An uninvited guest: The positron in early 1930s physics

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A few months before its "official" discovery in September 1932 by Carl D. Anderson at Cal Tech in Pasadena, the positron was almost simultaneously observed by no less than two additional research teams: one at Cavendish Laboratory in Cambridge, England, and one at Institut du Radium in Paris, France. In this paper, we examine this curious case of multiple independent experimental observations by studying primary literature. This study identifies the motivations that led these researchers to independently design experiments suitable for the detection of this novel particle, and shows that none of these three teams was looking for a positive electron.

I. INTRODUCTION

One of the most important discoveries of early elementary particle physics was the experimental discovery of the positron (the positive electron) by Carl D. Anderson in 1932. In this paper we provide evidence that, while Anderson indeed deserves full credit, two additional research teams also observed, but did not identify, the positron in 1932. These teams were located in France and in the United Kingdom (UK). It is even possible that other researchers encountered the positron earlier,[1] but we will we confine our attention to Anderson and the France and UK research teams because their contributions provide interesting insights into the mechanism of scientific discovery.

Through the study of primary archival sources, we show that while there were multiple observations of the positron, the idea behind the discovery was not "in the air" because nobody was actually looking for this particle. As we will show, the multiple observations of the positron, and in some sense the inevitability of its discovery, intimately belongs to the concrete world of apparatuses and experimental setups rather than the world of bold hypotheses about new particles.

II. ON A MATTER OF SCATTERING

On close inspection, the history of the experimental discovery of the positron is actually a set of different, independent histories. One of these histories is of a young Cal Tech physicist named Carl D. Anderson who, while looking for something else, discovered the positron and eventually received the Nobel prize in physics.

In 1931, in order to get a direct measurement of the energy spectrum of the secondary electrons produced in the atmosphere by incoming cosmic radiation, an important research program was started by Anderson under the directorship of Robert Millikan at the Cal Tech Laboratory in Pasadena. This program made use of a vertical cloud chamber operating in a strong magnetic field. Using this setup, Millikan and Anderson were confident they would be able to capture photographs and measure the energy of the expected secondary electrons emitted by the primary cosmic radiation. (According to the contemporary view, the primary cosmic radiation was electromagnetic in nature.)

On December 19, 1931, the Science News Letter briefly reported about an alleged disintegration effect of cosmic rays discovered by Anderson. The news was accompanied by a cloud chamber photograph collected by Anderson and showing two tracks of opposite curvature, the positive one being due "probably" to a proton.[2]

On April 12, 1932, Anderson and Millikan reported having recorded several tracks left by "positive particles" while using a 17 000-gauss magnetic field.[3] The detection of positive particles was stated again on June 28,

following Anderson's analysis of 3 000 photographs. The assumption that the particles were travelling downwards through the vertical cloud chamber led to the outcome that "the tracks are deviated in a sense to indicate the presence of positively charged particles as well as electrons" (Ref. 4, p. 406). Because the specific ionization along the tracks showing positive particles was in most instances "*not much greater than that for electrons*" [emphasis added], and since it was known that for high energies, "protons and electrons ionize the same," Anderson concluded that "the positives can only be protons," the only known light positively charged particles besides alpha particles.

So as of June 1932, it seemed that both negative particles (likely electrons) and positive particles (likely protons) were present in cosmic radiation. But how can one distinguish positive and negative particles? According to the standard history, dating back to Anderson's 1936 Nobel lecture, "to differentiate with certainty between the particles of positive and negative charge it was necessary only to determine without ambiguity their direction of motion." To accomplish this, the Cal Tech physicist set up the following experimental arrangement:

> "a plate of lead was inserted across a horizontal diameter of the chamber. The direction of motion of the particles could then be readily ascertained due to the lower energy and therefore the smaller radius of curvature of the particles in the magnetic field after they had traversed the plate and suffered a loss in energy."[5]

The contents of Anderson's June 1932 paper, however, are at odds with the reconstruction provided by Anderson himself in his Nobel lecture. In June, Anderson had indeed made clear that some positive particles could actually be negative particles traveling upward rather than positive particles traveling downward as the majority of cosmic rays:

> "A possibility to be borne in mind is that, in rare cases, the tracks of curvatures that indicate positives might be in reality electrons scattered backwards by the material underneath the chamber and are traversing it from bottom to top" (Ref. 4, p. 418).

