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On dust, fogs, and particles: The history of the cloud chamber

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Summary. — In this paper we give a brief overview of the history of the Wilson cloud chamber from its development in the late 19th century as a device for estimating the number of dust particles in the foggy cities of the Victorian age to its glorious entry into the emerging fields of nuclear and particle physics in the 1920s and 1930s. Although the cloud chamber is no longer used in cutting-edge physics or university teaching, this device could play a new role in physics education, for example in meteorology and climate studies, and as a historical case study for teaching aspects of the nature of science.

1. – Introduction

The *cloud chamber* is one of the most important devices in the development of 20th-century physics, particularly in nuclear physics and cosmic ray physics [1-5], and as such it has played a fundamental role in teaching physics to generations of students [6]. In this paper, by retracing its history, we will show how and why it can take on new significance in the context of physics education.

This is especially true in the field of thermodynamics and in the highly relevant context of atmospheric physics, meteorology, climate studies, and development of corresponding models, also enabling interdisciplinary links to chemistry and biology. In fact, the mechanisms of cloud formation continue to be the subject of various studies aimed at understanding and evaluating how condensation nuclei form, around which the water vapor particles contained in the air condense, creating the water droplets that make up clouds [7], including the effects of plants and cosmic rays (see `https:`

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`//cloud.web.cern.ch/`). An essential prerequisite for the condensation of water vapor into droplets is that the air is saturated with water vapor and brought to supersaturation. The metastable state of supersaturation can be achieved in the laboratory using various methods, which enable the investigation of cloud formation processes under controlled conditions. In this context, the construction of a do-it-yourself cloud chamber as part of the S'Cool Lab at CERN (see `https://scoollab.web.cern.ch/cloud-chamber`) is a very interesting proposal for education.

However, the educational interest of this device goes far beyond its ability to illustrate issues of nuclear or atmospheric physics. Its history is indeed a significant example of how science evolves, particularly in relation to chance in scientific discoveries. Indeed, the cloud chamber originated as part of studies of fog in Victorian cities at the end of the 19th century, and within a few decades it eventually became one of the cornerstones of the emerging field of nuclear and particle physics.

2. – Origins of the cloud chamber

At the origin of the *cloud chamber* lie those insignificant tiny particles that make up the dust or, as the poet Milton put it, "*the gay motes that people the sunbeams*" ([8], p. 37). It was just to study dust particles as atmospheric condensation nuclei that the Scottish meteorologist and physicist John Aitken (1839–1919) begun, at his personal laboratory in Falkirk, his several decades work, showing in 1880 that "dust is the germ on which fogs and clouds are the developed phenomena" ([9], p. 195). Already in 1875, the French pharmacist and chemist Paul-Jean Coulier (1824–1890) made the very first observations on the need of nuclei of condensation such as airborne dust and microscopic particles to obtain fog and cloud formation, showing that, after filtration, condensation was reduced if not even prevented [10].

Anyway, it was without any knowledge of Coulier's work, and with the goal of exploring the phenomenon of town fog of Victorian era, whose "increased frequency and density [...] is becoming so great as to call for immediate action" ([11], p. 352), that Aitken proved in 1881 that dust particles act as condensation nuclei for water droplets in supersaturated air and started designing an instrument for measuring the number of dust particles in air. Although sun's rays are a "powerful [...] dust revealer" to detect Milton's gay motes, Aitken felt confident that "we have in the fog-producing power of the air a test far simpler, more powerful and delicate, than the most brilliant beam at our disposal" ([11], p. 344). Thus in 1888 he created the first ever *expansion apparatus* for estimating the number of dust particles in air by producing supersaturated air and counting through a lens the number of water drops falling on a surface (fig. 1 (left)) [12].

A few years later, in 1894, another Scottish man attracted by Scottish clouds and other atmospheric optical and electrical phenomena, such as glories and coronas seen around the Sun and on the clouds, Charles Towsend Rees Wilson (1869–1959), spent some weeks at the Ben Nevis meteorological observatory, in Northern Scotland, where he managed to observe several "wonderful optical phenomena". As he later wrote, this experience "greatly excited my interest and made me wish to imitate them in the laboratory" ([13], p. 194).

