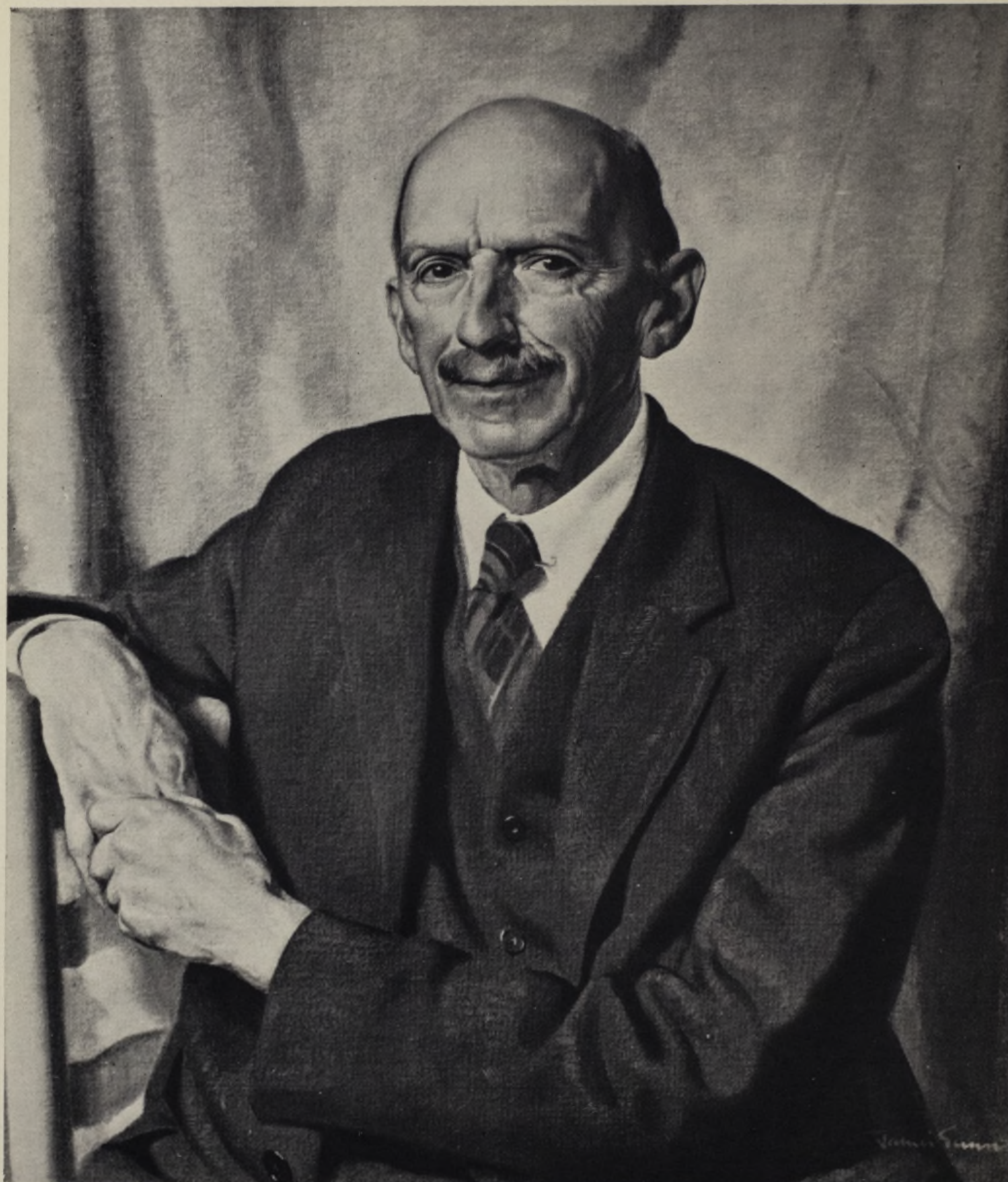

C. T. R. Wilson

CHARLES THOMSON REES WILSON

1869-1959

CHARLES THOMSON REES WILSON was born on 14 February 1869 at the farmhouse of Crosshouse near Glencorse in the Pentland Hills near Edinburgh. He was the youngest of eight children by the two marriages of his father John Wilson, a very progressive sheep farmer, whose family had farmed in the neighbourhood for generations, and who himself had published papers in the *Journal of the Highland and Agricultural Society* on various experiments in farming. Charles's mother, Annie Clark Harper, was a second cousin of her husband and came of a Glasgow family, who in the eighteenth century had been prosperous thread makers and muslin manufacturers, as well as burgesses of the city, but whose business had latterly declined. Some of the family attended Glasgow University. The Harpers had literary inclinations: George Harper, Professor of English Literature at Princeton and a distinguished author, was a second cousin of Charles.

When Charles was 4, his father died aged 53 and his mother was left with three young children of her own and four stepchildren. The whole family, which was a very united one, moved to Manchester to be near Mrs Wilson's parents, who had moved there from Glasgow. The elder brothers were determined that their two young half-brothers, Charles and George, in whom they had great faith, should achieve the university education which they themselves had missed. One of them, William, went into business which took him in 1877 to Calcutta, where he rose to be a partner in his firm, a town councillor and a member of the Calcutta Chamber of Commerce. For many years he supplied the main part of the family income. He died of tuberculosis in 1892 at the age of 35, on his way home to England.

Charles attended Greenheyes Collegiate School at Manchester from the age of 9 to 15. There was no science taught at the school, but Charles and his brother George spent a great deal of time studying beetles and pond life and made good use of a microscope which Charles had been given when he was 13; they constructed a microtome and became skilled in preparing zoological and botanical specimens.

When Charles was 15, he and his brother went to the island of Arran in the Clyde, and he commented later that his visit to North High Corrie was a wonderful revelation to him of the beauty of the world and inspired him to study nature in all its aspects. If it was this first visit to the Scottish mountains which did much to arouse Charles's desire to investigate natural phenomena, it was another visit ten years later, this time to Ben Nevis, which defined the field of his life's work, that of condensation phenomena and atmospheric electricity.

Through the financial help of his half-brother William in Calcutta, Charles was enabled to enter Owens College, Manchester, in 1884, when he was 15, registering as a medical student but intending to take a science degree first. For three years he studied physics, chemistry, botany, zoology and geology, taking a B.Sc. when he was 18, followed by a fourth year studying philosophy, Latin and Greek. In 1888, at the age of 19, he won an entrance scholarship at Sidney Sussex College, Cambridge, and by the time he arrived there he had definitely decided to be a physicist; so he took physics, together with chemistry, geology and botany in Part I of the Tripos and physics and chemistry in Part II. His half-brother William died three months before Charles took his Cambridge degree in 1892, and Charles wrote of him: 'His encouragement and faith in me and my desire not to disappoint him had been among the strongest influences of my life.'

It now became essential for him to help his family, who were now back in Scotland within a few miles of their old home. He stayed on in Cambridge after taking his degree, doing a certain amount of demonstrating in physics and chemistry, and also set to work on a research problem. This made use of an optical method of studying the distribution of a substance in a liquid which was kept hotter at the top than at the bottom, comparing it with the behaviour of a gas. However, in 1894 he felt that his career in Cambridge was very precarious and the burden of coaching prevented him making progress with his researches, so he accepted an offer of a post as assistant master at Bradford Grammar School. Though he enjoyed teaching boys and later spoke of the pleasure he had in introducing them to geology, he realized that he would never get any research done and that he must escape before it was too late to change his career again. So he returned to Cambridge, to live in very dreary lodgings and with no prospect of definite employment but with the determination that he must make another attempt to get some experiments done. Later he used to comment on the transformation of his outlook when he was given work demonstrating to medical students by Dr Fitzpatrick: this gave him just enough to live on and a connexion with the Cavendish Laboratory, where J. J. Thomson had already, at the age of 38, held the Cavendish Chair for ten years. In this and the following year, C. T. R. Wilson had two experiences which were to shape his research career: these are best told in his own succinct words, the first taken from his Nobel Lecture delivered in Stockholm, 12 December 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 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.'

