CHARLES T. R. WILSON

On the cloud method of making visible ions and the tracks of ionizing particles

Nobel Lecture, December 12, 1927

In September 1894 I spent a few weeks in the Observatory which then existed on the summit of Ben Nevis, the highest of the Scottish hills. The wonderful optical phenomena shown when the sun shone on the clouds surrounding the hill-top, and especially the coloured rings surrounding the sun (coronas) or surrounding the shadow cast by the hill-top or observer on mist or cloud (glories), greatly excited my interest and made me wish to imitate them in the laboratory.

At the beginning of 1895 I made some experiments for this purpose - making clouds by expansion of moist air after the manner of Coulier and Aitken. Almost immediately I came across something which promised to be of more interest than the optical phenomena which I had intended to study. Moist air which had been freed from Aitken's dust particles, so that no cloud was formed even when a considerable degree of supersaturation was produced by expansion, did appear to give a cloud if the expansion and consequent supersaturation exceeded a certain limit. A quantitative expansion apparatus (Fig. 1) was therefore made in which given samples of moist air could repeatedly be allowed to expand suddenly without danger of contamination, and in which the increase of volume to be made could be adjusted at will.

It was found that there was a definite critical value for the expansion ratio ($v_2/v_1 = 1.25$) corresponding to an approximately fourfold supersaturation. In moist air which had been freed from Aitken's nuclei by repeatedly forming a cloud and allowing the drops to settle, no drops were formed unless the expansion exceeded this limit, while if it were exceeded, a shower of drops was seen to fall. The number of drops in the shower showed no diminution however often the process of producing the shower and allowing the drops to fall was repeated. It was evident then that the nuclei were always being regenerated in the air. A note describing these experiments was read before the Cambridge Philosophical Society in May 1895.

Further experiments with somewhat more elaborate apparatus (Fig. 2)

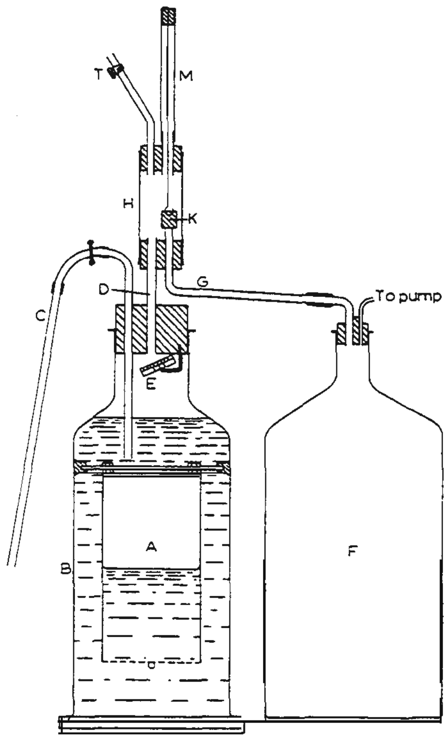

Fig. 1.

which allowed of more sudden expansion showed that there was a second critical expansion corresponding to an approximately eightfold supersaturation of the vapour. With expansions exceeding this limit, dense clouds were formed in dust-free air, the number of drops in the cloud increasing with very great rapidity as the expansion was increased beyond it and giving rise on account of their small and uniform size to very beautiful colour phenomena. The number of drops for expansions between the two limits remained small - the resulting condensation resembling a shower of rain rather than a cloud. The results were not essentially different in the various pure gases tried - although the expansion required to produce a given supersaturation was naturally different.

While the obvious explanation of the dense clouds formed when the second supersaturation limit was exceeded was that here we had condensation occurring in the absence of any nuclei other than the molecules of the vapour or gas - those responsible for the rain-like condensation which occurred when the supersaturation lay between the two limits from the first, excited

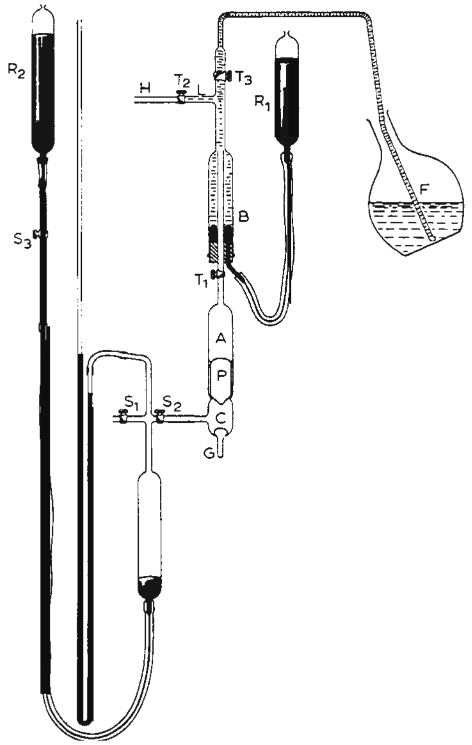

Fig.2.

my interest. The very fact that their number was so limited and yet that they were always being regenerated, together with the fact that the supersaturation required indicated a magnitude not greatly exceeding molecular dimensions, at once suggested that we had a means of making visible and counting certain individual molecules or atoms which were at the moment in some exceptional condition. Could they be electrically charged atoms or ions?*

