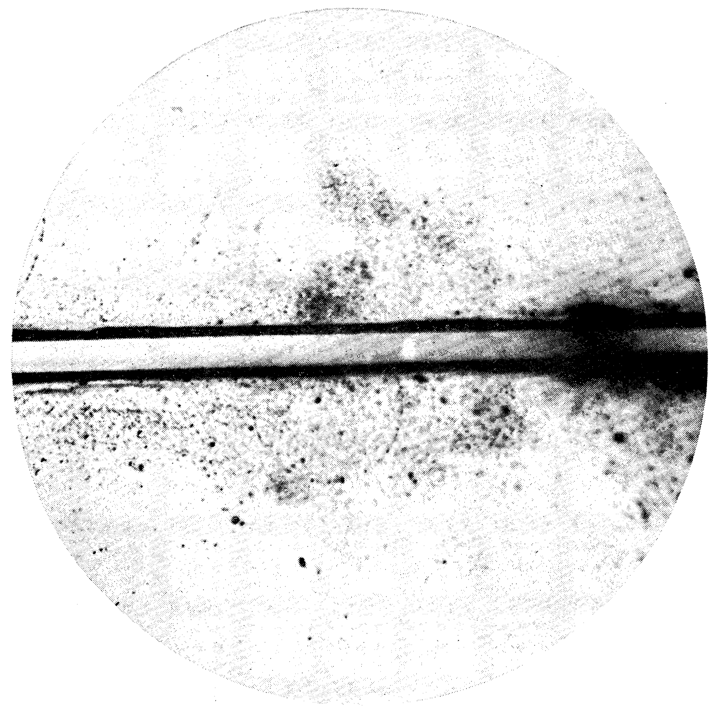


Fig. 15.

Fig. 14. 12,000 gauss. An electron of 18×10^6 volts energy.

Fig. 15. 12,000 gauss. An electron of 4.6×10^6 volts energy emerging from the lower surface of the lead. No track is seen entering the lead thus indicating a photon encounter. Above the plate to the left is another electron of 9×10^6 volts energy.

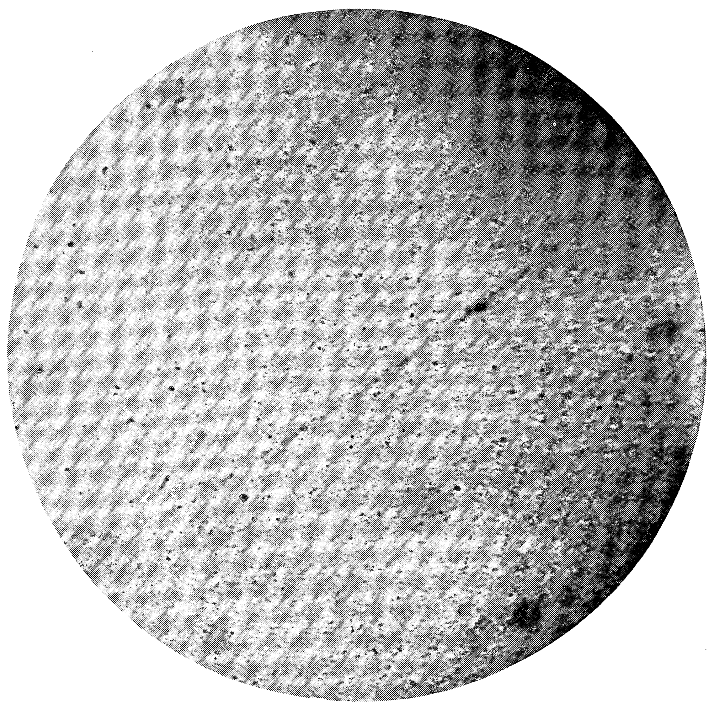


Fig. 16. 12,000 gauss. A proton of 30×10^6 volts energy.

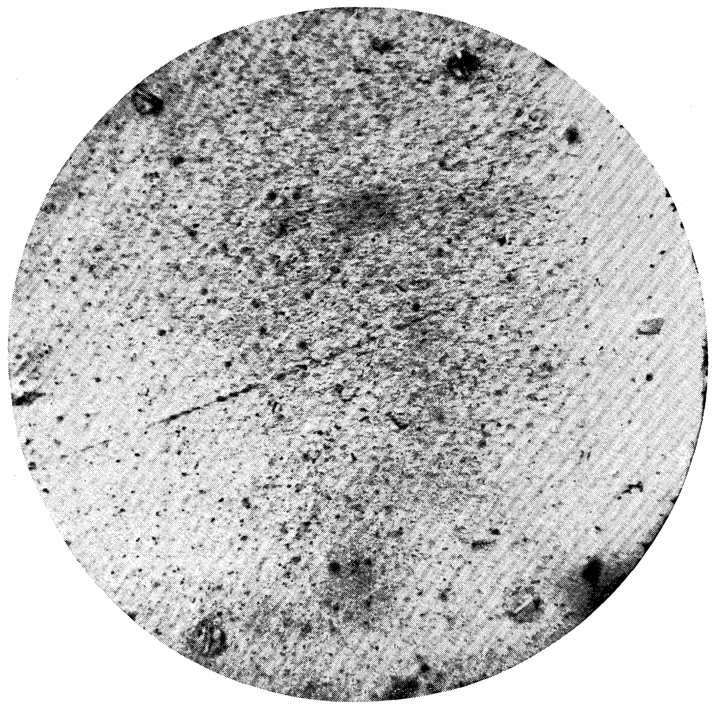


Fig. 17. 17,000 gauss A proton of 130×10^6 volts energy, slightly scattered.

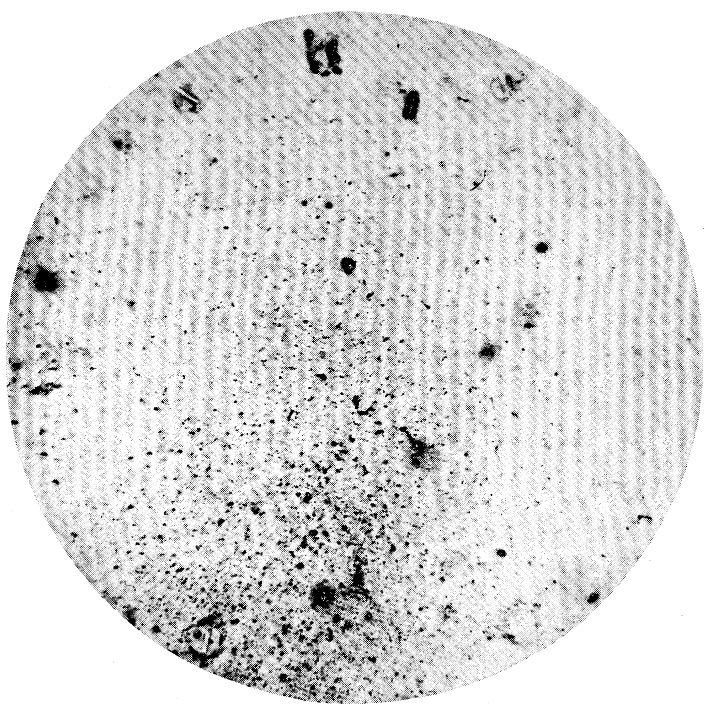


Fig. 18. 17,000 gauss. A proton of 450×10^6 volts energy.