But in June 1932, Anderson himself suggested that measuring the specific ionization rather than studying the effect of plates of lead would settle the matter. "Precise data on the specific ionization of the low-energy positives will distinguish […] between downward positives and upward negatives" (Ref. 4, p. 418).

As reported in the "scattering of the cosmic particles" section of his paper, we may observe instead that plates of lead were felt to be useful to study another topic. With the goal of pursuing the study of the scattering of cosmic rays, and owing to his experimental observation that some of the tracks showed "sudden though very small deflections, within the gas or from the walls of the chamber," Anderson indeed planned to collect data on the scattering of cosmic particles in lead by introducing a plate of lead in the middle of the chamber. Preliminary results of this in-progress work led to no

less than three photographs showing very small deflections of particles traversing a 6-mm thick lead plate (see Fig. 1) (Ref. 4, pp. 410, 417).

In a few weeks, effects were discovered whose interpretations seemed to Anderson "to call upon a positively charged particle having a mass comparable with that of an electron" (Ref. 6, p. 239). The main evidence for this statement was found in three photographs collected while studying the scattering in lead and was first discussed in a September 2 letter to *Science*. Figure 2 shows the most significant photograph, where one may observe the tracks of a particle on both sides of the lead plate. The change of curvature below and above the plate shows that the particle went upwards and lost energy while crossing the lead shield. Since the sign of curvature indicated that the particle had a positive charge, while the length of path and the specific ionization were electron like, Anderson concluded that the particle behaved as a positive electron. Figure 3 shows two tracks of opposite curvature appearing below the lead. According to Anderson's interpretation, a positive particle of small mass and an electron emerge from the same point in the lead. Finally, in the third photograph reported by Anderson two tracks, possibly left by positive particles of small mass, appeared below the lead. Of course different, unlikely interpretations were possible, as reported by the same Anderson. But the interpretation of these tracks as due to protons or other heavier nuclei was ruled out on the basis of range and curvature:

> "Protons or heavier nuclei of the observed curvatures could not have ranges as great as those observed. The specific ionization is close to that for an electron of the same curvature, hence indicating a positively charged particle comparable in mass and magnitude of charge with an electron" (Ref. 6, p. 239).

This positive particle, discovered by looking at the behaviour of tracks passing through screens of lead, was eventually named the positron.[7]

III. ON PARTICLES PHOTOGRAPHING THEMSELVES

A second, independent history of the positron is the history of two physicists, Patrick M.S. Blackett and Giuseppe Occhialini, at the Cavendish Laboratory in Cambridge, who were unlucky enough to develop a "temperamental" device: the counter-controlled cloud chamber.[8]

In summer 1931, Occhialini, a young Italian physicist working at the Istituto di Fisica in Florence, got a CNR (Italian National Council of Research) fellowship to learn the cloud chamber technique at Cambridge under the direction of Blackett.[9] Occhialini's arrival at the Cavendish Laboratory marked a change in the priorities of work there: "in the autumn of 1931 in collaboration with Occhialini I started to study the energetic particles found in cosmic rays by means of the cloud method" (Ref. 10, p. 104).

As the standard cloud chamber method needed much time and photographic film, Blackett and Occhialini planned to devise an alternative method. They planned to use a coincidence counter, which guaranteed a particle had travelled through the cloud chamber, to trigger a photograph of the cloud chamber. This collaboration was a perfect marriage of Blackett's expertise on cloud chambers, dating back to the days of the first visualization of an artificial disintegration, and Occhialini's mastery of the Geiger-Muller coincidence technique acquired at Bruno Rossi's school in Florence. According to this method, a cloud chamber was arranged with its plane vertical. Two Geiger-Muller counters were placed one above and one below the chamber so that any ray that passed straight through both counters also had to pass through the illuminated part of the chamber (see Fig. 4). The counters (B_1 and B_2) are then connected to a coincidence circuit arranged to record only simultaneous discharges of the two counters. A magnetic field was applied at right angles to the plane of the chamber by means of a copper solenoid surrounding the chamber.