At the beginning of 1895, at the Cavendish Laboratory in Cambridge, Wilson started making some experiments with the goal of obtaining clouds by expansion of moist air following the idea of the expansion apparatus utilized by Aitken, and, almost immediately, he came across "something which promised to be of more interest than the optical phenomena which I had intended to study" ([13], p. 194). By modifying Aitken's expansion apparatus, Wilson observed that it was possible to obtain condensation, that is water droplets, even in the absence of dust particles, if the expansion ratio was greater than a certain threshold, which he found to be 1.25 (fig. 1 (center)) [14]. In 1896, Wilson discovered, through further experiments with a more complex apparatus (fig. 1 (right)), that the recently discovered Röntgen rays (X-rays) increased the number of droplets produced with an expansion ratio greater than 1.25 (whereas at $v_2/v_1 < 1.25$ no condensation occurs even when such rays are used) [14]. But in those turbulent years, another radiation became available. When the sensitive volume of another version of the expansion apparatus was exposed to the uranium radiation discovered by Becquerel, condensation "nuclei" of exactly the same nature "are produced in moist air" ([15], p. 337). In 1897 Wilson concluded that "the electrical properties of gases under the action of Röntgen and Uranium rays point to the presence of free ions. It is natural to identify with these the nuclei made manifest [...]" ([15], p. 337). The condensation nuclei in dust-free air were *ions*.

Wilson eventually discovered that there were *two* critical expansion ratios, the well-known ratio of 1.25 and a second of 1.31, and, by following Sir J. J. Thomson's hypothesis that these two different ratios were due to condensation on ions with different charge signs, in 1899 he found that the ratio of 1.25 was sufficient for the condensation of water around negative ions; to catch the positive ions, on the other hand, the limit of 1.31 had to be exceeded [16]. As later emphasized by Wilson, this discovery "marked the completion of a stage in my work, the behavior of ions as condensation nuclei. It was now possible to make visible the individual ions and to distinguish between positive and negative ions. This found its immediate application in the determination of the charge carried by an ion by Thomson and later by H. A. Wilson" ([13], p. 197). On Thomson's and Wilson's determinations of the charge of the ions and on the successive much celebrated Millikan's oil drop experiment for the accurate measurement of the elementary charge see [17].

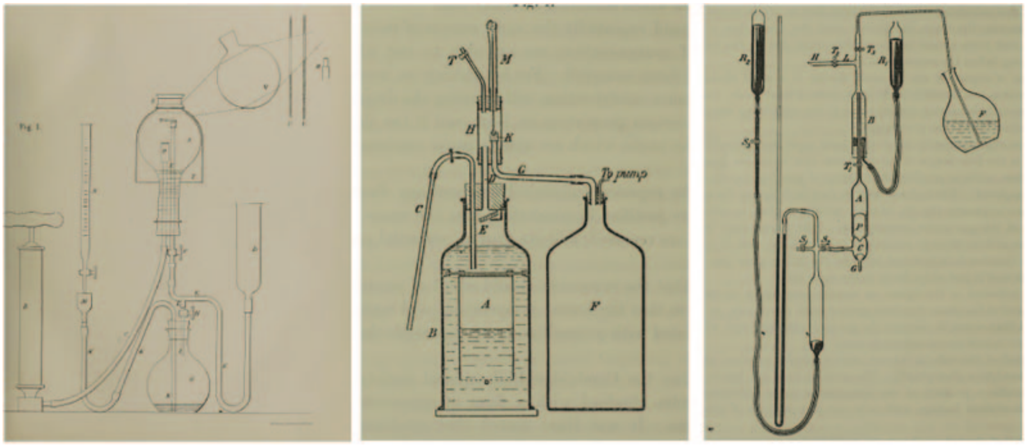

Fig. 1. – Aitken's method for counting dust particles (left). Condensation takes place in a glass flask (A). The water droplets (surrounding a single dust particle) are counted with a lens (S) ([12], p. 20). Wilson's expansion apparatuses revealing that no dust is required to obtain condensation if a given threshold of expansion ratio (1.25) is reached ([14], p. 268) (center) and that X-rays increase the number of droplets (again if the expansion ratio is greater than 1.25) ([14], p. 276) (right). In both apparatuses, the sensitive volume is again labeled A.

