EUGENIO BERTOZZI*

Establishing and Consolidating a Research Field: The Biography of the Wilson Cloud Chamber in the History of Particle Physics

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ABSTRACT

This paper retraces the biography of a milestone instrument in the history of physics—the cloud chamber—introduced by Charles Thomson Rees Wilson in 1911 and vastly adopted in successive studies on particle physics. It offers a comprehensive reading where the development of the instrument is kept in tight connection with the knowledge of microphysics from the late nineteenth century to the 1960s: it shows how the inception of the Wilson instrument of 1911, even in its smallest constructive details, can be seen as strongly influenced by the physics discoveries through the nineteenth and the beginning of the twentieth centuries. The confirmation of preliminary observations obtained with early versions of the cloud chamber drove, as in the case of the positron, further evolutions of the instrument into a "golden age" of the apparatus within particle physics research. The "sunset" will see the attempt to overcome the limitations of a fully developed apparatus by flexibly intervening in the geometry of the experiment, moving it up to the mountains or at different distances from the particle accelerator by stressing at maximum, and then exhausting, the generation of new knowledge from it. In doing so, the paper brings into light original aspects not yet explored in historical studies on the cloud chamber, such as Wilson's contribution to the field after 1911.

KEY WORDS: Wilson cloud chamber, history of twentieth-century physics, biography of scientific instruments, history of experiments, discoveries, evolution of experimental technique, production of knowledge

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*University Museum Network and Department of Physics and Astronomy, University of Bologna, Via Zamboni 33, 40126, Bologna, eugenio.bertozzi2@unibo.it.

The following abbreviation is used: CERN, European Council for Nuclear Research.

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1. INTRODUCTION

The Wilson cloud chamber is one of the most famous instruments in the history of physics. Introduced by Charles Thomson Rees Wilson at the Cavendish Laboratory in 1911/1912, the apparatus allowed for the first time to visualize particle phenomena as trails of condensed vapor and to obtain a photographic recording of the microscopical events normally invisible to the eye. When, in 1927, Wilson was awarded the Nobel Prize, his method was already well known within the physics community and adopted for the study of radioactivity; at the same time, a season of applications and adaptations of the method to a vast class of physical problems, which would continue for many years, had just begun.

The origin of the cloud chamber as a device for the study of atmospheric physics in the late nineteenth century, the relationship of the methodology it established with particle physics experiments in the second half of the century, the close understanding of the Wilson apparatus of 1912, together with the replication of his experiments, have all been objects of a thorough historical research and of interesting scholarly debates, duly recalled in the course of this paper.

Moving from this scholarship, the paper posits the Wilson instrument as a central object to observe how the particle physics field was established and consolidated in the first half of the twentieth century. By developing a comprehensive reading where the evolution of the instrument and the emerging knowledge of the field are kept in tight connection, the paper articulates the relationship between the material adaptations of the instrument to the observation of unfamiliar phenomena in the establishment of the particle physics research field and the creation of its specialist knowledge.

More specifically, Section 2.1 retraces how the final shape of the Wilson instruments of 1912, even in the smallest constructive details, can be seen as strongly influenced by the physics discoveries through the nineteenth and early twentieth centuries, absorbed by Wilson during his activity at the Cavendish Laboratory in Cambridge. Section 2.2 shows how the vast adoption of the Wilson method by the physics community and its successive adaptations to the study of new research topics led to further discoveries and to a "golden age" of the instrument. Notable case studies—such as the discovery of the positron in 1932—are reviewed, according to the aim of the paper, by showing how the apparatus was deeply revised to stabilize an initial, accidental observation into a series of systematic confirmations. The sunset of the instrument, Section 2.3, will see the attempt to overcome the limitations of a fully developed apparatus by flexibly intervening in the geometry of the experiment, moving it up to the mountains or at different distances from the accelerator by stressing at maximum, and then exhausting, the generation of new knowledge from it. Some crucial parameters leading these interventions—such as improvement of the apparatus' efficiency or the need for higher-energy sources of particles—have already been identified in historical studies of the cloud chamber. The current analysis brings into light original ones related to the inner core of the instrument, such as the improvement of quality and persistence in track formation pursued by Wilson himself after 1912. Between the multitude of physical interventions to "improve" the apparatus and the vertiginous list of successive discoveries that challenged theoretical speculations toward newer frontiers, the language developed for interpreting the visual patterns captured in the cloud chamber's recordings stands out as the real "stable center of gravity" that gave an enduring coherence to the research field. This language is the opening subject of the biography.

2. THE BIOGRAPHY OF THE WILSON CLOUD CHAMBER AS AN INSTRUMENT FOR RESEARCH

Introduction "in media res": Applications, language, and objectivity during the "golden age"

"Where many indirect evidences fail to convince, a single cloud-chamber picture is often sufficient and carries out convinction." So read the first lines of a compendium about the instrument published in 1946, "A Report on the Wilson Cloud Chamber and Its Application in Physics."[1]

This Report is a journey across the golden age of the instrument; it illustrates the status of research on traditional cloud chamber topics—alpha, beta, X, and gamma rays—and on more recent ones, such as artificial disintegration or uranium fission. Expectations are expressed in relation to new hot topics, such as the production of mesotrons in cosmic ray experiments. The straightforwardness of the authors in addressing the persuasive character of the cloud chamber pictures attests to the widespread view of them as self-evident and objective recordings.[2] In 1946, a specific technical language for interpreting the

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[1] N. N. Das Gupta and S. K. Ghosh "A Report on the Wilson Cloud Chamber and Its Applications in Physics." *Reviews of Modern Physics* 18 (1946): 225–90, on 225.

[2] A wide discussion on these themes is found in P. Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), 135–41.

pattern of particle tracks portrayed in the pictures had been entirely developed, although both a complete understanding of the theory *behind* the visualized entities and a complete grasp on the processes *underlying* visualization itself were still missing. In relation to the second point, the Report reads:

> Although the Wilson chamber has been developed to such a great extent during the 34 years since its inception, the fundamental processes of its operation, viz., the formation and rapid growth of drops in supersaturated vapor, are not yet fully understood.[3]

The independence of the tracks language from pure theories is instead plainly stated in the foreword of another milestone publication of the time: the second volume of the atlas of the cloud chamber published in 1952. In it, P. M. S. Blackett, Nobel Prize recipient in 1948 for the development of the Wilson cloud chamber method, assures the non-physicist reader that the atlas

> must surely helps us to make clear that this world of subatomic events is one which can be easily visualized and understood without the aid of complicated mathematics or mastery of the theories. If one asks why these events happen, one may be led into the subtle intricacies and uncertainties of modern fundamental theoretical physics, but if the experimenter contents himself with asking how they happen, then these pictures, and the attached commentaries, are an ideal guide to the world of elementary particles.[4]

In the wake of its predecessor,[5] the second volume of the atlas is a collection of the most significant pictures portraying particle phenomena and was principally meant to tutor the eye of young researchers in distinguishing the already known from a potentially new discovery. A special feature of the second volume is its focus on cosmic rays, from the first picture of a cosmic ray ever taken at sea level (Leningrad, 1929) to a cosmic ray of the highest energy, taken at an altitude of 3,027 m (Echo Lake, 1949).

The two atlases crystallize the notion of objectivity ascribed to the cloud chamber method: pictures taken by famous experimenters, most adept with the instrument, whose value was, however, their independence from

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[3] Das Gupta and Ghosh, "Report" (ref. 1), 227.

[4] G. D. Rochester and J. G. Wilson, *Cloud Chamber Photographs of the Cosmic Radiation* (London: Pergamon Press, Ltd., 1952), VII.

[5] W. Gentner, H. Maier-Leibnitz, and W. Bothe, *Atlas typischer Nebelkammerbilder* (Berlin: Springer, 1940).

provenance.[6] In a picture, the objective representation of the phenomena appeared to be guaranteed by the chemical processes employed in photograph development, which excluded, at least to a certain extent, the intervention of the experimenter and the possible introduction of personal biases. Besides, as described in the next section, objectivity was further stressed by automation of the apparatus introduced by Wilson since 1912. Such extraordinary methodological stability had developed on the base of a third, highly changeable layer, which moves between the drops, forming the tracks, and the theories that aimed at interpreting them: the chain of the physical, material transformations of the apparatus itself.

In the following, I will try to point out how the discoveries of late-nineteenth and early-twentieth-century physics played a substantial part in shaping the development of the Wilson instrument of 1912 and how, afterward, the material manipulations of the apparatus became a way of generating new knowledge through further discoveries within the field of particle physics. The sunset of the instrument will see the attempt to overcome the limitations of a fully developed apparatus by flexibly intervening in the geometry of the experiment, moving it up to the mountains or at different distances from the accelerator by stressing at maximum, and then exhausting, the generation of new knowledge from it. In doing so, this paper articulates a dialectical relationship between the historically well known layer of the phenomenology discovered by the massive employment of the cloud chamber in physics research and the less investigated chain of material adaptations the apparatus went through during its life cycle.

