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Some Photographs of the Tracks of Penetrating Radiation.

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[Plates 21-24.]

1. *The Experimental Method.*

We have recently developed a method by which the high speed particles associated with penetrating radiation can be made to take their own cloud photographs.* By this means it is possible to obtain these photographs very much more speedily than by the usual method of making expansions at random. For when this latter method is used it is only on a small fraction of the photographs that a track will be found. The average number of photographs required to obtain one track will depend on the size and orientation of the chamber and on the effective time of expansion. The latter is not likely to be more than 1/20 second. From measurements with counters it is known that about 1·5 fast particles fall, from all directions, on 1 sq. cm. per second. Roughly consistent with these figures are the results found with cloud chambers. Skobelzyn† has obtained as many as one track every ten expansions, but in the work of Anderson‡ the number of tracks which were long enough to be suitable for energy measurements was only about 1 in 50 photographs. By our method, tracks are found on 80 per cent. of the photographs. We intend to give a full account of the technique of this method of photography in a separate paper, confining ourselves here to a rough outline only.§

A cloud chamber of diameter 13 cm. and depth 3 cm. is arranged with its plane vertical and two Geiger-Müller counters, each 10 cm. by 2 cm. are placed one above and one below the chamber so that any ray which passes straight through both counters will also pass through the illuminated part of the chamber, fig 2. An alternative arrangement is described on p. 719. The

* 'Nature,' vol. 130, p. 363 (1932).

† 'C. R. Acad. Sci. Paris,' vol. 195, p. 315 (1932).

‡ 'Phys. Rev.,' vol. 41, p. 405 (1932).

§ Mott-Smith and Locher 'Phys. Rev.,' vol. 38, p. 1399 (1931); vol. 39, p. 883 (1932) have found a correlation between the occurrence of these tracks and the discharge of a counter, and Johnson, Fleischer and Street, 'Phys. Rev.,' vol. 40, p. 1048 (1932) have used coincidences to operate the illuminating flash of a continuously working closed chamber.

counters are connected to a valve circuit arranged to record only simultaneous discharges of the two counters.*

The piston of the chamber is a light aluminium disc attached to the rest of the chamber by means of a rubber diaphragm and so free to move sufficiently to make the expansion. Before an expansion the piston is in equilibrium under the pressure of gas in the chamber, about 1·7 atmospheres, and the same pressure of air below it. The expansion is caused by opening a valve which allows the air under the piston to escape to the atmosphere. The sequence of events during operation is as follows. When a coincidence occurs the grid of a thyratron connected to the amplifier becomes positive, so that the thyratron short circuits a small magnet, which had previously held up a light armature against a spring. The armature flies off and moves a catch which releases the valve under the piston, and so causes the expansion. By careful attention to the detailed design of the various parts it has been possible to make the total time from the discharge of the counters to the end of the expansion as small as 1/100 second. In this time the ions produced by an ionizing particle only diffuse a short distance from the position where they are formed : the resulting tracks have a breadth in oxygen at 1·7 atmospheres of only 0·8 mm. and this breadth, though of course much larger than that of tracks formed by particles passing through at the end of the expansion, is small enough to allow very accurate measurements. The observed breadth is in good agreement with that calculated from the known rate of diffusion of the ions.†

About 1/100 second after the expansion the illuminating flash begins. This lasts about 1/30 second and is produced by passing a large transient current from a 4000-volt transformer through a capillary mercury lamp.

The whole chamber is placed in a water cooled solenoid capable of maintaining a field of 3000 gauss over the whole chamber. Two cameras are employed, one with its axis coincident with the axis of the chamber and so parallel to the magnetic field, and one with its axis making an angle of 20° with this direction. The two photographs of a track were not viewed stereoscopically, as the angle of 20° is too large for this, but the plates were replaced in the cameras and illuminated from behind, so as to throw two images back into the object space. Wire models of the tracks could thus be built up full size in the object space. This method of stereoscopic reprojection is essentially that used by Curtiss,‡ and by Williams and Terroux.§ It is of the utmost

* Rossi, 'Nature,' vol. 125, p. 636 (1930).

† Blackett and Occhialini, *loc. cit.*

‡ Curtiss, 'Bur. Stand., J. Res.,' vol. 4 p. 663 (1930).

§ Williams and Terroux, 'Proc. Roy. Soc.,' A, vol. 126, p. 289 (1930).

importance to use two cameras, to give two photographs from different directions, for one photograph alone gives little definite information.

The average time of waiting from the moment of making ready to the first coincidence was found to be about 2 minutes, which is in agreement with the observed *rate* of about two coincidences a minute.

Over 700 photographs have been made in this way and on over 500 of these are found the tracks of particles of high energy.

In order to investigate the interaction of these particles with matter, plates of various metals were in many experiments placed across the middle of the chamber. Anderson* has used a lead plate in this way and we have used in addition to lead both copper and tungsten plates. In some recent experiments thick metal blocks have been placed immediately over the upper counter (B 1, fig. 2) to investigate the nature of the secondary particles produced by various metals.

2. *The Photographs.*

About 75 per cent. of the successful photographs show a single track caused by a particle which has passed through both counters. The majority of these are not appreciably deflected in a magnetic field of 2000 gauss. Since the minimum deflection which we could consider significant was a little over one degree, they must have therefore a radius of curvature greater than about 500 cm. and so an $H\rho$ greater than 10^6 gauss-cm. Since the energy E of an electron, expressed in electron volts, is given approximately by $E = 300\ H\rho$ (provided $E \gg mc^2 \sim \frac{1}{2} \times 10^6$ volts), the mean energy of the undeflected particles, assuming them to be electrons, is greater than about 300 million volts. Many curved tracks are also observed, corresponding to electrons of lower energy.†

By using magnetic fields up to 18,000 gauss, both Millikan and Anderson,‡ and Kunze§ have been able to deflect nearly all the particles. The results of the two investigations do not appear to be in complete agreement, but both find that deflections in either direction occur with comparable frequency. The distribution seems roughly continuous up to a maximum $H\rho$ of about 7×10^6 gauss-cm. corresponding to an electron energy of 2×10^9 volts.

The remaining 25 per cent. of the photographs show either a single track not

* Anderson, *loc. cit.*

† An electron must have an energy greater than about 5×10^6 volts in order to be able to pass through the 5 mm. glass walls of the chamber and the 1 mm. brass walls of the counters.

‡ 'Phys. Rev.,' vol. 40, p. 325 (1932); Anderson, *loc. cit.*

§ 'Z. Physik.,' vol. 79, p. 203 (1932).

passing through both counters or else they show the groups of two or more tracks, which were first discovered by Skobelzyn* and which are now so well known a feature of penetrating radiation. The occurrence of these multiple tracks is clearly related to the various secondary processes occurring when penetrating radiation passes through matter. The investigation of these secondary particles by means of counters was first carried out by Rossi† and later by Johnson and Street.‡

A most striking result of the present work has been to reveal the astonishing variety and complexity of these multiple tracks. Already 18 photographs have been obtained on which are the tracks of more than 8 particles of high energy and four photographs show more than 20 tracks.

Thirteen photographs are reproduced on Plates 21 to 24, and a detailed description is given of each.

A very lengthy investigation will certainly be required before it will be possible to give a complete interpretation of the extraordinarily complex atomic phenomena which are responsible for these groups of tracks. In this paper a preliminary and mainly qualitative account will be given of some of the more striking phenomena observed in the photographs, leaving almost all the details and the measurements for subsequent reports.

The most noticeable feature which is common to many of these multiple tracks is the occurrence of a group of several tracks diverging, mainly downwards, from some region in the material surrounding the chamber. (Nos. 1 and 2, 3, and 4, 8, 9, 10, 11, 12 and 13, Plates 21 to 24.) Sometimes a group of these tracks appear to diverge fairly accurately from a single point; sometimes two or more such radiant points can be detected and often there are stray tracks not obviously related to the main groups. The majority of the tracks forming these groups are not appreciably deflected by the magnetic field of 2000 gauss. When such a shower of particles is seen to have entered the top of the chamber, it is not infrequently found that a subsidiary radiant point occurs in the metal plate, which in some of the experiments is placed across the chamber (Nos. 8, 11). When this occurs it is sometimes found that particles of great energy are thrown backwards in a direction nearly opposite to that of the incident shower (No. 11).

