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Particles that take photographs of themselves: The emergence of the triggered cloud chamber technique in early 1930s cosmic-ray physics

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One of the major accomplishments of early elementary particle physics research was the development of an apparatus able to efficiently collect photographs of cosmic-ray particles. This accomplishment was achieved in 1932 at the Cavendish Laboratory in Cambridge by triggering a cloud chamber with two appropriately connected counters. A careful analysis of the literature reveals that the development of the Cavendish apparatus was preceded and, in some respect, influenced by hybrid counter – cloud chamber devices devised previously in two U.S. laboratories.

I. INTRODUCTION

The triggered cloud chamber was invented by P. M. S. Blackett and G. Occhialini in 1932, although its history began in 1912 with V. Hess' study of atmospheric ionization at high altitudes.[i] Hess found that the ionization levels could not be explained by natural radiation alone. He concluded that a new penetrating extra-atmospheric γ-like radiation (*Höhenstrahlung*, meaning radiation from above), must be responsible. This phenomenon eventually became known as "cosmic rays," a phrase coined by R. Millikan.[ii] In the late 1920s, the cosmic γ-ray hypothesis rested on the empirical measurements obtained by closed vessels filled with gases at atmospheric or higher pressures (ionization chambers and electroscopes). Although the total ionization in the vessel was easily determined by this method, no information was available on the details of the production of this ionization.[iii]

The issue of the mechanism originating this ionization began to be reconsidered in 1929, largely because of the use of cloud chambers and counters in coincidence. With these devices, the detection of individual charged particles became possible and made possible the discovery of high-energy particles with great penetrating power.[iv] This discovery suggested a possible connection to the radiation believed to cause by high altitude ionization. However, the relation between these particles and the penetrating radiation was far from clear. The discovery of the former posed a serious problem in understanding the nature of cosmic γ-ray interaction with matter. In late 1920s it was believed[v] that the absorption of high energy γ rays was by Compton collisions as governed by the Klein-Nishina formula, which, was of uncertain reliability at such high energies.

A great step forward in resolving the issue of cosmic γ-ray interaction with matter was taken when cloud chambers and coincidence counters merged into a single device: the triggered cloud chamber. In this apparatus "an event could be made to trigger a cloud chamber, and, so to speak, take a photograph of itself, thus enabling rare events to be picked in the presence of a large unwanted background."[vi] Among the rare events buried in loads of unwanted background events were positrons. In 1933 the triggered cloud chamber provided a wealth of evidence for the existence of positrons in cosmic rays. This evidence lead to the discovery of a new kind of interaction, leading to pair creation and annihilation.[vii] Pair creation, rather than the Compton effect, governed many of the phenomena observed in cosmic-ray physics.

Considering the productivity of the triggered cloud chamber, it is surprising how much its has been neglected by historians of physics. The development of the triggered cloud chamber has been studied only as it pertains to Blackett and Occhialini's achievements.[viii] Little or no effort has been made to place it within the broader history of high energy particle detection since the late 1920s. However, if this effort is made, many interesting and enlightening details emerge on the origin of this important device.

II. DETECTING IONIZING EVENTS WITH CLOUD CHAMBERS

The study of radioactivity in the early 1900s led to the reliable detection of single ionizing particles produced by radioactive decay. One of the methods was the zinc sulphide technique, which detected particles as bright spots of light in a scintillator crystal.[ix] Using this apparatus, conclusive evidence for the atomic nucleus (Geiger-Marsden, 1909)[x] and the proton (Rutherford, 1919)[xi] was collected.

The zinc sulphide technique had major drawbacks, including its dependence on the visual perception of the experimenter, and a sensitivity limited to massive particles. A far more versatile, but technologically challenging approach, proved to be the cloud chamber. The cloud camber was developed in 1911 by the Scottish physicist C. T. R. Wilson, and made it possible to view and photograph the paths of both heavy and light ionizing masses such as α and β particles.[xii] The apparatus consisted of a closed cylindrical expansion chamber, whose movable base slid inside a cylinder and served as a piston. The expansion of water saturated, dust-free air in the cylinder created the medium through which these ionized particles travelled. Their detection was based on the fact that the particles acted as nuclei of condensation in such a medium, which allowed their paths to be seen as vapor trails.