2.1. Genesis

The instrument that gave "the world a new sense"[7] was introduced by Charles Thomson Rees Wilson at the Cavendish Laboratory in Cambridge in 1911–1912. In two milestone publications, Wilson described an apparatus that

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[6] The emergence of *objectivity* in the mid-nineteenth-century sciences and the role that the atlases—from anatomy to the physical sciences—have played in conveying this notion in the twentieth century has been investigated by Lorrain Daston and Peter Galison. The present reading of the cloud chamber recordings largely relies on those studies. L. Daston and P. Galison, "The Image of Objectivity," *Representations* 40 (1992): 81–128; L. Daston and P. Galison, *Objectivity* (New York, Zone Books, 2007).

[7] P. M. S. Blackett, "Charles Thomson Rees Wilson 1869–1959," *Biographical Memories of Fellows of the Royal Society* 6 (1960): 269–95, on 289.

made fully visible to the eye and to the camera lense phenomena that had been formerly detected only indirectly.[8]

Peter Galison and Alexi Asmuss offered a view of the instrument as the material embodiment of two different approaches: the analytic approach to the study of matter of the Cavendish Laboratory in Cambridge, and the mimetic approach to nature in the Victorian context of the late nineteenth century.[9] Wilson's commitment to the phenomena of the weather, his amateur practice of nature photography, and his excursions at the Observatory of Ben Nevis in Scotland, together with the knowledge acquired therein on Atkin's work on cloud formation, merged with his absorption of ion theory developed at the Cavendish by J. J. Thomson and triggered his development of the instrument. Besides, Richard Staley remarks how the timing of Wilson's work and goals might have been influenced by a further, intermediary tradition already present at the Cavendish Laboratory: the meteorological studies developed by W. N. Shaw. According to the Cambridge historian, "along with Ben Nevis haloes and Cambridge matter physics, Cambridge fogs played their part in inspiring a new use of the cloud chamber."[10]

In this section, the path by which the first Wilson apparatus for clouds was developed into the Wilson cloud chamber of 1912 is retraced in terms of a piece-by-piece construction that tightens the discoveries and theoretical programs to the constructive details of the in-progress instrument.

Dust-free and expansion ratio

To show that the presence of dust particles is not a necessary condition for the formation of clouds is the first result achieved by Wilson in 1895. In a one-page paper, Wilson reports the ratio between the initial and final volume of the

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[8] C. T. R. Wilson, "On a Method of Making Visible the Paths of Ionising Particles through a Gas," *Proceedings of the Royal Society* 85 (1911): 285–88; C. T. R. Wilson, "On an Expansion Apparatus for Making Visible the Tracks of Ionising Particles in Gases and Some Results Obtained by Its Use," *Proceedings of the Royal Society* 87 (1912): 277–92.

[9] P. Galison and A. Assmus, "Artificial clouds, real particles," in *The Uses of Experiment: Studies in the natural sciences*, eds. David Gooding, Trevor Pinch, and Simon Schaffer (Cambridge: Cambridge University Press, 1989), 225–73.

[10] R. Staley, "Fog, Dust and Rising Air: Understanding Cloud Formation, Cloud Chambers, and the Role of Meteorology in Cambridge Physics in the Late 19th Century," in *Intimate Universality: Local and Global Themes in the History of Weather and Climate*, eds. James R. Fleming, Vladimir Jankovic, and Deborah Coen (New York: Science History Publications, 2006), 93–113, on 103.

vapor at which the condensation, upon an adiabatic expansion, can be observed: 1.258 at 16.7°C.[11]

Galison and Asmuss detect an influence of J. J. Thompson and his matter theory of ions, already in these early experiments, since the entities at the base of Thomson's theory of matter—the electric ions—provided good candidates once the well-known condensation nuclei—the dust particles—had been removed. In this perspective, the introduction of a cotton filter, the key element assuring that all the air going into the vessel would be dust free, is a decisive, artificial aspect departing from the mimetic tradition and motivated by Thomson's in-progress theory.[12] On the other hand, Staley notices the resemblance between Wilson's instrument of 1895 (Fig. 1) and the demonstration apparatus used by a lecturer in experimental physics at the University of Cambridge, William Napier Shaw, who, on March 20, 1895, gave a lecture before the Royal Meteorological Society in London on the topic of cloud formation. Shaw's ideas were based on the hypothesis that, when clouds form in rising air, the nuclei that acted as source for condensation initially, would eventually be left behind by the vapor, and if further condensation happened at a higher level of the atmosphere, it would have been caused by other agents. A week after Shaw's lecture, under a notebook section entitled "Metereology," Wilson writes: "above the clouds the air will be supersaturated but devoid of nuclei."[13] Even though Shaw is never mentioned by Wilson, the instrument and the notes suggest that Shaw's meteorological investigations might have provided a further motivation to these early experiments.

Radioactive rays, sources, and electric field within the chamber

The effect of increased condensation—more clouds—observed when the newly discovered Röntgen and uranium rays cross the dust-free chamber are reported by Wilson soon after their discovery in 1895 and 1896, respectively.[14] Wilson's decision to use an electric field to investigate the electric nature of the condensation nuclei that generated so much additional cloud shows to what

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[11] C. T. R. Wilson, "On the formation of cloud in the absence of dust," *Proceedings of the Cambridge Philosophical Society* 8 (1895): 306.

[12] Galison and Asmuss, "Artificial clouds" (ref. 9), 245.

[13] Wilson notebook A1, 27–28 Mar; Staley, "Fog, Dust" (ref. 10), 103.

[14] C. T. R. Wilson, "The effect of Röntgen's rays on cloudy condensation," *Proceedings of the Royal Society of London* 59 (1896): 338–39; C. T. R. Wilson, "On the action of the uranium rays on the condensation of the water vapor," *Proceedings of the Cambridge Philosophical Society* 9 (1897): 333–38.

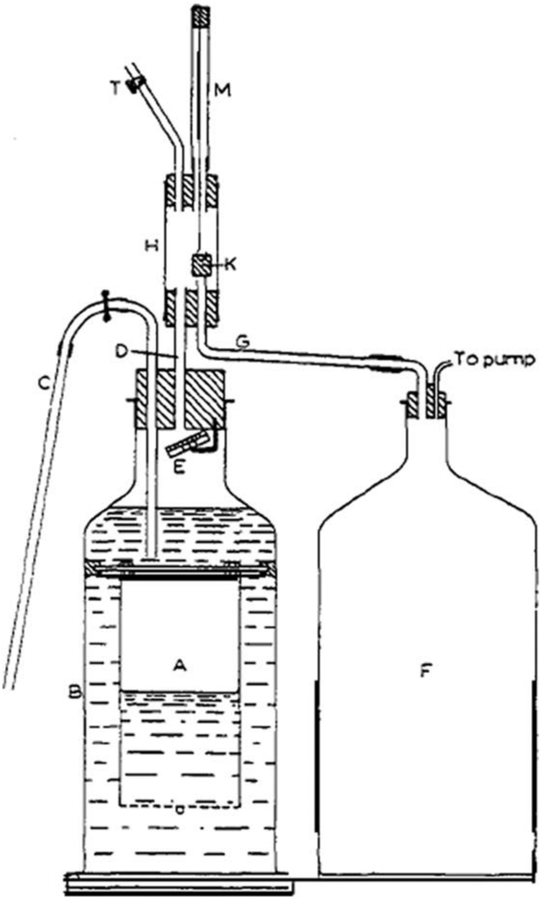

FIG. 1. Wilson's 1895 cloud apparatus. Moist air purified from dust is introduced in A, and the vacuum is made in F. When the connection between the two vessels is opened (valve K), the level of the water in the first vessel rises, reaches the top, and closes the connection again (valve E). Meanwhile, the moist air in A has expanded and condensed. *Source:* Wilson, "On the cloud method" (ref. 20). Copyright 1927 by The Nobel Foundation.

extent the material assembly of the apparatus should be seen as influenced by its contemporary discoveries.

After having claimed that cathode rays are streams of elementary particles and that the charge-to-mass ratio was constant for these particles, J. J. Thomson was keen to adopt the Wilson method to determine the electric charge of the new entities:[15] the sophisticated procedure put in place by Thomson foresaw the counting of the number droplets contained in the clouds produced by the Wilson instrument, upon the assumption that each droplet contained a single ion of charge "e." Such a count was carried out by observing how quickly the produced clouds fell under gravity. An electric field crossing the chamber did not serve the purpose of measuring the falling velocity of the cloud, but another, more preliminary purpose: the identification of the condensation nuclei for the cloud with the ions foreseen by Thomson's theory. In his paper of 1898, by describing the failure of the attempt to measure the electric charge,[16] Thomson remarks nevertheless on the successful identification allowed by the use of the electric field:

> If the ions produced by the Röntgen rays act as nuclei for the drops, then, since these ions can be withdrawn from the gas by applying to it a strong electric field, it follows that a cloud ought not to be formed when the air which is expanded is exposed to a strong electric field while the rays are passing through it. This was found to be the case, and the experiment is a striking one.[17]

On the other hand, Wilson looked at the electric field from a meteorological perspective: if the Earth is negatively charged, what are the external forces that maintain this condition? In this respect, if negative ions were more likely to cause condensation, rain would bring the negative charge down to the Earth, thus maintaining the fair-weather gradient. By dividing the chamber in two sectors—middle plate grounded, left plate at positive potential, right plate at negative potential—he could determine whether positive charges differed from negative in their ability to condense water vapor. Borrowing from Thompson's unsuccessful method, Wilson counted the number of charges in the two sides and found that negative charges precipitated water, but positive did not.[18]

In 1899, Wilson's research on condensation vis-à-vis positive, negative, or neutral ions (charged atoms) had developed along the understanding of the phenomena of condensation itself and put forward the existence of four

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[15] J. J. Thomson, "Cathode rays," *Philosophical Magazine V*, 44 (1897): 293–316.