* Skobelzyn, 'Z. Physik,' vol. 54, p. 686 (1929); 'C. R. Acad. Sci. Paris,' vol. 194, p. 118 (1932); Auger and Skobelzyn, 'C. R. Acad. Sci. Paris,' vol. 189, p. 55 (1929); Mott-Smith and Locher, *loc. cit.*

† 'Phys. Zt.,' vol. 33, p. 304 (1932); 'Acad. Lincei,' vol. 15, p. 734 (1932).

‡ 'Phys. Rev.,' vol. 40, p. 635 (1932).

3. *The Nature of the Particles in the Showers.*

To begin to unravel these complexities it is first necessary to identify the particles producing the tracks. It is not always easy to do this as the evidence furnished by the photographs is often inconclusive. But it will be shown that it is necessary to come to the same remarkable conclusion that has already been drawn by Anderson* from similar photographs. This is that some of the tracks must be due to particles with a positive charge but whose mass is much less than that of a proton.

The most important measurement is the curvature of the track by the magnetic field, as expressed by the product $H\rho$, of the magnetic field by the radius of curvature of the track.

In addition the ionization density along the track can be roughly estimated, and, in some cases, the direction of motion of the particles can be inferred. In rare cases a particle stops in the gas of the chamber so that its range can be measured, and even when this is not so, the knowledge that the range is greater than a definite amount is sometimes of decisive importance.

Now the ionization density due to a fast particle depends only on its charge and velocity, but not on its mass. But the velocity of a particle of given $H\rho$ depends on its mass, so two particles *with the same* $H\rho$ but *different masses* will ionize differently.† Consequently the simultaneous observation of the $H\rho$ of a track and the ionization along it allow, in principle, the mass of the particle to be determined.

Now the variation of ionization density along the track of a β-particle has been determined experimentally‡ for values of v/c up to $0\cdot95$, and can be estimated theoretically for higher values. For our purpose it is convenient to take the values for the rate of loss of energy obtained theoretically by Bethe.§ The two curves, fig. 1, show the energy loss along the track of an electron and a proton as a function of $\log_{10}(H\rho)$. It can be seen that there is little difference between the ionization due to the two kinds of particles when their $H\rho$ is greater than about $1\cdot5 \times 10^6$ gauss-cm. But for smaller values of $H\rho$, the

* 'Science,' vol. 76, p. 238 (1932).

† The relation between the velocity v and $H\rho$ is

$$\frac{v}{c} = H\rho \Big/ \left\{\left(\frac{mc^2}{e}\right)^2 + (H\rho)^2\right\}^{\frac{1}{2}},$$

where m is the mass and e the charge in e.s. units.

‡ Williams and Terroux, *loc. cit.*

§ 'Ann. Physik,'; 'Z. Physik,' vol. 76, p. 293 (1932).

heavier particle, in consequence of its smaller velocity, ionizes much more readily. Consequently, if a track is observed to have an Hρ less than, say, $1\cdot0 \times 10^6$, it is easily possible to decide if the mass is of the order of that of an electron or that of a proton. In a similar way the observation of the Hρ

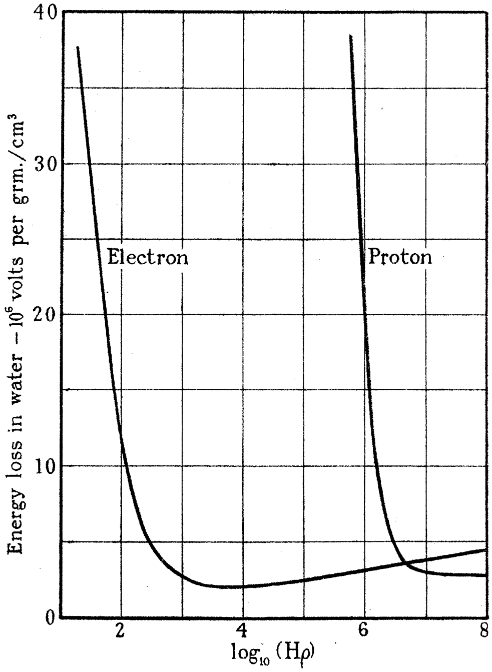


FIG. 1.

of a track and its *range* allows the mass of the particle to be estimated. In Table I are given the ranges and velocities* of protons and alpha-particles of given Hρ.

Table I.—Relation between Hρ, Velocity and Range of Protons and Alpha-Particles.

$H\rho \times 10^{-5}$ gauss-cm.	0·5	1·0	2·0	3·0	4·0
Protons—					
Velocity $\times 10^{-9}$ cm./sec.	0·48	0·96	1·92	2·87	3·83
Range, cm. air 15° C.	0·19	1·0	6·9	25·7	69·7
Alpha-particles—					
Velocity $\times 10^{-9}$ cm./sec.	0·12	0·24	0·49	0·72	0·97
Range, cm. air 15° C.	0·05	0·13	0·35	0·64	1·1

* Blackett, 'Proc. Roy. Soc.,' A, vol. 135, p. 132 (1932).

Anderson reports having found several tracks which must be attributed to positively charged particles of small mass, and discusses these photographs in detail, though the photographs themselves are not reproduced. In one the direction is given by the change of curvature in going through a lead plate, in another two tracks curved in opposite directions appear to leave the plate, and in a third two particles appear to leave the plate with a curvature corresponding to a positive charge. For all these, Anderson states that the ranges and specific ionization show that positively charged particles must be present with a mass much less than that of a proton.

To decide the sign of the charge of a particle it is necessary to know in which direction it was moving. There are four ways of obtaining this information from a photograph. (*a*) If a particle passes through a metal plate, which is thick enough to cause it to lose an appreciable part of its energy, then the particle must have moved from the side of greater $H\rho$ to that of less, since the possibility that the particle has gained energy in the plate may be neglected. If the particle is quite slow it may be possible to detect the change of $H\rho$ owing to the loss of energy while passing through the gas. (*b*) Again, if a particle produces a secondary of sufficient energy by collision with, say, a free electron, then the direction of the secondary will indicate the direction of motion of the particle. (*c*) If a group of tracks diverge from some point or some small region of space, then there is a high probability, but no certainty, that any one particle did actually move away from this region. (*d*) If a track is observed in a nearly vertical direction, then it is more probable that the particle has moved downwards than upwards. The evidence for this last assumption is the fact that the ionization from penetrating radiation increases upwards. It is hard, however, to estimate these probabilities numerically, as the frequency of such events as in No. 11, Plate 23, where at least one particle of high energy is thrown upwards, is unknown.

Now on photographs 3 and 4 the majority of the tracks are undeflected ($H\rho > 10^6$), but there are some which are definitely curved and of these some are curved in one direction and some in the other.* The appearance of the whole group strongly suggests that the particles have diverged downwards, and if this is assumed true, those bent to the left are negatively charged and those bent to the right are positively charged. There are two of the latter,

* A single nearly vertical track will be said to have a positive curvature if curved as for a positive charge moving downwards. A track which forms part of a shower will be said to have a positive curvature if curved as for a positive charge moving away from the apparent region of divergence of the shower. Similarly for negative curvatures.

with values of $H\rho$ of $0 \cdot 4 \times 10^5$ and $1 \cdot 5 \times 10^5$ gauss-cm. If these two tracks were due to protons their ranges could only be $0 \cdot 2$ cm. and 3 cm., in air, whereas their actual lengths *in the chamber* are about 12 cm. of air at N.T.P. So these tracks are certainly not due to protons, but to particles of much smaller mass. Two similar tracks can be seen in photographs 1, 2, one in 9, one in 10 and probably two in 13.

The study of the ionization density along the tracks entirely confirms these conclusions.

It is strikingly evident from their appearance that the ionization density along the positively curved tracks in the photographs mentioned is very nearly the same as that along the undeflected and negatively curved tracks. It is, unfortunately, not possible to make a precise count of either the primary or the total ionization along these tracks without special experiments,* but rough counts have shown that the ionization density common to all these tracks is approximately that to be expected for fast electrons. Further, by comparing the appearance of an undeflected track with that of a slow secondary β-particle of known energy, it becomes clear that any track, along which the ionization is about three times greater than this, can be easily recognized. (See description of No. 11.) Consequently it is legitimate to conclude that these tracks cannot possibly be due to protons. If they were due to protons the ionization would be between 10 and 100 times as heavy, and the tracks would look like that in No. 14 where there is an undoubted proton track of $H\rho \sim 3 \times 10^5$ gauss-cm.