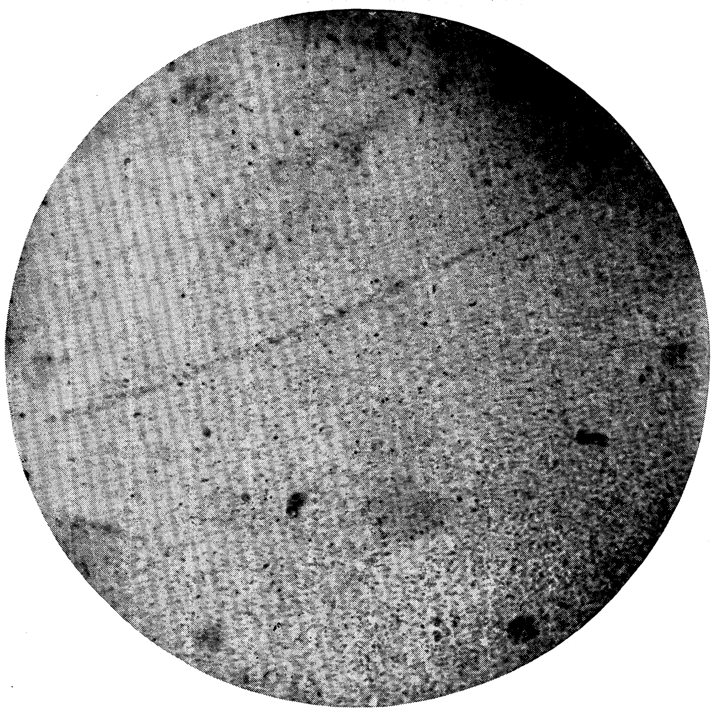


Fig. 19. 12,000 gauss. A proton of 40×10^6 volts energy.

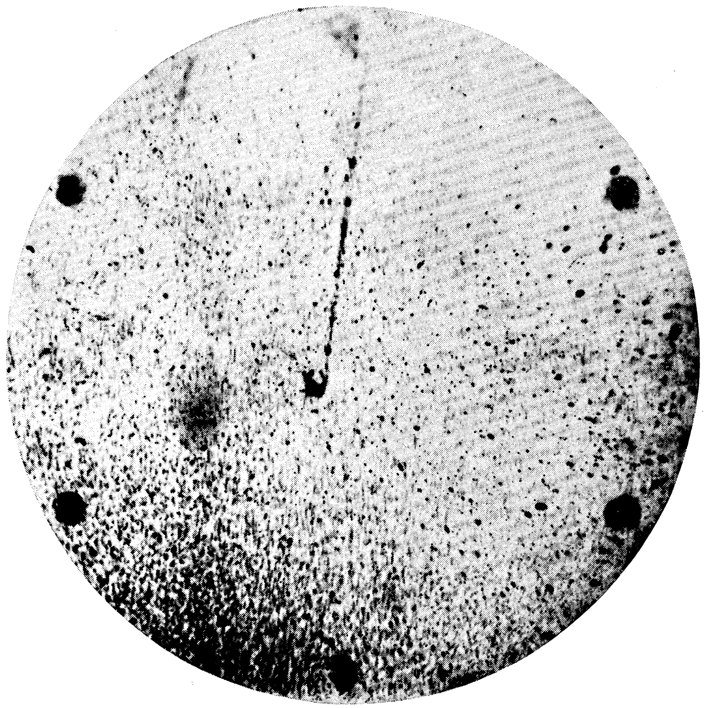


Fig. 20.

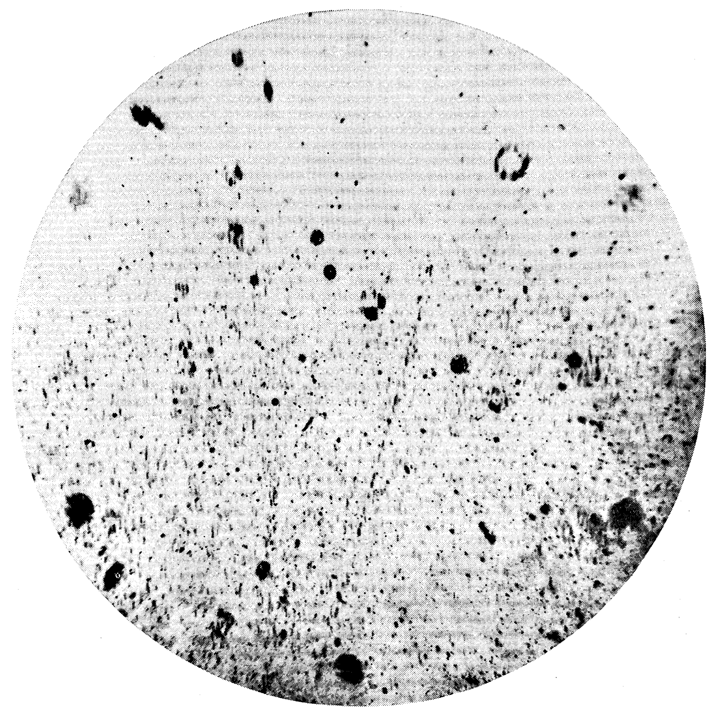


Fig. 21.

Fig. 20. 12,000 gauss. A particle of doubtful sign of charge. If an electron, the minimum energy is 600×10^6 volts, if a proton, the minimum energy is 400×10^6 volts. A close encounter with an electron takes place in the wall in which about 400,000 volts energy is transferred to the electron, shown by the small circle at the lower end of the track.

Fig. 21. 12,000 gauss. A high-energy particle of uncertain sign, photographed in helium. The energy, whether the particle is assumed to be an electron or a proton, exceeds 10^9 volts.

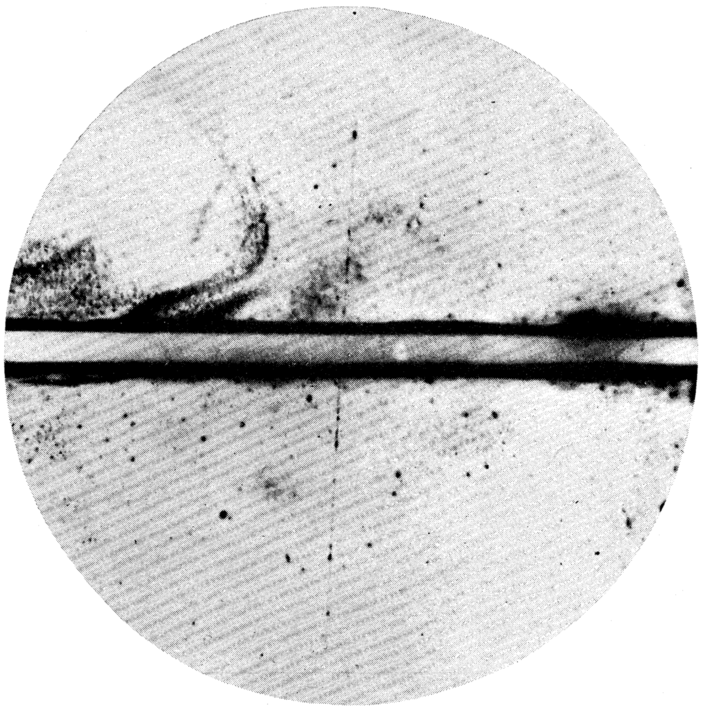


Fig. 22.