During the spring of 1932, Blackett and Occhialini worked hard on a potentially fatal experimental problem due to this arrangement. In the time between the discharge of the counters and the photograph, the ions produced by an ionising particle would diffuse some distance from the position where they are formed. The resulting track would therefore have a breadth large enough to preclude accurate measurements. The only way to overcome this difficulty was to carefully design the apparatus with the goal of making the

total time from the discharge of the counters to the taking of the photograph as small as possible. In an undated spring 1932 letter (preserved by the Occhialini-Dilworth archives at the University of Milan), Occhialini reported to his father, the physicist Raffaele Augusto, about this "struggle with time:"

> "Every morning, Rutherford questions me about the experiment and I will not have peace until it is complete. Since it is a struggle with time, the time between the passage of the quantum and the photography must be as low as possible, and it is not, the technique must be perfect".[11]

On a whole other level, a number of experimental accidents made the struggle with time difficult. In June 1932, Occhialini wrote to his father:

> "I felt the need of a little rest after all the work in May. When I came back a counter was broken. The air filter I use to fill them was poisoned by the fumes of a gas (the filter was in the chemistry lab) and I worked for a week to see what was wrong. Then, when all seemed over, a spark of 40 000 V has thrown in the air the whole registration due to an earth disconnected in a high-voltage apparatus in the laboratory. Then, I worked with Blackett a week without being able to operate the Wilson cloud chamber. Only yesterday things started to work, with unexpected results."[12]

In summer, the counter-controlled cloud chamber eventually began to work as expected and Blackett and Occhialini started to collect photographs of cosmic rays tracks. The drawbacks, however, were far from over, and the

collection of data proceeded slowly and in an uneven manner. As reported by Occhialini on September 7, soon after the summer vacation:

> "The last month before leaving [Cambridge] the Wilson chamber has absolutely refused to work and think I've disassembled, cleaned and put it in order at least 50 times. It is a *temperamental instrument*, and it seems almost *miraculous that it works*. The result was that we had only 100 tracks before the closure of the laboratory" [emphasis added].[13]

In the meantime, on August 21 Blackett and Occhialini sent a letter to *Nature* about the results obtained with the counter-controlled method. According to the Cavendish researchers, 100 photographs had been collected until then, and 76 of them showed cosmic-rays tracks (a result to be compared with the 2% efficiency of the standard cloud chamber method). Moreover, many tracks were actually "multiple tracks" of "various complexity," and only 10% of the tracks were measurably deflected in the magnetic field.[14]

During the fall months the picture grew clearer and clearer. As Blackett and Occhialini reported in their February 1933 paper to the Royal Society, during the late autumn of 1932, they accumulated some 700 photographs of cosmic rays, 18 of which showed more than 8 tracks of high-energy particles. The multiple tracks turned out to be a frequent phenomenon consisting of groups of associated rays diverging from a point in the matter around the chamber that came to be known as "showers" of cosmic ray particles.[15]

About half of the shower rays photographed by Blackett and Occhialini were apparently due to positively charged particles and half to negatively charged particles. Out of a number of criteria, and most notably the one stating "if a group of tracks diverge from some point or some small region of space, then there is a high probability […] that any one particle did actually move away from this region" (Ref. 15, p. 705), they measured ionization and range of the tracks and conclusively established that the masses of the positive particles were comparable with that of an electron rather than with that of a proton. As of February 1933, 14 tracks occurring in showers "must almost certainly be attributed to such positive electrons."

> "It is, of course conceivable that some of these tracks are caused by negative electrons moving upward, which only by chance pass through the region from which the other tracks appear to diverge. It is difficult to estimate this chance numerically, but the presence of these positively curved tracks is so common a feature of these showers that this explanation can hardly be maintained for them all" (Ref. 15, p. 706).