The only possible conclusion of the argument both from the range and from the ionization is that these tracks are due to positively charged particles with a mass comparable with that of an electron rather than with that of a proton. It is, of course, conceivable that some of these tracks are caused by negative electrons moving upwards, which only by chance pass through the region from which the other tracks appear to diverge. It is difficult to estimate this chance numerically, but the presence of these positively curved tracks is so common a feature of these showers that this explanation can hardly be maintained for them all.

Altogether we have found 14 tracks occurring in showers which must almost certainly be attributed to such positive electrons, and several others which are less certain.

* This can be done by working with H_2 or He, as has been done by Anderson and the writers, or by introducing a time delay into the mechanism so as to allow the ions time to diffuse away from each other.

Until larger fields are available it will not be possible to find the ratio of the number of the positive and negative particles in the showers, but there seems some slight evidence that in some showers at least the numbers are about equal. Of the tracks which are appreciably deflected in photographs 1, 2, Plate 21, and 3, 4, Plate 22, about equal numbers go to the right and to the left. In general, however, negative particles are more frequent.

Additional evidence, independent of the showers, for the existence of a positively charged particle with a mass comparable with that of an electron is found in photograph No. 7. In this, the particle passes through a 4 mm. lead plate. The track is seen to be more curved below the plate than above, so the particle must have moved downwards unless it be assumed that it gained energy in traversing the plate ; hence it had a positive charge. Corresponding to the final $H\rho$ of $1 \cdot 2 \times 10^5$ gauss-cm. it would only have had a range of $1 \cdot 5$ cm. in air if it had been a proton and it would have ionized more than 100 times as much as a fast electron. Its range is certainly greater than 5 cm. and it ionizes just like a fast electron.

Several tracks have been observed in which the presence of a secondary formed in the gas indicates the direction of motion of the particle passing through both counters, and in most cases the direction indicated is downwards as is to be expected. But on photograph No. 14, Plate 24, a track is seen which can only be due to a positive electron, if the evidence of the secondary is to be trusted. There is always, however, the possibility that such a slow secondary (about 35,000 volts) may have been deflected by a subsequent collision so that its apparent direction of projection is not its original one. So not much weight can be put on this one track.

No. 5 shows a secondary produced in the plate indicating a downward direction of motion and one of the two tracks below shows a positive curvature, which, though small, does seem to be considerably greater than any possible fictitious curvature owing to distortion by movement of the gas.

It is unfortunate that in our experiments the magnetic field was not sufficient to deflect appreciably the majority of the tracks, either those appearing singly or those in showers. But, as has already been mentioned, the measurements of Anderson and of Kunze were made with much larger fields, and though not in complete agreement with each other show conclusively that about equal numbers are deflected either way, and this is also true of those tracks in our photographs which are appreciably deflected. Anderson and Kunze find respectively that 30 per cent. and 60 per cent. are positively deflected.

Now it is certainly possible that almost all the single tracks are due to particles which have originated as part of showers, which have occurred higher up in the atmosphere or in other material far above the chamber. If this is so, one would expect to find about the same ratio of the numbers of positive and negative particles amongst the single tracks as are found in the showers. What experimental evidence is available suggests that this may be so.

But the evidence of such photographs as No. 11, Plate 23, shows that fast particles are sometimes projected upwards, so that it is certain that a few of the single tracks are due to particles moving upwards and not downwards.* It is impossible, therefore, to be certain of the sign of the charge of the particle, producing a particular single track, from the curvature alone, unless other evidence of its direction is available. Still it is certainly safe to conclude that the majority of the positively curved tracks are due to positive particles moving downwards.

However, it is not easy to agree with Anderson and Kunze that the positively curved tracks are mainly due to protons. For, as already mentioned, it is a striking feature of our photographs that the great majority of the tracks have almost the same specific ionization. Now Kunze finds that the mean energy of the protons (for this he assumes the positively curved particles to be) is about 4×10^8 volts. Protons of this energy ($H\rho \backsim 3 \cdot 5 \times 10^6$ gauss-cm.) ionize not very differently from electrons (see fig. 1). But if such fast protons are present, then there must also be some slower ones present, for the stream of descending particles must certainly be fairly heterogeneous at the bottom of the atmosphere, whatever it may be at the top, and these slower tracks will ionize more strongly and so produce noticeably denser tracks. Four tracks have been found showing the character of proton tracks of which two are on No. 14 and one on 13, but in no case are they to be classified with the main group of downward moving particles, but rather with some local nuclear disintegration process. Further, all the single tracks which do show marked positive curvature have nearly the same specific ionization as the undeflected ones, so are either negative electrons going up, or positive electrons coming down. By a positive electron is meant a particle with unit positive electronic charge and with a mass very much less than that of a proton.

So the conclusion seems justified that the main beam of downward moving particles consists chiefly of positive and negative electrons. Some protons are probably also present.

* Skobelzyn has also shown the existence of such particles 'C. R. Acad. Sci. Paris,' vol. 195, p. 315 (1932).

4. *The Frequency of the Showers.*

It seems plausible to assume that the showers of particles arise from some nuclear disintegration process stimulated by particles or protons of high energy associated with the penetrating radiation. The fact that most of the showers diverge downwards makes this probable.

It is possible that these showers of particles are related to the occurrence of the bursts of ionization found originally by Hoffmann* and studied by Steinke, Schindler, Messerschmidt, and others. These have been definitely shown to be correlated with the intensity of the penetrating radiation by experiments in deep mines. It is hoped to investigate in a similar way the frequency of the showers by means of multiple coincidence counting. It is, however, conceivable that some part of the phenomena of the showers may be of spontaneous nuclear origin.

These showers are certainly much rarer in comparison with the single tracks than their frequency of occurrence on our photographs would seem to indicate. For the frequency of occurrence of a given type of track depends on the product of its actual frequency of occurrence multiplied by the probability that when it occurs both counters will be operated. This last probability is very different for showers and single particles. We find about one shower to every *thirty* single tracks. But the actual ratio of the number of showers crossing the chamber to single tracks is certainly much less than this. For if a single particle crosses the *chamber*, there is only a small chance (about one in 200) that it will pass through both *counters*, while if a shower of many particles passes through the chamber there may be quite a high chance, perhaps as high as 1 in 5, that a coincidence will result. So the ratio of showers to single tracks on our photographs may be forty times greater than the ratio of their actual occurrence.

The showers appear to originate indifferently in any of the material surrounding the chamber. Since the chamber is nearly surrounded by the copper solenoid the majority originate in the copper, but radiant points have also been located in the glass walls and roof of the chamber, in the aluminium piston and in the air of the room. When plates of lead and copper have been placed across the centre of the chamber groups of tracks have been found to radiate from points in the plate. A tungsten plate has also been used for a few photographs, but nothing of special interest has been found with it.

* Full references are given by Hoffmann, 'Phys. Z.,' vol. 17, p. 633 (1932); Steinke and Schindler, 'Z. Physik,' vol. 75, p. 115 (1932); 'Naturwiss.,' vol. 26, p. 491 (1932); Messerschmidt, 'Z. Physik,' vol. 78, p. 668 (1932).

It is of interest to make a rough estimate of the frequency of these showers in relation to the number of nuclei in the surrounding material. One coincidence occurs every 2 minutes, and one shower with more than 8 tracks about every thirty coincidences; that is, once every hour. These come predominantly from the part of the copper solenoid above the chamber, say, from a mass of 10 kg. of copper. Taking the chance to be 1 in 5 that a shower which has originated in this copper will set off the counters we get that one shower originates in 10 kg. of copper about every 10 minutes. Expressed in the form of a mean life one finds a value of about 10^{18} years.

Alternatively we can obtain a rough lower limit for the effective area of a copper nucleus for the production of such showers by assuming that all the incident fast particles are effective. Since there are about $1 \cdot 5$ of these per sq. cm. per minute, we find the affective area of a copper nucleus to be about 10^{-27} sq. cm.

It is possible to make a rough estimate of the amount of ionization which would be produced in an ionization chamber of the type used by Steinke and Schindler by such a shower as that in photographs Nos. 1 and 2. The photographs show about 20 tracks with energies very much more than sufficient to pass right across such an ionization chamber. Taking the air equivalent depth of the ionization chamber as 240 cm., and allowing 80 ion pairs per centimetre of path, we get for the total ionization produced about 4×10^5 ion pairs. Though this is less than the value of 3×10^6 given by Messerschmidt (*loc. cit.*) for the lower limit of the ionization bursts, there are almost certainly, in the showers, many more particles than actually pass through the cloud chamber, and some of these may be of greater mass and charge and so have a larger specific ionization. The evidence of Nos. 14 and 15 shows that some protons at least are produced. And there may be still other particles with still greater ionizing power which only rarely succeed in entering the gas of the chamber so as to become visible.