The second experience is described by him in an article 'Ben Nevis sixty years ago' in the magazine *Weather* in 1954:

'On the afternoon of 26th June, 1895, I was standing on the summit of the Carn Mor Dearg. The sky had become overcast as I climbed up from the allt a'Mhuiliunn and mist hid the top of Ben Nevis; there was a faint muttering of distant thunder. Suddenly I felt my hair stand up; I did not await any further developments, but started to run down the long scree slope leading to the bottom of the corrie. The storm broke overhead with a bright flash and loud thunder just after I had left the summit. This experience drew my attention very forcibly to the magnitude of the electric field of a thundercloud and to its sudden changes.' C. T. R. Wilson ends this article with the following words: 'The whole of my scientific work undoubtedly developed from the experiments I was led to make by what I saw during my fortnight on Ben Nevis in September 1894. It is hardly necessary for me to say that these experiments might have had little result had it not been that they were made in the Cavendish Laboratory at the beginning of the wonderful years of the discovery of the electron, X-rays and radioactivity.'

'C.T.R.', as he was soon to become affectionately known, held the Clerk Maxwell Studentship from 1896 to 1899, after which he spent a year working on atmospheric electricity problems for the Meteorological Council. In 1900 he was elected a Fellow of his College, Sidney Sussex, and appointed a University Lecturer and Demonstrator. He was elected Jacksonian Professor in 1925 and remained in Cambridge until 1936, two years after his retirement from the Chair. The Royal Society elected Wilson to the Fellowship in 1900, and awarded him the Hughes Medal in 1911, a Royal Medal in 1922 and the Copley Medal in 1935. In 1927 he was awarded a Nobel Prize for Physics with A. H. Compton for their contributions to the understanding of the scattering of high energy photons.

Many details of his early family life and his time at Manchester and the early days at Cambridge have been told in his own words in a manuscript completed ten days before his death in his ninety-first year on 15 November 1959, and published by the Royal Society in *Notes and Records*.

In 1908, at Bellshill, Lanarkshire, C. T. R. Wilson, at the age of 39, married Jessie Fraser Dick, daughter of the Rev. George Hill Dick. They had three children, a boy and then two girls: Mrs Wilson and the three children survived him.

C.T.R.'s scientific work will be described in detail in the subsequent sections dealing with the four main fields of his achievements, which are condensation phenomena, the conductivity of air, atmospheric electricity and the cloud chamber. The invention and perfection of the cloud chamber in 1911 and 1912 was the high point of his long and fruitful scientific life, and by it he first revealed to the eyes of mankind the intimate details of the behaviour of the elementary particles of nature. J. J. Thomson, who communicated all C.T.R.'s early papers to the Royal Society, and to whom Wilson many times expressed his gratitude for support and encouragement, wrote much later in the 'Recollections and Reflections':

'This work of C. T. R. Wilson, proceeding without haste and without rest since 1895, has rarely been equalled as an example of ingenuity, insight, skill in manipulation, unfailing patience and dogged determination. Those who were not working at the Cavendish Laboratory during its progress can hardly realize the amount of work it entailed. For many years he did all the glass-blowing himself, and only those who have tried it know how exasperating glass-blowing can be, and how often when the apparatus is all but finished it breaks and the work has to be begun again. This never seemed to disconcert Wilson; he would take up a fresh piece of glass, perhaps say "Dear, dear", but never anything stronger, and begin again. Old research students when revisiting the Laboratory would say that many things had altered since they went away, but the thing that most vividly brought back old reminiscences was to see C.T.R. glass-blowing. The beautiful photographs that he published required years of unremitting work before they were brought to the standard he obtained. The method has been quickened up and made automatic by other workers, but though they can turn out more photographs in a given time, the photographs themselves are no better than those got by C.T.R. more than twenty years ago. It is to him that we owe the creation and development of a method which has been of inestimable value to the progress of science.'

Condensation nuclei

While holding the Clerk Maxwell Studentship, C. T. R. Wilson made a series of simple and well-designed experiments, which brought clarity and understanding into the hitherto confused situation with regard to the formation of clouds in supersaturated vapours. This work was first described in 1895 and 1896 in two preliminary notes in the *Proceedings of the Cambridge Philosophical Society* and in the *Proceedings of the Royal Society*, followed by three major papers in the *Philosophical Transactions of the Royal Society* entitled: 'Condensation of water vapour in the presence of dust-free air and other gases' (42 pages) in 1897; and in 1899 two papers, 'On the condensation nuclei produced in gases by the action of Röntgen rays, uranium rays, ultra-violet light, and other agents' (50 pages), and 'On the comparative efficiency as condensation nuclei of particles and negatively charged ions' (19 pages). Wilson was then 30 years old.

The major experimental innovation in the first paper consisted in the construction of various ingenious types of apparatus which allowed repeated and very accurately controlled fast expansions of the gas in a glass vessel under conditions of great chemical cleanliness. A reproduction of Wilson's figures describing his first two forms of apparatus has been produced in *Notes and Records*. The first form was of a gasometer type, with the air under investigation contained in an inverted glass vessel dipping into water in a larger container, so that the gas was trapped in the upper part of the vessel. By an ingenious system of valves, taps and subsidiary vessels, the water level in the gasometer could be suddenly lowered, so expanding the gas.

The fundamental discovery made with this apparatus was that once the dust particles, whose role as nuclei of condensation had been studied by Aitken, had been removed from the gas by repeated small expansions, no condensation drops occurred unless the volume expansion ratio exceeded 1·252 in air: the precision of the determination of the volume ratio is typical of his experimentation. The second important result was that for somewhat larger expansions, a few drops were always produced however many times the expansions are repeated. This rain-like condensation must therefore be due to some kind of nuclei which are always present in small numbers, and as fast as they are removed are replaced by others.

Wilson then constructed another much smaller apparatus which allowed greater speed of expansion and still kept the gas from contact with any material but glass and a minimum amount of water. A cylindrical glass bulb was ground to slide as a piston up and down a glass tube, which had a coned constriction at its lower end, against which the piston was ground to fit accurately. By an arrangement of gas and water handling systems, the piston could be made to float at the required height in the glass tube. Then, by suddenly opening a valve at the bottom of the tube, the gas under the piston, which had been adjusted to a suitable pressure in excess of that of the atmosphere, escaped to the atmosphere and the piston moved down very rapidly, in certainly less than 1/100 s, to seat itself on the constriction and so to produce a seal. The construction of the sliding piston and its conical seal in its bottom position was evidently a tricky operation of glass grinding, and Wilson records that many of his pistons shattered on first use. It may well have been in connexion with this apparatus that many stories of Wilson's uncommon patience originated.

With this apparatus Wilson confirmed that no condensation took place in air unless the volume expansion ratio, calculated from pressure measurements, exceeded 1·252, and that this critical ratio did not change appreciably between temperatures of 18 and 28 °C. The number of drops observed was quite small, perhaps of the order of $100/cm^3$ and increased rather slowly with expansion ratio until the ratio reached 1·37, when a rapid increase in numbers took place until at 1·38 the condensation no longer gave a rain-like cloud but a fog, taking a minute or more to settle. For still larger expansions, the fog, when suitably illuminated, gave marked diffraction rings which widened as the drops became smaller with increasing expansion. Between expansion ratios of 1·40 and 1·42 there is a very rapid change from blue through violet to red—the violet 'sensitive tint' only existing within a range of 1 or 2 mm difference of initial pressure, the ratio v_2/v_1 being 1·419. Below 1·38 the drops are too few to produce colours, above 1·44 they are too small.

In saturated air, the expansion ratio to produce a fog-like condensation, as contrasted with the rain-like condensation, began at an expansion ratio of 1·37 to 1·38. Nearly identical results were found with oxygen and nitrogen, but in hydrogen, while the fog limit was the same, there were so few rain-like drops for lower expansion ratios that Wilson could not define a lower limit accurately. This was mainly due to the small size of the apparatus. Carbon dioxide gave values of 1·36 for rain-like condensation and 1·53 for fog.