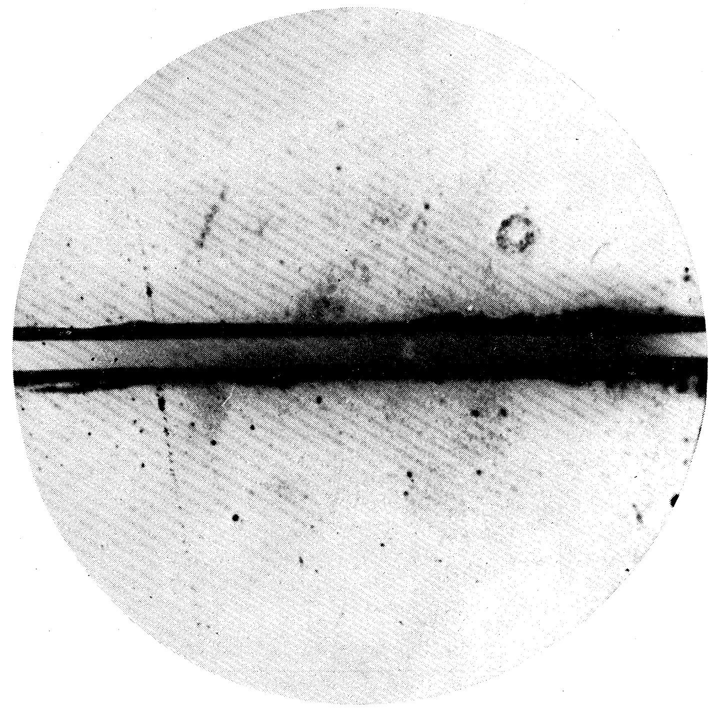


Fig. 23.

Fig. 22. 12,000 gauss. A particle of uncertain sign of charge of energy exceeding 200×10^6 volts if a proton is assumed and exceeding 600×10^6 volts if an electron is assumed. In traversing the 6.0 mm lead plate it suffers a deflection of 0.5 degrees as measured in the plane of the chamber.

Fig. 23. 12,000 gauss. A particle of uncertain sign of charge of energy exceeding 100×10^6 volts if a proton is assumed and exceeding 450×10^6 volts if an electron is assumed. The deflection in traversing the 6.0 mm lead plate is 0.8 degrees. A double scattering, however, is indicated by the sidewise displacement of the portion of the track below the lead as compared to that above the lead.

Specific Ionization

A few tracks photographed in an atmosphere of helium with 5 percent air show about 14 ion pairs per cm at standard pressure, a value close to that found for electrons of about 10^6 volts energy from Ra gamma-rays, which show about 13 ion pairs per cm in the same gas. The specific ionization for an electron remains practically independent of its energy for energies ranging from about 300,000 volts to several hundred million volts. For a given velocity, protons and electrons ionize the same, and for high energies where the velocities of both the electrons and the protons are of the order of the velocity of light it becomes impossible to distinguish electrons from protons by their ionization. Only at lower energies where the proton velocities are appreciably less than the velocity of light will protons show an appreciably greater specific ionization than electrons of the same energy. Nuclei of higher atomic charge would, for a given velocity, produce many more ions per cm, the specific ionization being to a first approximation proportional to the square of the charge on the nucleus.

The specific ionization along the tracks showing positives is in most instances not much greater than that for the electrons. It is concluded, therefor; that the positives can only be protons, and cannot themselves represent nuclei of higher atomic number than unity.

The projection of whole nuclei by the penetrating radiation produced in the bombardment of beryllium with alpha-particles has been reported in recent experiments. For the explanation of this fact, on the basis of the conservation laws, Chadwick[3] postulates a neutron. For the interpretation of the cosmic-ray effects so far observed such a neutron is not demanded on the basis of the energy-momentum arguments which apply in the experiments of Chadwick. Further work will show if the associated tracks of cosmic rays represent an effect similar, but on a higher energy scale to the disintegration tracks photographed by Feather[4] in the neutron experiments, though the frequent occurrence of electron tracks in the cosmic-ray experiments seems to indicate a different type of phenomenon.

A possibility to be borne in mind is that, in rare cases, the tracks of curvature that indicate positives might be in reality electrons scattered backwards by the material underneath the chamber and are traversing it from bottom to top. Precise data on the specific ionization of the low-energy positives will distinguish, however, between downward positives and upward negatives.

Associated Tracks

A well-known characteristic of the cosmic tracks is their tendency to occur in groups.[5,6,7] Of the 55 photographs showing cosmic tracks, 7 show double tracks and 1 shows three tracks.

[3] Chadwick, Nature **129**, 312 (1932).
[4] Feather, Proc. Roy. Soc. **A136**, 709 (1932).
[5] Skobelzyn, Zeits. f. Physik **54**, 686 (1929).
[6] Auger and Skobelzyn, C. R. **189**, 55 (1929).
[7] Locher, Phys. Rev. **39**, 883 (1932).

In general, for paired tracks, the energy of one of the associated pair is considerably less than that of the other, in some instances 10^6 volts and less. One of the associated pair is also in all cases definitely an electron.

The associated tracks have been assumed to be due to the simultaneous ejection by a photon of two particles from an atomic nucleus.[1]

Another effect which may give rise to associated tracks is a close encounter between a cosmic particle and an electron. Fig. 20 is an example of an encounter of this type, the encounter taking place in the wall. For such an encounter where an electron of high energy (energy$\gg mc^2$) produces a secondary track, giving to the secondary electron an energy E, the angle θ between the primary and secondary electron is given by $\tan\theta = (2mc^2/E)^{1/2}$. The two tracks of Fig. 10 might represent an effect of this type, the relation above being satisfied within experimental uncertainty. The possibility also exists that a proton may by direct impact give to an electron energy sufficient to produce a secondary track. It is pointed out, however, that on the basis of the conservation laws, due to the relatively large proper mass of a proton, it is difficult to explain the associated tracks as a binary collision between a proton and an electron because of the prohibitively high energy which would have to be assigned to the proton in this case to account for the electron energies observed. To produce an electron of 100×10^6 volts would require a proton energy of 10^{10} volts. In both Figs. 8 and 11 one of the associated pair has a curvature to indicate a positive, and therefore, if these curvatures are correctly measured these cases cannot represent such encounters. Even if these are incorrectly measured and are in reality electrons then for Fig. 11 the value of θ calculated for an energy of 27×10^6 volts is 11°, which would agree with the angle indicated by the photograph within experimental uncertainty. But for the case of Fig. 8, the calculated value of 17° and the measured value of 25° are in conflict. Again the associated pair of Fig. 5 can not possibly be interpreted as due to a binary collision. The hypothesis of simple binary collisions is inadequate to account for all the associated tracks. Furthermore, encounters of this type in which a large amount of energy is transferred to an electron are not to be expected frequently, and the abundance of associated tracks coupled with the fact that positives as well as electrons appear, is strong evidence that the associated tracks represent a quite different phenomenon, i.e., the ejection of two particles from a nucleus.

Scattering of the Cosmic Particles

Certain of the tracks, Figs. 11 and 17, show sudden though very small deflections identical in appearance with the deflections observed in alpha-particle tracks due to nuclear encounters, but which are to be expected in the gas only rarely on the basis of the present scattering laws for high energy electrons or protons. The deflections in some instances represent scattering from the walls of the chamber. An example of large angle scattering from a lead surface is shown in Fig. 8. In Fig. 10 another instance of large angle scattering is shown, the electron being scattered by the glass wall of the chamber.

Experiments are now in progress to study the scattering of cosmic particles in lead. Figs. 22 and 23 show particles traversing 6.0 mm of lead, the angle of scattering being in each case readily measurable.

Energies

The energies of the cosmic particles as determined from the radii of curvature of the tracks range from values below 10^6 electron-volts to, in a few cases, values of the order of 10^9 electron-volts. The greater part of them, however, have energies below 500×10^6 volts.

Precautions were taken to reduce to a minimum the effects of air movements in the expansion chamber which tend to distort the tracks. The energies of the higher energy tracks, i.e., protons of energies of the order of 500×10^6 volts and electrons of the order of 10^9 volts, can be determined only roughly due to the small curvature in the magnetic field.