It must be remembered that the chance that an ionizing particle, which originates at some random point in the walls of the chamber or the surrounding material, should be observed as a track, is proportional to its range and so is inversely proportional to its ionizing power. In general, heavily ionizing particles will not reach the chamber at all and so will not be observed. It is not impossible therefore that such short range particles are produced along with the penetrating ones in the processes giving rise to the showers.

It seems, therefore, likely that the phenomena of the showers in a cloud chamber and these ionization bursts are related, though the latter are both rarer and show greater ionization than any showers that we have yet observed.

The total energy of the particles crossing the chamber in photographs Nos. 1 and 2 is more than 2×10^9 volts ; this is obtained by assuming 20 tracks of 100×10^6 volts each.

5. *The Mechanism of the Showers.*

The showers are almost certainly due to some process that involves the interaction of particles or photons of high energy with atomic nuclei. Existing theory appears to be able to deal approximately with the interaction of such particles and photons with the extra-nuclear electrons, and Heisenberg* has recently collected the relevant results for comparison with such experiments as these on penetrating radiation. We intend to study the frequency of occurrence, on our photographs, of the scattering processes and of the production of secondaries, both by particles and photons. Photograph No. 5, Plate 22, shows the production, by a fast particle, of a secondary particle of energy about 60 million volts.

The effective area of cross-section for the collision of an electron or proton of very high energy with a free particle of mass m and unit electronic charge is

$$2\pi e^4/mc^2\varepsilon, \tag{1}$$

where ε is the energy given to the particle initially at rest. The direction of projection θ of this particle is given by

$$\tan^2\theta = 2mc^2/\varepsilon. \tag{2}$$

It will be noticed that the mass of the incident particle does not enter into these expressions. Several collisions, in which this last relation is approximately satisfied, have been photographed.

From (1) we find that the free path in lead for the production of a secondary electron with energy of 100 million volts is about 16 cm. ; our experiments confirm this as regards order of magnitude. It is clear from this figure that the chance of two or more secondaries being produced independently nearly at the same point is very small. So when one track is seen to branch at one point into three or more tracks, it is impossible to resist the conclusion that some nuclear interaction has taken place. If an incident photon is considered the same argument is valid.†

* 'Ann. Physik,' vol. 13, p. 430 (1932) ; 'Naturwiss.,' vol. 21, p. 365 (1932).

† Millikan and Anderson, *loc. cit.* ; Skobelzyn, *loc. cit.*

It is clear that there are several distinct processes giving rise to the complex tracks. In a few cases the processes seem fairly simple. An incident particle probably a negative or positive electron ejects three or more particles presumably from a single nucleus. No. 15 shows probably that an incident particle has ejected two electrons (both with $E_e \sim 13$ million volts) from a copper nucleus together with one proton. Other particles may have been ejected also, but may have had too small a range to escape from the plate. No. 11 shows two electrons ($E_e \sim 10$ and 13 million volts) ejected downward from a lead nucleus and two tracks of greater energy ($E_e > 100$ million volts) directed upwards. It is possible that one of the latter represents the incident particle causing the disintegration and that the other is an ejected particle moving upwards, or that both are ejected particles, in which case the disintegration must be attributed to some non-ionizing agency.

But these two cases are comparatively simple compared with the complexity of the larger showers. In these, the typical process seems to be the simultaneous ejection of a number of particles of high energy. These particles seem usually to be projected in directions lying within a fairly narrow cone, but there are occasions (No. 10) when the cone is fairly wide. It seems reasonable to seek the explanation of the narrow cone of projection in the momentum imparted by the collision of some incident particle of very high energy. It is not possible, as yet, to tell the nature of all the particles, but negative and positive electrons seem to predominate and there is some slight indication that in some cases they occur with about equal frequencies.

The origin of these particles is of great interest, particularly as they certainly often arise in materials of low and medium atomic weight, since radiant points have been located in air, glass, aluminium and copper. Now on recent views* of nuclear structure there are no free negative electrons in such light nuclei. Yet at least seven positive and negative electrons have been found diverging from a single point in glass, copper and lead (Nos. 10, 9 and 8), and presumably therefore from single nuclei.

There are three possible hypotheses that can be made about the origin of these particles. They may have existed previously in the struck nucleus, or they may have existed in the incident particle, or they may have been created during the process of collision. Failing any independent evidence that they existed as separate particles previously, it is reasonable to adopt the last

* Heisenberg, 'Z. Physik,' vol. 77, p. 1 (1932); Iwanenko, 'Phys. Z. Soviet Union,' vol. 1, p. 820 (1932); Mandel, 'Phys. Z. Soviet Union,' vol. 2, p. 286 (1932); Perrin, 'C. R. Acad. Sci. Paris,' vol. 195, p. 236 (1932).

hypothesis. Further, in view of the well-known difficulties* in treating electrons in a nucleus as independent mechanical entities, the last hypothesis becomes perhaps the most convenient. One would then describe these showers (in common with ordinary β-ray disintegrations) as involving a creation of particles.

This question is intimately bound up with that of the constitution of the neutron.† On the view that a neutron is a complex particle, the negative electrons in the showers might be produced by the disintegration of neutrons into negative electrons and protons, but this picture gives no explanation of the origin of the positive electrons. It also leads one to expect more proton tracks on the photographs than are actually observed.

On the view that the neutron is an indivisible particle and that there are no free negative electrons in light nuclei, it follows that both the negative and positive electrons in the showers must be said to have been created during the process. If, however, the conservation of electric charge is to be fulfilled, then positive and negative electrons must be produced in equal numbers, for there can hardly be many protons created on account of the large energy ($E \sim Mc^2 = 940$ million volts), required to create one.‡

In this way one can imagine that negative and positive electrons may be born in pairs during the disintegration of light nuclei. If the mass of the positive electron is the same as that of the negative electron, such a twin birth requires an energy of $2mc^2 \sim 1$ million volts, that is much less than the translationary energy with which they appear in general in the showers.

Though one of the ultimate objects of the experiments must be to obtain the evidence on which to draw up a balance sheet of number of particles and of mass and energy, this will certainly prove exceedingly difficult to do. To attempt this, it will certainly be necessary to obtain a shower which originates in the gas of the chamber, so that the tracks of all the particles can be observed.

The fact that some of the showers show groups of nearly parallel tracks suggests at once a possible relation to the prediction by C. T. R. Wilson§ that "run away" electrons and protons of high energy are produced by the electric field of a thunderstorm. But if these particles, which certainly must exist,

* Bohr, "Report of Congress in Rome," (1931); 'J. Chem. Soc.,' p. 349 (1932).

† Chadwick, 'Proc. Roy. Soc.,' A, vol. 136, p. 693 (1932).

‡ Another possible way in which electric charge may be conserved during a process involving the emission of an electron from a nucleus has been suggested to us by Professor Dirac. This is that a neutron may be converted into a proton simultaneously with the creation of a negative electron.

§ 'Proc. Camb. Phil. Soc.,' vol. 22, p. 534 (1925); 'Proc. Phys. Soc.,' vol. 31, 32D (1925).

appeared in the chamber, one might expect to find groups of widely spaced parallel tracks of varying breadth, owing to their having been formed at varying times before and during the expansion. Now it is characteristic of the showers that the tracks are almost always slightly diverging, that they are bunched together and that they have appreciably the same breadth, indicating that the particles passed through the chamber within a time small compared with the time of expansion (1/100 second). So it is certain that the showers are not themselves due to groups of "run away" electrons.

6. *The Hypothetical Properties of the Positive Electron.*

The existence of positive electrons in these showers raises immediately the question of why they have hitherto eluded observation. It is clear that they can have only a limited life as free particles since they do not appear to be associated with matter under normal conditions.

It is conceivable that they can enter into combination with other elementary particles to form stable nuclei and so cease to be free, but it seems more likely that they disappear by reacting with a negative electron to form two or more quanta.