An important improvement of this device was developed in 1921 by the Japanese physicist T. Shimizu.[xiii] By suitably connecting the piston to a motor, the cloud chamber could be cyclically expanded and contracted, thereby allowing the user to take many photographs within a reasonable time (one photograph every 10-15 s). Among the most prominent achievements using this tool was the first visualization of the artificial transmutation of a nitrogen nucleus by α particle bombardment by P. M. S. Blackett at the Cavendish Laboratory (1924).[xiv]

A few years later, the Russian physicist D. Skobeltsyn (Leningrad Polytechnic) discovered that the cloud chamber method might be useful in cosmic-ray research. Skobeltsyn had been systematically investigating the recoil electrons released by radium γ-rays due to the Compton effect by means of a cloud chamber immersed in a magnetic field. His results confirmed Compton's theory.[xv] Between 1927 and 1929 Skobeltsyn did a detailed follow-up of this investigation using a chamber immersed in a 0.15 T magnetic field. Out of 600 stereoscopic photographs, Skobeltsyn observed 32 electron-like tracks with very little curvature, indicating an energy over 15 MeV. This energy was much higher than any known β particle at the time. He eventually concluded that the tracks were due to the passage of the secondary electrons emitted by energetic cosmic radiation according to a Compton process.[xvi]

By the time of Skobeltsyn's observation, it was believed that the absorption of high-energy γ-rays was mostly by Compton collisions as governed by the Klein-Nishina formula. If this formula is applied to contemporary measurements of the cosmic-ray absorption coefficient, it would predict that cosmic-ray electrons have energies of the order of 10^3 MeV in contrast to about 1 MeV for the most energetic radioactive decay products.[xvii] Most absorption coefficient data had been obtained by ionization chamber measurements under deep lakes by R. A. Millikan (Cal Tech) in the late 1920s. Is it correct to extrapolate the Klein-Nishina formula to cosmic-ray energies? Experiments performed in Millikan's laboratory by C. Y. Chao showed that the absorption of hard gamma rays exceeded that estimated by this formula. Was it correct if the nucleus participates in cosmic-ray absorption? [xviii] In February 1929 J. R. Oppenheimer warned Millikan that it seems "of particular importance […] to determine definitely whether the absorption of the cosmic rays is to be ascribed entirely to the extranuclear electrons" because the formula would not hold "if the nuclei play an appreciable part in the absorption."[xix] Millikan understood that Skobeltsyn's experimental approach, by enabling a direct measurement of the energy of cosmic-ray electrons, bypassed these problems. For this reason in 1930, Millikan charged C. D. Anderson, a young National Research Council fellow, to work on the design of a vertical cloud chamber set in a powerful magnetic field (2 T). By the summer of 1931, Anderson succeeded in developing an apparatus capable of measuring energies of the order of magnitude to be expected in high energy cosmic-ray photon encounters with electrons and nuclei.[xx]

III. DETECTING IONIZING EVENTS WITH COUNTERS

In the meantime, another apparatus with the power to detect a single ionizing event had entered nuclear and cosmic radiation physics, the Geiger-Müller or "tube" counter. The Geiger-Müller counter, which was developed in 1928 by H. Geiger and W. Müller as an improvement of the 1913 "point" counter,[xxi] is still widely used in particle physics experiments. It consists of an inert gas-filled tube with a wire stretched along the axis of the tube and a potential difference applied between the tube and the wire. The passage of ionizing radiation through the tube produces a short, intense current between the electrodes which is counted by the device.