3. – The Wilson cloud chamber

In the first decade of the 20th century, there were no new developments in the expansion technique for studying condensation nuclei. In this decade, some dissatisfaction of Wilson with the reliability of the condensation method (*e.g.*, applying an electric field to the apparatus did not seem to be able to rid the sensitive volume of all the ions that are constantly present in dust-free air) led him to suspect that the persisting ions might be an artefact of the condensation method, and he turned to a "purely electrical method for detecting ionisation" ([18], p. 152). This state of the art changed abruptly in 1911, when Wilson invented the so-called classical *Wilson cloud chamber* [19]. What were the reasons for this sudden development?

A first reason was the growing knowledge on the radiations that constitute the natural radioactivity. As remarked by Wilson, in the first decade of the new century "ideas on the corpuscular nature of α and β-rays had become much more definite" ([13], p. 199). If in 1900 it was established that the negatively charged β-rays were indeed the recently discovered *electrons*, in 1903 Rutherford discovered that the α-rays were massive, positively charged particles, and it was not until 1909 that Rutherford himself provided the decisive proof that the α-rays were charged helium atoms. This awareness led him to expect with a certain degree of confidence that "the track of individual α- or β-particles, or of ionising rays of any kind, through a moist gas may be made visible by condensing water upon the ions set free" ([19], p. 285). Of course, a suitable form of expansion apparatus was required for the purpose. In order that the clouds formed should give a true picture of the trails of ions left by the ionising particles, it was indeed necessary that "little or no stirring up of the gas should result from the expansion". Also, it was desirable that "no interval long enough to allow of appreciable diffusion of the ions should elapse between their liberation and the production of the super-saturation necessary for the condensation of water upon them; and that the cloud chamber should be free from all ions other than those in the freshly formed trails" ([19], p. 285). The form of the expansion chamber that best implemented the necessary requirements was just the Wilson cloud chamber shown in fig. 2 [20].

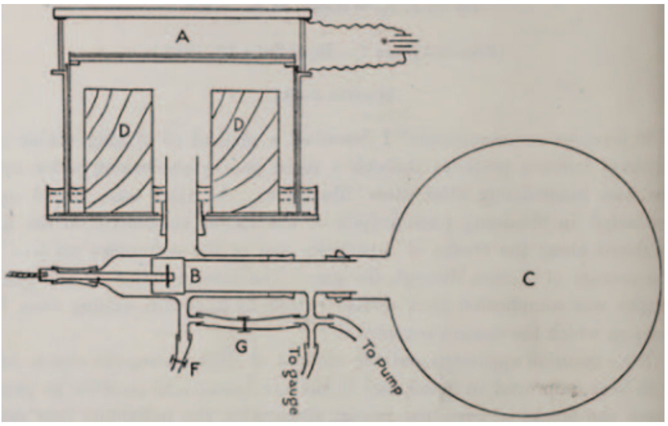

Fig. 2. – The classical Wilson cloud chamber. The sensitive volume, *i.e.*, where the ionizing rays are made to pass and where the supersaturation is established by means of a sudden expansion, is A ([20], p. 278).

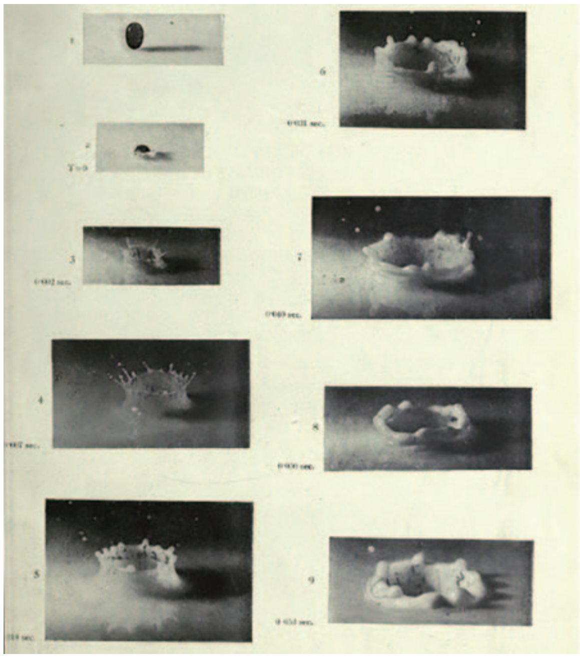

Fig. 3. – High-speed photographs of a drop of water falling into milk mixed with water ([21], p. 17).