In the autumn of 1895 came the news of Röntgen's great discovery. At the beginning of 1896 J. J. Thomson was investigating the conductivity of air exposed to the new rays - and I had the opportunity of using an X-ray tube of the primitive form then used which had been made by Prof. Thomson's assistant Mr. Everett in the Cavendish Laboratory. I can well recall my delight when I found at the first trial that while no drops were formed on expansion of the cloud chamber when exposed to X-rays if the expansion were less than 1.25, a fog which took many minutes to fall was produced

* The striking effect of point discharges on condensation in a steam jet had been attributed to ions by H. v. Helmholtz and Richarz.

when the expansion lay between the rain-like and cloud-like limits; X-rays thus produced in large numbers nuclei of the same kind as were always being produced in very small numbers in the air within the cloud chamber.

A short note describing this experiment was communicated to the Royal Society in March 1896.* The full paper containing the detailed account of the measurement of the two cloud limits in different gases was communicated a year later.

During the following two years I investigated by means of the expansion apparatus the condensation nuclei produced in gases by X-rays, by the newly discovered uranium rays, by ultraviolet light, by point discharges and other agents.

The purely ionizing agents all produced nuclei, identical as regards the minimum supersaturation required to cause water to condense upon them.

The condensation nuclei produced by these ionizing agents were shown to be indeed themselves the ions by their behaviour in an electric field. They could be completely removed by applying an electric field before expansion - so that no cloud was formed.

Uncharged nuclei, not removable by a field, were also found to be produced in various ways and their properties were investigated.

A paper describing these investigations was communicated to the Royal Society in the autumn of 1898.

The following winter was occupied in studying separately the phenomena of condensation on positive and negative ions. It was found that the measurement of the least expansion required to condense water in ionized air or other gas had all been concerned with the negative ion; to catch the positive ion the expansion ratio v_2/v_1, had to exceed a limit of about 1.31, corresponding to an approximately sixfold supersaturation instead of the fourfold supersaturation required by the negative ion.

This paper marked the completion of a stage in my work, the behaviour of ions as condensation nuclei. It was now possible to make visible the individual ions and to distinguish between positive and negative ions.

This found its immediate application in the determination of the charge carried by an ion by Thomson and later by H. A. Wilson. The method used by the latter of partially balancing the weight of a charged drop by a known electric field and determining the change in the rate of fall did not however

* Richarz about the same time described the action of X-rays on condensation in the steam jet.

really depend essentially on the charge being due to condensation on an ion; and Millikan, whose earlier experiments were made by H. A. Wilson's method, soon abandoned the use of water drops and the expansion method.

It is, I think, of some interest that the value of the elementary charge <<e>>, deduced directly from the degree of supersaturation required to cause negative ions to grow into visible drops, is 4.9×10^{-10} e.s.u.; it agrees within 1 per cent with Millikan's accurately determined value.

My own researches at this time were directed in another direction. Since the nuclei responsible for the rain-like condensation in air not exposed to known ionizing agents require just the same degree of supersaturation to make water condense upon them as do the ions produced by X-rays and other ionizing agents, it seemed almost certain that they also are ions. Experiments were therefore made to find if there was a measurable conduction of electricity through air in a closed vessel containing dust-free air. These led at once to positive results, and proved that the air in a closed vessel is always ionized. Quite independently and approaching the matter from a different side, Geitel was working at the subject in Germany and arrived at the same conclusion; his paper was published very shortly before mine. My own experiments were performed on a small scale, the method used being one afterwards very largely employed, in which the rate of loss of charge was measured from an insulated system consisting of a short metal rod with a gold leaf attached which was suspended in an ionization chamber in such a way that the possibility of leakage along the supports was eliminated.

These experiments were carried out in 1900, and they led me naturally to further experiments on conduction in closed vessels, to the direction of radioactive matter carried down by rain and snow, to the direct measurement of the current between the atmosphere and the earth, and to the study of atmospheric electricity generally.

With the exception of some experiments published in 1904 proving directly that the nuclei causing the ordinary rain-like condensation are removable by an electric field and are therefore ions (an experiment which required for success a somewhat larger expansion apparatus than that which had been used in the condensation experiments on the ions produced by X-rays) my experimental work on condensation phenomena was not resumed for many years.

Among the experimental work on the subject carried out by others in this period, in addition to the determination of the electronic charge, that on condensation phenomena in other vapours than water by Przibram and by

Laby should be mentioned. These investigations showed that water vapour is quite exceptional in condensing more readily on the negative than on the positive ion; a connection between the relative efficiency of the positive and negative ions and the sign of the electrical charges developed on splashing - the Lenard effect - was established.

Towards 1910 I began to make experiments with a view to increasing the usefulness of the condensation method.

I had from the time of my first experiments on condensation of water vapour on the ions had in view the possibility of determining the ionic charge by a direct method, in which the ions carrying a known charge were to be made visible by condensation, photographed and counted. The plan which I had in view on resuming the work was that of measuring an intermittent current from a negatively charged plate exposed to ultraviolet light within the cloud chamber, thus obtaining a stream of ions divided into groups, and finding the number of ions per group by the condensation method.