Wilson proceeded to calculate the supersaturation attained at the end of the adiabatic expansion, when the initially saturated gas reached its lowest temperature; the supersaturation was defined as the ratio of the actual vapour pressure π_1 to the equilibrium vapour pressure π_2 over a flat surface at the lowest temperature, and was given by

$$S = \frac{\pi_1}{\pi_2}\left(\frac{v_1}{v_2}\right)^{\gamma}$$

where γ is the ratio of the specific heats of the gas and v_1 and v_2 are the initial and final volume. In air, N_2 and O_2 ($\gamma = 1\cdot41$), the rain-like cloud limit $v_1/v_2 = 1\cdot252$ corresponds to a supersaturation of 4·2, and the fog limit of 1·38 corresponds to a supersaturation 7·9. In CO_2 ($\gamma = 1\cdot31$) the two expansion limits were 1·36 and 1·56 respectively, but the calculated supersaturations were almost unchanged.

Wilson calculates the number of drops in the cloud obtained with $v_2/v_1 = 1\cdot42$ by assuming from their optical properties that they must be somewhat smaller than the wavelength of light in the brightest part of the spectrum, and so he takes their diameter to be 5×10^{-5} cm. Their volume is then divided into the volume of water that must condense out of the vapour by the end of the expansion; he found in this way that there must be about 10^8 droplets per cm^3.

The last part of the paper describes the effect of X-rays on the condensation phenomena. It is shown that for $v_1/v_2 < 1\cdot252$ no cloud is produced, but for larger expansions a huge number of drops are formed so as to give a slowly falling fog. Further, if the X-rays were switched off half a minute before the expansion was made, no condensation was found—other than the normal few rain-like drops. The nuclei produced by X-rays thus required exactly the same supersaturation as those occurring spontaneously in normal air: moreover, they disappeared completely in less than half a minute.

By using Kelvin's expression for the equilibrium vapour pressure over a curved surface, and by assuming for simplicity that the surface tension T remains the same for very small drops, which he knew from the properties of thin films not to be strictly the case, Wilson calculated the radius of the drops as

$$r = \frac{2T}{R\theta \log_e S}$$

where R is the gas constant and θ is the lowest temperature reached. The radius of a drop just large enough to grow in vapour supersaturated to the extent required to make rain-like condensation in air, is found to be $8 \cdot 6 \times 10^{-8}$ cm, while the size to make drops grow when the supersaturation is enough to make a dense cloud is $6 \cdot 4 \times 10^{-8}$ cm. Wilson considers that the vast numbers, of the order of 10^8 per cm^3, of the latter type of nuclei can be none other than simple aggregations of water molecules such as may come together momentarily through random encounters of water molecules. He ends this paper as follows: 'The nuclei which bring about rain-like condensation, and the greater number of which appear to be equivalent in their power of causing condensation to water drops of not much less than $8 \cdot 7 \times 10^{-8}$ cm, are probably of a different character. As, however, I am continuing these experiments, it would be premature at the present stage to discuss the various views that might be held as to their nature.'

Nowhere in this first long paper are the nuclei identified with charged ions, but in a subsequent short paper in the *Proceedings of the Cambridge Philosophical Society* (**9**, 333, 1897) Wilson definitely identified the nuclei produced by both X-rays and the rays from uranium with the nuclei which are always present in small numbers and which produced the rain-like condensation in clean air: for all these required identical expansions.

Since the electrical properties of gases exposed to these rays showed the presence of free ions, it became highly probable that the nuclei were in fact free ions, and Wilson used a theoretical result by J. J. Thomson, published in 1893, to show that the electric charge of a free ion should encourage the process of condensation.

The systematic continuation of this experiment was described in 1899 in the second of his three big papers in the *Philosophical Transactions of the Royal Society*, and was directed to the study of the efficiency as nuclei of condensation of the carriers of electricity in gases, when these are made in different ways. With his usual concern for verbal clarity, he explains that he will talk of the expansion required to 'catch' nuclei as meaning the expansion required to cause water to condense on them: the terms 'larger' and 'smaller' are used of nuclei to denote that they require smaller or larger degrees of supersaturation respectively—a nucleus is said to grow when it becomes larger in this special sense. Wilson suggests that the terms 'larger' and 'smaller' are probably to be taken literally, since the nuclei are most likely very small drops of water which are able to persist in spite of their small size, because the effect of the curvature of their surface in raising the equilibrium vapour pressure is balanced by the opposite effect due to the drop being charged electrically or due to it containing some substance in solution.

A number of different forms of apparatus were constructed to make various types of observations and measurements; all were simple and very suitable for their purpose. The results with X-rays reported in the previous paper were confirmed by the additional observations that prolonged exposure to the rays does not cause the nuclei to grow: for instance, a 10 s exposure followed by an expansion with $v_2/v_1 = 1 \cdot 271$ produces a dense fog, but a 10 min exposure followed by an expansion of 1·245 produces no drops at all. The rapid decrease in the numbers of drops when the expansion is made some seconds after the exposure is attributed to the recombination of the ions. Uranium rays and X-rays were shown to produce identical types of condensation nuclei, as had already been reported in the short earlier paper.

Then comes a long section dealing with the nuclei produced by ultra-violet light from an electric spark admitted through a quartz window, this extending the earlier work of Lenard and Wolff. It is shown that these nuclei grow larger with larger exposure and greater intensity of the radiation, and in extreme cases form without any expansion at all: they are thus essentially different from ions. A number of different experiments were made which prove that the nuclei are produced in the volume of the gas and not, as thought by some workers previously, by the ejection of particles from the walls of the vessel; it is also proved that pure oxygen and water are alone needed for this production. The suggestion is made that under the influence of the ultra-violet rays, H_2O_2 is formed which dissolves in the droplets and lowers the vapour pressure, so allowing them to grow.

The effect of sunlight is then investigated and it is found that nuclei are produced when the rays have to pass through a blue glass screen but not through a red one. It is suggested that sunlight might be able to produce large enough nuclei in the atmosphere to produce drops with very small or no supersaturation and that these might be the particles which produce the scattering resulting in the blue colour of the sky (see *Proc. Camb. Phil. Soc.* **9**, 392, 1897). The effect of metals was then studied, and a fresh metal zinc surface, especially when amalgamated with mercury, was found to produce condensation nuclei. Condensation nuclei were also found when an electrically charged platinum wire was used, but only when the point of the wire was luminous when viewed in the dark.

The final proof that the condensation nuclei produced by X-rays and uranium rays consist of ions was obtained by applying an electric field across the expansion space, when it was found that the fog, produced in the absence of the field, disappeared. Rutherford's measurements of the mobility of ions was used to calculate that ions would be swept away by the field of 150 volts/cm in less than 1/100 s—this fully explained the observation. On the other hand, an electric field produced no reduction of the fog caused by ultra-violet light, thus showing that the nuclei were uncharged.

In the last section of the paper, Wilson calculates the approximate value of the electric charge e which would balance the effect of the curved surface and so prevent the droplet from evaporating. Making use of an expression obtained by J. J. Thomson, he obtained the relation

$$e^2=16\ Ta^3$$

where T is the surface tension and a the radius. Putting $a = 8{\cdot}6\times10^{-8}$ cm, as obtained in the previous paper, e is found to be $1{\cdot}5\times10^{-9}$ e.s.u. which is, of course, about three times the actual electronic charge.

Wilson's third long paper (*Phil. Trans.* A, **193,** 289, 1899) was communicated to the Royal Society by the Meteorological Council, and was concerned with the difference in efficiency of positive and negative ions as condensation nuclei. He mentions that J. J. Thomson had pointed out in the *Philosophical Magazine* (**46**, 528, 1898) that if such a difference existed, then one might find in the atmosphere clouds of water drops condensed on ions of one sign only. Then the fall of these drops under gravity would separate positive and negative electricity and so provide a possible mechanism for the field in a thunder cloud.

Wilson constructed a horizontal and shallow cylindrical chamber with metal roof and floor and passed through it a narrow beam of X-rays very close to the lower plate. If the electric field between the plates was upwards, then positive ions would move upwards into the main part of the chamber, while the negative ions would move downwards into the plate, so allowing the behaviour of a cloud of positive ions to be studied; by reversing the field, the chamber would contain negative ions. In this way the expansion required to condense water or positive ions was found to be greater than in negative ions, thus making it clear that all the previous experiments on the least expansion to make condensation take place on ions had been concerned only with the negative ions.