A second reason was the emergence, in the meantime, of methods of high-speed photography, like those making possible to get high-speed splash pictures of drops of water into milk mixed with water (fig. 3) [21]. As in the case of individual α- or β-particles, the study of splashes required the possibility of recording "the progress of a multitude of events, compressed [...] within the limits of a few hundredths of a second, but none the less orderly and inevitable, and of which the sequence is in part easy to anticipate" ([21], p. 1).

In the case of splashes, we must let a drop of water fall in a dark room and illuminate the drop with a flash of short duration when it touches the surface and photographing this stage. Then we must replace the plate with a new one and drop a second drop of the same size and photograph it in the same way, with the flash now set to fire at a slightly later stage of impact, and so on.

It was found that this objective could be accomplished by an apparatus arranged as in fig. 4, where the flash is produced by a spark gap between magnesium terminals connected to two large Leyden jars and the discharge takes place by means of a falling metal ball, the triggering of which is controlled by an electromagnet that is the same as the one that triggers the drop: the two electromagnets are in the same circuit so that the drop and the falling ball are triggered simultaneously.

The synchronization technique used in the Wilson cloud chamber is similar to the one described above. The arrangement for firing the spark at a specific interval after expansion is shown in fig. 5: a falling metal ball triggers the expansion of the chamber through a string, and when the ball passes the primary spark gap, it closes a circuit that causes the illuminating spark [20].

With his new, innovative expansion apparatus, Wilson succeeded for the first time in photographing the tracks of α-particles passing through a mass of moist gas by allowing

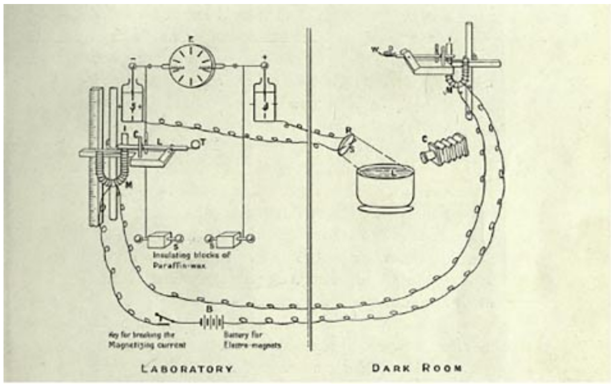

Fig. 4. – Arrangement of apparatus for photographing splashes ([21], p. 7).

water to condense on the ions immediately after their release. These particles were emitted from a tiny amount of radium at the tip of a wire projecting into the cloud chamber or from radon and later radioactive products when the wire with the radium tip had been in the cloud chamber for a few days and was then removed ([20], p. 282 and plate 6).

Wilson also succeeded in taking photographs of tracks left by α-particles showing abrupt bends—the first ever detected—indicating single scattering phenomena and sometimes also showing a well-defined spur "which is difficult to interpret otherwise than as being due to ionization by the recoil of the atom, by collision with which the course of the α-particle has been abruptly changed" (fig. 6) ([20], p. 284). By carefully positioning the camera in relation to the illumination source, Wilson was also able to photograph the tracks of β-particles that were produced together with α-particles either by radium or by its decay products. Other β-particles were the result of the passage of a narrow beam of γ-rays through the cloud chamber or the by-product of an X-ray beam passing through the cloud chamber immediately after expansion while the gas was in a supersaturated state.

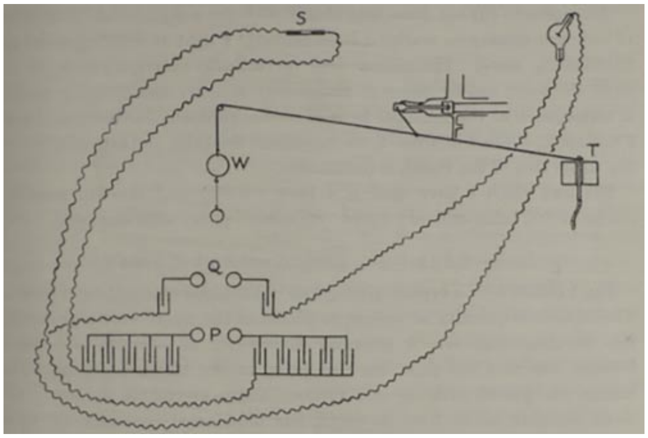

Fig. 5. – Arrangement of apparatus for firing the spark at a definite interval after the expansion of the Wilson cloud chamber ([20], p. 281).