TABLE I. *Energy distribution.*

Number of electrons	Number of protons	Energy range in electron-volts
2	0	Below 10^6
4	0	From 10^6 to 10×10^6
6	1	" 10×10^6 to 20×10^6
4	1	" 20×10^6 to 30×10^6
3	3	" 30×10^6 to 50×10^6
1	3	" 50×10^6 to 100×10^6
5	5	" 100×10^6 to 200×10^6
4	2	" 200×10^6 to 300×10^6
5	2	" 300×10^6 to 400×10^6
1	4	" 400×10^6 to 500×10^6
3	3	" 500×10^6 to 700×10^6
2		" 700×10^6 to 1000×10^6

TABLE II. *Energies of the associated tracks in electron-volts.*

Group 1	Proton	130×10^6	See Fig. 5
	Electron	120×10^6	
	Electron	30×10^6	
Group 2	Probably proton	150×10^6	See Fig. 6
	Probably proton	400×10^6	
Group 3	Probably proton	450×10^5	See Fig. 11
	Electron	27×10^6	
Group 4	Proton	20×10^6	See Fig. 7
	Electron	4×10^5	
Group 5	Probably proton	$\sim100\times10^6$	See Fig. 8
	Electron	11×10^6	
Group 6	Electron	170×10^6	See Fig. 10
	Electron	11×10^6	
Group 7	Electron	180×10^6	See Fig. 9
	Electron	2×10^6	
Group 8	Electron	4×10^5	See Fig. 20
	Electron or proton	$\sim400\times10^6$	

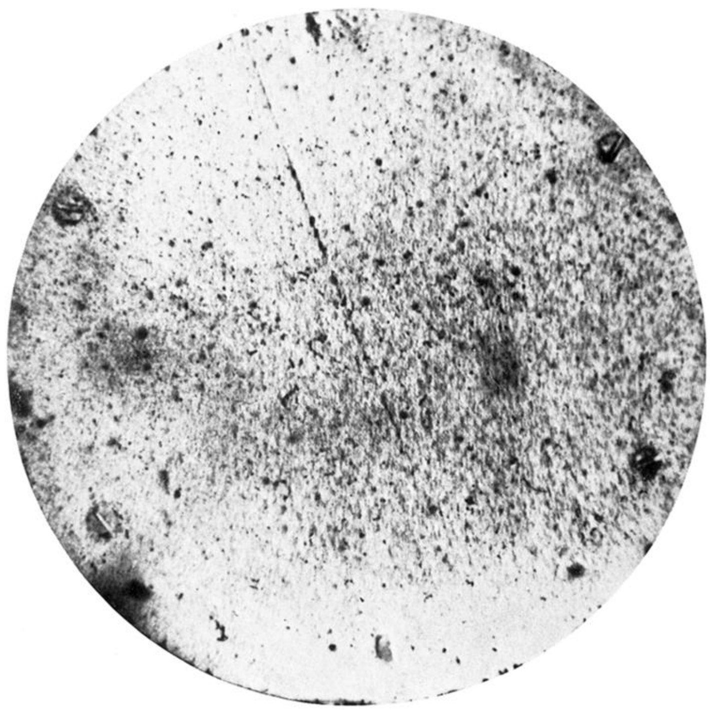
Table I gives the distribution in energy of the electrons and protons. The number of protons and the number of electrons in various energy ranges are listed. It is to be noted that there may be many more electrons in the energy range below 10^6 volts than those listed. Since this includes the energy region of radio-activity, it is impossible to distinguish between electrons from radio-active sources and low-energy electrons due to cosmic rays. Therefore only those very low-energy electrons which are associated with other cosmic-ray tracks, and are definitely to be attributed to cosmic rays are listed in Table I.

There are in addition 5 tracks whose sign of charge is doubtful due to the lack of an appreciable curvature in the magnetic field. For these it is possible only to assign a lower limit to the energy, i.e., 450×10^6 volts on the supposition that they are electrons and 100×10^6 volts on the supposition that they are protons. There is one track, Fig. 21 to which an energy in excess of 10^9 volts must be assigned whether it is assumed a proton or electron.

In Table II are given the energies of the 8 groups of associated tracks.

I wish to thank Mr. Seth H. Neddermeyer for assistance in the measurement of the photographs.

Fig. 16. 12,000 gauss. A proton of 30×10^6 volts energy.



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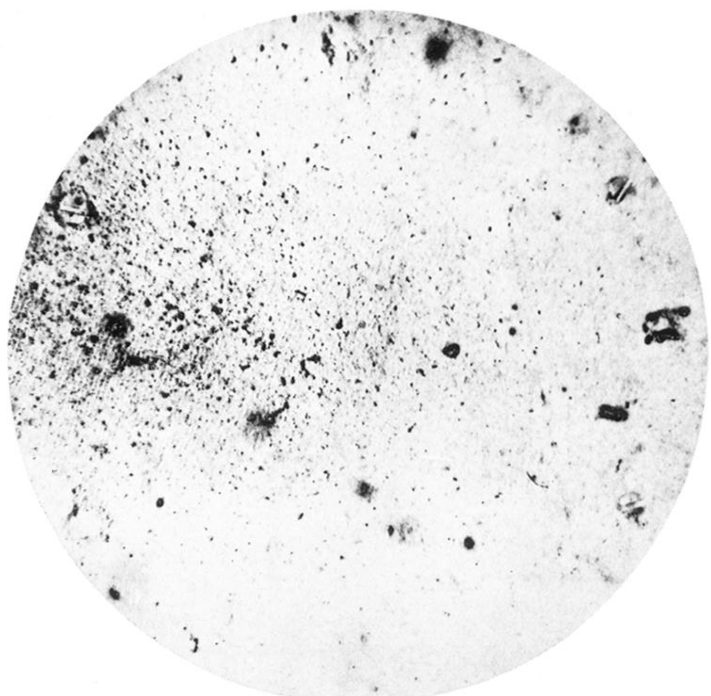
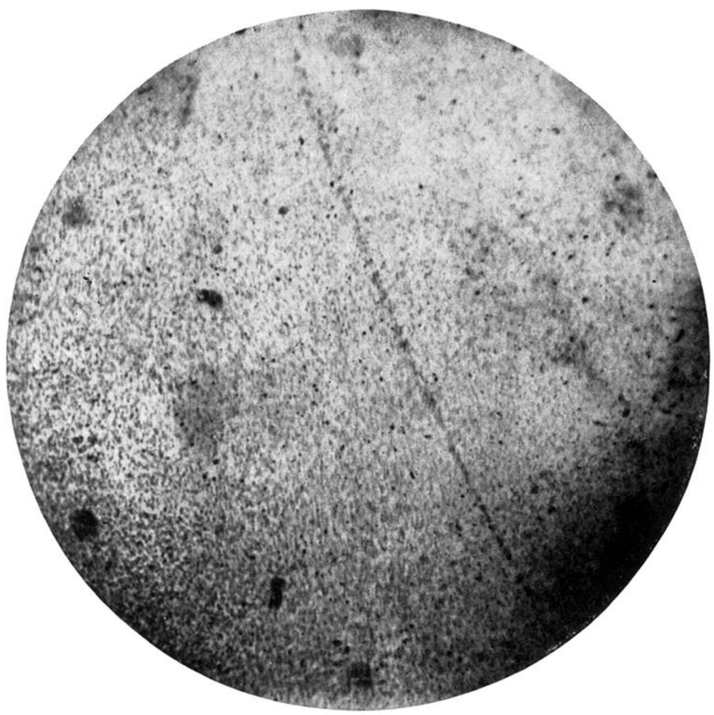


Fig. 18. 17,000 gauss. A proton of 450×10^6 volts energy.