Again in the years which had elapsed since my earlier experiments, ideas on the corpuscular nature of α- and β-rays had become much more definite, and I had in view the possibility that the track of an ionizing particle might be made visible and photographed by condensing water on the ions which it liberated. As I succeeded in this latter aim, and Millikan had by this time rendered the other project unnecessary, the determination of "e", by the method of direct counting of drops was never carried out.

Much time was spent in making tests of the most suitable form of expansion apparatus and in finding an efficient means of instantaneous illumination of the cloud particles for the purpose of photographing them. In the spring of 1911 tests were still incomplete, but it occurred to me one day to try whether some indication of the tracks might not be made visible with the rough apparatus already constructed. The first test was made with X-rays, with little expectation of success, and in making an expansion of the proper magnitude for condensation on the ions while the air was exposed to the rays I was delighted to see the cloud chamber filled with little wisps and threads of clouds - the tracks of the electrons ejected by the action of the rays. The radium-tipped metal tongue of a spintharoscope was then placed inside the cloud chamber and the very beautiful sight of the clouds condensed along the tracks of the a-particles was seen for the first time. The long thread-like tracks of fast β-particles were also seen when a suitable source was brought near the cloud chamber.

Some rough photographs were obtained and were included in a short communication to the Royal Society made in April 1911.

The summer of 1911 was occupied in designing improved apparatus. The expansion apparatus (Fig. 3) was constructed in the workshop of the Cavendish Laboratory and is the one which I have had in use up to the present time. In the winter which followed, the photographs were obtained which formed the basis of a paper communicated to the Royal Society in the following June (1912).

The essential conditions to be fulfilled if good pictures of the tracks are to be obtained are mainly these. The expansion must be effected without stirring up the gas; this condition is secured by using a wide, shallow cloud chamber of which the floor can be made to drop suddenly and so produce the desired increase of volume. The cloud chamber must be freed not only from "dust" particles, but from ions other than those produced by the ionizing particles under observation; an electric field maintained between the roof and floor of the cloud chamber serves this purpose.

For the purpose of obtaining sharp pictures of the tracks, the order of operations has to be: firstly, the production of the necessary supersaturation by sudden expansion of the gas; secondly, the passage of the ionizing par-

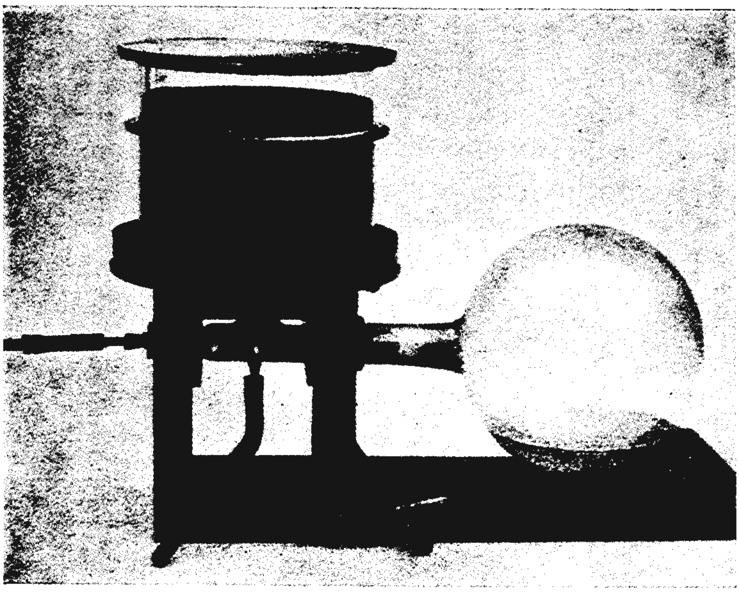

Fig.3.

ticles through the supersaturated gas; and finally, the illumination of the cloud condensed on the ions along the track.

Perhaps the most important purpose that the photographs obtained at this time served, was to confirm, in a way which was free from ambiguity, conclusions which had already been reached by less direct means and which in some cases, but not in all, had come to be generally accepted.

I remember showing W. H. Bragg one of the first good pictures of α–ray tracks very shortly after it was obtained. He at once showed me a diagram which he had just published showing examples of what he considered likely forms for the paths of α– rays. The similarity between the actual photograph and Bragg's ideal picture was astonishing. (Lantern slides from photographs of α-particle cloud-tracks taken at this time were shown - Figs. 4 and 5.)

Fig. 4.

Fig. 5.

Fig. 6.

The tracks of electrons were of remarkable straightness when the velocity was high, but slower electrons (Fig. 6) showed both sudden deflections through large angles and gradual deviations due to an accumulation of small deflections - Rutherford's single and compound scattering. Both types of scattering were also shown in the last part of the course of the α-particles.

The pictures of the clouds condensed in air exposed to a beam of X-rays showed perfectly clearly that the primary effect of the rays is to eject electrons with considerable velocity from atoms in the path of the beam, and that the ionization is due to the action of these secondary β-particles. This was in accordance with the conclusions at which W. H. Bragg had arrived.

Information as to the nature of the ionization by β-particles was afforded by the photographs (e.g. Fig. 6). As was stated in the paper published in 1912, the ions along the track of a β-particle occur partly in pairs, partly in groups; and the groups were interpreted as indicating that in certain cases an electron ejected from an atom by a β-particle may itself have energy enough to ionize. This result appeared to be overlooked in later discussions as to the nature of ionization by β-particles.