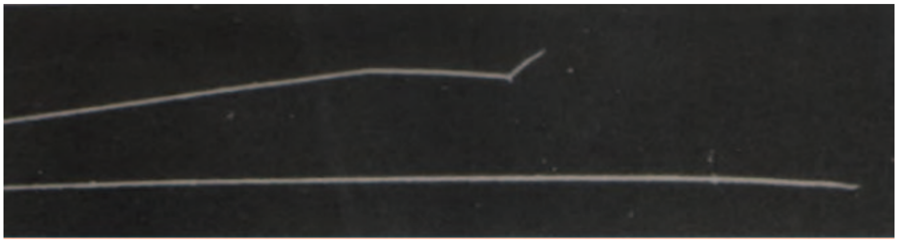

Fig. 6. – Typical tracks left by α-particles. The above track shows a scattering phenomenon ([20], plate 6).

4. – The cloud chamber and the new discoveries in nuclear physics

The development of the cloud chamber coincided with the months in which Rutherford (1871–1937) proposed a new paradigm for the structure of atoms: the modern atomic nucleus. Although the cloud chamber was not responsible for either the stimulation of Rutherford's theory or its confirmation (both were achieved by the zinc sulphide scintillation technique in the hands of Geiger and Marsden [22] by the end of the 1910s) it was clear that this apparatus offered great possibilities in the field of newborn nuclear physics.

4·1. *The discovery of the proton.* – Rutherford, who had discovered in 1919 with the help of scintillation technique that it was possible to produce the artificial disintegration of light nuclei by bombarding them with α-particles and the associated ejection of hydrogen nuclei—soon to be called *protons*—and discovered that these particles are a constitutive component of all nuclei, made the following remark in his Bakerian lecture in 1920:

> In our ignorance of the constitution of the nuclei and the nature of the forces in their immediate neighbourhood, it is not desirable to enter into speculations as to the mechanism of the collision at this stage, but it may be possible to obtain further information by a study of the trails of α-particles through oxygen or nitrogen by the well-known expansion method of C. T. R. Wilson. [...] In this way we may hope to obtain valuable information as to the conditions which determine the disintegration of the atoms, and on the relative energy communicated to the three systems involved, *viz.*, the α-particle, the escaping atom, and the residual nucleus ([23], p. 393).

In 1924, Patrick Maynard Stuart Blackett (1897–1974) succeeded in confirming Rutherford's discovery of the proton by modifying the Wilson apparatus, which made it possible to generate periodic expansions several times per second so that the traces of many particles could be examined in a reasonable time. Examining over 400000 tracks of α-particles passing through nitrogen and oxygen, Blackett discovered eight anomalous tracks due to the ejection of a proton from a nitrogen nucleus, in addition to a large number of bifurcations due to elastic collisions between α-particles and nuclei (fig. 7) [24].

The cloud chamber enabled Blackett to discover what could not be observed with a zinc sulphide screen, namely the fact that all anomalous tracks showed only two emerging particles (the proton and the recoil nucleus, without any track due to a scattered α-particle), "so proving that the assumed "disintegration" of nitrogen by alpha particles

Fig. 7. – Stereoscopic image of an upward beam of α-particles passing through a mass of nitrogen and oxygen. The image shows an event of proton ejection plus recoil nucleus ([24], plate 7).

was in reality an "integration" process" ([25], p. 101). The nitrogen nucleus disintegrates with emission of a proton and an isotope of oxygen (not yet known at the time) according to reaction (1):

$$ {}^{4}_{2}\alpha + {}^{14}_{7}\mathrm{N} \to {}^{17}_{8}\mathrm{O} + {}^{1}_{1}p. \tag{1} $$

4·2. *The discovery of the neutron.* – Although Wilson's cloud chamber technique played no part in the discovery of the proton —even though it provided spectacular confirmation of that discovery— the discovery of the other nucleon was the result of experiments with two types of apparatus, one of which was indeed the cloud chamber.