[16] Thomson's first attempt, even though failed, established a method that Robert Millikan later exploited in his famous oil-drop experiment, which provided the measurement of the electric charge; Galison and Assmus, "Artificial clouds" (ref. 9), 252.

[17] J. J. Thomson, "On the charge of electricity carried by the ions produced by Röntgen rays," *Philosophical Magazine* 46 (1898): 528–45.

[18] C. T. R. Wilson, "On the comparative efficiency as condensation nuclei of positively and negatively charged ions," *Philosophical Transactions A*, 193 (1899): 289–308.

regimes bounded by three values of the expansion ratio (instead of two bounded by one): no condensation in dust-free air below 1.25, distinct rain drops between 1.25 and 1.31, sudden increase in the number of drops at 1.31, dense fog above 1.37.[19]

Downtime in the assembling

The long period between 1899 and 1910 sees Wilson searching for a mimetic sense to his experiments; questioning the nature of ionic charge and atmospheric phenomena led him to study the radioactivity brought to Earth by rain and snow with the use of electroscopes—without, however, advancing a cosmic ray hypothesis, which came a decade later.

In his Nobel Lecture of 1927, Wilson speaks about a decision, which occurred in 1910, to increase "the usefulness of the condensation method" and triggered by the fact that "ideas on the corpuscular nature of alpha- and beta-rays had become much more definite."[20] More specifically, a notebook passage written (probably) in May 1909 explicitly refers to a new focus, the tracks photography: "Methods depending on instantaneous photography of drops immediately after their production are superior to those in which drops falling through an illuminated layer are counted."[21] However, for at least a "rough version" of the instrument, a further element was still missing.

Gelatine on the glass and first assembling of a "rough apparatus": A beautiful sight

Gelatine is the opening subject in Wilson's notebook on Christmas Eve, 1910.[22] Once coated on the glass of the observation chamber, it would offer a way to prevent fogging and, at the same time, a good conducting surface for the electric field. On the same day, Wilson sketched the first concept of the instrument as a "simple flash form" chamber for photographing individual drops condensing on produced ions, a second concept to measure the effect of the electric field, and a third to search for particle tracks.

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[19] C. T. R. Wilson, "On the condensation nuclei produced in gases by Röntgen rays, uranium rays, ultra-violet light, and other agents," *Proceedings of the Royal Society of London* 64 (1899): 127–29.

[20] C. T. R. Wilson, "On the cloud method of making visible ions and the tracks of ionizing particles," *Nobel Lecture* (1927): 194–214, on 199.

[21] The passage, which appears in Wilson's notebook (A9) between 10 April and 17 July 1909, is currently thought to have been written in May 1909; Galison and Asmuss, "Artificial clouds" (ref. 9), 259n.136.

[22] Wilson's notebook (A9), 24 Dec 1910; Galison and Asmuss, "Artificial clouds" (ref. 9), 261n.138.

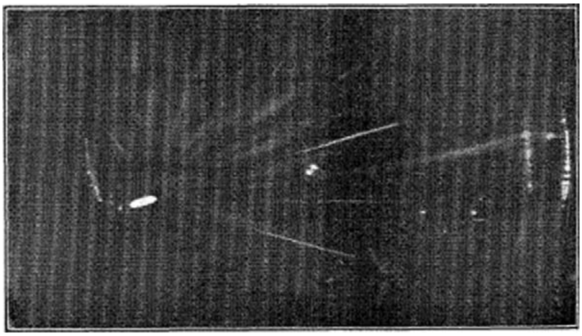

FIG. 2. The first published image of the trajectory of an alpha particle in the Wilson cloud chamber. *Source:* Wilson, "On a Method of Making Visible" (ref. 8), Plate 9, Fig. 1. Copyright 1911 by The Royal Society.

It is with this preliminary apparatus that Wilson tried to get the first view of the chamber crossed by the x-rays and, eventually, the "beautiful sight" of the cloud condensing along the track of an alpha particle emitted by the radium source. The two pictures of this phenomena are reported in Wilson's first publication of 1911 (Fig. 2).

Falling piston and illumination synchronized: The Wilson cloud chamber of 1912

The following year, Wilson described the apparatus in its final shape together with a collection of 19 pictures whose level of detail and quality witnesses the complete achievement of the experimental method (see, for instance, Fig. 3).

In the new instrument, the floor A is also the head of a piston that, once connected with the vacuum flask C (connection valve B), is suddenly sucked down and produces the desired increase of volume (Fig. 4). The chamber hosts a radioactive source and is constantly crossed by an electric field whose function is to keep the volume clean from all the ions except those produced by the ionizing particle emitted by the source.[23] The third element is the presence of an illumination system.

This paper also provides the details of an "automated" connection between the first element, the piston, and the third one, the illumination system, by means of a falling weight: Wilson's drawing, shown in Figure 5, portrays the

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[23] Even in a dust-free instrument, cosmic rays or earth radiation create ions that act as condensation nuclei for the vapor. The electric field keeps these ions on top and bottom of the chamber as soon as they are created.

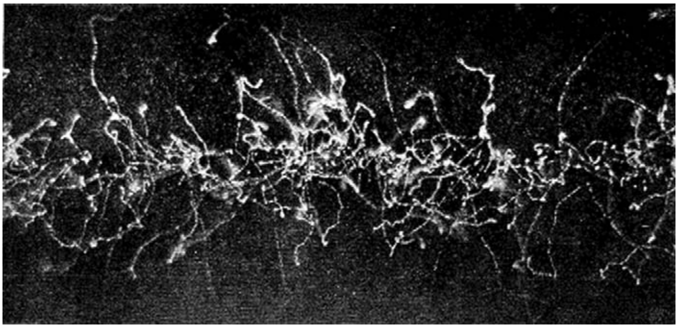

FIG. 3. Secondary electrons emitted by the vapor after X-rays had crossed the chamber. *Source:* Wilson, "On an Expansion Apparatus" (ref. 8), Plate 8, Fig. 3. Copyright 1912 by The Royal Society.

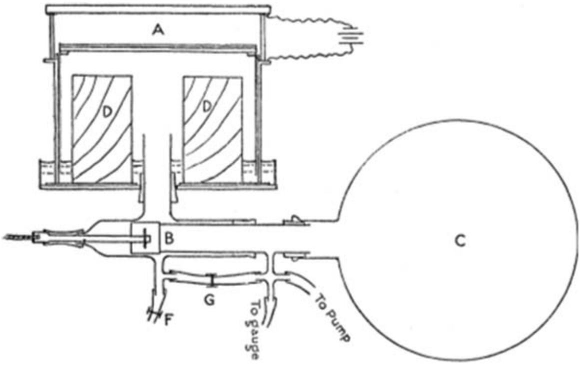

FIG. 4. Schema of the Wilson cloud chamber of 1912. *Source:* Wilson, "On an Expansion Apparatus" (ref. 8). Copyright 1912 by The Royal Society.

circuit of threads, weights, and the currents needed for the instrument to function. The sequence of actions starts with freeing trigger T, where a chord is kept in tension by weight W. The weight falls until a second chord, shorter and connected to the first, is stretched tight. The stretching of this second chord opens a valve, which opens the connection between the piston and the vacuum chamber and causes the falling of the piston/chamber's floor. In this instant, the weight W comes to a stop while a thin thread connecting W to a steel sphere breaks. The sphere continues to fall, finally passing to "spark-gap"[24] which, by closing an electric circuit, activates the illumination of the lamp (S).

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[24] The primary spark gap "Q" is not comprised in this reconstruction since it was used only for experiments with x-rays. For further details on the Wilson instrument of 1912 see M. Leone

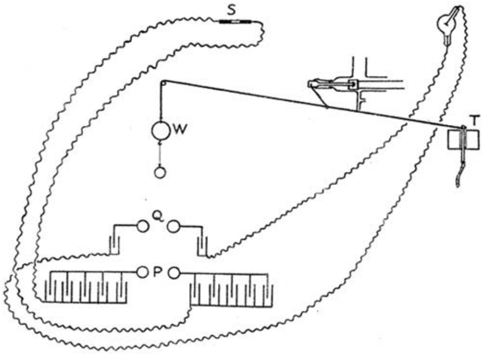

FIG. 5. Circuits of the apparatus. *Source:* Wilson, "On an Expansion Aparatus" (ref. 8). Copyright 1912 by The Royal Society.

The system is set so that the illumination system switches on an instant after the piston starts falling: tracks, which appear when the piston has come to a halt—are illuminated as soon as they form, in their best shape.