Further photographs were taken in the winter of 1912-1913, especially illustrating the effects of X-rays. Some of these were exhibited at lectures before the Royal Institution and the French Physical Society, and published in their journals. Among these were pictures showing the effects of placing a sheet of metal, e.g. silver (Fig. 7), in the path of a beam of X-rays. These showed very clearly the absorption by the screen of the primary radiation; and the absorption by the air of the characteristic radiations from a copper or silver screen was also shown by the clouds condensed along tracks of the electrons which they ejected.

The tracks of the electrons ejected from a thin copper screen as a result of the absorption of the primary X-rays was also well shown (Fig. 8); the excess of the number ejected on the side of emergence being conspicuous. In obtaining the pictures which best showed this effect, the intensity of the radiation was reduced by introducing a plate of aluminium about 1 cm in thickness which removed especially the less penetrating rays. A very interesting feature appears in these photographs. It is described in the concluding paragraph of the Journal de Physique paper:

"A great number of the rays emitted by the copper and the air under the influence of the X-rays are extraordinarily long; some attain a length which in air at atmospheric pressure corresponds to nearly three centimetres. It should be added, however, that on the path of the primary X-rays one can see a large number of little patches of cloud, which perhaps represent the paths of exceedingly short cathode rays, and of which the interpretation requires further investigation."

These very short tracks, we now know, are due to the Compton effect; they are the tracks of recoiling electrons, each of which has scattered a quantum of radiation.

At this stage of the work, some stereoscopic pictures of cloud tracks were obtained; and the advantages of such virtually three-dimensional pictures were so apparent that henceforth this method was exclusively used. A number of stereoscopic pictures of α-ray tracks and of the tracks of electrons ejected by X-rays had been obtained when war broke out.

Work on the tracks was entirely laid aside during the war. When it was resumed (at the Solar Physics Observatory, to which I was now attached) it was some time before good pictures were obtained, not till the autumn of

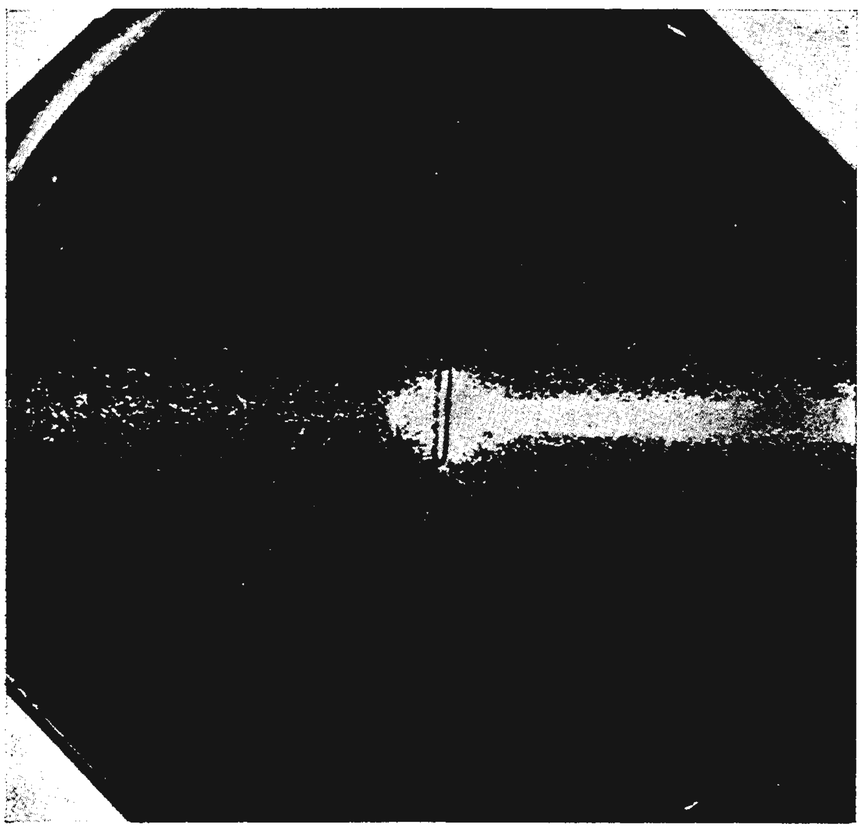

Fig. 7.