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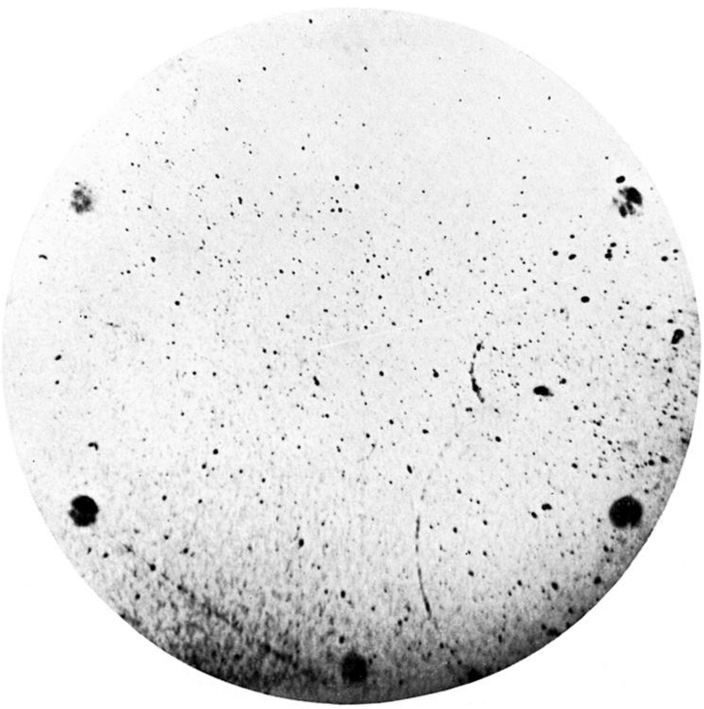
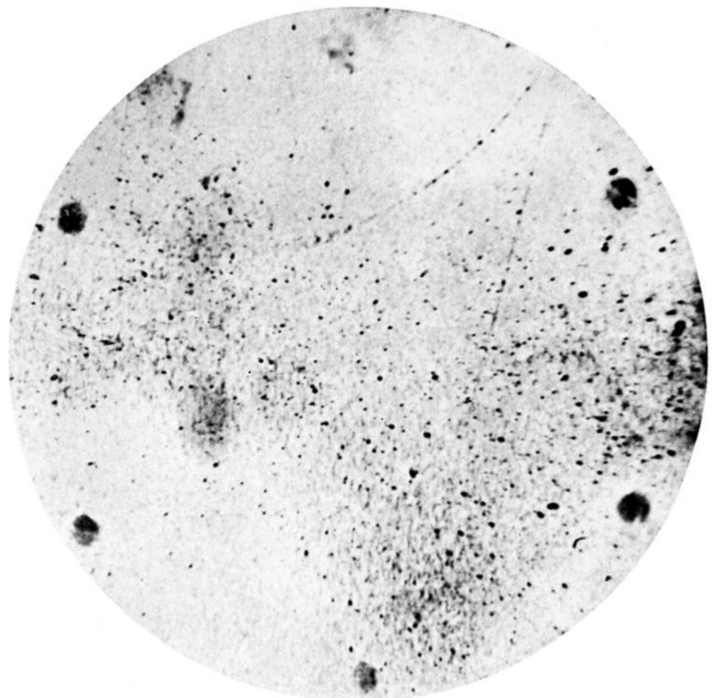


Fig. 10.



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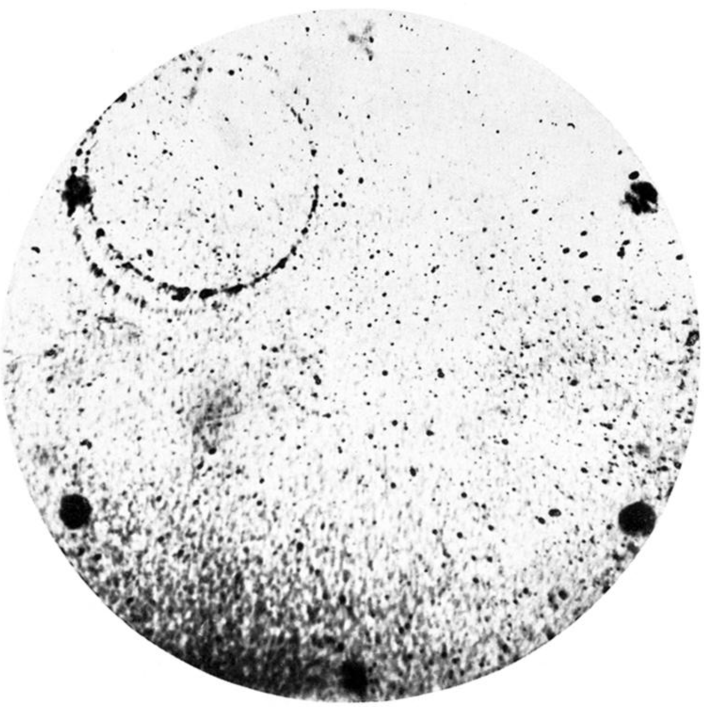

Fig. 12.

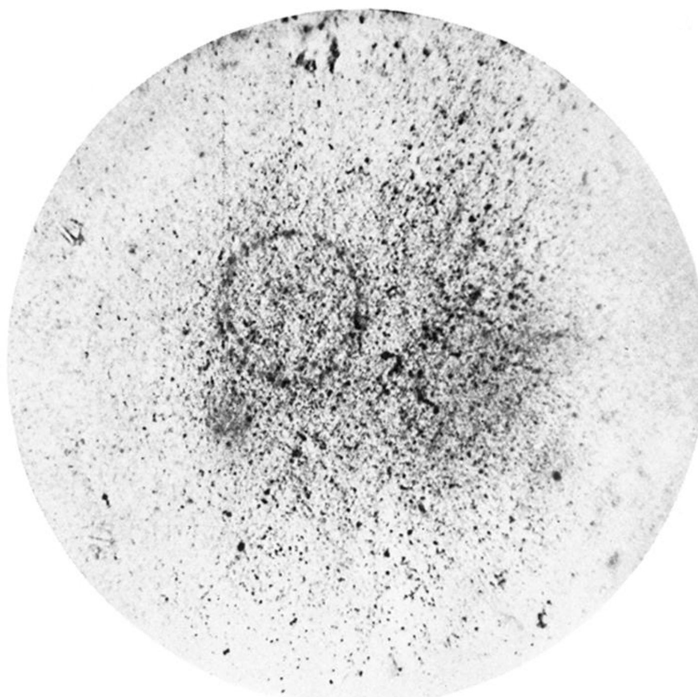

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Fig. 13. 17,000 gauss. An electron of 7×10^6 volts energy.

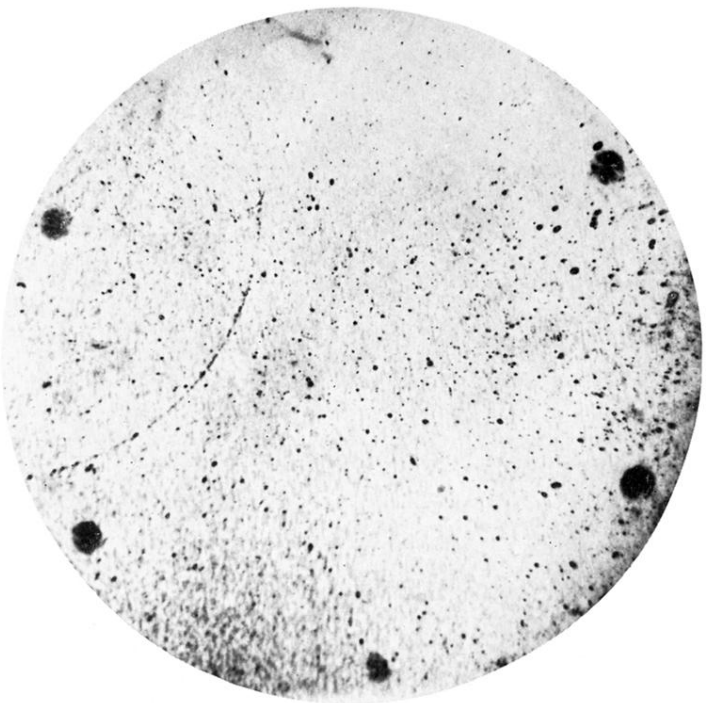

Fig. 14.

