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A note on the Wilson cloud chamber (1912)

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Abstract

A technical description of the 'Wilson cloud chamber' developed by C T R Wilson in 1911–12 will be given here. This instrument soon became a fundamental tool of research in nuclear, cosmic ray and elementary particle physics. The close examination of the expansion apparatus, the illumination method and the photographic method shows that the cloud chamber is a fine example of experimental ingenuity.

1. Introduction

As is well known, the Wilson cloud chamber played a very important role in the development of modern physics. Among the most prominent achievements using the cloud chamber we recall the visualization of Compton recoil electrons (1923); the discovery of the positron (1932) and the muon (1937) by Carl Anderson; the observation of a new class of 'strange' particles by Rochester and Butler (1947); the visualization of the first artificial transmutation of a nitrogen nucleus carried out by Blackett (1925) and that of the processes of 'pair creation' and 'annihilation' of electrons and positrons by Blackett and Occhialini (1933).

Thomson deemed the Wilson cloud chamber 'of inestimable value to the progress of science' [1]. Rutherford called it 'the final court of appeal' [2] in physics, by which 'the validity of our explanations can be judged' [2]. 'Where many indirect evidences fail to convince'—it had also been said—'a single cloud-chamber picture is often sufficient and carries conviction' [3]. A remarkable feature of this novel tool was indeed the lack of controversy over the evidence furnished by the Wilson method: 'it was a novel form of instrument, revealing hitherto invisible phenomena, and yet there was no resistance to its acceptance as a valid, authoritative representation of microphysical entities and events' [4].

In spite of the important role of the Wilson cloud chamber in 20th century physics, the actual development and description of its apparatus is somewhat neglected in the history of modern physics literature. Most of the papers devoted to the cloud chamber concern either the early phases of expansion techniques [5] or the Wilson chamber's impact upon modern physics under sociology of science perspectives [4]. Unlike previous studies, our paper is aimed at addressing the development of the Wilson chamber with a particular focus on its original technical description (1911–12) and its first applications.

2. Pre-Wilson chamber

Though developed by Wilson in 1911–12, the history of the Wilson cloud chamber began at the end of the 1800s with the research of Coulier [6], Kiessling [7] and Aitken (1880–1916) [8] on the role played by dust particles in the condensation of water vapour into cloud drops [5]. The principles of cloud formation were known to the physicists of the time. When an air mass saturated with water vapour is borne upwards by convection currents, it expands adiabatically, i.e. without exchange of heat, temperature falls, as shown by the adiabatic relation $TV^{\gamma-1} = K$ (where T is the temperature, V is the volume and K is a constant). The excess water vapour separates out in the form of liquid drops which appear as cloud or fog. Through laboratory experiments, Coulier, Kiessling and Aitken discovered that the cloud resulting from small adiabatic expansion of moist, dusty air disappears completely if the air is first made dust free. This discovery led for sometime to the belief that the formation of clouds can be ascribed in all cases to dust alone.

In 1895 Wilson developed an ‘adiabatic expansion chamber’ where the gas filling a glass vessel could be expanded through a system of valves connected with a vacuum tube (figure 1) and demonstrated that under certain conditions, even when no dust particles are present, condensation can take place. Wilson had previously observed that by filling his expansion chamber with dusty, moist air, a very slight expansion produced a dense fog. Such a fog was caused by condensation on dust particles because when the expansion was repeated several times and all dust was carried down by the cloud it was no longer possible to produce fog. However, through experiments with dust-free air, Wilson discovered that by gradually increasing the expansion ratios, i.e. the ratios of the final to the initial volume, no clouds were produced until a critical value for the expansion ratio (1.25) was reached (the *rain-like limit*). When the expansion ratio exceeded the value of 1.25 and was between 1.25 and about 1.38 a few rain drops were produced. Beyond 1.38 (the *cloud-like limit*) again a much denser cloud of smaller particles was formed, the density of the cloud increasing with the expansion ratio. In this way Wilson demonstrated that the presence of dust particles is not a *necessary* condition for condensation [9].

Thus, it was then question of identifying the nuclei on which cloudy condensation took place in the absence of dust. The first step towards answering this question was accomplished by Wilson in 1897, right after the discovery of x-rays. By means of an x-ray tube he discovered 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 [as opposed to the expected few drops] was produced when the expansion lay between the rain-like and cloud-like limit’ [1].