In 1929 W. Bothe and W. Kolhörster in Berlin (Physikalisch-Technische Reichsanstalt) used the counter to study cosmic rays via the "coincidence method."[xxii] In this method, two counters were placed one above the other in a vertical plane, and each one was connected to a separate fiber electrometer whose deflection was recorded on a photographic film. If the deflection occurred within a small fraction of a second, a single ionizing cosmic ray particle passed through both counters. Bothe and Kolhörster detected the passage of high-energy cosmic-ray particles able to cross a 4 cm thick gold brick inserted between the two counters. For comparison, the most penetrating charged particle known at that time was the β electron, which could be stopped by less than 1 mm of gold. They concluded that the ionization was not due to secondary Compton electrons from energetic γ rays, because these electrons would not have sufficient energy to pass into the second counter when the brick was placed in the middle. (Ref. 4)

The full potential of the coincidence method was achieved only by the development of electronic recording devices. In late 1929 Bothe devised a circuit that used a two-grid vacuum tube such that when pulses were applied to the two grids by simultaneous discharges of both counters, a current pulse appears in the plate circuit.[xxiii] In early 1930 a much better apparatus was developed by Bruno Rossi.[xxiv] Rossi used this new device to discover that a component of cosmic rays (later recognized as muons) was able to penetrate through 1 m of lead. Rossi succeeded also in detecting the production of abundant secondary radiation (later identified as electrons and positrons) by a threefold coincidence experiment.[xxv] Since then, the steady improvement of electronics performance and integration has led to detector systems for which the coincidence involves many millions of channels.[xxvi]

As of late 1931, it was generally agreed that counters in coincidence and cloud chambers in a strong magnetic field were, in principle, able to detect single ionizing events. It was agreed, as well, that both apparatuses had detected particles of cosmic origin. Furthermore, Skobeltsyn and Bothe-Kolhörster's papers showed that the cloud chamber and the coincidence counting methods yielded consistent results for the intensity of the cosmic radiation. Although Skobeltsyn had estimated an intensity of 1.2 electrons per cm^2 per minute (by considering the number of observed tracks, expansion time, and cloud chamber size: see Ref. 4, p. 687), Bothe and Kolhörster arrived at an estimate of 0.6 particles per cm^2 per minute (Ref. 4, p. 772). This experimental evidence opened the prospect for pursuing many different goals. Historically, the first question to be tackled was an obvious one: were different devices measuring the same physical phenomenon or a mere coincidence?

IV. CORRELATING DISCHARGES AND CLOUD CHAMBER TRACKS

In spite of the evidence I have cited, it was not obvious in 1930 that the two methods had detected the same phenomenon. The cloud chamber and counter techniques relied on different physical principles and provided different data. The cloud chamber technique (based on the ions as condensation nuclei) collected the tracks left by ionizing particles entering the cloud chamber. These tracks were photographed, and, if a magnetic field was applied, tentative estimates of the energy of the particle could be made. By the counter technique (based on the cascade effect), the coincidence rate detected by two counters separated by a screen of matter was measured, and therefore the penetration power of the particles could be estimated.

To understand if the two methods were detecting the same phenomenon, a hybrid counter-cloud chamber device was produced in 1931. On 25 March 1931, L.M. Mott-Smith (The Rice Institute) looked for "a definite correlation between coincidences in tube-counter and tracks in a suitably disposed cloud expansion apparatus."[xxvii] The confidence that such a correlation existed was expressed most clearly a few months later, when Mott-Smith and G. L. Locher "assumed that [the] radiation [detected by the cloud chamber method] is the same as that responsible for the coincidence effects."[xxviii] On 4 September 1931, Mott-Smith and Locher reported the results of their attempt to correlate cloud chamber tracks and counter discharges. A cyclic-expansion cloud chamber was "interposed between two counters so that every particle which operates the counters by passing through them must also pass through the chamber."[xxix] As Mott-Smith and Locher wrote,

> "A track in the chamber will only be formed during a time interval of about 0.05 s just after the expansion is completed, so that only particles which operate the counters during this interval can be expected to produce a track. Since with the counting rates attainable the chance of obtaining more than one discharge during the 'sensitive' interval is negligibly small, the appearance of the tracks at the expansions for which the counters discharged during this interval is a *definite indication that the discharge and the track were produced by the same particle* emphasis added)"(Ref. 28, p. 1400).

As shown in Fig. 1, the counters T were connected, via the amplifier A, to the relay R, which remained closed for somewhat less than 0.01 s at each counter impulse. The cyclic expansion of the cloud chamber was made by setting the cam M into rotation. On the same shaft was a finger F which closed a pair of contacts just after the expansion and kept them closed for a predetermined interval. This finger was adjusted so that it held the contacts closed only during the sensitive interval. Thus, the signal lamp L lit only when a coincidence occurred.