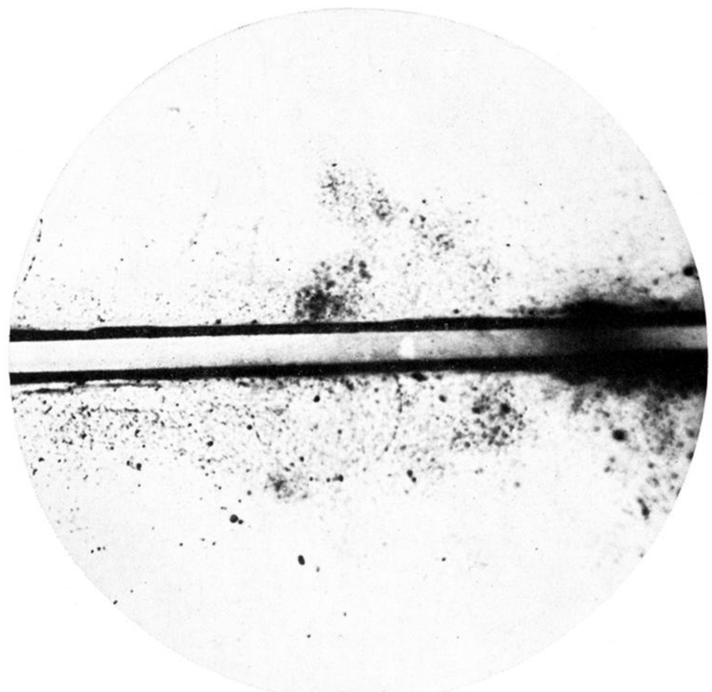

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Fig. 14. 12,000 gauss. An electron of 18×10^6 volts energy.

Fig. 15. 12,000 gauss. An electron of 4.6×10^5 volts energy emerging from the lower surface of the lead. No track is seen entering the lead thus indicating a photon encounter. Above the plate to the left is another electron of 9×10^5 volts energy.

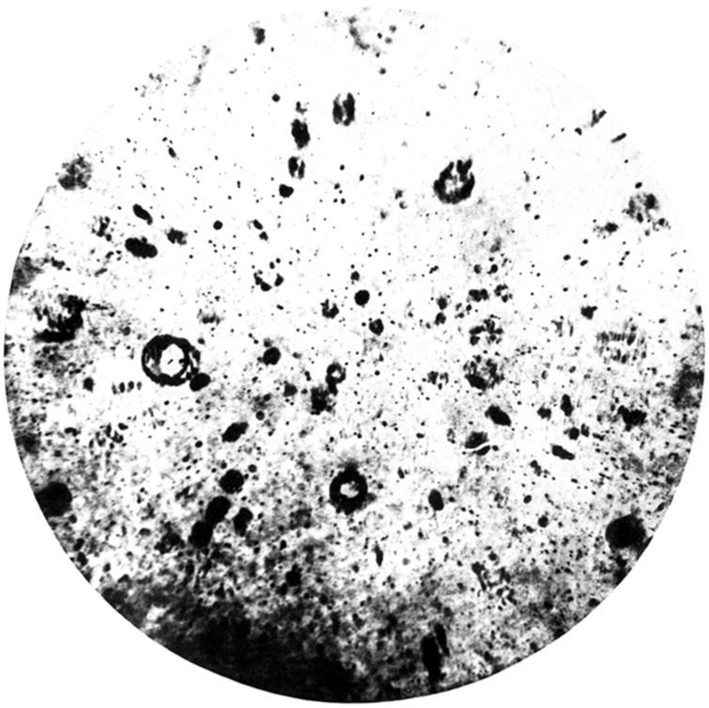

Fig. 2.

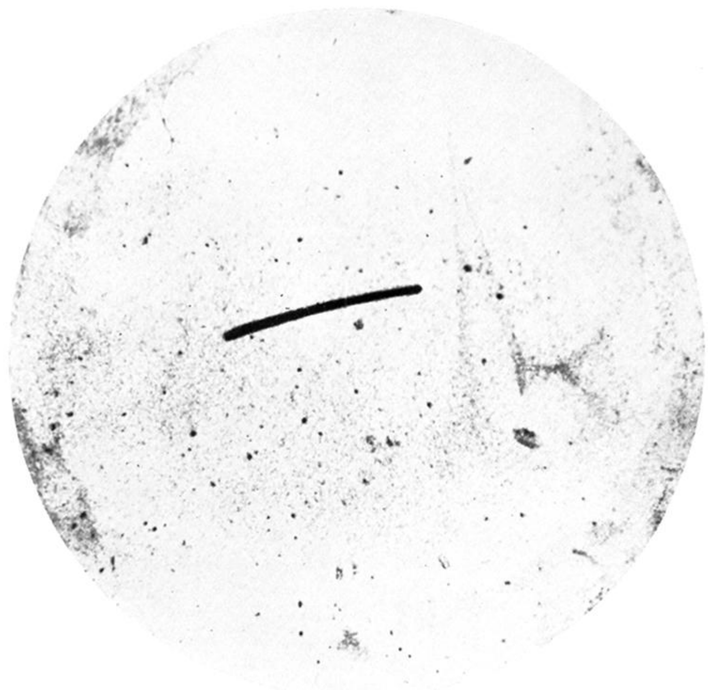

Fig. 3.

Fig. 2. 12,000 gauss. A test photograph showing tracks in air of secondary electrons ejected by gamma-rays from Ra, filtered through 2.5 cm of steel. The energies of the electrons range from 10^6 electron-volts down.

Fig. 3. 12,000 gauss. An α-particle trajectory of 3.85 cm range photographed in air.

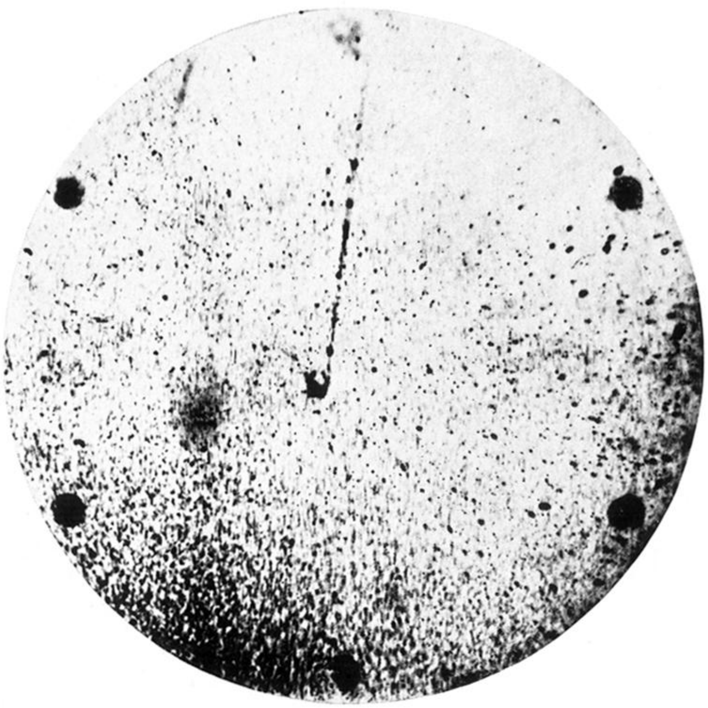

Fig. 20.