The use of gravity to limit the intervention of the experimenter and automate the system certainly aimed at achieving precision and removing disturbances or personal influences in the experiment. For this reason, within the broader perspective of the history of science, the cloud chamber pictures and the Wilson instrument have been discussed in relation to the *ideal* of the experiment and *objectivity*.[25] That Wilson himself was devoted to this ideal has been investigated by Engels by means of an exact replica of the original Wilson instrument and the re-doing of his experiments (Fig. 6).[26]

The automated sequence is recalled by Wilson in his Nobel Lecture of 1927—this time, however, in the form of a "procedure" for obtaining good tracks:

> For the purpose of obtaining sharp pictures of the tracks, the order of operations has to be: firstly the production of the necessary supersaturation condition by sudden expansion of the gas; secondly, the passage of the ionizing particles through the supersaturated gas; and finally, the illumination of the cloud condensed on the ions along the tracks.[27]

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and N. Robotti, "A note on the Wilson cloud chamber (1912)," *European Journal of Physics* 25 (2004): 781–91.

[25] Daston and Galison, "The Image of Objectivity" (ref. 6), and *Objectivity* (ref. 6).

[26] W. Engels, "Die Nebelkammeraufnahme—das automatisch generierte Laborbuch?," in *Konstruierte Sichtbarkeiten: Wissenschafts- und Technikbilder seit der Frühen Neuzeit*, ed. Heßler, Martina (München: Wilhelm Fink, 2006), 57–74.

[27] Wilson, "On the cloud method" (ref. 20), 200.

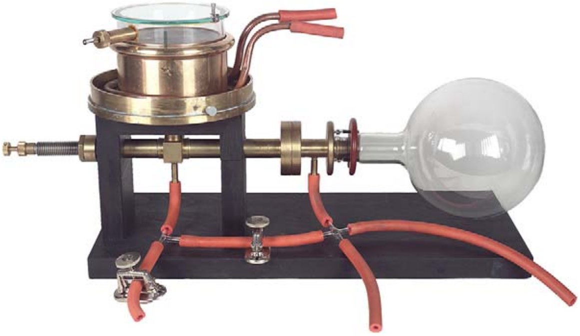

FIG. 6. Full-scale replica of the Wilson cloud chamber of 1912.
Source: Courtesy of Wolfgang Engels, University of Oldenburg.

However, as shown by Heering, the relation between a given procedure and the successful performance of the experiment must be considered with extreme care, especially when the instructions are given by the scientist himself.[28] In the present case, it will suffice to say that Wilson's 1927 indications do not exhaust the practical knowledge required for re-doing his experiments and duplicating the 1912 catalog of images.

2.2. Toward the Golden Age

In the successive decades, not only has the Wilson instrument been modified by placing the chamber horizontally, vertically, or by governing its functioning with engines or electronic circuits, but it has also been moved vertically, from the labs at sea level to the high mountains to get closer to the natural, cosmic source of particles. In its last, gigantic, and hyper-sophisticated version, the instrument will be shifted horizontally, at different distances from a particle accelerator to catch "in-flight" processes. This chain of Wilson cloud chambers produced images of events feeding multiple theoretical scenarios that were often developing in parallel and span from the early studies of radioactivity, to the theory of weak and strong interactions, to quantum electrodynamics. However, historical research has shown how—before the establishment of a cloud chamber physics community, where various groups adapted the Wilson method on their own initiative and started to produce their own results—for ten years after their publication, the 19 pictures published by Wilson in 1912 held the attention of

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[28] P. Heering, "An experimenter's gotta do what an experimenter's gotta do—but how?," *Isis* 101 (2010): 794–805.

all research: in this first phase, Wilson's method gained acceptance mostly thanks to what the others saw on Wilson's pictures. Chaloner reports how, in 1914, Ernst Rutherford saw them as "convincing evidence of the correctness of the view that large deflections do occasionally occur as a result of an encounter with a single atom"; and in 1915, Kovarick and McKeehan in America find Wilson's pictures in agreement with their own results from electrical counting methods; and Moore refers to Wilson's work as one of "numerous independent experiments" by which it is recognized "that ionization by X-rays is the result of corpuscular radiation liberated by the X-rays."[29]

Wilson himself, in the Nobel Lecture, reports that he showed W. H. Bragg one of the first good pictures of alpha particle tracks and found out that the renowned theoretical physicist had just theoretically derived the characteristics of an alpha particle track, and the theoretical prediction fit very well with the pictures obtained with the cloud chamber. Wilson's 1912 catalog, a total of 21 pictures, remained the only published visual material until 1921. In that year, Wilson resumed his activity, and by 1923, research with the Wilson instrument had begun in South Africa, India, and United States. From this period, Wilson's 1912 collection of historical pictures is successfully increased with recordings relying on substantial adaptations of the Wilson instruments by other physicists. Wilson continued his own research. Just as he had founded the study of "condensation physics" at the end of the nineteenth century and made it the conceptual terrain for the development of the cloud chamber, after 1912, he concentrated on the inner working of the instrument to improve the quality in tracks formation, the practical terrain on which the discoveries had been possible. And he kept this specialized subject alive for more than two decades after the introduction of the original instrument.

Making it meaningful to study radioactive processes: Tackling unpredictability

The automatic cloud chambers allowed prolonged observation of visible tracks by means of a reciprocating piston whose movement was driven either by an engine or by a spring. This adaptation was guided not so much by the desire to obtain a photographic recording of alpha particle tracks but, rather, of the collisions between the particle and one of the nuclei of the vapor inside the chamber. The observation of such collisions, though highly random, would

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[29] C. Chaloner, "The most wonderful experiment in the world: a history of the cloud chamber," *British Journal for the History of Science* 30, no. 3 (1997): 357–74.

have allowed testing of the hypothesis of disruption of the nucleus advanced by Rutherford in 1919:[30] having this goal in mind, the Cavendish researcher Takeo Shimizu developed in 1921 the first automatic cloud chamber in which the piston reciprocated two times per second and was kept at work for a timeframe of hours, while pictures were taken.[31] The "transmutation of the nitrogen" and the "Compton effect" are milestone achievements accomplished with this kind of apparatus.

In a chamber containing nitrogen (and a small portion of oxygen), bombarded by alpha particles emitted by a radioactive source, out of 23,000 photographs containing a total of approximately 415,000 tracks, the Cavendish physicist Patrick Blackett could identify six pictures showing evidence for a different phenomenon (Fig. 7): in each of them, the track of alpha particles coming from the source is interrupted to leave space showing track of a proton and a residual nucleus. The existence of two final tracks—neither of which was an alpha particle—led Blackett to abandon the idea of a process of "disintegration" and investigate instead a process of "integration" where the alpha particle is absorbed into the nitrogen nucleus, which, besides emitting a proton, turns itself into—or transmutes into—an isotope of a different chemical element (oxygen).[32]

The apparatus and the procedure used by Arthur Compton and Alfred Simon was similar to the one used by Blackett, but the investigated phenomenology was very different: in the 1920s, the general problem of understanding how radiation interacts with matter coalesced in a series of experiments investigating the correlation between x-rays scattered by a material. Compton's studies on the subject began in 1922, and the experiment of 1925 using the Wilson method produced evidence for the existence of directed quanta of radiation. As a result, interaction between light and matter could be modeled as an elastic scattering between an incoming photon of the radiation and a secondary electron of the atom, considered a free electron—which is the essence of the "Compton effect." Out of 850 plates, Compton and Simons identify 38 in which both an x-ray entering the chamber and a recoiled electron

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[30] E. Rutherford, "Collision of α particles with light atoms, IV: An anomalous effect in nitrogen," *Philosophical Magazine* 37 (1919): 581–87; E. Rutherford, "Bakerian Lecture: Nuclear Constitution of Atoms," *Proceedings of the Royal Society A*, 97 (1920): 374–400.

[31] T. Shimizu, "A Reciprocating Expansion Apparatus for Detecting Ionising Rays," *Proceedings of the Royal Society A*, 99 (1921): 425–31.

[32] P. M. S. Blackett, "The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method," *Proceedings of the Royal Society A*, 107 (1925): 349–61.