Wilson had previously suspected an increase in the number of drops at an expansion of about 1·31, and states that J. J. Thomson had been led to consider that there might be a difference in behaviour of positive and negative ions by himself noticing such an increase. Wilson argued that the difference in supersaturation could not be due to the negative ions having, say, twice the charge, because equal numbers of positive and negative charges are produced when a gas is ionized.

Wilson then attempted to answer the question of whether ions are likely to be present in the atmosphere under normal conditions. The identity of the expansion limits for rain-like condensation and that required for condensation on ions strongly suggested that they were. Moreover, the number of these nuclei was too small to make the absence of a hitherto detectable electrical conductivity in air under ordinary conditions inconsistent with the view that they were ions.

Wilson reported, however, that all attempts to remove these nuclei by a strong electric field failed even when using a sensitive differential apparatus, and concludes his paper with the following statement:

'Such nuclei, therefore, in spite of their identity as condensation nuclei with the ions, cannot be regarded as free ions, unless we suppose the ionization to be developed by the process of producing the supersaturation. The question requires further investigation.'

He soon proved this conclusion wrong, for two years later, in 1901, in a paper entitled 'On the ionization of atmospheric air', he produced evidence that the lack of an apparent observed effect of an electric field was probably due to the small number of nuclei present. He used his experimental proof of the spontaneous ionization of air (described in his paper in the *Proceedings of the Royal Society* in 1901) to identify the nuclei of the rain-like condensation as being due to these ions.

Three years later Wilson returned to this work in greater detail. This was in a paper entitled 'The condensation method of demonstrating the ionization of air under normal conditions' (*Phil. Mag.* **7**, 681, 1904), in which he notes the absolute identity of the supersaturation required to condense rain-like drops on the nuclei always present in a gas, and those produced by an ionizing agent. He contrasts this with the lack of any reduction by means of a strong electric field of the former type of droplet but the very big reduction of the latter type. He concludes that his earlier suggestions that the nuclei might be produced by the expansion was probably wrong and that his experimental observations of the lack of influence of electric field on the number of drops must have been at fault, due to the too small size of apparatus, which meant very few observed drops. For since the former paper, he himself and Geitel independently had demonstrated the electrical conductivity of normal air, so that ions were definitely present. So a much larger apparatus was built, which incidentally was a major step towards the perfected cloud chamber of 1911.

The chamber in which the drops were formed consisted of a glass cylinder 18·5 cm in diameter and 6 cm high, sealed on the top by a brass disk and with its bottom resting on a rubber ring lying on an annular brass plate. A brass expansion cylinder 30 cm long and 10 cm in diameter was attached to the annular plate and contained a light floating brass piston with hemispherical top, which was lubricated and made gas-tight by the tube being nearly filled with water. By suddenly connecting the space under the floating piston to an evacuated vessel by means of a valve made out of a rubber cork, the piston could be suddenly lowered, so producing the required expansion in the shallow glass cylinder above.

With this apparatus it was found that a potential difference of 160 volts between the top and bottom of the chamber did make a big reduction in the number of rain-like drops: in fact, a potential difference of only 2 volts caused a noticeable reduction. It was concluded that in the earlier small chamber accidental differences of potential could have been sufficient to reduce the number of drops so much that the application of larger fields was not noticeable.

Wilson calculated the number N of ions in a vessel of height l, filled with a gas for which the ionic diffusion coefficient is D, to be $ql^2/3D$ where q is the rate of production of ions, and when no electric field is used. Using the values of q obtained by Cooke, about 13 ions of either sign produced per second in each ml., Wilson gets about a predicted value of 1000 for N in his large chamber. He states that he did not succeed in making a direct determination of the numbers, but made an indirect one, by the method used by J. J. Thomson to determine the ionic charge.

He pointed out that the total number of ions present when a steady state is reached, in the absence of an electric field, is such that the number removed by recombination and diffusion to the walls is equal to the number produced per second: in his experiments diffusion is shown to be more important than recombination, because of the small number of ions present. The effect of the electric field is just to sweep away the ions so as to reduce the number available to act as nuclei when the expansion is made.

The size of each drop is calculated from the rate of fall, using Stokes's formula, and the total mass of water condensed from the condition of an adiabatic expansion; assuming this is equally distributed among the drops, their number follows and was found to be in rough agreement with the previous estimate.

These simple but revealing calculations are a marked characteristic of Wilson's methods: he wanted always to understand quantitatively just what physical processes went on in his experimental apparatus—he usually succeeded.

Two other publications on condensation nuclei appeared in 1904, one being a report of a lecture at the Royal Institution on 19 February, in which he evidently showed many ingenious demonstration experiments, and the other a paper to the International Electrical Congress at St Louis, U.S.A. In the latter Wilson gives his most complete survey of the physics of condensation on nuclei. He extends Kelvin's well-known derivation of the difference of vapour pressure over a curved and a plane surface, as derived from the depression of a column of liquid in a capillary to much smaller drop sizes, obtaining the relation

$$\log_e \frac{P_2}{P_1} = \frac{1}{Rt}\frac{2T}{r}$$

where P_2 is the pressure of water vapour in equilibrium with a drop of radius r and surface tension T at temperature t and P_1 is the corresponding pressure for a flat surface. This equilibrium is clearly unstable: if a drop gets too big, it will grow; if too small, it will evaporate completely.

Wilson now gives J. J. Thomson's result for the effect of a surface electric charge, by calculating the change of height of the column of liquid due to the electric field producing the surface charge:

$$\log_e \frac{P_2}{P_1} = \frac{1}{Rt}\left(\frac{2T}{r} - \frac{e^2}{8\pi r^4}\right)$$

where e is the charge on the drop. The maximum vapour pressure occurs for $r^2 = e^2/4\pi T$ and has the value given by

$$\log_e \frac{P_2}{P_1} = \frac{3T}{2Rtr}$$

If the vapour pressure is increased above this value, an unstable condition results and the drop continues to grow so long as the supply of vapour is unlimited.

I still possess a much-thumbed reprint of this paper which, in 1921 when I started working on the cloud chamber, was the best account of the fundamental condensation phenomena underlying its operation. The application of these expressions to condensation phenomena ends by listing the three principal types of ions: '(1) The ions proper, requiring a four-fold or six-fold supersaturation to cause water to condense on them, and having a mobility exceeding 1 cm per second in a field of 1 volt per cm; (2) loaded ions, requiring little or no supersaturation to make water condense on them, and having a mobility generally less than a thousandth part of that of the ions proper; (3) uncharged nuclei, resembling the second class in requiring little or no supersaturation in order that visible drops may form on them.'

In 1903 Wilson reviewed critically in *Nature* a book by Barus on condensation phenomena, to which Barus replied with obvious annoyance. Wilson's comments on the reply had a caustic quality, of which those who only knew him in later life would not have expected him to be capable.

The conductivity of air

C.T.R.'s crucial discovery of the spontaneous ionization of air arose directly out of his attempts to explain the rain-like condensation observed when no ionizing sources were used; it was reported first in a short note in the *Proceedings of the Cambridge Philosophical Society*, 1900, entitled 'On the leakage of electricity through dust-free air'. In this paper he refers to the nearly simultaneous but quite independent discovery by Elster and Geitel (*Phys. Z.* **2,** 116, 1900) of the conductivity of air. Fuller details were given the next year in 'On the ionization of atmospheric air' in *Proc. Roy. Soc.* **68,** 151, 1901). The essential innovation was the complete avoidance of any leakage of electricity through the insulated supports of a gold-leaf electroscope by the following means. A sulphur bead was used to attach the gold-leaf system to a conducting rod which was kept at the initial potential of the leaf: thus any continuous fall of the leaf was necessarily due to leakage through the air and, moreover, if the insulator were imperfect, it would reduce and not increase the observed effect.