It is worth emphasizing that, as Blackett and Occhialini remarked, while radiant points had been located in the glass walls and roof of the chamber, and in the aluminium piston and the air in the room, the majority of the showers were found to originate in the copper. Such a fact was quite expected considering that the chamber was nearly surrounded by the copper solenoid.

In summary, use of their high-efficiency, counter-controlled cloud chamber allowed the cosmic-ray particles "*to take their own cloud photographs,*" (Ref. 15, p. 699). Blackett and Occhialini collected a number of photographs of associated cosmic-ray tracks, 10% of which were measurably deflected in the magnetic field. In due time, when the malfunctions of the device were overcome, the empirical basis grew considerably to the point where the associated tracks were understood to be electrons and positrons diverging from points in the matter surrounding the chamber. In fact, the large empirical basis collected by Blackett and Occhialini removed any remaining doubt about the positron's existence left by Anderson's observations. Because the counter-controlled cloud chamber was especially suitable to detect and simplify the identification of the positrons, the apparatus malfunctions were crucial in preventing the Cavendish researchers from arriving first at the discovery of the positron.

Beyond confirming the Cal Tech physicists' observations, Blackett and Occhialini also provided a general theoretical framework for the positron, namely P. A. M. Dirac's theory of the electron. In particular, they identified the positron as the "anti-electron," *i.e.* the positive charge and electronic mass particle that Dirac had introduced in 1931 with the goal of explaining the negative energy states that, together with the positive ones, were expected by his equation of the electron. Did Dirac's theory guide Blackett and Occhialini's research program? At the October 1933 Solvay conference, Rutherford expressed his regret at the way the positron was discovered:

> "[In] some way it is regrettable that we had a theory of the positive electron before the beginning of the experiments. Blackett did everything possible not to be influenced by the theory, but the way of anticipating results must inevitably be influenced to some extent by the theory. I would have liked it better if the theory had arrived after the experimental facts had been established" (Ref. 16, p. 177-178).

Although the actual influence of Dirac's theory on Blackett and Occhialini's work is a matter of speculation, a far more concrete influence on their work was the behavior of the counter-controlled cloud chamber. On the one hand this temperamental instrument refused to work for some time, making the collection of tracks slow and nerve-racking; on the other hand this particular device was very well suited to capture a new face of cosmic radiation, given that "a good portion of the tracks is extremely complicated." As Occhialini wrote in September 1932, it was just this occurrence that made Blackett believe that only after having collected two thousands tracks it would be possible to "clear the field" (Ref. 14). Since a good portion of these tracks was left by positrons it is legitimate to conclude, as Dirac himself wrote years later, that "if Blackett had been less cautious, he could have been first in publishing evidence for the positron" (Ref. 17, p. 62).

IV. ON ELECTRONS TRAVELLING IN THE WRONG DIRECTION

The third, independent history of the positron is the unfortunate history of two French scientists—Joliot and Curie—who, after having just missed the discovery of the neutron, would just miss the discovery of the positron.[18]

In late January 1932, Frederic Joliot and his wife Irene Curie, daughter of Madame Curie, observed the neutron during an ionization chamber experiment without recognizing it. By means of this experiment at the Institut du Radium in Paris, they had observed that the so-called "penetrating radiation" emitted by beryllium upon polonium alpha-particle bombardment (Po+Be, onwards) is able to project recoil protons out of hydrogenated substances.[19] Notwithstanding a serious incongruence of this explanation, involving the mass defect and the available energy, Joliot and Curie kept believing in the standard view—that the penetrating radiation was a sort of energetic gamma radiation. However, James Chadwick, Assistant Director of Research in the Cavendish Laboratory in Cambridge, had a different view. Soon after reading Joliot and Curie's report, Chadwick carried out further experiments and concluded that no incongruence existed if the Po+Be radiation was assumed to consist of new particles of mass 1 and charge 0. Chadwick himself named these new particles "neutrons."[20]

In February 1932, independent of Chadwick's efforts, Joliot and Curie attempted to use the Wilson cloud chamber technique to replicate their previous finding about the Po+Be ability to project protons. While performing this experiment, however, Joliot and Curie obtained, in addition to the

expected proton tracks, a number of high-energy electron tracks whose energy might be estimated by placing the cloud chamber in a magnetic field and measuring the radius of curvature of the tracks. They concluded that "these likely are electrons projected by Compton effect" and that these electrons "will be studied by using [magnetic] fields of greater magnitude" (Ref. 21, p. 709).