By introducing two parallel plates into the chamber containing dust-free air and by applying a strong field between the plates, Thomson later showed that the dense cloud that was previously produced when the chamber was traversed by x-rays, disappeared in the presence of the electric field [10]. From this and other observations, it was clear that the nuclei responsible for condensation in dust-free air with expansion between 1.25 and 1.38 are charged ions produced in the gas by the action of the radiation [3].

Towards 1910, Wilson began to make experiments with a view to making visible the ionizing particles, in particular the alpha and beta particles—previously identified as helium nuclei and electrons respectively—which were emitted by the radioelements. In this perspective these new experiments increased the usefulness of the condensation method. As

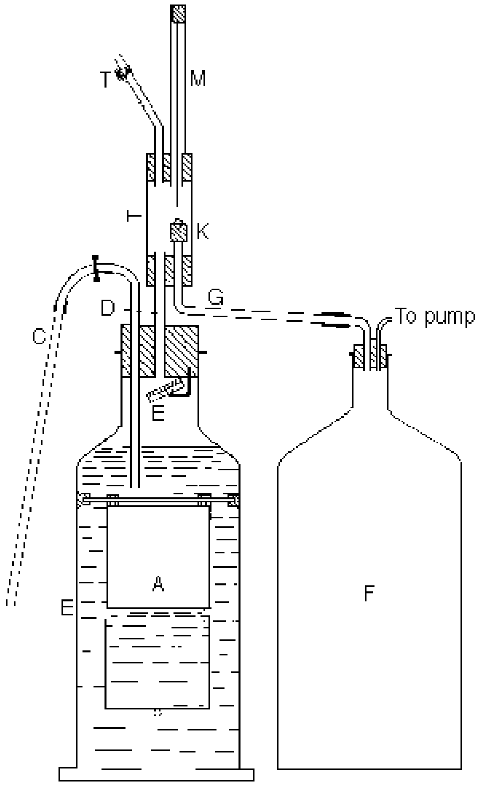


Figure 1. Wilson's 'adiabatic expansion chamber'. A is a glass vessel containing a saturated gas, F is a vacuum tube, E and K are valves, and D and G are tubes connecting F with the valves. By opening K the air in B flows towards F, the gas in A expands itself, the water in B rises up to close valve E, thereby stopping the gas expansion.

was recollected by Wilson in his Nobel lecture, delivered in Stockholm on 12 December 1927:

> [In] the years which had elapsed since my earlier experiments, ideas on the corpuscular nature of alpha- and beta-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. [1, p 199].

In 1911–12, Wilson spent much time 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 [11, 12].

By expanding suddenly a definite volume of air saturated with water vapour, the system was led to a supersaturated state where the air now at the lower temperature contained more vapour than it could hold in suspension in the saturated state. The excess water vapour condensed on ions as nuclei and an instantaneous photograph of the drops made the path of the charged particle visible.

In order to get the picture of the particle path, Wilson developed a method—later to be called the Wilson cloud chamber—whose 'beauty and ingenuity [· · ·] can hardly be exaggerated' [3]. Before the discovery of the Wilson chamber, 'it was possible only to observe the behaviour of matter in bulk', while the chamber 'enables us to study the behaviour

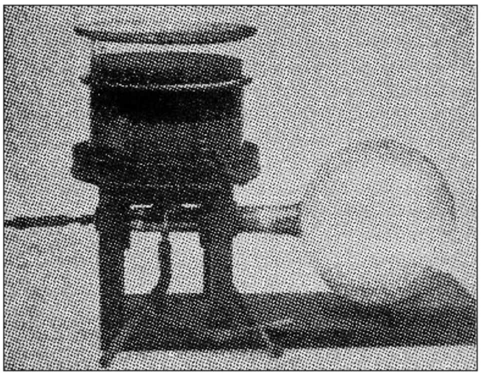


Figure 2. Wilson cloud chamber.

of individual atoms' and 'to visualize and photograph the actual paths of atoms and electrons through gases' [3].