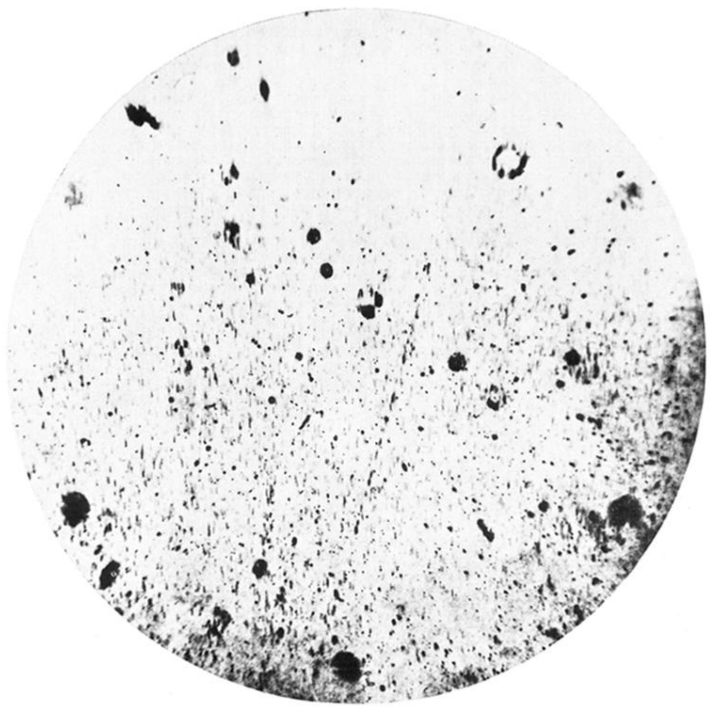

Fig. 21.

Fig. 20. 12,000 gauss. A particle of doubtful sign of charge. If an electron, the minimum energy is 600×10^6 volts, if a proton, the minimum energy is 400×10^6 volts. A close encounter with an electron takes place in the wall in which about 400,000 volts energy is transferred to the electron, shown by the small circle at the lower end of the track.

Fig. 21. 12,000 gauss. A high-energy particle of uncertain sign, photographed in helium. The energy, whether the particle is assumed to be an electron or a proton, exceeds 10^9 volts.

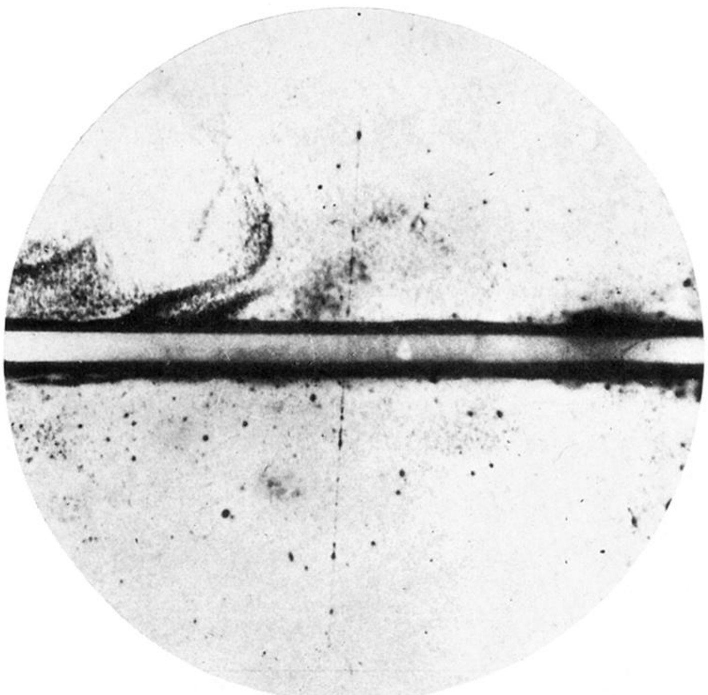

Fig. 22.

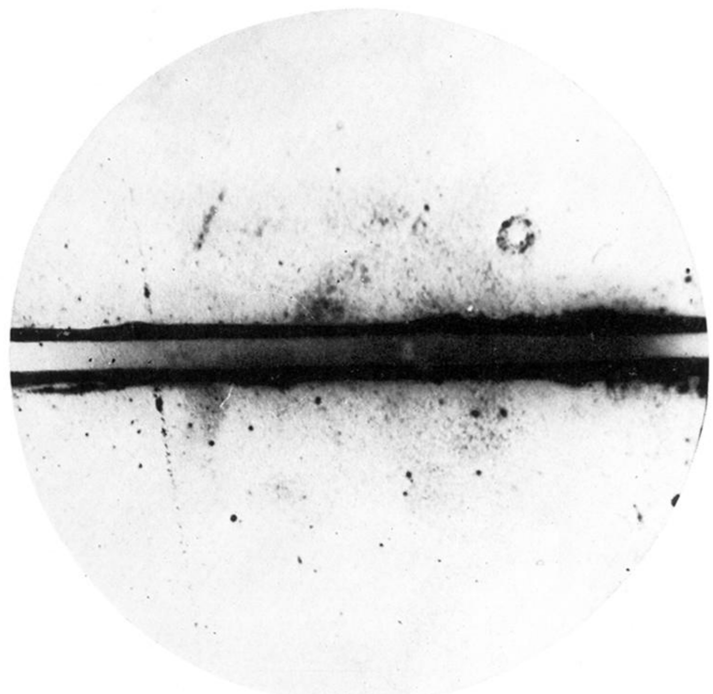

Fig. 23.

Fig. 22. 12,000 gauss. A particle of uncertain sign of charge of energy exceeding 200×10^6 volts if a proton is assumed and exceeding 600×10^6 volts if an electron is assumed. In traversing the 6.0 mm lead plate it suffers a deflection of 0.5 degrees as measured in the plane of the chamber.

Fig. 23. 12,000 gauss. A particle of uncertain sign of charge of energy exceeding 100×10^6 volts if a proton is assumed and exceeding 450×10^6 volts if an electron is assumed. The deflection in traversing the 6.0 mm lead plate is 0.8 degrees. A double scattering, however, is indicated by the sidewise displacement of the portion of the track below the lead as compared to that above the lead.

Fig. 4.

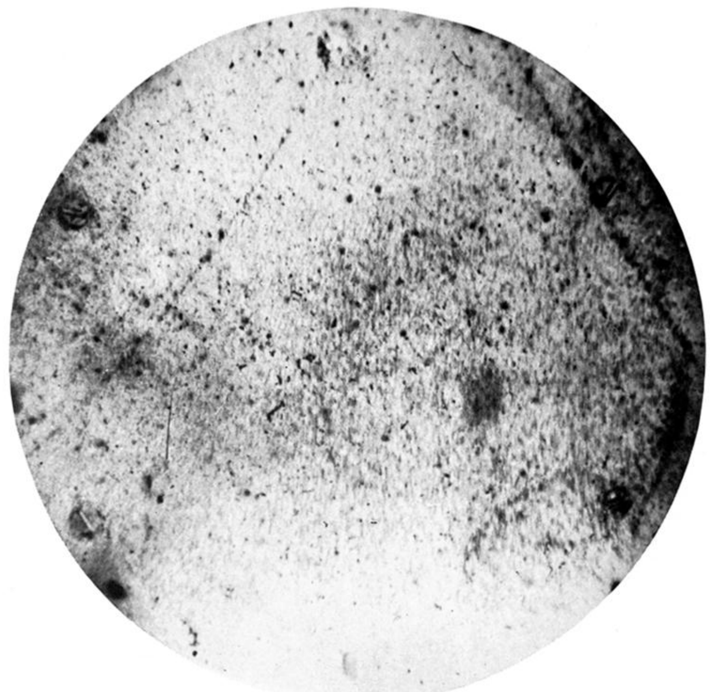

Fig. 5.