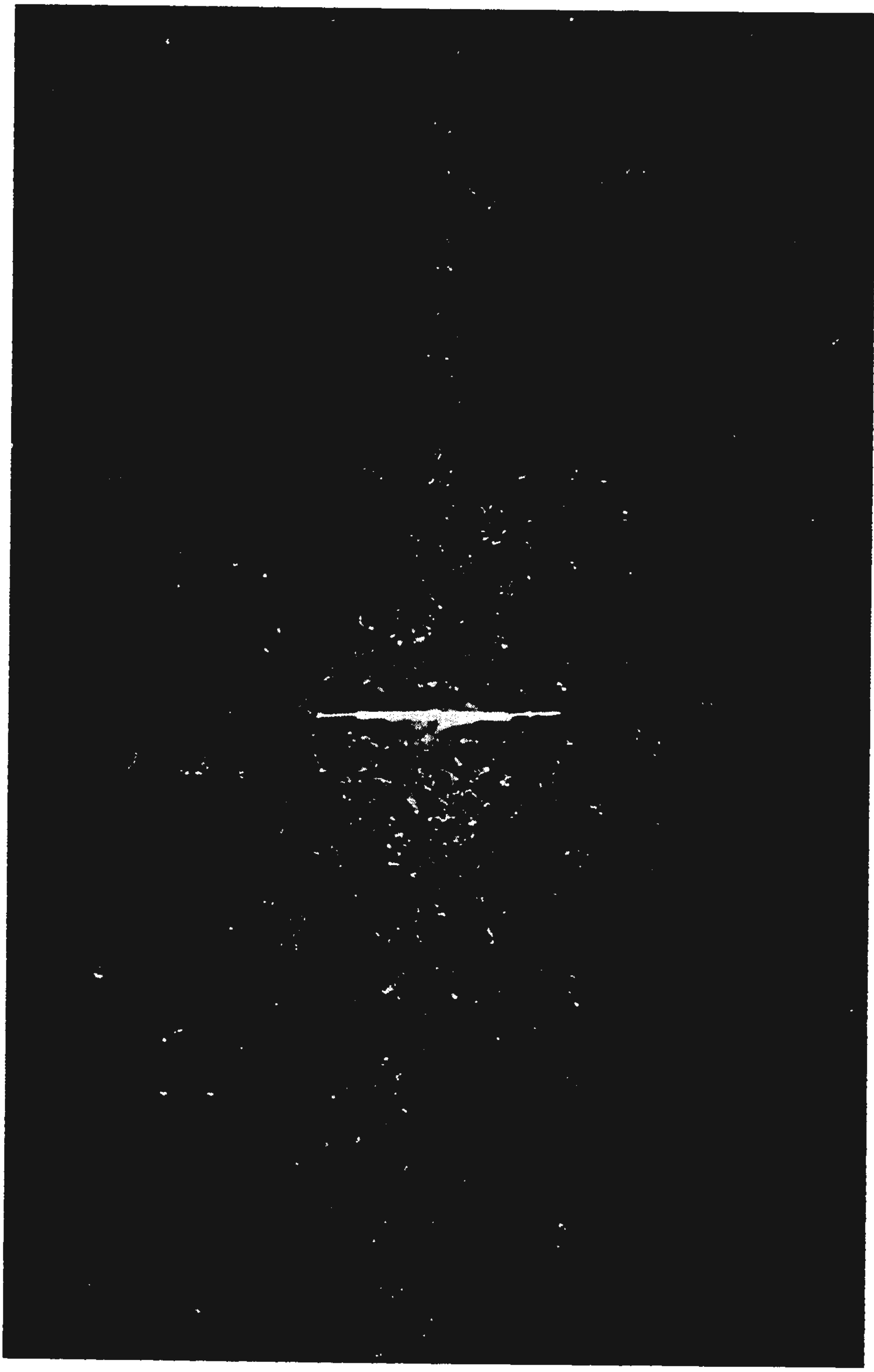

Fig. 8.

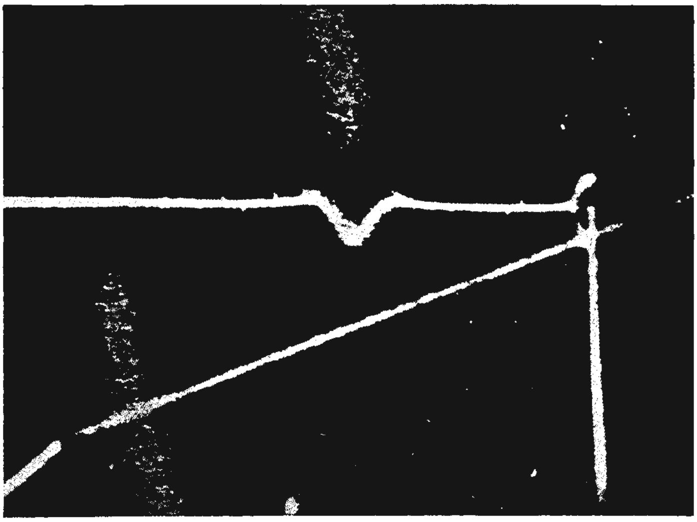

Fig. 9.

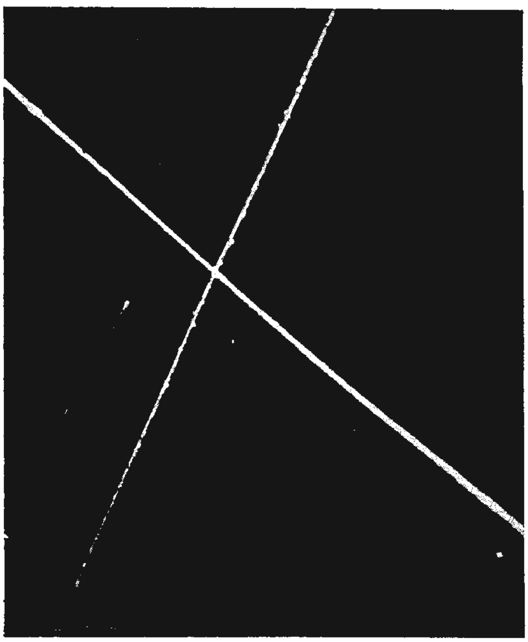

Fig. 10.