Mott-Smith and Locher took over 1200 cloud chamber photographs, 38 of them showing significant tracks. By comparing the probability of finding a track on a photograph taken when no discharge of the counters occurred to that of finding a track coincident with a discharge, they observed that a considerably higher value was found for the latter. They concluded that "the track is produced by a cosmic-ray particle which travels through both the counter and the chamber," and "the best assumption we can make is that these particles are electrons."[xxx] "Only a fast material particle like an electron could score such double hits."[xxxi] In spite of this positive result, no further attempt was made by them to use a combined chamber-counter apparatus to obtain information on cosmic rays.

V. VISUALIZING COSMIC RAYS OVER EXTENDED PATHS

By operating a cloud chamber in the close proximity of a pair of counters it was discovered that both techniques were measuring the same phenomenon. In a few months, Mott-Smith and Locher's experiment was made more definitive by a different experimental arrangement whose goal was the visualization of cosmic rays over much longer distances than previously thought possible by a standard cloud chamber.

This goal was pursued by researchers at the Bartol Research Foundation of The Franklin Institute, in Swarthmore, Pennsylvania, headed by W. F. G. Swann.[xxxii] In April 1932, at the Washington Meeting of the American Physical Society, three research fellows of the Bartol Foundation, Jabez C. Street, Thomas C. Johnson, and W. Fleischer, Jr.,[xxxiii] reported on "an expansion chamber of new design."[xxxiv] According to the authors, three of these chambers of new design were under development with the goal of "studying cosmic ray tracks over extended lengths of their paths" by making the cloud chambers to work simultaneously.[xxxv]

The new chamber operated continuously and was "illuminated by photoflash lamps exploded by the coincident discharge of two Geiger-Müller counters placed above and below the chamber." The illumination took place "only if the coincident discharge of the counters occurs during the sensitive interval of the chamber." By this arrangement, "a large percentage of the photographs obtained […] contain straight tracks in the line of the counters." Johnson, Fleischer, and Street had succeeded in obtaining a tracks per photograph ratio much higher than before (for example, Mott-Smith and Locher had obtained as many as one track every thirty expansions). The success of the Bartol apparatus was lessened by the fact that only a small fraction of coincidences was able to trigger the device. The high percentage of photographs containing significant tracks was obtained by taking photographs only when a random event (a discharge produced by the passage of an ionizing particle) and another short-lived independent event (the expansion of a standard cloud chamber) occurred at the same time.

Notwithstanding this drawback, according to Johnson, the Bartol Foundation cloud chamber "of new design" was a success: "with this arrangement, out of fourteen photographs which were taken, ten contained tracks which would have passed through the counters"[xxxvi] (Fig. 2).

VI. LETTING PARTICLES TAKE THEIR OWN PHOTOGRAPHS

The automatic chamber devised at the Bartol Foundation with the goal of visualizing the cosmic rays particles over extended paths yielded a cosmic-ray tracks per photograph ratio much higher than before. However, this device had a major deficiency, namely, the very poor size of the sample of photographs that could be collected within a reasonable time. This deficiency was eliminated a few months later in Europe.

In summer 1931 the cloud chamber expert P. M. S. Blackett was joined at the Cavendish Laboratory in Cambridge by Giuseppe Occhialini, a young Italian physicist. Occhialini had become familiar with the Geiger-Müller counter technique while working in Florence with Bruno Rossi of coincidence counting fame. In the autumn of 1931, Blackett and Occhialini made the most of their expertise and jointly started to study the cosmic rays by improving the cloud chamber method.[xxxvii] The results obtained by the Cavendish researchers were first published in a letter sent to Nature on 21 August 1932,[xxxviii] and then in a detailed paper communicated to the Royal Society in February 1933.[xxxix]

A major consideration guiding Blackett and Occhialini's efforts was the agreement in intensity of the radiation. "From measurements with counters it is known that about 1.5 particles fall, from all directions, on 1 sq. cm. per [minute]," and that "roughly consistent with these figures are the results found with cloud chambers" (Ref. 39, p. 699). Another factor was the previous attempts to reconcile the evidence obtained by the cloud chamber method with that by the coincidence counting techniques:

> "Mott-Smith and Locher had previously found a correlation between the occurrence of these tracks and the discharge of a counter, and recently Johnson, Fleischer and Street have used the coincidence of the discharges of two counters to operate the flash which illuminates a continuously working cloud chamber." (Ref. 38)

Most importantly, the Cavendish researchers knew that when the cyclic cloud chamber method was applied to cosmic-ray phenomena a problem concerning the empirical base arose. Because the phenomena of interest were random and occurred rarely, the standard chambers were at a disadvantage because of the very short sensitive time.[xl] To overcome this problem, many photographs was collected and the method was therefore very time consuming and required much photographic film.

Blackett and Occhialini devised an expansion method that enabled the cosmic-ray particles "to take their own cloud photographs" (Ref. 39, p. 699). They arranged that "the simultaneous discharge of two Geiger-Müller counters due to the passage of one of these particles shall operate the expansion itself" (Ref. 38). As in the former methods, two counters were placed above and below the cloud chamber so that any particle that passed straight through them also had to pass through the illuminated part of the chamber (Fig. 3).

The counters were connected to a valve circuit arranged to record only simultaneous discharges of the two counters. The sequence of events was as follows. When a coincidence occurs, the grid of a thyratron [a gas-filled relay] connected to the amplifier becomes positive, so that the thyratron short circuits a small magnet that had previously held a light armature against a spring. The armature flies off and moves a catch, which releases the valve under the piston, and so causes the expansion (Ref. 39, p. 700).

An obvious property of this setup is that the chamber can expand only after the passage of the particle through its sensitive volume. As a consequence, the diffusion of the ions during the time between the passage of the cosmic-ray particle and the attainment of the supersaturation might negatively affect the sharpness of the tracks. (This inconvenience was not at issue in the Bartol machine because an automatic expansion occurred there.) By carefully designing the various parts of the apparatus, the Cavendish researchers were able to overcome this problem. "It has been possible to make the total time from the discharge of the counters to the end of the expansion as small as 1/100 s. In this time the ions produced by an ionizing particle only diffuse a short distance from the position where they are formed: the resulting tracks have a breadth […] small enough to allow a very accurate measurement" (Ref. 25, p. 700).

This counter-controlled, or triggered, cloud chamber was a significant improvement on the standard cyclic expansion methods, notably for its greater efficiency in collecting cosmic-ray tracks. As Blackett and Occhialini reported, "on more than 75 per cent of the photographs so obtained […] are found the tracks of particles of high energy,"[26] in contrast to the 2% obtained from the standard cloud chambers. The triggered cloud chamber was also a dramatic improvement over the Bartol apparatus because each coincidence discharge was, in principle, able to operate the cloud chamber expansion. In contrast to the Bartol machine the coincidence discharge could trigger the illumination apparatus only when the chamber was in the "right" phase of its expansion cycle. And, *a fortiori*, the Blackett and Occhialini apparatus was much better than Mott-Smith and Locher's, which signalled only when an impulse out of the coincidence circuit was temporally coincident with the expansion of a cyclic expanding cloud chamber. Figure 4 illustrates the different effects produced by the passage of a cosmic-ray particle (dashed arrow) through the counters of each of the three apparatus we have discussed.

The new method quickly proved very useful. As reported in February 1933 (Ref. 39), during late autumn 1932, Blackett and Occhialini accumulated some 700 photographs of cosmic-rays, including groups of associated rays that came to be known as "showers" of cosmic ray particles. Eighteen photographs were obtained on which there were tracks of more than eight high energy particles, and four photographs show more than twenty tracks. They quickly collected large data sets on range, ionization, curvature, and the direction of tracks, and concluded that the showers "consists chiefly of positive and negative electrons" (Ref. 39, p. 708) (Fig. 5). According to Blackett and Occhialini, (Ref. 39, p. 714) the existence of positrons and electrons in the cosmic ray showers could be explained by a pair production mechanism proposed by P. A. M. Dirac, who was a few hundreds of meters away from the Cavendish Laboratory.[xli]