In the 1920s, experimental nuclear physics essentially meant bombarding a light element with the α-particles emitted by a radionuclide (typically radon or other elements of the radium radioactivity chain) and thereby causing the artificial disintegration of the element, the ejection of a proton and the creation of another element (*i.e.*, a transmutation of the elements according to the rules of conservation of atomic number and atomic weight). At the end of the 1920s, this research program led to the expectation that proton emission could be accompanied by γ radiation, and consequently to research aimed at detecting such radiation. When Walter Bothe (1891–1957) and his collaborator Herbert Becker discovered signs of a very *penetrating radiation* when bombarding *beryllium* with α-particles in 1930, this came as quite a surprise, as it was known that beryllium does not emit protons when bombarded with α-particles [26]. So, a new kind of nuclear reaction (2) was proposed:

$$ {}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \to {}^{13}_{6}\mathrm{C} + \gamma. \tag{2} $$

In January 1932, Frédéric Joliot (1900–1958) and Irène Curie (1897–1956) discovered something even more astonishing: this supposed γ radiation was so energetic that it was able to eject from a hydrogenated substance a strongly ionizing but weakly penetrating radiation, which was soon identified as consisting of protons. Hence, Joliot and Curie expected the supposed γ-ray quantum to be of enormous energy, *i.e.*, more than 50 MeV, based on an analogy with the Compton effect [27]. However, James Chadwick (1891–1974) pointed out in February 1932 that the γ-ray hypothesis would lead to an experimental inconsistency if this radiation were used to eject a nitrogen atom:

> If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar

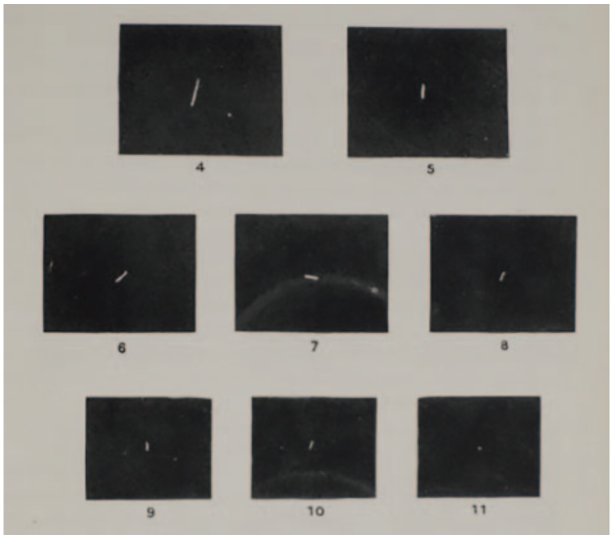

Fig. 8. – Cloud chamber tracks of nitrogen recoil nuclei produced by collision with neutrons ([30], plate 15).

> process should have an energy not greater than about 400000 volts, should produce not more than about 10000 ions, and have a range in air at N.T.P. of about 1.3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30000 ions ([28], p. 312).

It was using a cloud chamber (fig. 8) that, to test this expectation, Chadwick, together with Norman Feather (1904–1978), measured the range of the nitrogen atoms recoiled due to the penetrating radiation emitted by beryllium [29, 30]. The results were inconsistent with a 50 MeV quantum. On the contrary, the 3.5 mm range of the nitrogen (as opposed to an expected range of 1.3 mm) was consistent with the hypothesis that the penetrating electromagnetic radiation from beryllium is actually not radiation, but a massive and neutral particle with a mass close to the mass of the proton produced according to reaction (3),

$$ {}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n, \tag{3}$$

where the new neutral particle is symbolized by "n". For some years now we have had a name for Chadwick's particle: as Chadwick recalls, in his 1920 Bakerian Lecture Rutherford had indeed assumed "a proton and an electron in close combination" ([29], p. 697) and called it a "*neutron*".

4˙3. *Cosmic rays' studies, Anderson's positron, and Dirac's antielectron.* – In the early 1930 s, in addition to the radiation emitted by beryllium when bombarded with α-particles, another penetrating and high-energy radiation was investigated: radiation "raining" down from above, also known as *Höhenstrahlung*, as German physicists said, or cosmic rays, as Robert Millikan (1868–1953) said. Beginning in late 1931, Millikan and his young collaborator Carl Anderson (1905–1991) studied this radiation at CalTech using a very large automatic (*i.e.*, cyclically expanding) cloud chamber immersed in a strong magnetic field. In June 1932, after a considerable number of cloud chamber exposures had been made, Anderson discovered traces of positive particles that he thought were “probably a proton” ([31], p. 420). In September 1932, when some of these particles were photographed crossing a 6 mm thick lead plate (inserted into the cloud chamber to study the interaction of cosmic rays with matter) with a measurable curvature (fig. 9) [32, 33], Anderson considered a number of equally disturbing possibilities:

> 1) a positive particle of small mass penetrates the lead plate and loses about two thirds of its energy; or 2) two particles are simultaneously ejected from the lead, in one direction a positive particle of small mass, in the opposite direction an electron; or 3) an electron of about 20000000 volts energy penetrates the lead plate and emerges with an energy of 60000000 volts, having gained 40000000 volts energy in traversing the lead; or 4) the chance occurrence of two independent electron tracks in the chamber, so placed as to give the appearance of one particle traversing the lead plate ([32], p. 238).