1921. A number of stereoscopic pictures of a-ray tracks were then obtained with some thorium emanation in the cloud chamber; some of these pictures were of interest and were published in November 1922. They showed well, for example (Figs.9 and 10), the separation by an electric field of the positive and negative ions liberated along the track of an cc-particle which traversed the cloud chamber before expansion; the two associated tracks of a-particles from an atom of thorium emanation and from the resulting thorium A atom; the track of the recoiling atom which has ejected an a-particle; and the tracks of δ– rays (electrons ejected by the cc-particle with velocity comparable with its own) projecting from the initial portions of cc-ray tracks. The tracks of δ– rays due to a-rays in hydrogen had been photographed some years before by Bumstead in America.

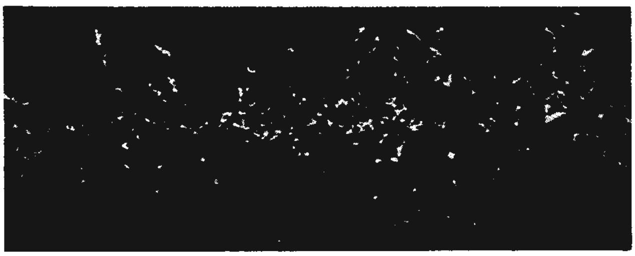

Fig. II.

The experiments on the effects of X-rays and of the electrons ejected by them, which had been interrupted by the war, were now resumed, and a number of stereoscopic pictures were obtained between December 1921 and July 1922. These contained a large amount of material for study and the results were not ready for publication till June 1923. When the cloud chamber is momentarily traversed by a beam of X-rays of suitable intensity a picture (Fig. II) is obtained (in three dimensions if the stereoscopic method is used) of the tracks of all the electrons ejected from a given volume of the gas by the action of the X-rays, primary and secondary. An examination of the picture shows at once : (I) the point of origin of each ray (electron track); (2) its initial direction (i.e. the direction in which an electron has been ejected from its parent atom by the action of the radiation) ; (3) its range or total length of its path; (4) the form of the track, its sudden or gradual bends, and the number and direction of emission of any secondary rays (branches); and (5) the variation of ionization along the track; under favourable conditions the number and distribution of the ions along the tracks may be obtained by direct counting.

The general results obtained can hardly be indicated otherwise than by showing examples of the photographs. Unfortunately I am not able to show them stereoscopically on the screen.

1. The first picture (Fig. 12) shows the absolutely straight track of a fast electron, and the devious tracks of electrons of which the energy corresponds to less than about 20,000 volts.

2. This (Fig. 13) shows the track of an electron of moderate energy: the straightness of the initial portion - a deviation through a large angle as a result of a close approach to the nucleus of an atom - the increasing curvature of the track and increasing ionization as the velocity diminishes.

3. Here (Fig. 14) the primary electron has ejected from an atom a secondary electron with energy enough to form a conspicuous branch track.

4. This (Fig. 15) is the track of a very fast electron passing through air at rather low pressure. In this picture the drops condensed on positive and negative ions are individually visible, and occur sometimes in pairs, sometimes in groups. The electron ejected from an atom by the primary β-particle has in many cases emerged with insufficient energy to produce further ionization; in other cases the energy of the ejected electron has been sufficient to produce one or more additional pairs of ions by collision.

5. In a large number of cases (e.g. Fig. 16) while the individual ions could not be counted, it was easy to determine the number of groups, i.e. the primary ionization or number of atoms from which an electron was ejected per cm of path.

6. This (Fig. 17) shows the tracks of electrons ejected by the K-radiations from silver.

7. The next picture (Fig. 18) shows the tracks of those ejected under identical conditions by the K-rays from copper.

From data such as those contained in these two pictures it was possible to measure the ranges of electrons of known initial energy. The range in air was found to be 1 cm for an electron of about 21,000 volts, and to vary according to Whiddington's law of the fourth power of the velocity. This result was utilized in determining the primary ionization for electrons of approximately known velocity.

8. The next picture (Fig. 19) was obtained by passing a very narrow beam of hard X-rays through a thin copper plate. Only two tracks appeared in the photograph, that of an electron ejected from the copper by the primary

beam, and a short one, in the air outside the primary beam, of range corresponding to ejection of an electron by copper K-radiation. We almost certainly have here the tracks of the copper K-electron whose ejection was followed by the emission of a quantum of copper K-radiation, and of the electron ejected from nitrogen or oxygen as a result of the absorption of this same quantum of copper K-radiation.

9. A quite similar picture (Fig. 20) obtained with a narrow beam of hard X-rays passing through a platinum plate.

10. Similarly related tracks may occur, both of which have their origin in the air. This picture (Fig. 21) shows the most common case (one independently discovered by Auger and explained, and very thoroughly investigated by him). Here both tracks start from the same atom; the K-radiation (or the energy which might have been spent in emitting it) being used in ejecting an outer electron from the atom from which the X-rays had ejected a K-electron.