The essential conditions—discovered by Wilson—to be fulfilled for the purpose of obtaining good pictures of the tracks are as follows. The expansion had to be made without stirring up the gas; such a condition was obtained by using a wide, shallow cloud chamber of which the floor was made to drop suddenly and therefore producing the desired increase in volume. The cloud chamber had to be freed not only from 'dust' particles, but also from ions other than those produced by the ionizing particles under observation; an electric field maintained between the roof and the floor of the cloud chamber served this purpose. In order to get sharp pictures of the tracks, the order of operations had to be first the production of the necessary supersaturation by sudden expansion of the gas; second the passage of the ionizing particles through the supersaturated gas; and last, the illumination of the cloud condensed on the ions along the track [1, pp 200–1].

The following sections will be devoted to a description of the Wilson cloud chamber (figure 2), as conceived in 1912, as well as of the operations to be followed in order to obtain good pictures of the tracks left by the ionizing particles laid inside the chamber [12].

3. The expansion apparatus

The expansion apparatus (figure 3) consisted of a cylindrical chamber, 16.5 cm in diameter and 3.4 cm in height, whose roof, walls and floor were of glass and were coated inside with gelatine in order to isolate the system. Besides serving as a cement to attach the glass roof of the cloud chamber, 'the gelatine avoids altogether one of the principal sources of trouble in all cloud experiments, the deposition of dew on the inner surface of the glass' [11, p 285]. The floor was blackened by adding black ink to allow the observation of the traces on a black screen. The plate glass floor was fixed on the top of a thin-walled brass cylinder (the 'plunger'), 10 cm high, open below, and sliding freely within an outer brass cylinder (the 'expansion cylinder') of the same height and about 16 cm internal diameter. The expansion cylinder supported the walls of the cloud chamber and rested on a thin sheet of India rubber (i.e. caoutchouc) lying on a thick brass disc, which formed the bottom of a shallow receptacle containing water to a depth of about 2 cm. Wilson's goal was to separate completely the air in the cloud chamber from that below the plunger.

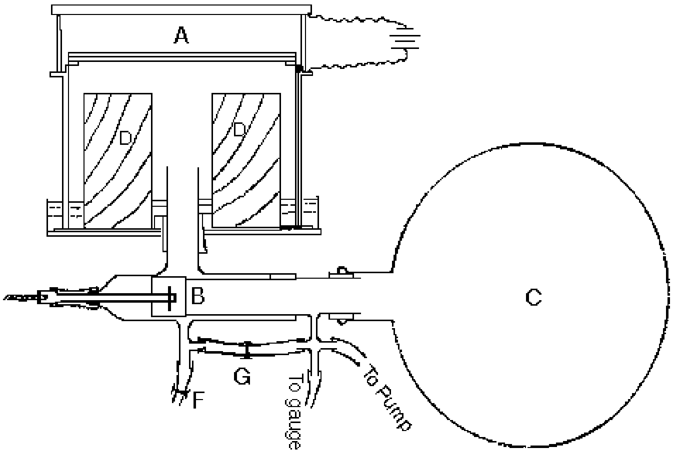


Figure 3. Expansion apparatus.

The expansion was made by opening the valve B via the fall of a weight W released by a trigger arrangement T (figure 5). This operation allowed us to put the space under the plunger in communication with the vacuum chamber C through 2 cm wide glass tubes. As a consequence of the following difference of pressure, the floor of the cloud chamber dropped suddenly until brought to a sudden stop when the plunger stroked the caoutchouc-covered base plate, against which it remained firmly fixed by the pressure of the air in the cloud chamber. In order to reduce the volume of air passing through the connecting tubes at each expansion, the wooden cylinder D was inserted in the air space below the plunger.

Pinch cocks F and G were two clamps that allowed us to regulate the flow of air through the flexible pipes. When the valve was closed, the opening of F allowed the communication of the chamber with the atmosphere: as a consequence, the plunger rose and so reduced the volume A. By means of the two pinch cocks F and G, the plunger could be adjusted to give any desired initial volume v_1 between the upper limit v_2—i.e. the volume of the cloud chamber itself—and the lower limit reached when the pressure below the plunger was that of the atmosphere, namely, when, by opening the pinch cock F, the plunger rose to the upper limit of the expansion cylinder. As remarked by Wilson, the final volume was always the same (about 750 cm^3) and the expansion ratio v_2/v_1 depended only on the initial volume. A scale attached to the side of the cloud chamber enabled the position of the top of the plunger to be read. Since the area of the cross-section of the plunger and the maximum volume v_2 of the cloud chamber were known, this allowed the initial volume to be determined.