With this apparatus he showed that the leakage was the same in daylight and in the dark, and whether the charge was positive or negative, and whether the initial potential was 120 or 210 volts. All these three conclusions had also been arrived at by Geitel. Wilson added two more: that the rate of leak is proportional to the pressure and that the rate is equivalent to the production of about 20 ions of either sign in each cm^3 per second at atmospheric pressure. After giving the details of these measurements, Wilson, without any prelude, makes the laconic but historic statement: 'Experiments were now carried out to test whether the production of ions in dust-free air could be explained as being due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or like cathode rays, but of enormously greater penetrating power.' A portable form of electroscope was made and taken at night into the Caledonian Railway tunnel near Peebles, when it was found that the rate of leak was the same, within the experimental error, as in the open. Wilson, concludes: 'It is unlikely, therefore, that the ionization is due to radiation which has traversed our atmosphere; it seems to be, as Geitel concludes, a property of air itself.' This historic experiment is rightly held by historians to be the beginning of the great and fertile subject of cosmic rays. However, it was not until 1912 that the extra-terrestrial origin of these rays was finally proved by Hess.

An account of the origin of the hypothesis that very penetrating rays might be reaching the earth from outside the atmosphere is to be found in a paper reviewing the state of knowledge of atmospheric electricity published two years later in *Nature* (**68**, 102, 1903). In this paper Wilson discusses the difficulty of understanding how the earth's negative electric charge could be maintained, especially in view of the recently discovered conductivity of the atmosphere, and writes as follows:

'It is quite conceivable that we may be driven to seek an extra-terrestrial source for the negative charge of the earth's surface. The study of the aurora borealis has led several observers to the conclusion that the sun emits kathode rays, which are deflected by the earth's magnetic field, and travel in helical paths round the magnetic lines of force towards the poles. It is conceivable that very penetrating rays of this type (i.e. negatively charged electrons) may traverse our atmosphere unobserved, and be stopped in the solid mass of the earth, giving to it their negative charge.'

As often in the history of science, a plausible hypothesis, even though later proved to be false, has provided a valuable stimulus to further experiment and so to important discovery. The earth is being bombarded by energetic particles of extra-terrestrial origin. But they are mainly positively charged and are not the cause of the earth's negative charge.

In a second paper in 1901 (*Proc. Roy. Soc.* **69**, 277) Wilson showed that the leakage current in different gases was nearly proportional to the density (hydrogen excepted) and, moreover, the relative conductivity (air = 1) was the same for polonium α-rays and for penetrating radium γ-rays. He concludes: 'Until, however further experiments have been made it would, I think, be premature to conclude that the ionization is due to radiation from the walls of the vessel.'

After a short paper on the radioactivity carried down by rain and snow, Wilson in 1903 gave an account of his well-known tilted electrometer. This depended for its sensitivity on the use of an auxiliary electrode disposed and charged in such a manner as to allow the gold-leaf to be brought to a state of near instability. By this ingenious trick Wilson raised the sensitivity by a factor of 100. The paper ends with a remark which shows C.T.R.'s constant concern for the simple and practical: 'The instrument may be carried about without risk of injury to the gold-leaf; it is only necessary to charge up the plate to such a potential that the gold-leaf (connected to the case) is stretched straight out towards the plate, which it is just too short to touch. The apparatus may then safely be inverted or carried in any position; the gold-leaf remains steadily pointing towards the plate.'

C. T. R. Wilson's main interest in the next few years, that is, after about 1904, lay in the field of atmospheric electricity and thunderstorms, and it was not until about 1910 that he again worked actively at condensation phenomena—to produce the cloud chamber in 1911. In the next section Wilson's work on atmospheric electricity, which continued right up to his death, will be discussed.

Atmospheric electricity and thunderstorms

As has been related, Wilson's interest in atmospheric electrical phenomena arose from his own experiences as a youth on a mountain in a storm and he continued to study the subject all his working life. His last scientific paper, 'A theory of thundercloud electricity', was communicated to the Royal Society in 1956 in his eighty-seventh year, when he was the oldest Fellow. It is believed that not for three hundred years has the oldest Fellow communicated a paper to the Society.

As mentioned above, Wilson wrote a survey of the state of knowledge of atmospheric electricity in 1903. Then in 1906 he published his first major paper on atmospheric electricity entitled 'On the measurement of the earth-air current and on the origin of atmospheric electricity'. He describes observations of the earth-air current by a novel and simple method, which can best be described in his own lucid words:

'An insulated conductor connected to an electrometer is initially at zero potential and under a metal cover. The earth connexion is broken and the cover removed, the conductor being thus exposed to the earth's electric field. The potential of the conductor is thus raised, but is at once brought back to zero by means of a compensator. When this adjustment has been made, we know that the charge removed from the electrometer and its connexions by the displacement of the compensator is equal and opposite to that held on the exposed part of the conductor when at zero potential under the action of the earth's field. When the compensator has once been standardized, its readings measure the charge on the exposed conductor when kept at zero potential; this charge will be the same as if the conductor were earth-connected. If now by means of the compensator the conductor be maintained at zero potential for a few minutes and the cover be then replaced, the new reading of the compensator, when again adjusted to bring the electrometer reading back to its zero, measures the charge which has entered the conductor from the atmosphere in the given time.'

With this apparatus erected on the top of Hamildon Hill near Peebles in Scotland, Wilson found that the average dissipation of the electric charge on the exposed conductor was about 5 per cent per minute, but varied considerably with the weather conditions. He investigated the charge on and the current through a growing plant in a flower-pot placed on the test plate. No marked difference was found for the dissipation rate for the plant and for the test plate alone. In a theoretical note at the end of the paper the maintenance of the normal electric gradient in the atmosphere is discussed, and it is held to be probable that the negative charge carried down by rain is possibly sufficient to balance the positive charge flowing downwards into the earth due to the positive potential gradient and the conductivity of the air. The possibility, already discussed in 1903, that the maintenance of part of the negative charge on the earth's surface might be due to a penetrating radiation reaching the earth's surface from cosmical sources, is again mentioned.

A continuation of these experiments was reported in a paper in 1908 in the *Proceedings of the Royal Society*. Among many results Wilson showed that the dissipation was not greater in bright sunlight, as would be expected if the loss of negative charge of the test plate had been due to a photoelectric effect. The electric charge on growing turf was always about three times that on the bare test plate but the leakage was also about equally greater, so giving the same rate of dissipation. In the case of the turf the charge was concentrated on the tips of the leaves. Wilson concludes that these experiments demonstrated that the fraction of the charge per unit area of the ground which is neutralized per minute is the same as that found for the test plate of the apparatus. It thus became useful to calibrate the instrument in absolute units, by comparing the charge and current measured with the original small test plate, which stood well above the ground, with the current and charge for a larger test plate placed with its upper surface very little raised above the surface of the ground. For a number of days in 1906 and 1907 Wilson found that the mean downward electric current was $2 \cdot 22 \times 10^{-16}$ amp per cm^2, which was in close agreement with some measurements by Gerdien in 1905 of the conductivity and the potential gradient. The average charge on the surface was found to be $16 \cdot 6 \times 10^{-14}$ coulombs per cm^2 and the corresponding potential gradient was about 200 volts per

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metre. The dissipation factor was least (6·6 per cent) for the calm and cloudless days, and greatest (11·2 per cent) for days with cumulus clouds.

In 1916 and 1920 Wilson published important papers on the determination of the sign and magnitude of the electric discharge in lightning flashes. He starts by pointing out that only the roughest estimate of the charge in a lightning flash then existed. Schuster had used two determinations by Pockels of the maximum current as measured by its magnetizing effect, and assumed that the duration was 1/1000 second and so found that the charge brought down was about 10 coulombs. Wilson set out to measure the change of the vertical electric field at the surface of the earth when a lightning flash occurs. If a charge Q at a height H passes to earth, the change of the vertical field at a distance R will be $2QH/R^3$. The apparatus was a development of that already described and consisted essentially of an insulated circular conductor, 59 cm in diameter, placed in a pit in the ground near the Solar Physics Observatory, Cambridge, with its upper surface level with the ground. The conductor was connected to earth through an electrometer of a special type developed by Wilson from Lippmann's design. Whenever the charge on the conductor changed so as to raise its potential above that of the earth, the mercury column in the capillary moved in such a way as to bring the potential back to zero, while the displacement of the mercury measured quantitatively the amount of charge received by the conducting plate. An earthed cover normally screened the plate from the earth's electric field. When this was removed so as to expose the plate, the plate acquired a charge, and the amount of this was measured by the displacement of the capillary electrometer. When a lightning flash occurred, the change of the vertical electric field was determined by the displacement of the mercury column of the electrometer, and, together with the distance R of the storm (as obtained from the time from flash to thunder), gives the product HQ, that is, the electric moment destroyed by the flash.