The existence of positrons in the showers raised the question of why they had previously eluded observation. According to Blackett and Occhialini, it seemed likely that the positrons "disappear by reacting with a negative electron to form two or more quanta" as expected by Dirac's theory of the electron. According to this theory, "all but few of the quantum states of negative kinetic energy, which had previously defied physical interpretation, are taken to be filled with negative electrons. The few states which are unoccupied behave like ordinary particles with positive kinetic energy and a positive charge" (Ref. 39, p. 714). In 1931, Dirac found that these "holes" have the same mass as negative electrons. Thus, the showers had previously eluded observation because the positrons should have a short life "since it is easy for a negative electron to jump down into an unoccupied state, so filling up a hole and leading to the simultaneous annihilation of a positive and negative electron, the energy being radiated as two quanta" (Ref. 39, p. 714). Blackett and Occhialini concluded that the life time of the positron "is long enough for it to be observed in the cloud chamber but short enough to explain why it had not been discovered by other methods" (Ref. 39, p. 716).

Blackett and Occhialini were able to collect no less than fourteen positron tracks (Ref. 25, p. 706), therefore providing in February 1933 compelling evidence for the existence of positrons. However, in spite of the high efficiency of the counter-controlled cloud chamber in showing positron tracks, Blackett and Occhialini narrowly missed the actual discovery of the positron. Evidence for the positron was first obtained a few months earlier by Anderson in the context of his Millikan driven study of cosmic radiation (see Sec. II). While studying the scattering of cosmic rays in a lead screen placed within a cloud chamber immersed in a strong magnetic field, Anderson obtained in August 1932 a few tracks that were likely due to positive particles of electronic mass.[xlii] The irony is that Anderson overtook Blackett and Occhialini by means of a low efficiency cyclic cloud chamber, that is, by an apparatus where the collection of an ionizing track was a chance occurrence (Anderson took over 3000 photographs to obtain a meager harvest of three positron tracks).

VII. EPILOGUE

Although cloud chambers have inherent limitations, rooted in the low density of the gas so that very few particles collide with the nuclei inside the chamber, the approach underlying this apparatus, that is, the visualization of particle tracks, survived well into the second half of the twentieth century. In the late 1940s, the nuclear emulsion technique, coupled with precision microscopy, emerged. This technique used a photographic plate made by a dispersion of silver bromide crystals in a gelatine matrix. By exposing this emulsion to ionizing radiation, silver atoms are produced which are not visible until the emulsion is developed. Cecil Powell received the Nobel prize in physics in 1950 for discovering the pion by means of this method. By the early 1950s, another visualization technique was successfully pursued, the bubble chamber. In close analogy with the cloud chamber technique, the bubble chamber was based on the principle of bubble formation in a liquid heated above its boiling point. If the liquid is suddenly expanded, the passage of ionizing particles can be detected by the trails of bubbles formed along the tracks of particles and captured by high speed photography. The development of the bubble chamber led to a Nobel prize in physics (Donald Glaser, 1960)[xliii] and notable discoveries (for example, weak neutral currents, 1973).[xliv]

Geiger-Müller counters (as well as scintillation detectors) were replaced by spark chambers and wire chambers. The spark chamber was devised in the early 1950s and is a direct outgrowth of the spark counter, which was a variation of the Geiger-Müller counter geometry. The observation that the spark between parallel plates occurs along the path taken by a particle as well as a number of important improvements, made the spark chamber one of the principal particle detectors until the early 1970s. Out of the spark chamber, in turn, came the wire chamber, a sort of spark chamber with wires instead of plates, the multiwire proportional chamber (whose invention by George Charpak garnered the Nobel Prize in Physics in 1992),[xlv] and the drift chamber (a multiwire chamber on its side). The wire chamber was used in the discovery of the charm quark in 1974 and in the discovery of the intermediate bosons in 1983 at CERN.[xlvi] By the early 1980s, fifty years after the development of the counter-controlled cloud chamber, the visualization and counting approaches advanced to a higher level through the production of electronically generated, computer-synthetized images.[xlvii]

VIII. CONCLUDING REMARKS

Historians of physics generally agree that the experimental expertise achieved at the Cavendish Laboratory in 1932 was fundamental to the development of the triggered cloud chamber. Surely, Blackett and Occhialini's expertises were crucial. We have shown that another far less acknowledged contribution existed, that is, the role of those researchers who, in earlier months, prepared the basis for the Cavendish project.