This latter mechanism is given immediately by Dirac's theory of electrons.* In this theory all but a few of the quantum states of negative kinetic energy, which had previously defied physical interpretation, are taken to be filled with negative electrons. The few states which are unoccupied behave like ordinary particles with positive kinetic energy and with a positive charge. Dirac originally wished to identify these "holes" with protons, but this had to be abandoned when it was found that the holes necessarily have the same mass as negative electrons.† It will be a task of immediate importance to determine experimentally the mass of the positive electrons by accurate measurements of their ionization and $H\rho$. At present it is only possible to say that no difference between the ionization from the tracks of negative and positive electrons of the same $H\rho$ has been detected so that provisionally their masses may be taken as equal.

On Dirac's theory the positive electrons should only have a short life, since it is easy for a negative electron to jump down into an unoccupied state, so filling up a hole and leading to the simultaneous annihilation of a positive and negative electron, the energy being radiated as two quanta.

* 'Proc. Roy. Soc.,' A, vol. 126, p. 360 (1930); A, vol. 133, p. 60 (1931).

† H. Weyl, "Gruppentheorie und Quantenmechanik," 2nd ed., p. 234 (1931).

We are indebted to Professor Dirac not only for most valuable discussions of these points, but also for allowing us to quote the result of a calculation made by him of the actual probability of this annihilation process. The area of cross-section for annihilation is*

$$\phi = \frac{\pi e^4}{m^2 c^4} f(\gamma), \tag{3}$$

where

$$f(\gamma) = \frac{1}{\gamma + 1}\left[\frac{\gamma^2 + 4\gamma + 1}{\gamma^2 - 1} \log \{\gamma + \sqrt{\gamma^2 - 1}\} - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}}\right],$$

and $\gamma = 1/\sqrt{1 - v^2/c^2}$ and v is the velocity of the positive electron.

Dirac has computed the following values for the mean free path in water for annihilation. This is $\lambda = 1/n\phi$, where n is the number of extra-nuclear electrons per unit volume.

Table II.—Free Path for Annihilation and Range of Positive Electron.

E Energy in million volts	200	100	50	20	10	5	2	1	1/10
λ cm. H_2O	833	471	270	133	78·8	47·6	25·9	17·5	7.2
R Range, cm. H_2O	52	28	16	7·7	4·3	2·2	0·9	0·45	0·05

In the last row of the table is given the range of an electron in water. The values for energies below 2 million volts are experimental† and the rest theoretical.‡

If the chance that a positive electron will disappear in this way while decreasing in energy from E_1 to E_2 is denoted by $\Phi(E_1 E_2)$, then it is easily shown that

$$\log [1 - \Phi(E_1 E_2)] = \int_{E_1}^{E_2} dR/\lambda,$$

when dR is an element of its path and λ is the mean free path for annihilation of a particle of energy E.

A rough numerical integration using the figures in the table, given for the probability of annihilation of a positive electron, while decreasing in energy from 200 million volts to 100,000 volts, the value

$$\Phi(E_1 E_2) = 0 \cdot 36$$

* Dirac, 'Proc. Camb. Phil. Soc.,' vol. 26, p. 361 (1930).

† Rutherford, Chadwick and Ellis, "Radiation from Radioactive Substances," p. 443.

‡ Heisenberg, *loc. cit.*

If the probability of annihilation in water *per unit time* is evaluated, it is found that this probability increases as the energy decreases and reaches a constant value of $2 \cdot 5 \times 10^9$ sec.$^{-1}$, for energies less than 100,000 volts. So those positive electrons which live till they reach this energy will then die according to a probability law, exactly analogous to a radioactive decay, except that their mean life is proportional to the concentration of negative electrons. In water, their mean life is $3 \cdot 6 \times 10^{-10}$ second.

When the behaviour of the positive electrons have been investigated in more detail, it will be possible to test these predictions of Dirac's theory. There appears to be no evidence as yet against its validity, and in its favour is the fact that it predicts a time of life for the positive electron that is long enough for it to be observed in the cloud chamber but short enough to explain why it had not been discovered by other methods.

It should be possible to find evidence on the photographs of positive electrons which have entered a metal plate but which do not emerge again owing to their annihilation while traversing the metal. It is also possible that the gamma-ray annihilation spectrum may be detectable by observations of the Compton recoil electrons. According to Dirac's theory, this spectrum should have a lower limit at an energy of $0 \cdot 5 \times 10^6$ volts and should extend through a maximum at a slightly greater energy to a steadily decreasing intensity for high energies.

It is not unlikely that positive electrons may be produced otherwise than in association with the penetrating radiation. Perhaps the anomalous absorption of gamma-radiation* by heavy nuclei may be connected with the formation of positive electrons and the re-emitted radiation with their disappearance. The re-emitted radiation is, in fact, found experimentally to have an energy of the same order as that to be expected for the annihilation spectrum.

Again the hypotheses of the existence of positive electrons amongst the secondary particles produced by neutrons, would provide an explanation of the curious fact discovered by Curie and Joliot† that fast electron tracks are found with a curvature indicating a negative electron moving *towards* the neutron source.

7. *The Non-ionizing Links and the Secondary Radiant Points.*

It is not possible to explain the appearance of the showers without assuming the existence in the showers of some non-ionizing agency. For it is not

* Gray and Tarrant, 'Proc. Roy. Soc.,' A, vol. 136, p. 662 (1932); Meitner and Hupfield, 'Naturwiss.,' vol. 19, p. 775 (1931); Chao, 'Phys. Rev.,' vol. 36, p. 1519 (1931).

† "Exposée de Physique Théorique," p. 21 (1933).

unusual to find that one or more tracks appear to originate in the plate without any track to correspond to an incident particle. To explain these secondary radiant points it is necessary to postulate that there exist in the showers non-ionizing particles or photons.

Now when two or more distinct radiant points are found above the chamber as in No. 1, it is reasonable to assume that one represents a secondary process caused by the other, or that both are secondary to some initial process. In either case, a surprisingly short free path for a further interaction must be

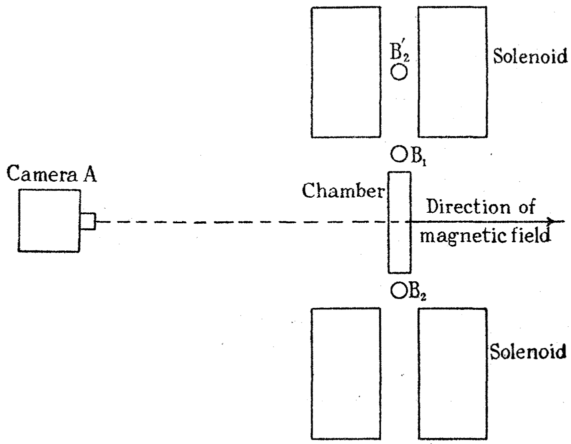


FIG. 2.

postulated for the particle or photon causing the secondary process. It can be seen from the photographs that when one shower occurs there is a surprisingly large chance that another will occur a short way below it. It will be of great interest to discover if this high probability can be explained by means of the assumption that the non-ionizing links are neutrons or photons.

The cost of the solenoid for producing the magnetic field was met by a grant from the Government Grant Committee of the Royal Society. One of us (G. P. S. O.) is indebted to the National Research Council of Italy for a grant to enable him to work in the Cavendish Laboratory.

We wish to express our appreciation of the skilful assistance given us by Mr. R. Aves, both in the construction of the apparatus and in the conduct of the experiments. We wish also to thank Mr. C. W. Gilbert, of Christ's College, for his invaluable assistance in the latter part of the investigations.

Summary.

(1) A short description is given of a method of making particles of high energy take their own cloud photographs.

(2) The most striking features of some 500 photographs taken by this method are described, and the nature of the showers of particles producing the complex tracks is discussed.

(3) A consideration of the range, ionization, curvature and direction of the particles leads to a confirmation of the view put forward by Anderson that particles must exist with a positive charge but with a mass comparable with that of an electron rather with that of a proton.

(4) The frequency of occurrence of the showers is discussed, and also their possible relation to the bursts of ionization observed by Hoffman, Steinke and others.

(5) The origin of the positive and negative electrons in the showers is discussed, and the conclusion is reached that they are best considered as being created during a collision process.

(6) The subsequent fate of the positive electrons is discussed in the light of Dirac's theory of "holes."

(7) The probable existence of non-ionizing links in the processes giving rise to the multiple showers is discussed.

DESCRIPTION OF PLATES.