Wilson found it possible to determine H and so Q separately by measuring the change of field with distance from nearby storms. For the field change due to a flash will have the opposite sign directly under the storm to that at a large distance, and there will be a critical distance at which the field change is zero. This method depended in practice on the observation that successive flashes from certain storms were very similar, so that measurements of the change of field from successive flashes from the same storm at different distances were equivalent to measurements of the same flash at different distances. By such means Wilson deduced that in the majority of storms there was an upper positively charged region and a lower negatively charged one, and also that the direction of the currents in the lightning flashes was upwards, that is, in the opposite direction to the fair weather atmospheric current. In the important 1920 paper, Wilson first made the definite suggestion that the electric fields and currents of fine weather could be maintained by the currents in storms and showers. The average quantity of electricity discharged at each flash was found to be close to 30 coulombs, but the distance between positive and negative charges before the flash was much less well determined and could have lain between 1 and 10 kilometres.

These pioneer results have been in general fully confirmed. Important factors in this achievement were Wilson's flair for designing simple but effective apparatus based on a clear understanding of the physical principles involved, and on a deep interest in natural phenomena.

In 1925 Wilson wrote a paper entitled 'The electric field of a thunderstorm and some of its effects'. Assuming that a thundercloud is an electric generator in which the separation of positive and negative charges occurs at a rate which corresponds to a current of some amperes and in which the potential difference between its poles amounts to about 10^9 V, the following effects are discussed. The electric field above the cloud should be sufficient to initiate a continuous or discontinuous discharge between the top of the cloud and the upper atmosphere at about some 60 km height, and this may be one of the causes of atmospherics arising from regions of rain unaccompanied by thunder. Then the electric field at the earth below a thundercloud may often exceed 10000 V/cm, and this is quite sufficient to produce a brush discharge from an elevated or pointed conductor, as, of course, has been known from the phenomenon of St Elmo's fire. Wilson had earlier made some experiments to find the potential gradient over grass-covered ground which would produce a measurable current, and found that above fields of 15000 V/m the current becomes quite large, of the order of 1 A/km^2. Lastly he refers to his paper of the previous year which showed that fast β-particles already present in the atmosphere should be accelerated by the strong electric fields associated with a thunder cloud to energies of 10^9 eV, that is, comparable to the energies of some cosmic rays.

In this former paper (published in *Proc. Camb. Phil. Soc.* 1925) Wilson drew attention to the decrease in the energy loss of a β-particle with increasing energy, so that there must be for any gas a given electric field above which a β-particle moving in the direction of the field will gain more energy than it will lose. In air at atmospheric pressure, a 20000 volt electron loses 10000 V/cm, so in a field of 20000 V/cm, it will gain energy at the rate of 10000 eV/cm. The effect of nuclear collisions in stopping the gain of energy by deflecting the particles is discussed in detail. Since a very fast particle only loses 1000 eV/cm, it would be accelerated in a field greater than this if moving in the direction of the field. It would still be accelerated even if initially moving within an angle only a few degrees short of 90° in a field of 20000 V/cm. From the amount of radium emanation in the atmosphere Wilson calculates that the number of β-particles emitted which would be capable of being accelerated should be about 10 $s^{-1}m^{-3}$.

In 1929 Wilson published in the *Journal of the Franklin Institute* a paper entitled 'Some thunderstorm problems', in which he first outlined his ideas on the mechanism of thunderstorm activity. 'According to this a thundercloud is essentially bipolar, the positive charge tending to be above the negative. The preponderance of negative potential gradients below shower clouds and thunderclouds is on this view due primarily to the negative charge of the cloud being nearer the ground than the positive; the cloud may in addition acquire an excess of negative charge when the loss of positive charge by conduction to the upper atmosphere exceeds the loss of negative charge to the ground. The prevailing positive charge on rain is on this view not the cause but the result of the negative potential gradient; the rain intercepts and returns to the earth a portion of the charge carried by the stream of positive ions which are being driven up by the negative potential gradient.

'There would probably be general agreement that the source of the electromotive force of a thundercloud is to be sought in the vertical separation under gravity of carriers of positive and negative electricity. Let us suppose that the small particles in a cloud, which only fall slowly relatively to the air, are positively charged, while the larger drops which fall with considerable velocity through the air are negatively charged. We may leave for the present the question how the carriers acquire their charges.

'Such a cloud, originally neutral, will at once begin to acquire a positive charge at the top and a negative charge at the bottom through the relative vertical motion of the two classes of carriers. The two equal and opposite charges thus accumulating at the top and bottom may be separated by a great thickness of neutral cloud. The accumulation of a positive charge above and a negative charge below results in the development of an electric field within the cloud, which tends to hinder the negative drops from falling and the positive particles from being carried up by the air stream.'

Wilson's last paper, 'A theory of thundercloud electricity' in the *Proceedings of the Royal Society* in 1956, includes work which had occupied him for very many years. The best summary is his own: 'The thundercloud is regarded as a great influence machine, the ionization currents associated with it being the agents by which its electromotive force is developed and maintained. The moving ions which constitute these currents may be intercepted by solid or liquid cloud elements so that it becomes possible for them to be carried against the field and so increase an existing electromotive force. The early stages in its growth are due to the ionization current within the cloud initiated by the earth's fine weather field. Later it is the external currents due to the thundercloud's own field which are effective. Lightning discharges may themselves contribute to the electromotive force of the thundercloud.' The argument is very detailed and reveals the deep knowledge which Wilson had acquired by many years of thought on the physical processes which must occur within a thundercloud. The main argument concerns the way in which falling water droplets of various sizes, and so with different rates of fall, acquire electric charges by collision with positive and negative ions moving in the existing vertical electric field. A falling drop is polarized by the field so that its lower half is positively charged, and so selectively attracts negative ions and thus acquires a net negative charge. As the drop falls towards the bottom of the cloud it thus augments the pre-existing downward-directed electric field—so making possible the building up of very large potential differences between the top and bottom of the cloud.

Though Wilson's mechanism must certainly operate, it is now believed that it cannot by itself produce a rapid enough separation of charge. Many other mechanisms have been suggested, but there is as yet no generally accepted mechanism of the charge separation in a thundercloud. It seems rather likely that the charge separation may occur in some rather complicated way during the collision of supercooled water drops with ice crystals.

Whatever explanation of the remarkable natural phenomenon of the thundercloud becomes finally accepted, there is no doubt that Wilson's pioneer work, with both its elegant experimentation and its deep physical thought, will remain a major contribution to its final understanding.

The cloud chamber

In his Nobel Lecture in 1927 Wilson states that after his experiments published in 1904, which proved that the nuclei producing the rain-like condensation are removable by an electric field, he did not resume his work on condensation phenomena until about 1910. As has been mentioned, these intervening years were mainly occupied with the investigation of atmospheric electrical phenomena. Moreover, these years had seen much more definite ideas develop on the nature of radioactive rays and X-rays, so that Wilson considered seriously the possibility of making the track of an ionizing particle visible by photographing the drops of water condensed on the ions in its track. He had also in mind developing a method of measuring the electronic charge by counting the number of drops produced by a given total measured electric charge; however, his own success with making tracks visible and Millikan's in the development of his oil drop method led him to abandon this.

The first photographs of the tracks of atomic particles were obtained in the spring of 1911 with a relatively rough apparatus and were published in the *Proceedings of the Royal Society* (A, **85,** 285, 1911). The main difference from the 1904 apparatus was in the shape of the expansion chamber itself, which was 7·5 cm in diameter, had a flat roof and floor and an expanded height of 6 mm. The experiment was made just as in 1904 by the sudden downward displacement of the floor which constituted the top of the light piston. The flat shape served to prevent the stirring of the gas on making an expansion.