Several months before the development of Blackett and Occhialini's chamber, two hybrid devices, with the same geometrical arrangement but different design, achieved some success in the characterization of cosmic radiation. Most notably, these devices showed that the same physical stimulus was involved in the cloud chamber and in the coincidence counting technique. This far from simple achievement was a direct result of the capability of mastering the new counters in the coincidence method as well as the old cloud chamber method. The development of the hybrid devices in Texas and Pennsylvania shows that the Cavendish Laboratory was not the only place where these capabilities existed. However, only the Cavendish-style counters and cloud chamber apparatus enjoyed lasting success. Blackett and Occhialini had grasped that the most fruitful way to merge the cloud chamber and the counter techniques was focusing on the efficiency of track collection. Before them, "the [cloud chamber] method to photograph cosmic rays somewhat resemble[d] that of a hunter shooting in the air and hoping that a bird will fly over."[xlviii] Following the development of the triggered cloud chamber, it is as if the bird had learned how to shoot itself.

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[xxv] M. C. Bustamante, “Bruno Rossi au début des années trente: une étape décisive dans la physique des rayons cosmiques,” Arch. Int. Hist. Sci. **44**, 92-115 (1994); M. Leone, A. Mastroianni, and N. Robotti, “Bruno Rossi and the introduction of the Geiger-Müller counter in Italian physics,” Physis Rivista Internazionale di Storia della Scienza **42**, 453-480 (2005).

[xxvi] W. Riegler, “High accuracy wire chambers,” Nucl. Instrum. Meth A **494**, 173-178 (2002), p. 173.

[xxvii] Mott-Smith had previously studied the possibility of determining by magnetic deflection the energy of the “cosmic β- particles discovered by Skobeltsyn and investigated by Bothe and Kolhörster.” See L. M. Mott-Smith, “Possibility of determining the energy of cosmic β-particles by magnetic deflection,” Phys. Rev. **35**, 1125-1126 (1930), p. 1125.

[xxviii] L. M. Mott-Smith and G. Locher, “A new experiment bearing on cosmic-ray phenomena,” Phys. Rev. **38**, 1399-1408 (1931), p. 1400.

[xxix] Reference 17, pp. 1400-1401.

[xxx] Reference. 17, pp. 1406-1408.

[xxxi] Mott-Smith and Locher held this opinion according to a 12 December 1931 Science News Letter report titled *Tracks of Cosmic Rays Seen by Experimenters*.

[xxxii] On the work at the Bartol Research Foundation concerning this subject see W. F. G. Swann, "Report on the work of the Bartol Research Foundation, 1933-34," J. Franklin Institute **218**, 188-96 (1934).

[xxxiii] Street and Johnson had previously developed a circuit for recording coincident discharges of two or more counters. See, J. C. Street and T. H. Johnson, "Experiments on the corpuscular cosmic radiation," Phys. Rev. **40**, 1048 (1932); T. H. Johnson, "Cosmic rays at forty billion volts," Scientific Monthly **35**, 475-76 (1932).

[xxxiv] T. H. Johnson, W. Fleischer, Jr., and J. C. Street, "A cloud expansion chamber for automatically photographing the tracks of corpuscular cosmic rays," Phys. Rev. **40**, 1048 (1932).

[xxxv] This goal was later pursued by Johnson also by a so-called "hodoscope" (from the Greek *ὅδος*, *track*, and *ςκοπεω*, *to view*), a large two dimensional array of counters. See, T. H. Johnson and E. and C. Stevenson, "The cosmic ray hodoscope," J. Franklin Institute **216**, 329-337 (1933).

[xxxvi] T. H. Johnson, "Cosmic rays – theory and experimentation," J. Franklin Institute **214**, 665-89 (1932), p. 679.

[xxxvii] G. Occhialini, "Le recenti ricerche intorno all'elettrone positivo," La Ricerca Scientifica **4**, 372-373 (1933).