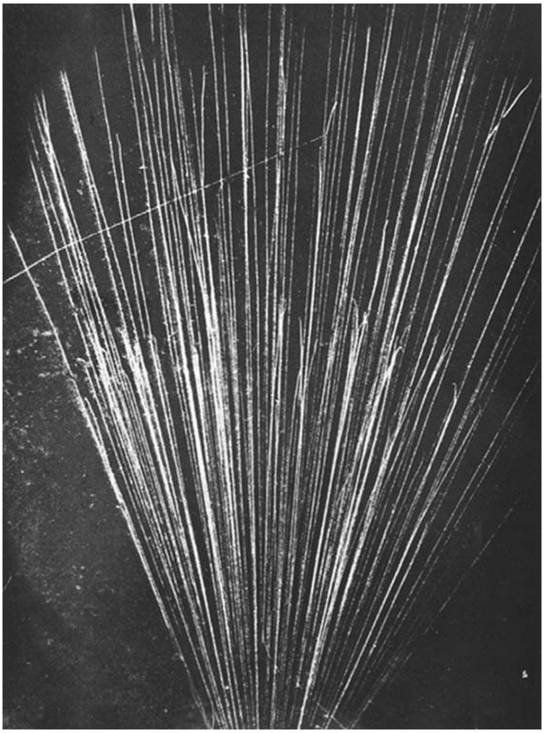

FIG. 7. Transmutation of nitrogen with a particularly long track for the proton. This picture is not taken from Blackett's 1925 paper but from a later one co-authored with D. S. Lees. However, due to its clarity (the track of the proton is particularly visible), this image is commonly used when discussing the observation of 1925. *Source:* P. M. S. Blackett and D. S. Lees, "Investigations with a Wilson Chamber. I. On the Photography of Artificial Disintegration Collisions," *Proceedings of the Royal Society A*, 136 (1932): 325–38. Copyright 1932 by The Royal Society

were portrayed (Fig. 8), and find that in 18 cases, the measured angles were compatible with the conservation of energy and momentum, under the assumption that light consists of quanta of energy hν.[33]

Several months before the publication of Compton and Simon's paper in the *Physical Review*—September 1925—the June issue of the *Zeitschrift für*

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[33] A. H. Compton and A. W. Simon, "Directed Quanta of Scattered X-Rays," *Physical Review* 26 (1925): 289–299.

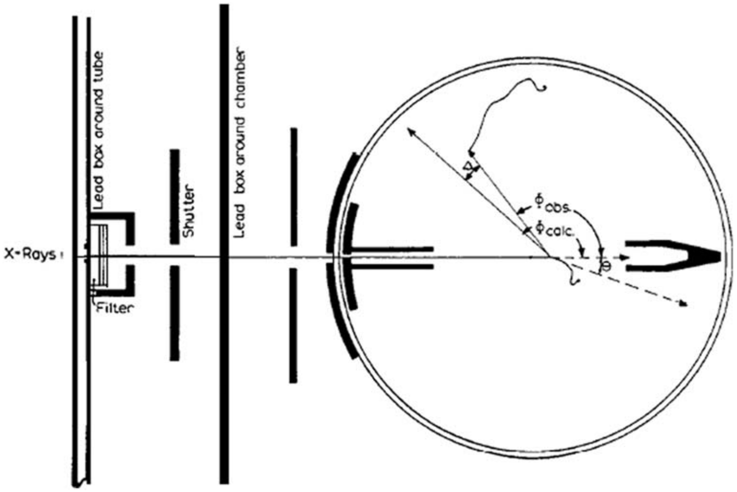

FIG. 8. Compton and Simon's experiment with the cloud chamber: an electron recoiling at an angle *q* is associated with a photon deflected through an angle *j*. In the image, the two curled lines represent electrons, one identifying the initial Compton scattering and the other caused by the scattered gamma rays. The two points of departure reveal the scattering angle for the gamma, which is then confronted with the predicted angle. The distribution of the difference between the predicted and observed angle strongly suggested the validity of the quantum hypothesis and the conservation law. *Source:* A. H. Compton, "X-rays as a Branch of Optics," *Nobel Lecture* (1927): 174–90, Fig. 10. Copyright 1927 by The Nobel Foundation.

Phisik reported an experiment by Bothe and Geiger that, although less definitive in its conclusions, analyzed the same effect with a different experimental technique: the Geiger-Müller countering method.[34] The Compton effect is an interesting case from the point of view of recent scholarship: investigated, almost contemporarily, with the Wilson cloud chamber and the Geiger-Müller countering method, it provided a stage for the two major traditions identified by Peter Galison throughout the twentieth-century particle physics investigation, the Image tradition and the Logic tradition. At the same time, the statistical use of cloud chamber pictures made by the physicists in the discovery of the Compton effect challenges Galison's view. This debate will be taken up in the following section, where a further notable case is discussed: the discovery of the positron.

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[34] W. Bothe and H. Geiger, "Über das Wesen des Compton-effekts; ein experimenteller Beitrag zur Theorie der strahlung," *Zeitschrift für Physics* 32 (1925): 639–63.

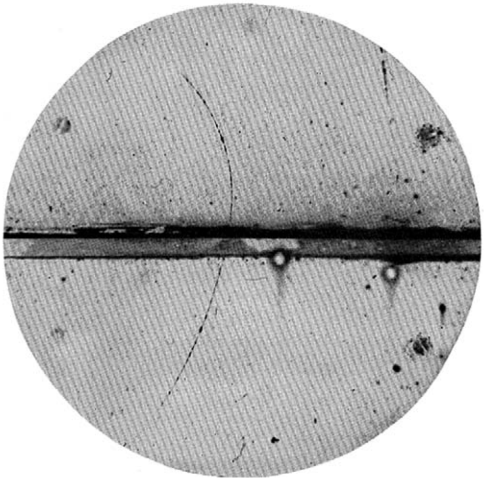

FIG. 9. Anderson's photograph of "positive electron" taken on August 2, 1932. The particle moves upward, crosses a lead plate of 6 mm, and its curvature is then increased due to the loss of energy while crossing the plate. *Source:* Copyright 1933 by The American Physical Society.

The end of the 1920s sees the employment of the cloud chamber for studying particles whose source is outer space, the cosmic rays, for which the automatic instrument was essentially unsuitable. In fact, because of the total randomness in the occurrence of a cosmic ray process within the chamber, most of the pictures didn't contain any interesting event, with a consequent waste of time and resources. Nonetheless, it is with an instrument of this sort, built by Carl Anderson and Robert Millikan at California Institute of Technologym that the first, *unsearched* evidence for an esoteric speculation was captured: the existence of antimatter, observed in 1932, and foreseen by Paul Dirac in 1928.[35] The interpretation of this first recording as "the positron" (Fig. 9)—the entity of antimatter predicted by Dirac—is strongly associated with two important manipulations of the apparatus. The first one is a horizontal lead plate crossing in the chamber, which allowed the direction of the particle to be observed. In fact, since November 1931, Anderson's instrument put forward recordings that showed a series of particles for which a two interpretations were possible: either

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[35] P. A. M. Dirac, "The Quantum Theory of the Electron," *Proceedings of the Royal Society A*, 177 (1928): 610–24.

protons proceeding downward—as suggested by Millikan—or positive electrons proceeding upward.[36] The knowledge about track ionization pointed toward the electron interpretation: the ionization produced by a particle depends on its velocity, and a particle with higher mass (a proton) produces more ionization and a darker track in the photographs. Anderson's track was a minimum ionizing track, suggesting a mass lower than the proton. The insertion of the lead plate and the detected smaller curvature of the track in the upper part allowed Anderson to substantiate the interpretation of the positive electron by adding that the particle was travelling upward, that it had crossed the plate and lost its energy.[37] The positive electron travelling upward would have been produced by a disruption of a nucleus happened in the lower part of the chamber.

With regard to the mentioned work of Galison and Asmuss on the origin of the cloud chamber, in which they regard the introduction of the cotton wool filter as a crucial departure from the mimetic tradition toward the making of real particles, the introduction of the lead plate in the positron discovery, while remaining within the same analytic tradition, marks a crucial indication of "antiparticles." However, interpreting the particle as a "positive electron" didn't coincide with recognizing it as proof for Dirac's theory and declaring antimatter's existence. This further step, discussed in the following section, called for understanding how these "positive electrons" were produced and, on this account, the second manipulation stands out.

Control over total randomness

Anderson's pictures and their problematic interpretation had been discussed by Millikan in late 1931 in two European conferences held in Paris and Cambridge.[38] Intrigued by the problematic interpretation of the tracks, the two Cavendish researchers, Patrick Blackett and Giuseppe Occhialini, address the problem of finding a way to improve the efficiency of the whole apparatus and

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[36] An extensive account on the debated interpretation can be found in P. Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987), 89–96.

[37] The two main publications of Anderson's observation are: C. Anderson, "Positives," *Science* 76 (1932): 238–39; C. Anderson, "The Positive Electron", *Physical Review* 43 (1932): 491–94. Other publications on the subject: C. Anderson, "Energies of cosmic rays particles," *Physical Review* 41 (1932): 405–21; C. Anderson, "Cosmic-Ray Positive and Negative Electrons," *Physical Review* 44 (1933): 406–16.

[38] R. C. Millikan and C. Anderson, "Cosmic-Ray Energies and Their Bearing on the Photon and Neutron Hypotheses," *Physical Review* 40 (1932): 325–28.

avoiding spoiling the pictures. One week before Anderson sent his observations with the lead plate to the journal *Science*—September 6, 1932—the two Cavendish researchers sent a letter to *Nature* in which they introduced the "counter-controlled cloud chamber":[39] the core idea of this new apparatus is effectively summarized by the incipit of the paper, in which the two aouthors claim to have found a method that leads cosmic particles "to take their own photograph."[40]

In the apparatus, the cloud chamber stands in a vertical position, and two Geiger-Müller counters are placed above and below. Counters and the camera are connected by means of a coincidence circuit so that a cosmic ray crossing the chamber would pass through both counters, trigger the coincidence, and activate the expansion and the camera: "When the cloud chamber has been made ready for use, the arrival of a coincidence is awaited. After an average wait of two minutes, a coincidence occurs and a relay mechanism starts the expansion."[41]

In February 1933, in a communication to the Royal Society, Blackett and Occhialini present a collection of 13 pictures selected out of 700 taken in a controlled chamber crossed by Anderson's plate: by means of these pictures, they both confirmed the existence of the "positive electron" and showed how it naturally fit in the pair production scheme foreseen by Dirac, in which high-energy photons created a positive and negative electron out of the vacuum. Antiparticles were finally made real.