The use of a moist gelatine layer on the glass surface was introduced, both to prevent the condensation of dew on the glass and to provide a conducting layer for the application of an electric field. To photograph the tracks, a condenser discharge through a capillary of mercury vapour at atmospheric pressure was used. Two photographs were published, one showing quite clearly a few α-ray tracks from a weak radium source and the other the short tracks of electrons due to the passage of an X-ray beam. Using a 30 mg radium bromide source, the tracks of many fast β-particles were observed, but no photograph was reproduced.

Wilson comments: 'Whether the original X-radiation has a continuous wave front, or is itself corpuscular as W. H. Bragg supposes, or has in some other way its energy located around definite points in the manner suggested by J. J. Thomson, remains undecided.' This remark clearly expresses the then still not quite clear concept of the photon structure of radiation.

In the following year Wilson published a detailed account of a new, larger and much improved cloud chamber (*Proc. Roy. Soc.* A, **87**, 277, 1912), with many exquisite photographs of α-, β- and X-ray tracks—they still remain among the technically best photographs ever made. The cloud chamber itself had taken on its final form, to remain for two decades a standard instrument of great simplicity and superb performance. Wilson never made another of this type, but used the same one right on into the 1920s.

The construction of the cloud chamber is so well known as hardly to need detailed description: it was 16·5 cm in diameter and 3·4 cm deep, with glass roof and glass floor fixed to the top of a thin-walled brass piston sliding freely in an outer bronze cylinder, and made gas-tight by a water seal. The expansion was made by connecting the space under the piston with an evacuated vessel using a rubber valve as in earlier experiments. Essentially the same type of capillary mercury vapour spark actuated by Leyden jars was used to provide the illumination. A simple arrangement of a single falling weight was used first to open the valve, then to energize the X-ray tube and finally to make the spark to illuminate the chamber. Photographs were taken with a stereoscopic camera.

Very fine photographs of α-rays, both from a minute amount of radium on the tip of a wire and from radium emanation in the gas, were reproduced. Several α-rays near the end of their range showed sudden changes of direction due to collisions with the nuclei of the atoms of air; in some cases the short track of the recoiling nucleus was clearly visible. It was the year before, 1911, that Rutherford had deduced the existence of the atomic nucleus from the observed large angle of scattering of α-particles.

The tracks of fast β-particles were also shown, with the individual droplets due to single ions clearly visible. Then came some exquisite photographs of the secondary electron tracks produced by a narrow beam of X-rays. Wilson emphasizes that there is no indication of any effect of the X-rays other than by the production of corpuscular radiation, thus confirming W. H. Bragg's view that ionization by X-rays is entirely a secondary process. He also notes that the secondary ionizing tracks (clearly electrons) show two kinds of deflexions as a result of their encounter with atoms of the gas—Rutherford's single and compound scattering. By flashing on the X-rays before the expansion, broad diffused tracks were obtained, allowing the number of positive and negative ions to be separately counted.

The impact on the scientific world of these wonderful photographs of atomic tracks was profound. Phenomena which had been deduced indirectly from electrical measurements and perhaps only dimly envisaged now became visible to the eye in all their finest details. Wilson had given the world a new sense. There are many decisive experiments in the history of physics which, if they had not been made when they were made, would surely have been made not much later by someone else. This might not have been true of Wilson's discovery of the cloud method. In spite of its essential simplicity, the road to its final achievement was long and arduous: 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.

As was to be expected, Wilson became much in demand as a lecturer, and this resulted in two further accounts of his work covering essentially the same field being published in 1913: one lecture being given to the Royal Institution on 7 March 1913 and the other to the Sociéte française de Physique on 18 March (published in the *Journal de physique*). These papers cover essentially the same ground as the 1912 paper in the *Proceedings of the Royal Society*, but include for the first time photographs of a narrow X-ray beam traversing the chamber and being partially absorbed in a thin metal target in the chamber.

It was not until after the end of the 1914-18 War that Wilson was able to continue this work, using the same cloud chamber—the only one of its type he had built, but with many improvements in detail. Wilson had moved from the Cavendish Laboratory to the Solar Physics Observatory on the Madingley Road, and all his subsequent work was carried out there.

Between December 1921 and July 1922 Wilson took 500 stereoscopic pairs of photographs and published the results in two big papers in *Proceedings of the Royal Society* A, **104,** 1, 192, 1923: 'Investigations on X-rays and β-rays by the cloud method. Part I: X-rays, Part II: β-rays.' In the first paper 22 superb photographs of the secondary electron tracks produced by X-rays were reproduced; many of them, along with some of the photographs from the 1912 paper, have been reproduced over and over again in textbooks of physics. The perfection of the technique is exceptional, the tracks are in perfect definition, the background is quite black (signifying a high degree of cleanliness of the glass surface), and water drops other than those on ions are almost completely absent.

The object of the experiment was to understand the detailed mechanism of the absorption of X-rays, in both gas and metal targets placed in the chamber. To this end a careful study was made of the visual appearance of the electron tracks, which were of three types: (*a*) long tracks with a range of several centimetres, (*b*) small spherical cloudlets, and (*c*) tracks of 1 to 2 mm range with the initial direction coinciding with the direction of the X-ray beam—Wilson called these 'fish tracks'. The long tracks were identified as electrons ejected from an atom by one quantum of radiation, that is, photoelectrons. On the other hand, the fish tracks, though certainly due to the direct action of the X-rays, were produced by an electron with an energy which was very small compared with the quantum of the primary radiation. Wilson related the tracks specifically to the scattering process suggested by

A. H. Compton, in which the recoil electron takes up the momentum of the quantum of radiation. The spherical tracks were held to be mainly the tracks of electrons of energy less than about 2000 V; these were explained as being mainly due to secondary quanta of radiation produced by atoms excited by the primary quanta. A statistical analysis of the directions of emission of the photoelectrons was made: the predominantly forward direction is well shown in the exceptionally beautiful photograph shown in his figure 6, and the occurrence of both forward- and backward-directed tracks in figure 7.

Detailed studies were made of the various types of associated tracks, in particular paired tracks, and most of these were related to the action of secondary quanta arising from atoms from which the K and L electrons had been ejected by the incident quantum. In his summary of his results, Wilson remarks: 'The cloud method is able to deal with individual quanta of radiation, in the sense that the tracks of the electrons ejected from the atom which emits the quantum of radiation and that of the electron ejected from the atom which absorbs the radiation may under suitable conditions be identified.' When supplemented twenty years later by the photographic emulsion technique and ten years later again by the bubble chamber method, this possibility of observing and studying individual quanta of radiation as well as individual particles of matter, whether charged or uncharged, has opened up whole new fields of fundamental physics.

In the second paper Wilson reproduces 17 beautiful photographs of β-rays from radioactive sources, together with some more secondary β-rays produced by X-rays. He finds that the tracks of fast β-particles are very nearly straight over distances of several centimetres. 'In the last 4 cm of the range, deviations are large and of three kinds: (*a*) sudden deviation often through large angles up to 180°, the result of a close approach to the nucleus of an atom: (*b*) the sudden deviation up to 45°, due to a close approach to an electron which is in consequence ejected to form a branch track, generally approximately at right angles to the primary track; (*c*) gradual deviation due to an accumulation of small deviations of (*a*) or (*b*) type, individually too small to be detected.' The variation of range with energy, as reported in the previous paper, was shown to be in agreement with Whiddington's law ($R \propto v^4$) and the primary ionization was found to agree with Thomson's theoretical expression, as did also the number of branch tracks. The number of deflexions exceeding 90° agreed with Rutherford's scattering formula.