The remaining pictures (Figs. 22, 23, and 24) show the cloud tracks obtained when horizontal beams of X-rays traversed the cloud chamber from right to left. They show, as some of the pictures obtained in 1913 had already indicated, that two classes of rays are produced by such rays, giving << long>> tracks and <<short>> tracks.

A <<long>> track is the track of a photoelectron, i.e. of an electron ejected as the result of absorption of a quantum of X-radiation. The number of short tracks was found to be very small relatively to that of the long tracks when the wavelength of the incident radiation is as great as one ångström. It increases rapidly as the wavelength diminishes, and for short wavelengths the number greatly exceeds that for the long tracks. At the same time the short tracks which are mere <<sphere tracks>> when they are due to the longer waves become <<fish tracks>>; they begin to have a measurable range, and their appearance shows that they are due to electrons ejected nearly along the direction of propagation of the primary beam.

It was pointed out in the 1923 paper that the phenomena relating to these tracks supported A. H. Compton's theory of the scattering of X-rays, and that they are in all probability just the tracks of the recoiling electrons which according to this theory have scattered individual quanta of radiation.

It was pointed out by Compton that the relative numbers of the short and long tracks for a given wavelength of the incident radiation in these photographs are in agreement with the ratio between the scattering and absorption coefficients, and that this in itself furnishes strong support for his theory.

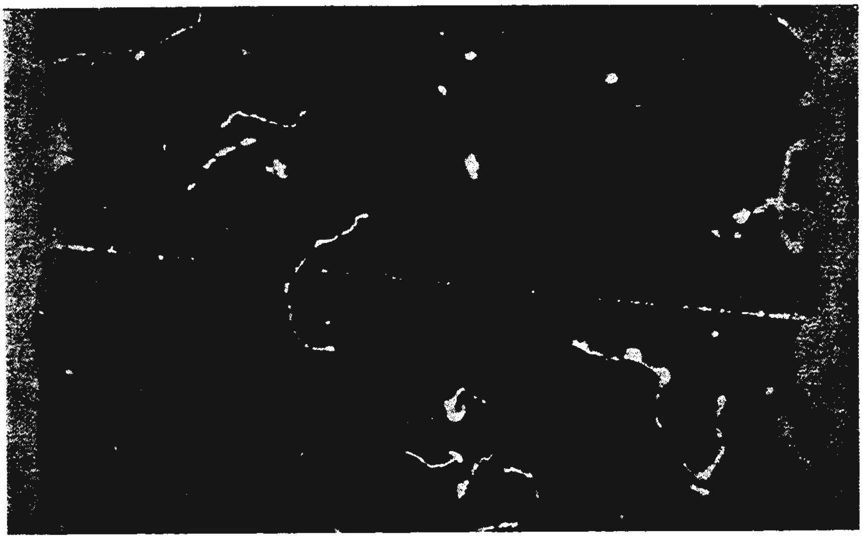

Fig. 12.

Fig. 13.

Fig. 16.

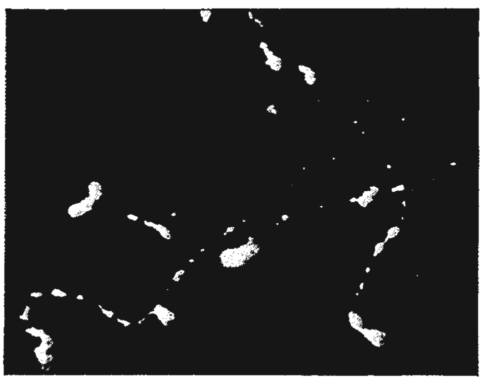

Fig. 14.

Fig. 15.

Fig. 18.

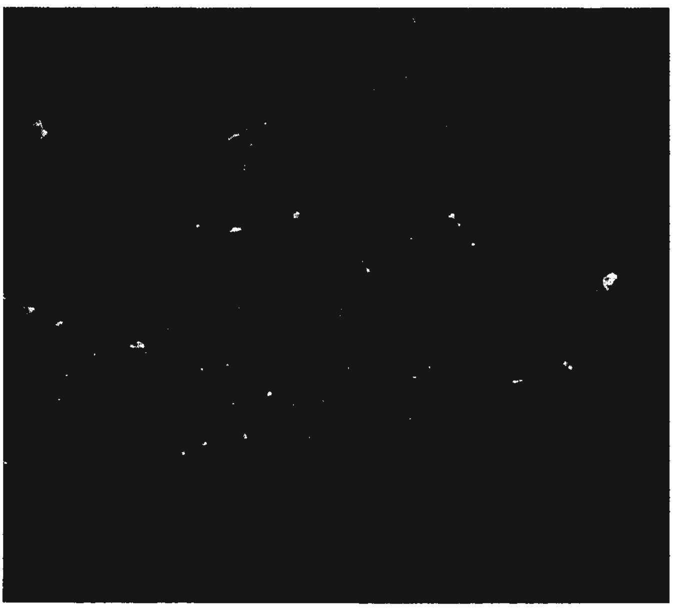

Fig. 17.