The plunger was placed on the rubber-covered base plate, and the expansion cylinder slipped over it. A hole on the side of the cloud chamber was opened at this stage to allow the escaping of the imprisoned air. By blowing in air through F, the plunger was driven up to a height great enough to allow the largest desired expansion to be made. The aperture on the wall of the cloud chamber was then closed, and the mass of imprisoned air remained unchanged during subsequent operations. The gelatine layer under the roof of the cloud chamber was connected to one terminal of a battery of cells to which the other terminal was connected with the layer of blackened gelatine on the floor of the cloud chamber. A roughly uniform vertical electric field of any desired intensity could thus be maintained in the cloud chamber [12, pp 278–9].

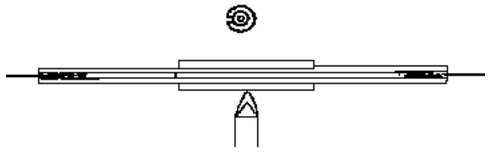


Figure 4. Illumination apparatus.

4. The illumination method

In order to obtain the instantaneous illumination of the cloud (resulting from the expansion of the camera), Wilson made use of a Leyden jar electric discharge through mercury vapour at atmospheric pressure. The Lejden jar is the earliest form of the condenser or capacitor[1]. It consisted of a thin glass jar partly coated inside and outside with tin foil. When the two metal surfaces were connected for a short time to the terminals of a source of electromotive force, electric energy was stored up in the condenser and could be recovered again in the form of an electric discharge.

Wilson used a silica tube about 15 cm long, whose internal diameter is about 1 mm, filled with mercury and enclosed, for the central 4 cm of its length, by silver tube about 2 mm thick, and having a slot about 1 mm wide extending from end to end (figure 4). The silver tube was heated by a flame to maintain the enclosed portion of the silica tube at a nearly uniform temperature, high enough to vaporize the mercury, and thus form a mercury-vapour spark gap. The connections with the Leyden jar were made through platinum wires inserted into the ends of the silica tube. When the mercury occupying the silver enclosed portion of silica tube had all been vaporized, the illumination apparatus was ready to be used.

The clever device used by Wilson to produce the spark was the one commonly employed to get instantaneous photographs through a Leyden jar spark.

The outer coatings of two sets of Leyden jars were connected to the terminals of the illuminating spark. The inner coatings were connected to two brass balls separated by a distance of about 5 cm, which formed the primary spark gap. The Leyden jars were charged to a strong voltage by a Wimshurst machine, i.e. an electrostatic generator commonly used in the 1800s for generating high voltages[2].

A metal ball, which was hung by a fine thread to a weight W that worked the valve of the expansion apparatus, was allowed to fall between the terminals of the primary spark gap, thereby causing a spark to pass at both gaps. The ingenious set-up for firing the spark right after the expansion is shown in figure 5. The weight W was attached to a cord which passed through an iron ring in a firm support, and thence nearly horizontally to the trigger T, to which it was attached by a loop. A second string linked a point on the first cord with the valve of the expansion apparatus. On pulling the trigger the cord attached to it was released and the weight fell until the second string was stretched tight. Thus, the weight arrived at a sudden stop, the valve was simultaneously opened and the expansion thereby effected. The thread broke at this moment and the steel sphere kept falling, finally passing through the primary spark gap, P, and causing the illuminating spark to pass at S [12, 280–1].

As we shall see, the upper spark gap (figure 5) was only employed in the experiments with x-rays.

[1] The first jars were made independently in 1745 by E G von Kleist in Germany and P van Musschenbroek of the University of Leyden, from whence the term Leyden jar.

[2] This electrostatic generator was invented by J Wimshurst in 1883.