In March and April 1932, Joliot and Curie repeated the cloud chamber experiment with a stronger (1 500 gauss) magnetic field and again obtained a number of high-energy electron tracks. In these latest experiments the Po+Be radiation was filtered by a 2-cm shield of lead placed between the source and the cloud chamber to ensure the absorption of the natural polonium gamma radiation.[22]

In April 1932, with the goal of reconciling the observation of protons—suggesting that neutrons were involved—with the existence of the high energy electrons—that pointed instead to the effect of gamma radiation—Joliot and Curie carried out a set of ionization chamber experiments (where the chamber was filled with argon, nitrogen, and helium) on the absorption of the Po+Be radiation for different thicknesses of lead layers. As a consequence of these experiments, Joliot and Curie concluded that the Po+Be radiation is complex, consisting of both neutrons and gamma rays, and that this last component produces high energy electrons due to the Compton effect.[23,24]

However, as reported on April 11, while closely inspecting the cloud chamber photographs of the neutrons plus gamma Po+Be radiation, Joliot and Curie observed a curious fact. Several Compton electrons seemed indeed to

behave strangely with respect to the direction of the magnetic field. They briefly reported that while some tracks could be ascribed to Compton electrons passing through the volume of the chamber, "several tracks, having the same appearance as the electron tracks, showed a curvature opposite to that of others" (Ref. 23, p. 1230). According to Joliot and Curie these tracks were likely left by "electrons emitted in the reverse direction of the incident beam" of gamma rays. Notwithstanding the anomalous sign of curvature, the estimates of energy obtained by the measurement of the radius of curvature of the tracks (2×10^6 eV) were consistent with the range of energy of the Compton electrons produced by Po+Be gamma radiation.[25]

Soon after having reported such an observation, Joliot and Curie asked the advice of Niels Bohr, with the goal of ascertaining the mechanism underlying the production of the backward tracks. On April 26, they sent Bohr a photograph (preserved by the Archives for History of Quantum Physics) showing "several electrons [that] are born far from the source and move toward it."[26] On the lower side of the photograph, they sketched the experimental set-up outside the chamber (Po+Be source and lead layer) and the curvature of the electron tracks due to the magnetic field. An electron track showing a curvature opposite to that of others was sketched as an electron moving towards the source (see Fig. 5).

According to Joliot and Curie, while "the high-energy electrons might be Compton electrons due to the beryllium gamma radiation accompanying the neutrons," they did not believe that the opposite curvature tracks were due to

Compton electrons projected by scattered Po+Be gamma radiation because, as later emphasized, "this would led to assign to this radiation an extremely high quantum energy" (Ref. 25, p. 31). But if so, what mechanism could be the origin of these oddly behaving electrons?

In their letter to Bohr, Joliot and Curie put forward a further possibility, namely that the opposite curvature electrons resulted from a "disintegration phenomenon induced by the neutrons on the traversed medium" (lead).[26] This disintegration might therefore be responsible, in Joliot and Curie's view, for the creation of secondary radiation within the lead absorber that, in turn, might be responsible for the electrons moving toward the source. Thus, two separate mechanisms were allegedly produced by Po+Be radiation: while the normally behaving electrons originated out of a Compton recoil produced by Po+Be gamma rays within the gas inside the cloud chamber, the oddly behaving ones were produced by a two-step effect induced by Po+Be neutrons (see Fig. 6). According to Joliot and Curie, the disintegration hypothesis was supported by the ionization chamber experiments on the absorption of the Po+Be radiation in lead they had previously covered in the April 11 note. The shapes of these absorption curves indeed seemed to indicate the slight production of secondary rays within the lead absorber that in turn "would explain the backwards electrons observed by the Wilson chamber" (Ref. 23, p. 1231).