The rather regular curvature of some slow β-ray tracks was commented upon and held to be inexplicable by a succession of randomly-oriented deflexions, and so suggested some kind of bias. Both Compton and Shimizu had noticed these curved tracks in Wilson's photographs and had suggested that the bias might be due to the electron being set in rotation. Wilson preferred to think that the effect might be due to the secondary radiation produced by the β-particles continually overtaking it and affecting the nature of the subsequent encounters of the β-particles. 'The bias causing the curvature may then not lie in the β-particle, but in the field of radiation in which it is moving.' As far as the writer known, this phenomenon of the appearance of a rather constant curvature of some β-ray tracks has never been re-investigated; there is no actual quantitative proof available that it is a purely random phenomenon, though this is far the most likely explanation: possibly the few smoothly curved tracks are merely those which have been visually selected out of a large number showing rather irregular curvature, and represent therefore a rare succession of random deflexions. It is, of course, true that a special kind of bias in multiple scattering of fast electrons is now well known, due to the interaction of the electron spin with the coulomb field of the scattering atom. However, existing theory would by no means predict the large effects noticed by Wilson.

In the same year, 1923, Wilson published a short paper entitled 'On some α-ray tracks' in the *Proceedings of the Cambridge Philosophical Society* (**21,** 405, 1923). Thorium emanation was used in the chamber and photographs were obtained showing the tracks of the α-rays from both the thorium emanation and the thorium A atom (lifetime 0·14 s). In certain cases the track of the first α-particle is complete, but the track of the second is split into positive and negative parts at its start due to the first track robbing the locality of water vapour. From the separation of the two parts of the track, the life of the particular thorium A atom could be measured. Observation and calculation was made of the δ-rays accompanying fast α-ray tracks.

This was Wilson's last paper giving results of his own observation of atomic phenomena with the cloud chamber. However, in 1933 he described a new and very simple type of cloud chamber, in which the moving piston was replaced by a fixed wire gauze behind which a rubber diaphragm was used to make the expansion. Wilson wrote that this type of chamber was very easily constructed and was much less restricted as to size and shape than the conventional cloud chamber. In fact very many of the cloud chambers, small and large (some with a volume of a cubic metre), which have been built since then have been derived essentially from this simple idea—and how obvious when once thought of.

Two years later, with J. G. Wilson (now Professor of Physics at the University of Leeds), C. T. R. Wilson described two more types of chamber. The first was a flat chamber designed to fit between the poles of a magnet, and at the moment of the expansion to fall freely under gravity so as to get clear of the pole pieces to allow a photograph to be taken. It was verified that the distortion of the tracks by convection was small because the convection forces vanish during a free fall. The actual expansion was made radially by means of a cylindrical slit system made of slate rings with gaps between them.

Though neither the falling nor the radial chamber has found any wide application, this conception was typical of Wilson's extreme originality concerning simple and ingenious ways of doing the things he wanted to do and of his clear understanding of the fundamental physical basis of the functioning of his apparatus.

C.T.R. was a lone worker at heart and had no research students working with him until the middle 1920s. C. F. Powell (now Professor of Physics at the University of Bristol) worked under him from 1925 to 1928 on the problem of the temperature variation of the supersaturation required to produce different types of condensation in air saturated with water vapour. Surprisingly this work had an important technological result, as it led to an explanation of a discrepancy between the calculated and observed flow of steam through nozzles and so became a standard feature of the theory of the steam turbine.

T. W. Wormell started work in 1925 with C.T.R. on atmospheric electricity problems. He wrote a number of important papers concerning lightning and its relation to the earth's electric field, and in all of which Wormell expresses his gratitude for C.T.R.'s help and guidance.

During and after World War I Wilson applied his unique understanding of electrostatic phenomena to problems of the protection of airships and balloons from the danger of fire due to electric discharges and lightning flashes. Several confidential papers were published by the Advisory Committee on Aeronautics.

P. I. Dee (now Professor of Physics at Glasgow) on graduating in 1926 worked with C.T.R. on cloud chamber problems, including the accurate counting of ions. This led Dee in 1932, when the neutron was discovered, to look for a direct interaction between neutrons and electrons, which was not then known not to exist.

As has already been mentioned, J. G. Wilson started work in 1933 with C.T.R. on developing the radial and freely-falling cloud chambers.

About the same time J. P. Gott worked with Wilson on various details of thunderstorm theory and carried out experiments on the capture of ions by drops falling in an electric field, and W. A. Macky investigated the distortion and rupture of drops in intense fields. Related to this was a joint paper by C. T. R. Wilson and G. I. Taylor on the bursting of soap bubbles in an electric field.

I first met C. T. R. Wilson just after World War I when I attended his lectures on light. His voice was not easy to follow and his writing on the blackboard was difficult to read, but somehow I took adequate notes and these are almost the only lecture notes of my student days to which I have repeatedly returned. He had a penetrating but very simple approach to wave phenomena, in particular to interference and diffraction effects, which he treated by the elegant use of amplitude phase diagrams. By these methods he conveyed a deep physical understanding of the Abbé theory of image formation and the closely related general relationship between the Fourier expansion of the light from a periodic object and the intensity of the resulting spectra. It may be that W. L. Bragg (now Sir Lawrence Bragg), who attended C.T.R.'s lectures just before the war, was aided by them in his later brilliant development with his father, Sir William Bragg, of the application of Fourier analysis to the elucidation by X-rays of complex crystal structures.

C.T.R.'s influence on the teaching of experimental physics in Cambridge was also profound: for many years he was in charge of the Third Year experimental class in the Cavendish Laboratory and early introduced the method of giving the students a few simple but searching experimental tasks, which demanded considerable experimental skill and had the character of minor research problems each requiring many weeks of work. This method was then in considerable contrast to the more usual practice of making the students, even in their final year, perform numerous rather stereotyped experiments. For very many years he gave devoted attention to the students who passed through the senior laboratory of the Cavendish and inspired them with a deep and lasting affection.

When I graduated in 1921, Sir Ernest Rutherford, as he then was, set me the task of using Wilson's cloud-chamber method to photograph the disintegration of atomic nuclei by α-particles. This I succeeded in doing in 1924, and for the next fifteen years I was personally engaged in researches with the cloud chamber. So of all my generation I perhaps am the most deeply indebted to C.T.R.'s genius which enabled him to perfect the first method of revealing the tracks of individual particles. Amongst the many discoveries made by the use of Wilson's cloud chamber, outstanding were those of the positive electron, pair production and cosmic ray shower phenomena, the μ-meson and its spontaneous decay, the charged and neutral V-particles and the negative cascade hyperon.

Shortly after Wilson's retirement in 1934 from the Jacksonian Chair at Cambridge, he returned to Scotland to settle eventually at the village of Carlops near Edinburgh, within a few miles of his birthplace. He continued to work actively at the theory of thunderstorms and published his long paper in the *Proceedings of the Royal Society* at the age of 87. He was as active physically as he was mentally. At the age of 82 he climbed on Caisteall Abhail in the Mountains of Arran, and when he reached the ridge remarked that it was 64 years since he first sat there.

In 1955 at the age of 86 he learned that students of meteorology at Edinburgh were allowed to fly in aeroplanes of the Royal Air Force, and enquired: 'Would I count as a student of meteorology?' Dr James Paton, who accompanied him on all his flights, wrote of them in the following words: 'With the pockets of his windcheater stuffed with maps and sandwiches, our new student would come in by bus to the Airport in the morning for flights to the Western Isles. During the flight he would move about eagerly from one side of the Anson to the other, identifying the peaks and lochs and watching the clouds. Once we had a very rough passage through a thunderstorm and were alarmed at the effect it might have on our 88-year-old companion. We need not have worried! There he was, straining at his safety belt and peering intently at the lightning flickering around us, quite oblivious of the bumps and rolls. He revelled in this, his first opportunity of seeing—and feeling—a thunderstorm at close quarters, after having spent a life-time studying it from the ground. The keen enjoyment and interest he showed on these jaunts never ceased to intrigue the pilots and navigators. He was a perpetual source of wonder to them, ever since on his first flight he had remarked to the pilot: " Do you know that you've taken me off the ground for the first time in 86 years?" '

C.T.R.'s life was a long and happy one and he died quietly at his cottage on 15 November 1959 after a brief illness, the only serious illness in his life. Of the great scientists of this age, he was perhaps the most gentle and serene, and the most indifferent to prestige and honour; his absorption in his work arose from his intense love of the natural world and from his delight in its beauties.

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