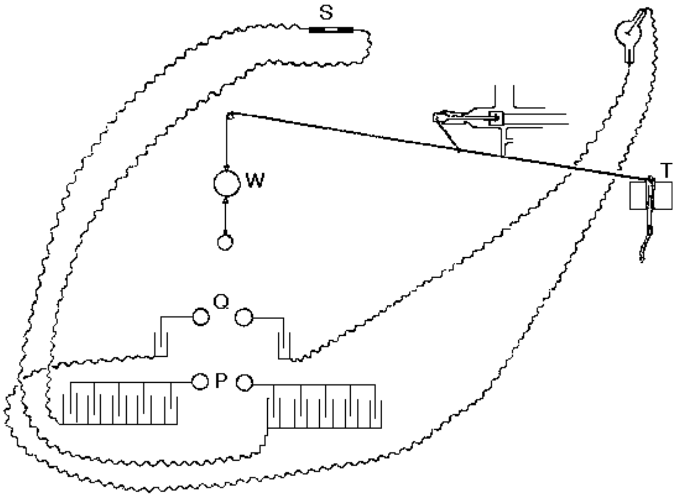
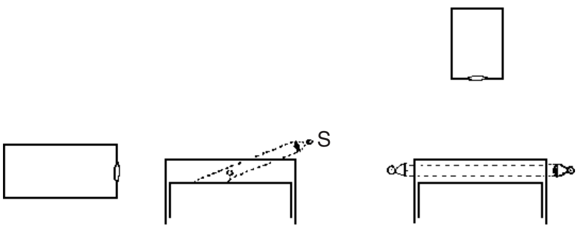


Figure 5. Arrangements for firing the spark at a definite interval after the expansion.



(a) (b)

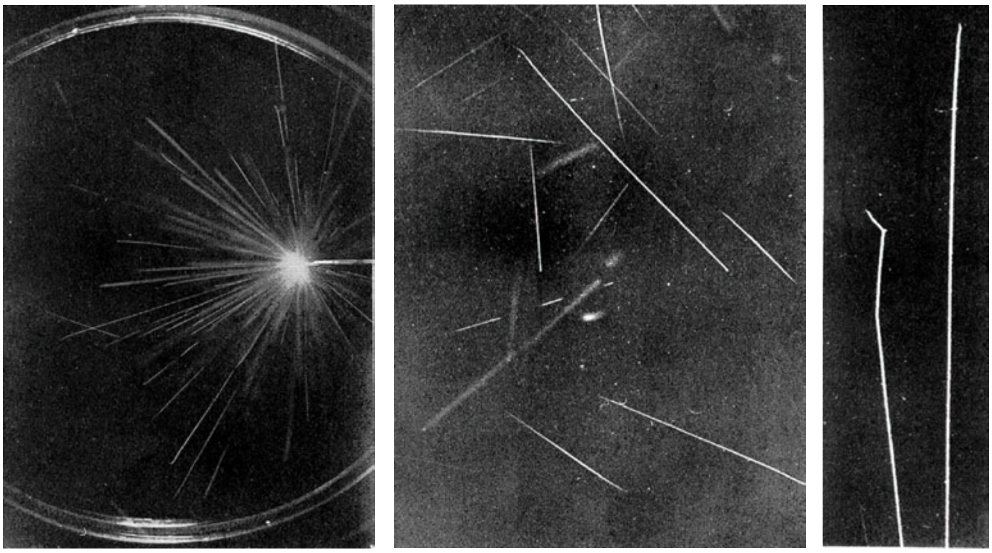
Figure 6. Arrangements for photographing the clouds.

5. The photographic method

In the Wilson experiments, the camera lens always occupied one of the two positions indicated diagrammatically in figure 6, where the small circle (figure 6(a)) represents a transverse section of a narrow horizontal beam of ionizing rays crossing a diameter of the cloud chamber. The camera looks in a horizontal direction normal to the ionizing beams. The source of light, i.e. the mercury spark gap, was at S, principal focus of a cylindrical lens about 20 cm long and 2 cm wide with a focal length of about 3 cm. In this way, the whole of the cloud was illuminated, while the direction of the incident light subtended an angle of about 25° with the axis of the camera.

The set-up in figure 6(a) was used in the beta ray experiments as it allowed us to 'enlarge' a small portion of the camera and to get clear photographs of the weakly ionizing electrons making up the condensation cloud. It was therefore possible to photograph the tracks of whichever ionizing particle, even if the number of ions per centimetre was very small.