The discovery of the positron is an interesting terrain from different scholarly perspectives: in Galison's view, the Anderson picture of 1932 (Fig. 9) is a *golden event*, a bright example of the Image research tradition, which strives for non-statistical demonstrations *and* for compelling, single events—"a single picture of such clarity and distinctness which commands acceptance."[42] Galison identifies the Wilson cloud chamber as the founder of such a tradition. The Image tradition is distinct from the Logic tradition, which, set by the Geiger-Müller counters, relies on statistical argument, i.e., occurrences standing out of the background. This view has been criticized by Kent Staley, who claims that twentieth-century microphysics should be understood as a shared commitment to a statistical form of experimental argument. Regarding the

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[39] P. M. S. Blackett, and G. P. S. Occhialini, "Photography of Penetrating Corpuscular Radiation," *Nature* 130 (1932): 363.

[40] P. M. S. Blackett and G.P.S. Occhialini, "Some photographs of the tracks of penetrating radiation," *Proceedings of the Royal Society A*, 139 (1933): 699–719.

[41] Blackett and Occhialini, "Photography" (ref. 39), 363.

[42] Galison, *Image and Logic* (ref. 2), 22.

positron, Staley points out that in both papers of 1932 and 1933, Anderson showed photographs of, respectively, three and four events, although he put the emphasis on a single event. By illustrating his interpretation of this picture, Anderson makes sure to exclude this event from a possible background effect: tracks of such curvatures occur in 1 of 500 photographs. To assume that the picture does not portray 1 positive electron moving upward, but instead 2 negative electrons moving up and down generated from a single point inside the plate, decreases the probability to 1 picture in 250,000, out of a total of 1,300 photographs.[43]

Despite offering interesting elements for debating the existence of two traditions of scientific arguments, when considered from the point of view of the experimental apparatus, the discovery of the positron suggests a distinction between the two traditions, but also of their merging into a stable apparatus where the selectivity of the first and the representational potential of the second are exploited. Even though the counter-controlled cloud chamber is extensively quoted in historical studies, no account refers to the second core aspect of the device, which made it ideal for the study of cosmic rays no less than the use of the counters. This further aspect concerns the inner core of the instrument and falls within Wilson's contributions to the improvement of quality in the visualization of tracks and in the taking of pictures.

Manipulating the core: From volume-driven to pressure-driven cloud chambers

In 1933, Wilson introduced an alternative mechanism to the one he had proposed in 1911: the new apparatus has a fixed floor, a porous diaphragm covered with dark velvet felt through which an amount of gas is sucked away by the downward motion of a sheet of thin elastic membrane placed underneath the floor. The vapor that remains within the chamber expands and then condenses in tracks. The "persistence of the super-saturation condition" is noted by Wilson as principal advantage of this "pressure-driven" cloud chamber, alternative to the "volume-driven" chamber of 1912.[44] The new mechanism for condensation is immediately exploited by cosmic ray physicists, as attested by an account given by Blackett in 1934 on the controlled-cloud chamber: the

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[43] K. Staley, "Golden Events and Statistics: What's Wrong with Galison's Image/Logic Distinction?." *Perspectives on Science* 7 no. 2 (1999): 196–230, on 214–17.

[44] C. T. R. Wilson, "On a New Type of Expansion Apparatus," *Proceedings of the Royal Society A*, 142 (1933): 88–91.

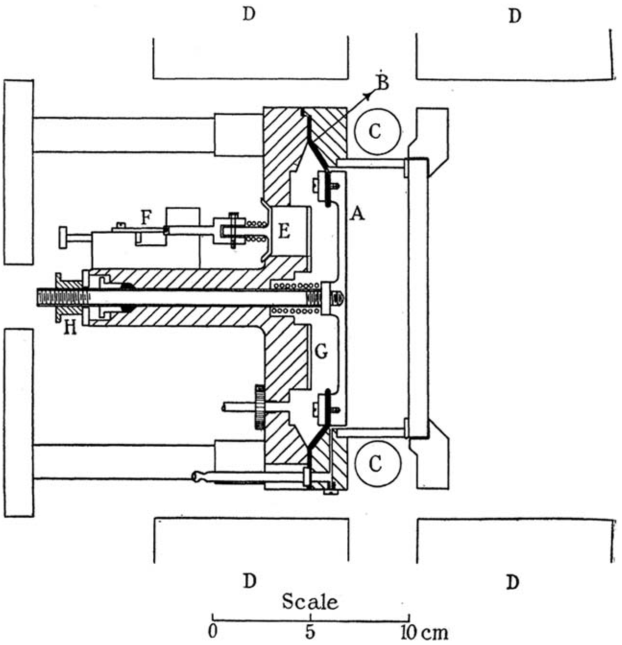

FIG. 10. Expansion system in the counter-controlled chamber. The chamber volume is indicated by A. The right side is made of glass; on the left is a thin layer of black velvet. Underneath the velvet, in central and horizontal position is a thin piston moving leftward under the command of the counters (C) to decrease the pressure within the volume. Magnets for curving charged particles are indicated with D. *Source:* Blackett, "On the Technique" (ref. 45). Copyright 1945 by The Royal Society.

chamber stands in vertical position, and a small piston quickly moves horizontally and decreases the pressure (Fig. 10).[45]

In 1935, a year after Blackett's publication, Wilson extends the pressure-driven mechanism to a cloud chamber of radial form in which the expansion moves a membrane moving outward: this geometry allowed the chamber to be positioned between the two poles of a magnet, an ideal placement within the magnetic field. At the same time, it allowed the chamber to slip from the magnets by letting it fall immediately after the expansion to optimize the photograph. The persistence of tracks lasting more than one second would

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[45] P. M. S. Blackett, "On the Technique of the Counter Controlled Cloud Chamber," *Proceedings of the Royal Society A*, 146 (1934): 281–99.

have allowed an "in-flight" photograph, which maximize both the magnetic and the optical conditions of observation.[46]

Wilson's long-standing dedication to the "art of images formation" set the foundation of the cloud chamber technique during the golden age; pros and cons of the two mechanisms of 1912 and 1933 were discussed in a compendium published in 1951, the volume defined as ideal as far the velocity of the expansion and sharpness of the tracks is concerned, the pressure defined for a prolonged persistence of the supersaturation.[47]

Changing the geometry vertically: The cloud chamber as a high mountains detector

The counter-controlled cloud chamber conceived by Blackett and Occhialini, with the lead plate introduced by Anderson and based on Wilson's mechanism of 1933, remained the central apparatus for successive studies on cosmic rays made on Earth in the first half of the twentieth century. In the apparatus, electron-positron couplets were observed within extended patterns called "electromagnetic showers" (Fig. 11).

The discovery of the muon showed that showers contained a richer phenomenology than the sole couplets. In the case of the muon, isolating the new phenomenology not only required a further manipulation of the apparatus—a further layer of material as for the positron—but also a change in the geometry of the experiment, displaced between a lab at sea level and a lab on the mountain, at an altitude of 4,300 meters.[48] By comparing the rate of showers production on the two sites—finding out that, on altitude, showers of positron-electron couplets appear more frequently and contain more numerous tracks—Anderson and Neddermayer selected 123 pictures out of 9,188, which also showed tracks of particularly penetrating particles, with a thickness similar to the one of a proton and bearing little relation with the direction of the shower.[49] As the two physicists suggested the existence of a new entity of electronic charge and intermediate mass between the electron and the proton,

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[46] C. T. R. Wilson and J. G. Wilson, "On the falling cloud-chamber and on a radial-expansion chamber," *Proceedings of the Royal Society* 148 (1935): 523–33.

[47] J. G. Wilson, *The Principles of Cloud-Chamber Technique* (Cambridge: Cambridge University Press, 1951), 37.

[48] For an extensive account on muon discovery, see P. Galison, "The Discovery of the Muon and the Failed Revolution against Quantum Electrodynamics," *Centaurus* 50 (1982): 105–59.

[49] C. Anderson and S. H. Neddermeyer, "Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level," *Physical Review* 50 (1936): 263–71; C. Anderson and S. H. Neddermeyer, "Note on the Nature of Cosmic-Ray Particles", *Physical Review* 51 (1937): 884–86.