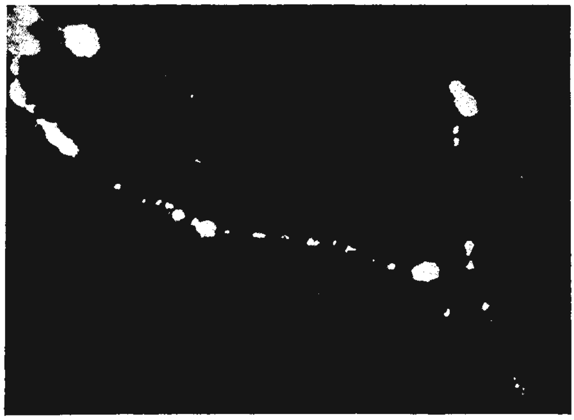

Fig. 21

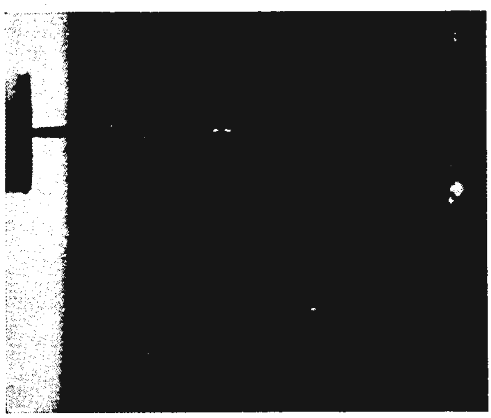

Fig. 20.

Fig. 19.

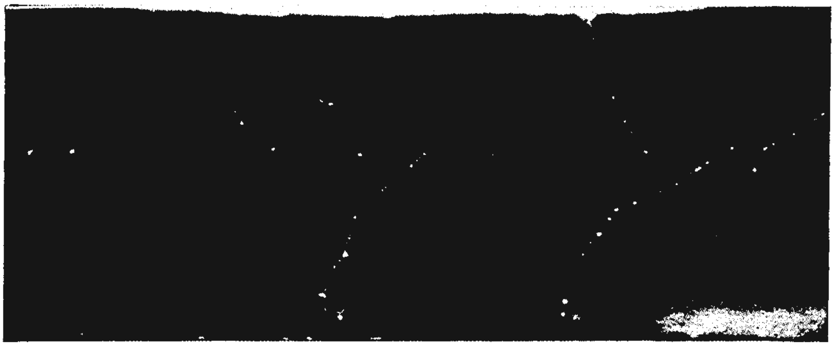

Fig. 22.

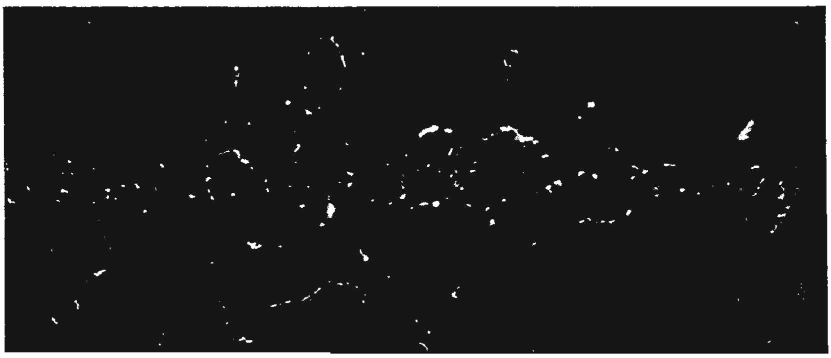

Fig. 23.

Fig. 24.

Nuttall and Williams have later investigated the relative numbers of long and short tracks in cloud photographs with homogeneous X-rays of different wavelengths in pure gases. This investigation as well as other recent cloud experiments, such as those of Compton and his collaborators, afford strong confirmation of Compton's theory and leave no room for doubt that the "fish tracks" are the tracks of the recoil electrons of that theory; each represents the scattering of a quantum of radiation.

The long tracks, i.e. the tracks of electrons ejected as a result of absorption of a quantum of radiation may be initially nearly at right angles to the beam of X-rays or may be inclined at considerable angles to this direction- In my own observations the number which had a forward component in their velocity was found considerably to exceed those with a backward component; and the ratio of the number with a forward to the number with a backward component increased with increasing frequency of the radiation. Qualitatively at least one may explain this result by saying that the momentum of the absorbed quantum is given to the ejected electron The matter has been investigated much more fully by Auger and others.

I have tried to give some account of the history of the development of the cloud method.

During the last few years many physicists have been using the method; in some cases with refinements which made it possible to attain an accuracy much exceeding that arrived at in my experiments. It would take too long even to enumerate these investigations. But I should like to mention as examples of the applications of the method: the work of Blackett on collisions of α-particles with atomic nuclei and on atomic disintegrations thus produced, on the ranges of individual α-particles by Mlle Curie and by Miss Meitner, on δ-rays by Chadwick and Emeleus, on the mobility of radioactive ions by Dee, on X-rays and the β-rays associated with them by Bothe, by Auger, by Nuttall and Williams, and by Compton and his collaborators; and on the study of the wavelengths of γ-radiations, by measurement of the ranges of the Compton recoil electrons, by Skobelzyn.