[xxxviii] P. M. S. Blackett and G. Occhialini, "Photography of penetrating corpuscular radiation," Nature **130**, 363 (1932).

[xxxix] P. M. S. Blackett and G. Occhialini, "Some photographs of the tracks of penetrating radiation," Proc. R. Society London, Ser. A **139**, 699-727 (1933).

[xl] In this experimental setup the "sensitive time" is the interval between the time when minimum supersaturation is first attained and the time at which it is last present as the whole of the gas of the chamber heats up.

[xli] On the development of Dirac's theory see H. Kragh, *Dirac: A Scientific Biography* (Cambridge University Press, New York, 1990), p. 109. See also P. Dirac, "Blackett and the positron," in *Cambridge*

Physics in the Thirties, edited by J. Hendry (Adam Hilger, Bristol, 1984), p. 61.

[xlii] C. D. Anderson, “The apparent existence of easily detectable positives,” Science **76**, 238-239 (1932). There is an extensive literature on the discovery of positron. See, N. R. Hanson, “Discovering the positron,” Brit. J. Phil. Sci. **12**, 194-214, 299-313 (1961); M. De Maria and A. Russo, “The discovery of the positron,” Rivista di storia della scienza **2**, 237-86 (1985); X. Roqué, “The manufacture of positron,” Stud. Hist. Phil. Mod. Phys. **28**, 73-129 (1997).

[xliii] D.A. Glaser, “Elementary particles and bubbole chambers”, Nobel lecture, December 12, 1960. See http://nobelprize.org/nobel_prizes/physics/laureates/1960/glaser-lecture.pdf.

[xliv] P. Galison, “How the first neutral-current experiments ended”, Rev. Mod. Phys. **55**, 477-509 (1983).

[xlv] G. Charpak, “Electronic imaging of ionizing radiation with limited avalanches in gases”, Nobel lecture, December 8, 1992. See: http://nobelprize.org/nobel_prizes/physics/laureates/1992/charpak-lecture.pdf

[xlvi] I. Kenyon, “The discovery of the intermediate vector bosons”, Eur. J. Phys. **6**, 41 (1985).

[xlvii] The discovery of W and Z particles in 1983 was “the first time a single electronic detection of an event had ever been presented to the wider physics community as compelling evidence in and of itself” (Galison, Ref. 5, p. 21).

[xlviii] This analogy was provided in 1934 by Enrico Persico. See, E. Persico, “Una finestra sul mondo atomico: la camera di Wilson,” Il Nuovo Cimento **11**, 725-735 (1934), p. 733. Persico was professor of theoretical physics in Florence at the time of Occhialini’s graduation, and was among the first supporters of modern physics in Italy.

FIGURE CAPTIONS

FIG. 1. A schematic diagram of the Mott-Smith and Locher apparatus. The lamp L lighted only

when a coincidence in counters T and cloud chamber E occurred.

FIG. 2. Cosmic ray tracks photographed by the Johnson-Fleischer-Street automatic camera. Source: T. H. Johnson, “Cosmic rays – theory and experimentation,” J. Franklin Institute **214**, 665-89 (1932), p. 676.

FIG. 3. Design of the Blackett-Occhialini chamber. The cloud chamber is placed between the counters (B_1 and B_2). A magnetic field is applied at right angles to the plane of the chamber.

FIG. 4. Schematic comparison of three devices merging cloud chamber and coincidence counting techniques. In the apparatus developed by Mott-Smith and Locher (a) a cosmic-ray particle passing through the counters must also pass through a cyclic expansion cloud chamber. A lamp shows when the expansion is coincident with a counter discharge. In the Johnson, Fleischer and Street counter-controlled apparatus (b) the coincidence operates the illumination apparatus when the cloud chamber is in the “right” phase of its expansion cycle. In the Blackett and Occhialini device (c) the coincidence operates the actual expansion of the cloud chamber.

FIG. 5**.** Photographs of “showers.” The track curved markedly to the right is due to a positron. Source: P. M. S. Blackett and G. Occhialini, “Some photographs of the tracks of penetrating radiation,” Proc. R. Society London, Ser. A **139**, plate 22 facing p. 722 (1933).