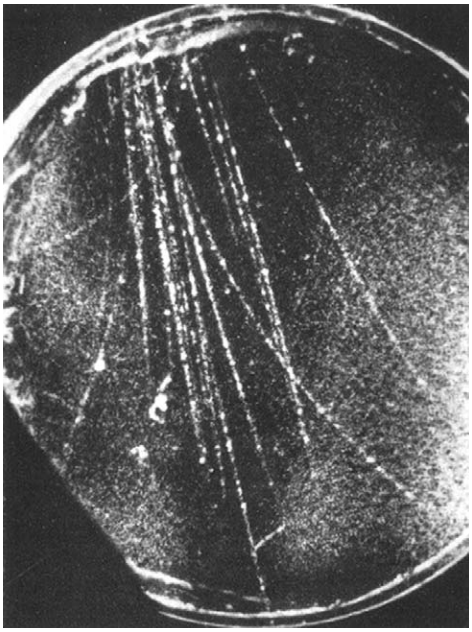

FIG. 11. Electromagnetic showers by Blackett and Occhialini in Cambridge. *Source:* Blackett and Occhialini, "Some Photographs" (ref. 40). Copyright 1933 by The Royal Society.

Street and Stevenson assembled the apparatus providing the evidence for it: in the apparatus (Fig. 12), a 10 cm filter of lead is placed above the chamber, and two Geiger counters are placed above and below the filter. The rationale is to stop the whole shower within the lead by letting into the chamber only the extremely penetrating particles. The system resulted in only 2 pictures out of 1,000 in which two particles with tracks very similar to a proton ended their run within the chamber. The study of their tracks' density and magnetic deflection revealed both a proton and a negative particle with a mass 130 times the mass of the electron, the muon.[50]

2.3. Toward the Sunset

In a myriad of variations, the previous constructive elements combine in the plethora of devices covering the whole range of applications described in the

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[50] J. C. Street and E. C. Stevenson, "New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron," *Physical Review* 52 (1937): 1003–04.

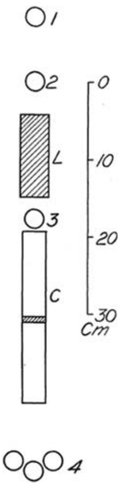

FIG. 12. Schema of the apparatus by Street and Stevenson. Numbers 2 and 3 are two counters placed above and below a lead filter L. The cloud chamber is indicated with C. *Source:* Street and Stevenson, "New Evidence" (ref. 50). Copyright 1937 by *Physical Review*.

1946 Report mentioned at the opening of this section. The Report, a current scientific form of communication, falls between the publication of the two volumes of the mentioned atlas in 1940 and 1952, an old literary genre appropriated by physicists for the first time: taken altogether, the three publications delimit a specific research field established by the Wilson method. The sunset starts when even a change in the geometry of the experiment—for instance, bringing it up to the mountains or shifting it at different distances from the particle accelerator—couldn't overcome its limitations in terms of efficiency and of the type of the observations it could reveal. The study of the "V particles" is a significant example.

In 1947, Rochester and Butler of the University of Manchester published two pictures, selected from some 5,000 taken in 1,500 hours of operation, that showed the peculiar signature of a "V" where two straight tracks generated from a single vertex.

Tracks analysis didn't allow the identification of any known particle, neither a better specification of the process than a spontaneous transformation, nor a decay of a new type of neutral particle into two charged ones, nor or of a new charged particle into a charged and neutral one.[51] Given no other

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[51] G. D. Rochester and C. C. Butler, "Evidence for the existence of new unstable elementary particles," *Nature* 160 (1947): 855–57.

"forked track" observed in all of 1948 and the first half of 1949, the Manchester group dismantled the instrument and, by October 1949, had it ready on the mountain site, Pic du Midi, in the French Pyrenees, at a 2,867 m altitude.[52] Their hypothesis was that, at this height, cosmic rays might still have sufficient energy to generate a higher number of those processes. In fact, during the successive seven months, 63 pictures out of 10,000 showed V particles.

In the nine years of experiments at Pic du Midi, the kind of questions faced by the researchers shows the extent of the complexity of the new subject, the phenomenology created by the nuclear interaction: whether two or three types of neutral V particles existed; whether, even though they decay into the same products, they could be distinguished before their decay.[53] Answering these questions will necessitate abandoning the naturalistic and random environment of the high mountain laboratories in favor of the Big Science laboratories that were emerging in the 1950s in Europe and United States, and where experiments could be performed in a more controlled, efficient, and artificial way. If the appropriation of the literary genre of the atlas had signified the triumph of the Wilson method, the decision to use letters taken from the Greek alphabet for describing the ungovernable multiplicity of the new entities should be probably considered as the literary expression of its sunset. This decision was taken by a commission of experts at the bottom of the Pic du Midi Mountain during the Congress held at Bagneres de Bigorre in 1953.

Changing the geometry horizontally: The Wilson cloud chamber as a Big Science detector

The biography of Wilson cloud chamber in research does not end with the mountain season of the cosmic rays' research nor with Wilson's return to the writing of a long-promised manuscript on the theory of thunder cloud electricity, to be published in 1956, three years before his death.[54] Rather, the cloud chamber will stay on the stage of particle physics research for more than ten years after the introduction, in 1952, of its biggest competitor detector—the

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[52] C. C. Butler, "Early cloud chamber experiments at the Pic-du-Midi," *Journal de Physique Colloques* 43 (1982): 177.

[53] A. Franklin, *Shifting Standards: Experiments in Particle Physics in the Twentieth Century* (Pittsburg: University of Pittsburg Press, 2013), ch. 8.

[54] C. T. R. Wilson, "A theory of thundercloud electricity," *Proceedings of the Royal Society A*, 236 (1956): 297–317.

bubble chamber. At the European Council for Nuclear Research (CERN) founded in 1954, besides the numerous Wilson instruments brought at CERN from the high-mountain sites, a Wilson cloud chamber has been specifically conceived and built as a Big Science apparatus for a joint use with the Proton Syncrotron—CERN's second accelerator and world most powerful one, operative since November 24, 1959.

With an illuminated volume of 40 cm height, 60 cm width, and 170 cm length, totally shielded by a magnet creating an induction of 10,000 to 11,000 gauss, the Big Wilson chamber had a fixed floor made of a perforated metal plate and covered with black velvet, and worked accordingly to the same pressure mechanism described by Wilson in 1933.[55] The unique experiment performed with this instrument between 1962 and 1963 was fully to studying the "strange particle," the neutral kaon (K), which, once artificially produced by the accelerator, appeared to show two different modes of decay, whereas any previously known particle had only one. Whereas catching the V particles required vertical movement of the instrument, toward the source, the study of these different, strange modes of decay of the K meson produced by the accelerator are searched by moving the instrument horizontally, collecting pictures when the instrument is placed at different distances from the place where the beam is generated. With a total of 3,500 pictures taken with the instrument at 30, 40, and 50 meters from the beam generation, the experiment provided a measure of the two-different mean lifetime of the kaon, according to which the two different decays take place.[56]

However, both strategies of moving the chamber, vertically or horizontally, were an attempt to overcome an inner limitation of the cloud chamber involving the very core of the instrument: the scarce effectiveness of the vapor in providing the suitable targets, the nuclei of the elements, to induce the production of the new entities, subatomic particles not belonging to ordinary matter, which, once artificially produced by nuclear collisions with cosmic rays, had a very short lifetime. As usually described in cloud chamber historical

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[55] PS experimental programme, 13th Session of the Council, 26 May 1959, and Executive Committe for the PS Experimental Programme, Eighteen Meeting, 3 Nov 1959, "The Plane for the use of the cloud chamber" (CERN archive).

[56] P. Astbury, A. Michelini, C. Verkerk, F. Verkerk, W. Beusch, M. Pepin, and M. A. Pouchon, "A measurement of the mean life of the K_0^2," *Physics Letters* 18, no. 2 (1963): 178–81. P. Astbury, A. Michelini, C. Verkerk, F. Verkerk, W. Beusch, M. Pepin, and M. A. Pouchon, "$K_0^2 \rightarrow \pi^+ \pi^- \pi^0$ decay: Branching ratio and πo energy spectrum," *Physics Letters* 18, no. 2 (1965): 175–78.

studies, the instrument as conceived by Wilson can't keep up with the new phenomenology and proves essentially ineffective in producing novel material for theoretical speculations. Besides, the tiding between the biography of the cloud chamber and the long-life contribution provided by its inventor displayed in this paper, must suggest a further consideration: whereas, in 1935, the incoming subject of cosmic rays had seen Wilson himself staging the first move to adapt his instrument—with the introduction of the "pressure-driven mechanism" that allowed the chamber to stand in vertical position—this was not the case for the emergent field of the strange particles in the mid-1950s. Wilson's potential move for a new adaptation was perhaps intercepted by Donald Glaser, who, concerned for the future of cloud chamber studies on the high mountains, had set his research question in a way that was essentially complementary to the one faced by Wilson in 1911: Under what condition can a liquid (vapor) boil (condensing) around the ions produced by a charged particle?[57] This question, answered in 1952, brought about the birth of a "new" instrument with the same identity—the bubble chamber.[58] The late 1950s and early 1960s saw the bubble chamber replacing the Wilson instrument: the liquid in the new device proved to be more effective than vapor for the study of the interactions between particles and nuclei. Since then, no CERN research activity mentions the Wilson instrument. However, in the light of its biography, a slight echo to its origins is probably sounded by the experiment CLOUD (Cosmics Leaving Outdoor Droplets), wherein a cloud chamber is jointly used with the Proton Synchrotron for a climate experiment focused on how clouds affect the Earth's temperature.