All the photographs were taken with the magnetic field at right angles to the chamber and directed *away* from the cameras, fig. 2. Consequently a downward descending particle will be deflected to the *right* as seen in the photographs if positively charged and to the *left* if negatively charged. Alternatively a positively charged particle will describe an anti-clockwise and a negatively charged particle a clockwise path, as viewed from the camera or in the photograph.

The photographs are reproduced 0·9 times the actual size of the tracks in the chamber. The gas in the chamber was in all cases oxygen, at an initial pressure of 1·7 atmospheres. An electric field of 3 to 4 volts per centimetre was maintained between top and bottom of the chamber. The expansion used was usually between 1·29 and 1·31.

Two cameras were used, (A) with its axis parallel to the magnetic field, (B) with its axis making an angle of 20° with this direction. Of the photographs reproduced, Nos. 1 and 2 are (stereoscopic) pairs, so are Nos. 3 and 4. All the rest are single photographs, either (A) or (B), depending on which showed the better detail.

The counters were usually arranged at positions B_1 and B_2, fig. 2, but sometimes the lower counter was removed from B_2 and placed at B'_2. Nos. 10 and 13 were taken with the latter arrangement, all the rest with the usual one. The usual position (B_1, B_2) gives the better yield of tracks, but the other position (B_1, B'_2) allows the photography of tracks which do not pass right through the chamber and the metal plate.

The angle between the axes of the cameras (20°) is too great for stereoscopic viewing and is so chosen as to give greater accuracy in reconstruction. Full size models of the complicated tracks were made with wire and plasticene by a method of stereoscopic reprojection.

In the description of the photographs the following abbreviations will be made :—

$H\rho$ = $H\rho$ gauss-cm. = product of magnetic field by the radius of curvature of the track.

E_e = energy calculated from $H\rho$ assuming mass to be that of an electron.

MV = million volts.

(A) or (B) indicates photograph from camera A or B.

On some photographs there is a noticeable distortion and broadening of the tracks owing to mass movement of the gas (see Nos. 8 and 11 on the right-hand side, and No. 15 in the centre). This distortion impairs the accuracy of observation. But in general it is concluded that a curvature of $\rho \sim 500$ cm. is significant when there is no plate in the chamber and one of $\rho \sim 200$ cm. when there is a plate.

Plate 21.

Photograph 1 (B) } Pair of photographs showing about 23 separate tracks. 4 mm. lead
Photograph 2 (A) } plate. H = 2200 gauss.

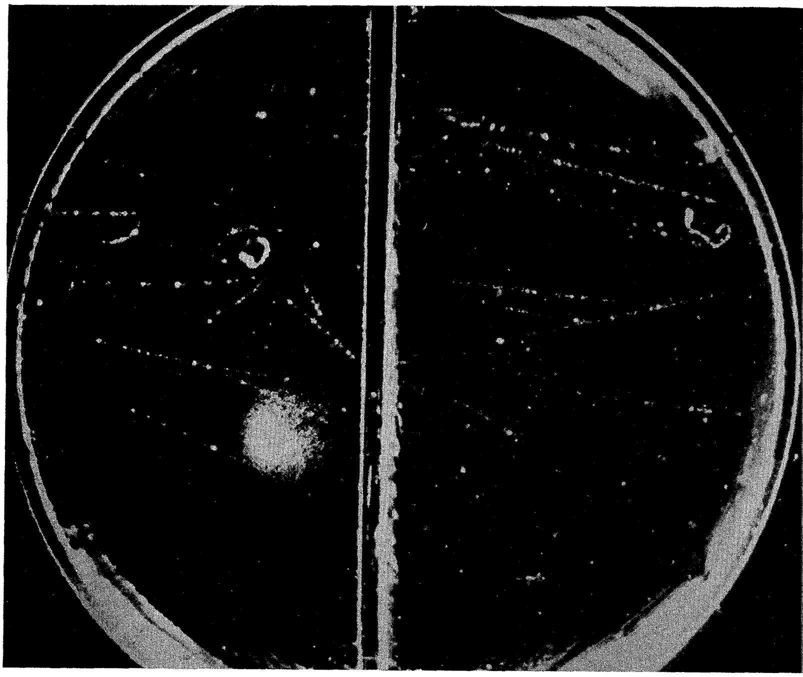
A group of tracks appear in the upper part of the chamber diverging downwards and somewhat forward from some region, in the copper solenoid. A second fairly distinct group appears on the right-hand side of the photograph.

Most of the tracks pass through the lead plate, but there are so many of them that it is difficult to identify them all separately in the two images. Several secondary processes, scattering, etc., take place in the plate.

The majority of the tracks are nearly straight corresponding to electron energies greater than 100 MV. But two tracks in the middle of the upper part of the chamber are bent to the left with $H\rho \sim 2 \times 10^5$, and so $E \sim 60$ MV. These tracks are almost certainly due to electrons.

There are also two tracks plainly bent to the right with $H\rho \sim 0{\cdot}7$ and $0{\cdot}5 \times 10^5$, and so with $E_e \sim 20$ and 15 MV. Since these tracks diverge from the same direction as the others they must be caused by positively charged particles. Since the ionization along them does not differ appreciably from that along the electron tracks, they must be due to particles with a mass comparable with that of an electron. The white blob is probably due to some heavily ionizing particle (? a contamination alpha-particle) passing through before the expansion.

The broad white band on the left of photograph B is caused by the reflection of the illuminated glass cylinder in the piston. It is very difficult to avoid this, but it does not appear in photograph A.



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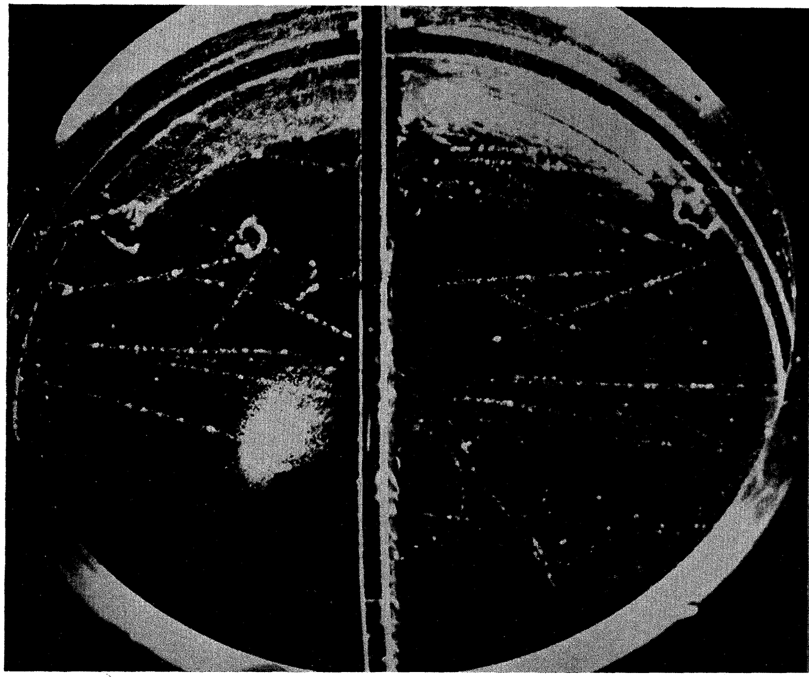

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PLATE 22.

PHOTOGRAPH 3 (B) } Pair of photographs showing about 16 separate tracks. H = 3100
PHOTOGRAPH 4 (A) } gauss.

The divergent point of the shower is again in the copper coils. On the left are two negative electron tracks with $H\rho \sim 0 \cdot 5 \times 10^5$ and so $E_e \sim 15$ MV.

On the right are two tracks curved markedly to the right, which must be due to positive electrons, with $H\rho \sim 0 \cdot 4$ and $1 \cdot 5 \times 10^5$, and so $E_e \sim 12$ and 45 MV.

Some of the other tracks are slightly curved, some one way, and some the other. Most of the nearly straight tracks seem to diverge from the same point, but the more bent ones probably diverge from a secondary radiant point lower down.

PHOTOGRAPH 5 (B). H = 2200 gauss. 4 mm. lead plate.