The arrangement in figure 6(b) was used chiefly with the alpha rays, which gave clouds of sufficient density to scatter a large amount of light at right angles to the illuminating beam. The camera lens is vertically over the centre of the cloud chamber. By means of two similar spark gaps arranged in series, each at the principal focus of the cylindrical lens as that used



(a) (b) (c)

Figure 7. Alpha particles emitted by a radium source (a) and by radium emanation (b). In (c) a track is represented showing an alpha particle scattering.

in (a), it was possible to illuminate a horizontal layer of about 2 cm in vertical thickness and to extend across the whole area of the vessel.

6. First applications

Following the development of his apparatus, Wilson employed it to the goal of studying the tracks left by alpha and beta particles, and by x-rays. According to Wilson,

> perhaps the most important purpose that the photographs obtained at this time served, was to confirm, in a way that 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. [12, p 201].

As regards the alpha particles, a minute amount of radium $\left({}^{226}_{88}\mathrm{Ra}\right)$ on the tip of a wire was used as a source (figure 7(a)). Another source of alpha particles was the radium emanation gas, i.e. the product of radium alpha decay $\left({}^{222}_{86}\mathrm{Rn}\right)$, at present known as 'radon' (figure 7(b)). Due to their great charge and slow speed, alpha particles produced thick tracks in the cloud chamber. As shown by the Wilson photographs, the alpha particles were generally straight over the greater part of their length, 'but they nearly all are bent, often abruptly, in the last 2 mm of their course' [12, p 283]. These sudden changes of direction were due to collisions with the atoms of air. In some cases, the recoiling atom track was clearly visible (figure 7(c)).

These experiences, which were carried out one year after Rutherford's discovery (1911) of the atomic nucleus from the observed large angle of scattering of alpha particles, were immediately interpreted by Wilson as empirical facts in agreement with the Rutherford theory on the single scattering. Wilson's photographs of alpha particle tracks became readily famous and are still reproduced in many nuclear physics manuals as examples of single scattering (figures 7(a)–(c)).

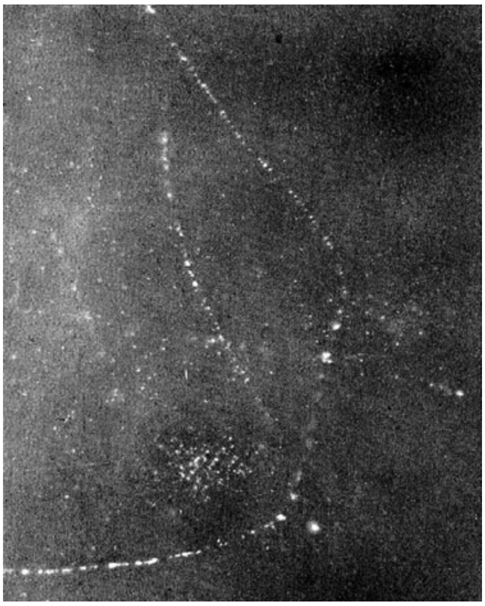


Figure 8. Tracks of beta particles.

Compared to alpha particles, beta particles produced thinner tracks inside the Wilson chamber. The beta particles studied by Wilson were emitted by a radium source or by photoelectric effect produced by gamma radiation interaction with the walls of the vessel. The photographs showed electron tracks 'of remarkable straightness when the velocity was high, but slower electrons showed both sudden deflections through large angles and gradual deviations due to an accumulation of small deflections' [1, pp 201–2]. In the beta particle photographs the individual droplets due to single ions were clearly visible (figure 8).

Wilson also tried to photograph the passage of x-rays. Although these rays cannot be directly photographed because they are neutral, they are evidenced by the electrons they produce through the effects of radiation-matter interactions, such as the photoelectric effect or the Compton effect. The photographs 'of the secondary electron tracks produced by a narrow beam of x-rays' [13] shot by Wilson are shown in figure 9.

These photographs required an ingenious refinement of the cloud chamber set up with the goal of synchronizing expansion, x-ray emission and illumination of the chamber. In order to obtain this synchronization, Wilson made use of a simple arrangement of a single falling weight (W).