On April 30, Bohr expressed scepticism about Joliot and Curie's disintegration hypothesis for backwards electrons. Rather than originating within the gas, Bohr suggested to the French researchers that the electrons

might instead "originate within the substance of the walls of the Wilson chamber or even outside these walls, if they are sufficiently thin." In that case, the existence of backwards electrons might be explained by the fact that "the electrons may suffer a high degree of scattering with the substance of the wall or even a bending of their path by the magnetic field in the space outside the chamber."[27] The same hypothesis was reiterated by Bohr in a May 2 letter to Ernest Rutherford, where the Danish physicist reaffirmed his conclusion that the electrons do not originate within the chamber but rather in the walls.[28] This letter demonstrates that the issue of the electrons moving towards the source, communicated by Joliot and Curie, was felt to be important enough to make Bohr write about it in a letter to Rutherford.

In their May 16 reply to Bohr, Joliot and Curie stressed that "all these tracks are of very high energy," and that therefore the tracks "do not originate within the walls of the chamber" since the wall had to slow down the electrons.[29] According to the Danish physicist's final May 19 reply, the high speed electrons tracks might be portions of spiral paths, "coming from outside or from the substance of the metal walls or glass cover," limited by the cover and piston of the chamber.[30]

In fact, Joliot and Curie had detected a new particle—a positive electron going away from the source and the screen of lead—without recognizing it. However, the exchange with Bohr did not stimulate Joliot and Curie to pursue further the issue of backward electrons. In a letter to *Nature* dated June 25,

while emphasizing that the Po+Be radiation is composed of both neutrons and gamma rays, they did not mention this problem.[31]

The capacity of Po+Be source to yield positrons was first appreciated in February 1933 by Blackett and Occhialini when they reported about "the curious fact," observed by Joliot and Curie, "that fast electron tracks are found with a curvature indicating a negative electron moving *towards* [a] neutron source" [emphasis in the original] (Ref. 15, p. 716). A few weeks later, in March 1933, independent confirmations of Blackett and Occhialini's suggestion that positrons may be produced otherwise than in association with the cosmic rays came almost simultaneously from research teams at the Kaiser-Wilhelm Institut für Chemie in Berlin and at the Cavendish Laboratory in Cambridge. Both teams replicated Joliot and Curie's April 1932 experiment with minor changes. On March 25, Lise Meitner and Kurt Philipp in Berlin submitted a paper where an experiment with a Po+Be source placed inside a cloud chamber and enclosed in a capsule of brass (as opposed to Joliot and Curie's lead shield) was discussed. As reported by Meitner and Philipp, besides the expected electron tracks, "remarkable was the frequent occurrence of electron trajectories of reverse curvature direction" (Ref. 32, p. 286) that they identified as positive electrons. Two days later, on March 27, Chadwick, Blackett, and Occhialini in Cambridge reported having placed a Po+Be source close to the wall of a cloud chamber in a magnetic field in such a way that a target of lead fixed within the chamber was exposed to the action of the Po+Be radiation, *i.e.* in accordance with Joliot and Curie's set-up. While most of

tracks were, from the sense of their curvature, clearly due to negative electrons, many examples were found of tracks "which had one end in or near the lead target and showed a curvature in the opposite sense," (Ref. 33, p. 473) and were identified as positrons. The main reason supporting the positron hypothesis was acquired by them placing a metal plate across the chamber so as to intercept their paths as in Anderson's arrangement to study the scattering of cosmic rays. The measurements of curvature carried out with this arrangement left no doubt that "the particles had their origin in or near the lead target and were therefore positively charged" (Ref. 33, p. 473).