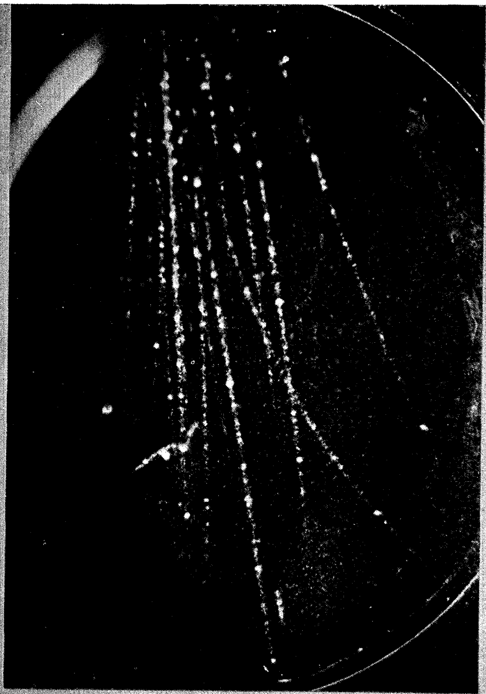
A single particle of too great energy to give a measurable curvature ($H\rho > 3 \times 10^5$, $E_e > 100$ MV), passes through the lead plate and produces a secondary (?). Below the plate one track is appreciably straight and the other is curved for a positive charge with $E_e \sim 60$ MV.

PHOTOGRAPH 6 (A). H = 2200 gauss. 4 mm. lead plate.

Two particles one of which passes through the plate and is straight above the plate $E_e > 100$ MV, but curved negatively below $E_e \doteqdot 30$ MV. The apparent energy loss is too great for normal absorption, for Anderson has found an energy loss of 35 MV per centimetre lead.

PHOTOGRAPH 7 (B). H = 2200 gauss. 4 mm. lead plate.

A track showing deflection at plate and a greater positive curvature below than above. The direction must therefore be downwards, and hence the charge positive. Above plate $E_e \sim 60$ MV. Below, $E_e \sim 22$ MV. Energy loss too great again, but this is not unexpected since energy may well have been lost in the collision causing the deflection.



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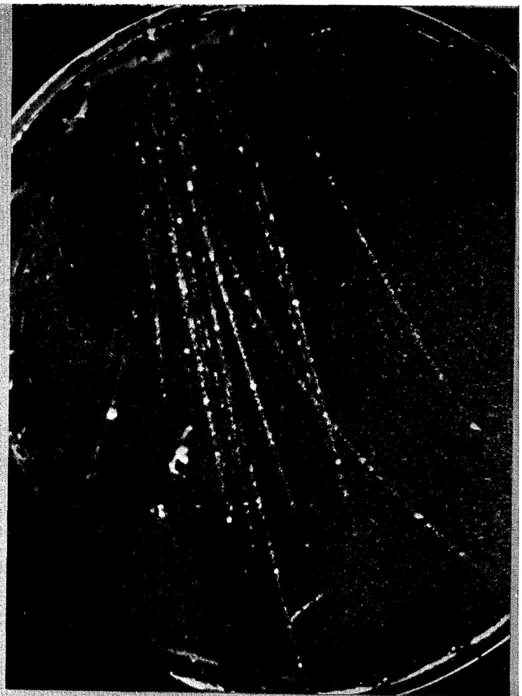

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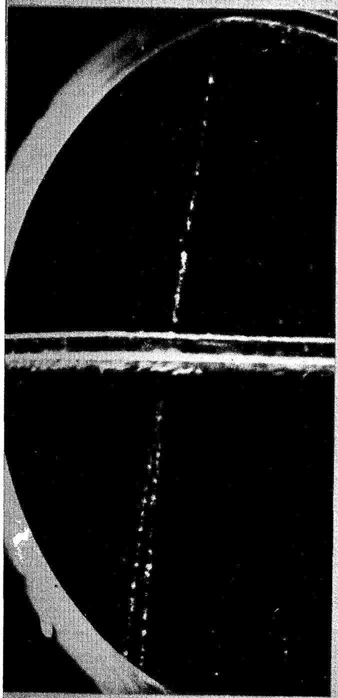

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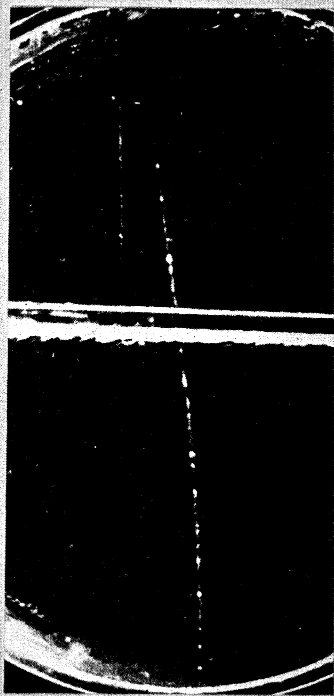

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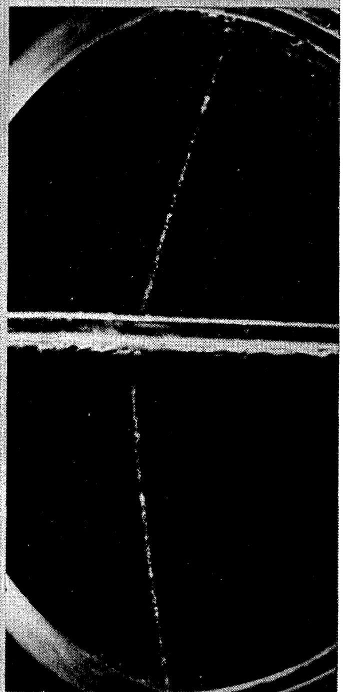

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PLATE 23.

PHOTOGRAPH 8 (A). H = 2200. 4 mm. lead plate.

A shower of about seven tracks comes through the roof of the chamber, radiating probably from the copper solenoid. A secondary radiant point occurs in the lead plate, from which a group of about six tracks diverge. From a careful study by stereoscopic reprojection it seems, but it is not quite certain, that no track of the primary shower passes through the point of origin of the secondary shower. If this is the case, it indicates that the secondary shower is produced by some non-ionizing agency in the primary shower. Below the plate, one track is negatively curved. The rest are nearly straight. Above the plate some tracks are broadened by distortion.

PHOTOGRAPH 9 (B). H = 2200 gauss.

A shower of four particles comes inclined through the top of the chamber.

Three more straight tracks diverge from a point in the glass roof. Above and to the left is a track curved to the left and in the middle is another track, coplanar with the former, curved to the right—probably a positive electron. These two tracks do not come from the same point as the three others, but from a neighbouring point.

The spiral track is a negative electron of energy about 130,000 volts, and may be due to the photoelectric absorption of a photon.

Several apparently unrelated tracks are to be noticed.

PHOTOGRAPH 10 (A). H = 700 gauss. 6 mm. copper plate.

Seven tracks diverge from a point in the glass roof of the chamber. The curved track diverges accurately from the same point as the other six and so the particle producing it probably actually came from the point. The sign of the curvature then indicates a positive charge. $E_e \sim 120{,}000$ volts.

This track is the lowest energy positive-electron track so far observed. Several other, apparently unrelated, tracks are present.

PHOTOGRAPH 11 (A). H = 2200. 4 mm. lead plate.

From a point in the lead two negative electrons of energy 13 and 10 MV diverge downwards, and two straight tracks diverge upwards. It is possible to assume (*a*) that one of the two latter is caused by a particle moving downwards and that the other is projected almost directly backwards and upwards, or (*b*) that both are projected upwards, in which case the disintegration process must be attributed to a non-ionizing agency. On either assumption the projection of at least one particle of high energy upwards is proved. This draws attention to the danger of assuming that *all* the penetrating radiation particles are moving downwards. On hypothesis (*a*) one of the particles can be considered as part of a primary shower from above the chamber, of which two other members are visible. Note secondary electron, $E_e \sim 5 \times 10^4$ volts, originating in gas. Such an electron ionizes between 2 and 3 times as much as a fast electron. Note great difference in appearance.