Since hypothesis 3) seemed to make little physical sense, a choice had to be made whether accepting the existence of a positively charged particle with a mass comparable to that of an electron (as postulated in 1) and 2)) or allowing the random appearance of independent tracks on the same photograph, placed in such a way as to indicate a common point of origin of two particles 4). As Anderson notes, “the latter possibility on a probability basis is exceedingly unlikely” ([32], p. 239). The discovery of these “easily deflectable positives” ([32], p. 238) was the birth of the *positive electron*, eventually called *positron* by Anderson in 1933) [33], a particle whose discovery was largely accidental and not theory-driven, although there was a theory—the relativistic quantum theory of the electron proposed by Dirac (1902–1984) in 1931—according to which the collision of two hard γ-rays (with an energy of at least half a million volts) could lead to the simultaneous production of an electron and an *anti-electron*.

The connection between Dirac’s anti-electron and Anderson’s positron was first established in February 1933 at the Cavendish Laboratory in Cambridge by Blackett and Giuseppe Occhialini (1907–1993). Using a new version of the Wilson cloud chamber

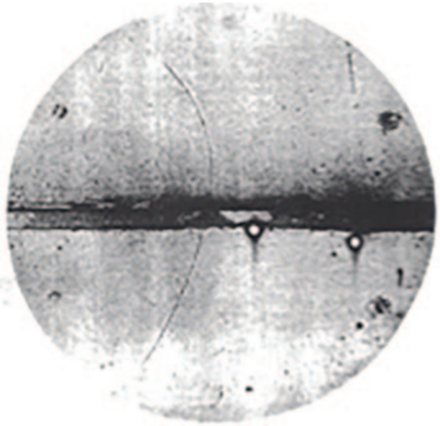

Fig. 9. – Anderson’s cloud chamber photograph of a positron traversing a 6 mm lead plate upwards [33].

—their recently developed *counter-controlled cloud chamber*, in which the ionizing particle is able to take its own *selfie*, *i.e.*, in which the expansion of the chamber is triggered by the coincidence of two Geiger-Müller counters— the Cavendish researchers actually succeeded in collecting numerous photographs showing positron traces, which they interpreted using the theoretical framework provided by Dirac [34].

5. – Concluding remarks

Today, the cloud chamber is no longer used in cutting-edge physics or in university teaching, although it has played a role in physics lessons for generations of students. Nevertheless, we believe that this device, which was described in a 1926 Cambridge Instrument Company advertisement as "the most wonderful experiment in the world", can assume a new significance in physics education.

As shown in our brief overview, the cloud chamber was developed at the end of the 19th century as an adiabatic expansion apparatus for meteorological and atmospheric studies, with the aim of reproducing and understanding the mechanisms of cloud formation. From an educational perspective, it can serve as an introduction to meteorology and climate studies to show that cloud formation requires supersaturation of the atmosphere with water and the presence of seed particles or nuclei around which water can condense. The operating principle can therefore be related to the laws of thermodynamics, the equations for the gas state and transformations, and the concepts of saturated and supersaturated vapors.

At the end of the 19th century, Wilson realised that positive and negative ions could also act as nuclei for water condensation: in the context of meteorology and climate studies, this offers the possibility of a link to modern studies of the possible effects of cosmic rays on cloud formation, while other interesting relationships to electron charge measurements and the role of a fertile research environment in the development of science can also be highlighted.

Finally, in the early 1910s, Wilson modified and redesigned the cloud chamber to visualize the trails produced by ionizing radiation. From then on, the use of the cloud chamber shifted from meteorology and atmospheric physics to its applications in nuclear, particle and cosmic ray physics, confirming the existence of the proton, proving the hypothesis of the neutron and enabling the discovery of the positron. In this respect, the history of the cloud chamber, with its changing forms and functions over time and with the image of the theory-experiment relationship it conveys, suggests that this historical case study could certainly contribute to a better understanding of the *nature of science*.

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