Fig. 4. 12,000 gauss. An α-particle trajectory photographed in helium, showing range of 10 cm.

Fig. 5. 17,000 gauss. A pair of associated tracks; at the left an electron of 120×10^6 volts energy, at the right a porton of 130×10^6 volts energy. Since protons and electrons, for a given velocity, have an equal specific ionization, then from the measurements of E. J. Williams and F. R. Terroux (Proc. Roy. Soc. **A126,** 300 (1929–30)) on the ionization by β-particles, the 120×10^6 volt-proton here is expected to ionize about $2\frac{1}{2}$ times as heavily as the electron.

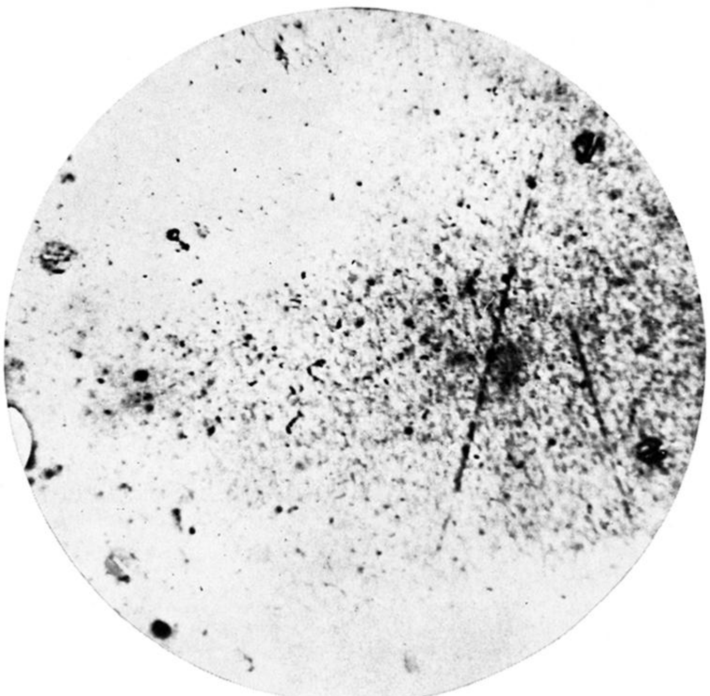

Fig. 6.

Fig. 7.

Fig. 6. 17,000 gauss. A group of three tracks; at the left an electron of 30×10^6 volts energy, at the right probably a proton of 400×10^6 volts energy. The center track, perhaps a proton of 150×10^6 volts energy, lies in a different plane from the other two, and because of its length there is a difficulty in associating it with the other two. The probability of its appearing here by chance is, however, very slight. A small scattering is noted in the center track.

Fig. 7. 12,000 gauss. A proton of 20×10^6 volts energy and an electron of about 400,000 volts energy.

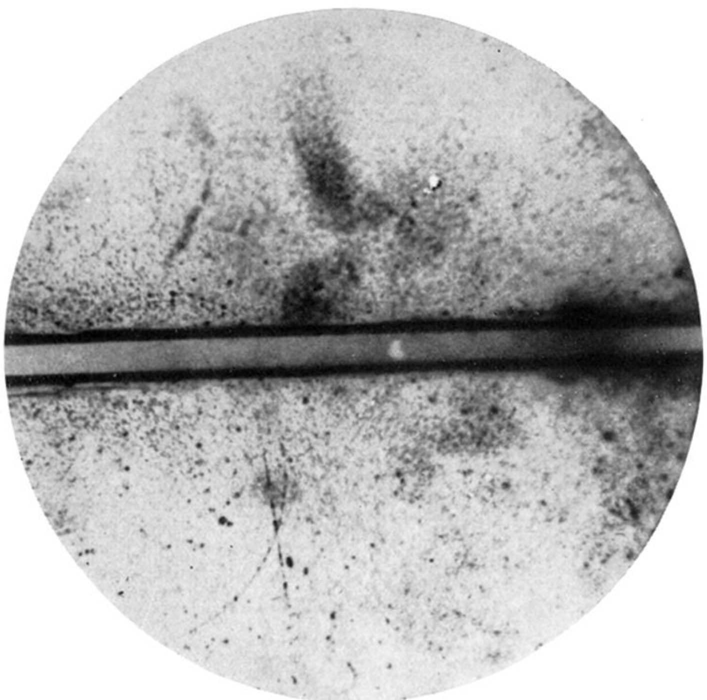

Fig. 8.

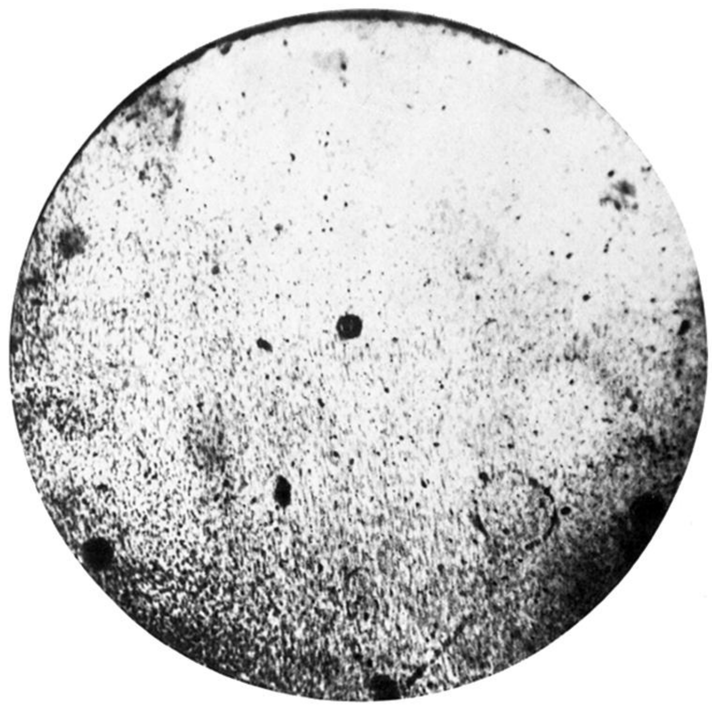

Fig. 9.

Fig. 8. 12,000 gauss. A plate of lead 6.0 mm thick extends horizontally across the chamber. Below the lead appear two tracks, one apparently a proton of about 100×10^6 volts energy, the other an electron of 11.4×10^6 volts energy which passes out through the 0.5 cm glass wall. Above the lead another electron enters through the glass wall, or perhaps the same electron after having been deflected into the chamber again by the magnetic field. It suffers a deflection of 80° upon striking the lead surface. Its energy is 8.2×10^6 volts. The assumption that the same electron re-entered the chamber above the lead is borne out by the fact that an energy loss of 3.0×10^6 volts is to be expected for an electron traversing the 0.5 cm glass wall twice as shown in the figure. The angle of divergence of the two associated tracks below the lead is 25°. (The track above the lead appears double due to a double reflection of the light before entering the camera.)

Fig. 9. 12,000 gauss. Two electrons of energy about 180×10^6 volts and 2×10^6 volts respectively.