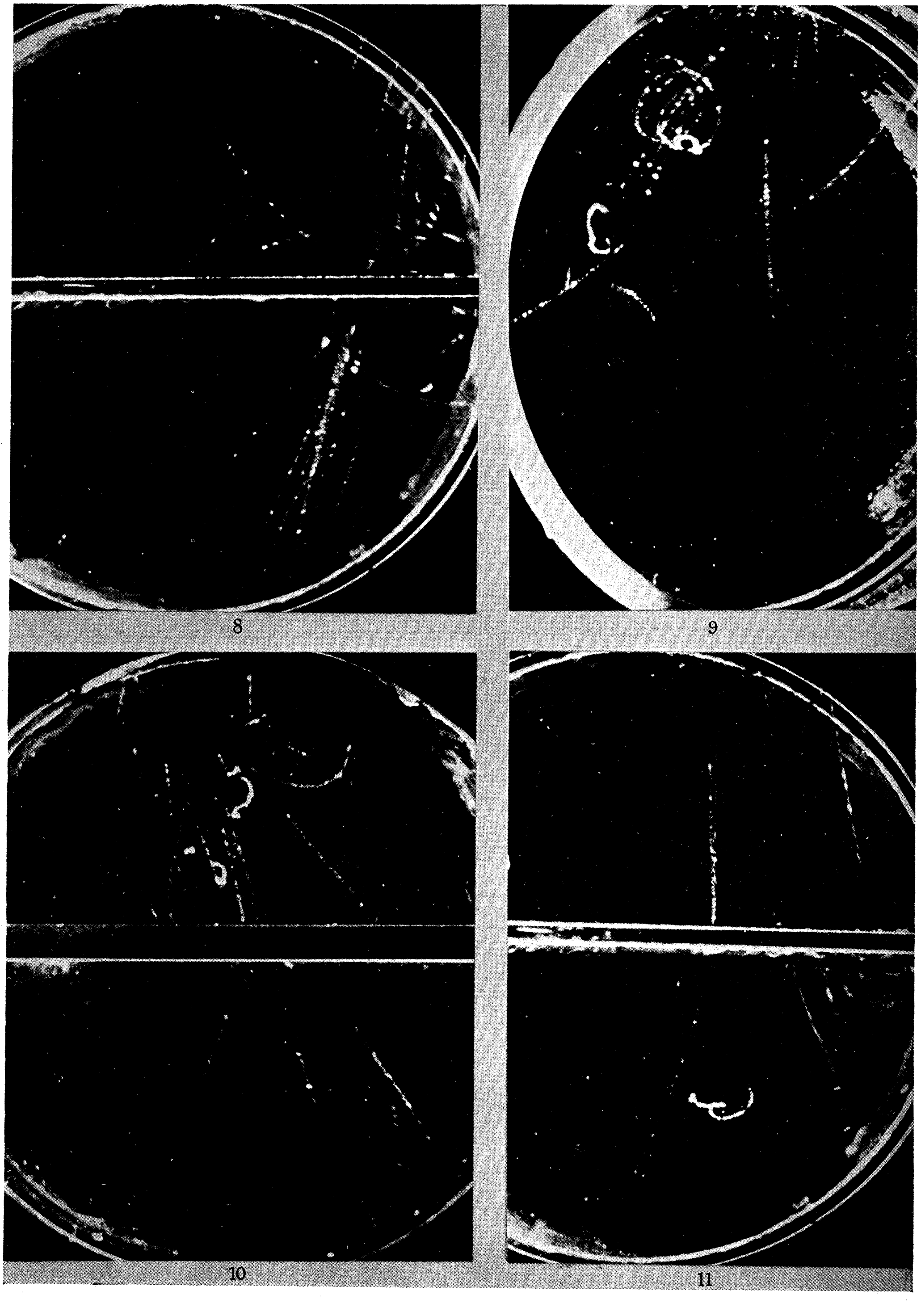

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PLATE 24.

PHOTOGRAPH 12. H = 2200 gauss. 4 mm. lead plate.

Shower of four tracks from copper solenoid. One track is deflected by plate and one produces a secondary with negative curvature.

PHOTOGRAPH 13. H = 2200 gauss.

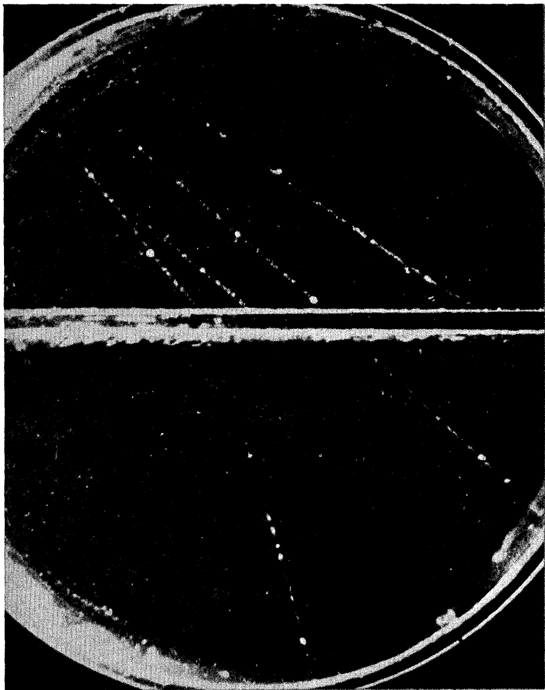
A complicated collection of curved tracks, three curved negatively and three positively, neglecting the lower short one. There appears to be a radiant region in the glass roof from which two negative and two positive electrons diverge, but it is not possible to say for certain that one of the positively curved tracks may not be due to a negative particle moving upwards.

PHOTOGRAPH 14. H = 3000 gauss.

Two proton tracks and two electron tracks. The thick horizontal track has an Hρ of 3×10^5 and is curved as for a positive charge moving to the right. It is almost certainly due to a proton. For this Hρ a proton would have a range of about 26 cm. in air at N.T.P. and would ionize about 100 times as much as a fast electron. This track cannot be due to an alpha-particle as its range would be only 0·6 cm. (Table I). The fine negatively curved track in the bottom left-hand corner is coplanar with the long proton track, but the assumption that they *come* from the same point is made doubtful by the appearance of the slow secondary near the bottom, which appears to indicate a motion upwards and so a positive charge.

PHOTOGRAPH 15. H = 2200 gauss. 6 mm. copper plate.

Presumably an incident particle which disintegrates a copper nucleus with the emission of two electrons $E_e \sim 12$ and 14 MV, and one heavier particle, which is either a proton or an alpha particle. Unfortunately the tracks are badly distorted near the plate by the swirling of the air. Another track seems to be thrown backwards, but the distortion is too great to be certain. The resemblance of this photograph to No. 11 is marked except for the absence, in the latter, of the proton track. But it is quite probable that such particles are produced also in No. 11 and many other photographs, but that they do not have sufficient range to emerge from the plate. In any case the chance that a proton will emerge from the plate with just sufficient energy to stop in the gas as it has done in No. 15 is very small.



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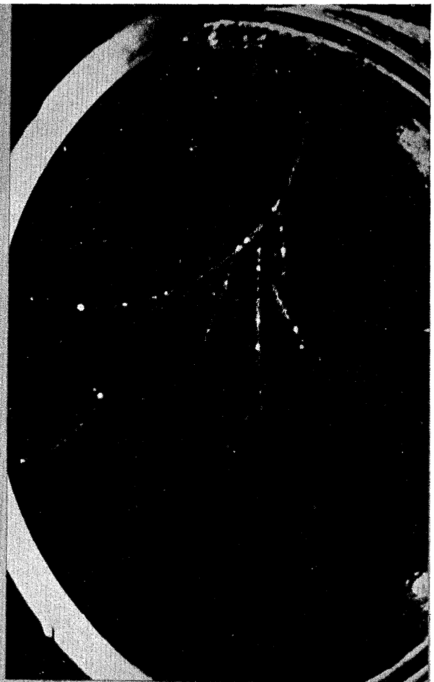

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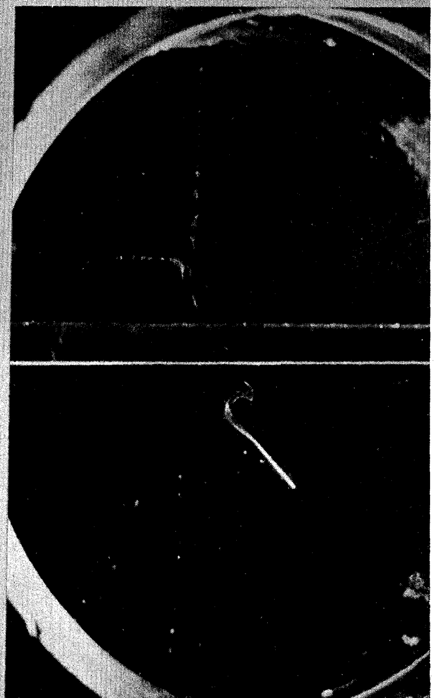

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