3. CONCLUSIONS

This paper retraced the biography of the cloud chamber introduced by Charles Thomson Rees Wilson in 1911, and vastly adopted in successive studies on particle physics. By developing a comprehensive reading wherein the evolution of the instrument and the emerging knowledge of the field are kept in tight connection, the paper articulated the relationship between *experimental technique* and *discoveries* during the establishment and

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[57] For an extensive account, see P. Galison, "Bubble Chambers: Factories of Physics," ch. 5 in *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997).

[58] D. Glaser, "Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids," *Physical Review* 87, no. 4 (1952): 665.

consolidation of the particle physics research field in the first half of the twentieth century. In so doing, it brought to light some elements that hadn't yet received the deserved attention within historical research on the cloud chamber and, at the same time, it offered more general insights concerning experiments in science. Of the first kind is certainly the discussion of Wilson's contribution after the introduction of the instrument in 1911, a contribution that continued for more than twenty years and set the foundation for an experimental technique lasted until the 1960s within the Big Science experiments performed at CERN.

At the same time, the biography touched several questions that are of interest for research in the history of science; they concern historiographical debates over experimental traditions in twentieth-century physics, the biographical frame for the narrative on an instrument, the notion of instrument's life-cycle trajectory, and the intersection of different biographies of subjects. To these questions the present section is devoted.

3.1. Was It Really a Sunset?

With the last CERN experiment, the cloud chamber seems to be back to its original context, the physics of the atmosphere. Accordingly, the trajectory of the instrument throughout the history of particle physics retraced in this paper features a transit into an area for which the instrument was not programmed: a chapter in a wider story moved by a cyclic dynamic opened and almost completely supervised by Wilson. The return of the cloud chamber to the native terrain of atmospheric studies allows us to observe how, in more than one century, not only have the locations for these studies changed—from the Observatory of Ben Navis to CERN—but their intents have changed as well: the amateur-oriented "mimetic approach" pursued by Wilson and guided by a sense of wonder toward Nature turned into a "simulation experiment" driven by a sense of alarm. Starting from the premise that clouds exert a strong influence on the Earth's energy balance, the CLOUD experiment investigates whether cosmic rays may influence cloud cover either through the formation of new aerosols (tiny particles suspended in the air that can grow to form "seeds" for cloud droplets) or by directly affecting clouds themselves. In a cloud chamber of 26 m^3, a simulation of the cosmic flux provided by the accelerator is injected; not collisions, but the evolution from gas molecules to clusters to particles under atmospheric conditions are studied. The extremely stable and reproducible environment of accelerator physics finally hosts the old-fashioned observations on the formation and growth of bubble and droplets already set in the nineteenth century and still alive in the 1946 Report quoted at the beginning of this paper. Historians of science have effectively used the biographical approach to investigate why phenomena or objects become the subject of scientific inquiry, why some fade from center stage while others remain provocative, and why objects sometimes return as the focus of research long after they had been abandoned.[59] Within this framework, the life cycle of the cloud chamber suggests that the return in focus of a specific subject—atmospheric studies, in this case—might be accompanied by experimental apparatuses or technical methods that are historically connected to it and whose relevance for the field has not been invalidated.

On the other hand, the relevance of the cloud chamber for particle physics studies had a proper course, carefully retraced in this paper, that allowed the biography to take shape. Viewed as transit, which necessarily implies the crossing of the borders between different disciplines, the trajectory of the cloud chamber throughout the history of particle physics appears particularly interesting from the point of view of the representation of processes and of the language used to interpret them:[60] Wilson's intuition of 1911—to use the time persistence of a thermodynamic phenomenon, condensation, to picture one particle's trajectory—is rapidly extended by cloud chamber physicists to bridge the past and the future of a single event—such as the transmutation of an element—by fixing in the same picture the tracks of the agents and of the products of a reaction. This achieved representation of the microworld generated a language for the interpretation of the visual recordings: cloud chamber pictures allowed the conservation laws, a real repository of trust for twentieth-century particle physicists creating their new theories, to be used and tested in a graphical manner. By putting the portrayed entities in relation to each other, the empirical recognition of the identity of one particle (from thickness or length, or the curvature of the track) could be supported with deductive consideration until the point of suggesting the existence of new entities and the necessity of modifying the theories. In this new language, entities are labelled by a letter of Greek alphabet, while the laws

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[59] L. Daston, *Biographies of Scientific Objects* (Chicago: University of Chicago Press, 2000).

[60] For an exemplary study on object biographies as a research necessarily located at the junction of different disciplines, see H-J Rheinberger, "Cytoplasmic particle, the trajectory of a scientific object," in *Biographies of Scientific Objects*, ed. Lorraine Daston (Chicago: University of Chicago Press, 2000), 270–84.

governing their interactions are codified in the patterns drawn by the ensemble of the tracks.

From the point of view of language and representation, the mentioned bubble chamber might be well considered as a new instrument with the same identity of the cloud chamber. However, one cannot neglect the implications of Glaser's technical findings, which strongly influenced the successive trajectory of the bubble chamber: the low persistence of the tracks in a bubble chamber made the instrument unsuitable for cosmic ray physics by bounding the device to the controlled pulses of the accelerators; the high-pressure regime in which the bubble chamber worked opened a new chapter where engineering, security issues, and procedures strongly changed the physic laboratory; the high efficiency of the instrument in providing a high number of pictures with potentially interesting events, allows the bubble chamber story to intercept contemporary issues such as Big Data handling and the search for strategies for data analysis connected to it.

3.2. Image or Logic? Perspectives on the Debate from the Cloud and the Bubble Chamber Biographies

The first official experiment with the new emerging detector, the bubble chamber, was performed at Brookhaven Laboratories in 1957 by an Italian and American collaboration that included Donald Glaser himself.[61] The experiment was the last of a chain of crucial tests—the first of which had been performed by a team led by the Sino-American physicist Chien-Shiung Wu of Columbia University in the last months of 1956—that led to the milestone discovery that the symmetry of parity is violated in weak interactions.[62] The comparison between the first and the last of these crucial tests gives the possibility of adding an element to a question already discussed in this paper; i.e., the existence of two traditions in experimental physics, in Galison's view, or the shared commitment to the same form of statistical argument, as in Staley's perspective. In fact, whereas the physicists of Brookhaven detected the effect by using a bubble chamber, Wu and collaborators used the Geiger-

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[61] F. Eisler, R. Plano, A. Prodell, N. Samios, M. Schwartz, J. Steinberger, P. Bassi, *et al.*, "Demonstration of Parity Nonconservation in Hyperon Decay," *Physical Review* 108 (1957): 1353.

[62] For an essential but complete account on the sequence of the crucial tests on parity violation, see E. Bertozzi, "Toward a history of explanation in science communication: the case of Madame Wu experiment on parity-violation," *Journal of Science Communication, Special Issue: "History of Science Communication," JCOM* 16, no. 03 (2017): A10, 1–13.

Mueller counters. In Wu's experiment the violation of parity is demonstrated by an asymmetry between the electrons shot in by a nucleus of cobalt and detected by two counters placed above and below. In the bubble chamber experiment, by contrast, the asymmetry is an anisotropy in the distribution of the decay angles of the neutral lambda, itself a decay product of a pion shot by the accelerator and hitting the protons of the bubble chamber:

$$\text{Wu and colleagues}: \mathrm{Co} \;\text{->}\; \mathrm{Ni} + \mathrm{e}^{-} + \bar{\nu}_e$$

$$\text{Brookhaven collaboration}: \Pi_{-\mathrm{i}} + \mathrm{p} \;\text{->}\; \Lambda_0 + \theta_0; \Lambda_0 \;\text{->}\; \Pi_{-\mathrm{f}} + \mathrm{p}$$

Whereas in the positron case previously discussed in Section 2.2., statistical arguments are used to support the credibility of the recording and to exclude competitive processes of production, in the case of parity, statistics are a part of the process under investigation. Coherently, no "golden event" is included in the bubble chamber paper, but distributions of probability derived from the measured angles are reported. This last episode corroborates Staley's view on statistics as the ultimate terrain for the experimental tradition of microphysics in the twentieth century and the existence of a shared commitment to a statistical form of argument. This conclusion doesn't affect, however, the existence of two distinct Image and Logic traditions, since the role played by statistics is different in each of them: to argue for the credibility of the recording by discarding competitive processes in the Image tradition; to construct the recording itself in the Logic tradition.

Perhaps the more interesting element deriving from the debate is the need of a more articulated notion of a golden event within the Image tradition: not only as a recording of notable persuasive power—the single picture of such clarity and distinctness that it commands acceptance[63]—but also as the result of a statistically based process of credibility building that, performed upstream, fully contributes to the persuasiveness by progressively reducing the space for alternative interpretations. As such, the notion of a golden event might deserve future studies in which Staley's analysis of Anderson's positron is tested against bubble chamber discoveries involving more populated samples: the particle called Omega-minus detected in 1964—a total golden picture in the tradition of Galison—was selected out of a sample of 100,000 pictures, instead of the 1,300 of Anderson's positron, and would be an interesting candidate for such a test.

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[63] Galison, *Image and Logic* (ref. 2), 22.

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