The x-rays source consisted of a typical cathode vacuum tube (then named 'Crookes tube'[3]), whose anode and cathode were suitably shaped, connected with a strong potential difference. X-rays were produced by the collision of the cathode rays against the anode when the discharge was primed. In the Wilson device the potential difference was supplied by two Leyden jars, whose outer coatings were connected to the x-ray source (shown in the upper right-hand corner of figure 5), while the inner coatings were connected to the terminals of the upper spark gap Q (figure 5). Thus, when the weight W (that previously had triggered the chamber expansion) passed through the spark gap Q, the discharge was primed and the x-ray emission took place. Afterwards, during its fall the weight W passed between the spark

[3] The Crookes tube was named after its designer, the British chemist and physicist Sir William Crookes.

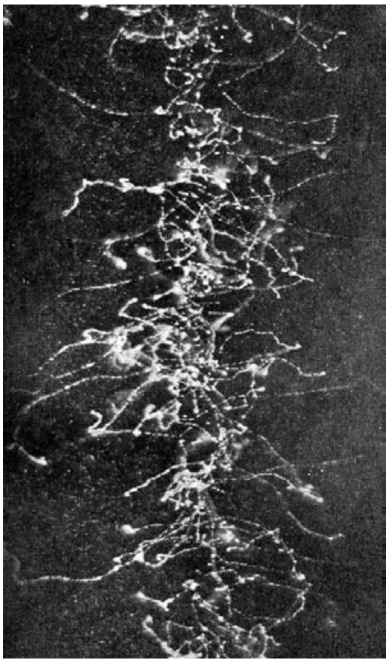


Figure 9. Ionization by x-ray beam.

gap P (connected to the source of illumination) and therefore caused the illuminating spark. Summing up, by means of the falling of the weight through the spark gaps Q and P, Wilson was able to synchronize cloud chamber expansion, x-ray emission and illumination of the chamber.

As remarked by Wilson, the moment of occurrence of the x-ray flash relative to the expansion was adjusted by varying the length of the thread suspending the steel ball [12, pp 286–7]. A series of tests was conducted using different lengths of thread. These photographs also furnished information on the rapidity of the expansion. It was found to be completed within about 1/50th of a second. Wilson emphasized that there is no indication of any effect of the x-rays other than the production of the corpuscular radiation. When the x-rays were 'flashed through the cloud chamber before the expansion of the air, diffuse double tracks are obtained, the positive and negative ions being separated by the electric field' [12, p 290]; this allowed the number of positive and negative ions to be separately counted.

In this way, through the awareness that the visualization of tracks left by ionizing particles and radiation was an accomplished step, a first phase of the cloud chamber history arrived at its close. In a short time the cloud chamber became the focus of interest of many researchers, and several improvements of the apparatus were realized, as the introduction of a magnetic field inside the chamber. Such improvements allowed the above-reported discoveries, and made the cloud chamber one of the most important devices in the 1930s physics.

7. Conclusions

As we have seen, the 'Wilson cloud chamber', in spite of its essential simplicity, was the outcome of a ten year long process. Such a process was first aimed at studying the condensation of water vapour, then at discovering the nature of the condensation nuclei under different working conditions and, finally, at developing a technique for photographing the tracks left by ionizing particles and radiation in supersaturated gases. This latest goal was reached by Wilson through the development of an ingenious ‘cloud chamber’ whose expansion apparatus was synchronized—by means of a mere falling weight—with the illuminating apparatus. As Blackett, a cloud chamber expert at the Cavendish Laboratory from 1924 to the end of the thirties, wrote, ‘without C.T.R. Wilson’s vision and superb experimental skill, mankind might have had to wait many years before someone else found the way’ [13, p 289]. As a matter of fact, Wilson’s idea concerning the cloud chamber, i.e. to try to visualize and photograph the tracks left by ionizing particles or radiation by condensing water on the ions which they liberate, was genius. On the other hand, the impact that the cloud chamber had on the physics of the time was astonishing: phenomena that formerly had been deduced *indirectly* from electrical measurements or through the light spots on zinc sulphide screens in darkened rooms, now became visible to the eye in all their finest detail. As remarked by Blackett, Wilson’s apparatus gave ‘the world a new sense’ [13, p 289] and it was not a mere chance that it deserved Rutherford’s appellative as ‘the most original and wonderful instrument in scientific history’ [14, p 216].

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