Joliot and Curie soon explained the results of all these experiments by the simultaneous creation of a positive and negative electron pair out of the interaction between a high-energy photon and a heavy nucleus. Joliot and Curie's discovery that the pair production was caused by gamma rays closed the circle started one year earlier by their photographs showing "tracks, likely due to swift electrons, of curvature opposite to that of others" (Ref. 24, p. 12). The study of these tracks, emitted by the Po+Be radiation, was a third possible road to the discovery of the positron.

V. DISCUSSION

The discovery of the positron required the development of methods for visualizing the tracks left by charged particles in motion and for establishing

the sign of charge. As is well known, the first condition was met in 1911 by the development of the cloud chamber technique by C.T.R. Wilson,[34] and the second one was partially fulfilled in 1923, when the cloud chamber was first coupled with strong magnetic fields by P. Kapitsa (to observe the bending of alpha particle tracks) and D. Skobeltsyn (in order to test the Compton effect).[35] Under these experimental conditions, to determine the sign of the charge of a particle it is necessary to know which direction it is moving. As was made clear by Blackett and Occhialini in February 1933, there are four ways of obtaining this information from a photograph:

(a) If a particle passes through a metal plate, thick enough to cause it to lose an appreciable part of its energy, then the particle must have moved from the side of greater to lesser $H\rho$ (the product of magnetic field and radius of curvature of the track), assuming the possibility that the particle has gained energy in the plate may be neglected. If the particle is quite slow it may be possible to detect the change of $H\rho$ owing to the loss of energy while passing through the gas.

(b) If a particle produces a secondary of sufficient energy by collision with say, a free electron, then the direction of the secondary will indicate the direction of motion of the particle.

(c) If a group of tracks diverge from some point or some small region of space, then there is a high probability (but not an absolute certainty) that any one particle did actually move away from this region.

(d) If a track is observed in a nearly vertical direction, then it is more probable that the particle has moved downwards than upwards. The evidence for this last assumption is the fact that the ionization from penetrating radiation increases upwards (Ref. 15, p. 705).

Methods (a), (b), and (c) were emphasized again in a letter sent by Occhialini to his father on March 9, 1933 (see Fig. 7). In this letter, Occhialini explained the "methods for recognizing [in which] direction [a particle was moving]". Besides the "insufficient" method of studying the deviation in a magnetic field, Occhialini listed the following:

- "energy loss (not in gas because too much energetic), put a lead screen;"
- "radiant point;"
- "direction of secondary [particles]."[36]

What is of the utmost significance for the argument developed here is that the whole set of ways of obtaining the information of sign of charge from a photograph was actually attempted in 1932 and, most importantly, each attempt was not aimed at looking for the positron, but rather was a by-product of converging experimental setups.

As discussed, the first method (placing a lead screen within the cloud chamber) was "chosen" by Anderson in the spring of 1932 with the goal of studying the scattering of cosmic rays in lead. Anderson's observation has therefore the hallmark of a serendipitous discovery rather than that of a

carefully planned search of a novel particle. Regarding the second and third methods, Blackett and Occhialini's high-efficiency apparatus maximized both the observation of the behaviour of secondary particles and the observation of diverging tracks. This method had an unplanned bias in favor of electron-positron showers, mostly originating in the copper solenoid, as opposed to single tracks. "If a single particle crosses the [cloud] chamber there is only a small chance that it will pass through both counters, while if a shower of many particles passes though the chamber there may be quite a high chance […] that a coincidence will result" (Ref.15, p. 709). Finally, the fourth method, establishing that nearly vertical tracks are likely due to downward particles, was put in perspective by the same Cavendish researchers through their remark that this method does not provide ultimate evidence "unless other evidence of […] direction is available." In some sense, this method was inadvertently set-up by Joliot and Curie. The geometry of their apparatus, where the lead plate was placed between the Po+Be source and the cloud chamber, provides indeed for a preferential direction of motion of particles. Unfortunately, they failed to consider the possibility that the electron-like tracks going toward the source actually were positive electrons going away from it.

VI. CONCLUSION

The positron was an uninvited guest knocking at the door of early 1930s physics. Neither Anderson nor Joliot and Curie were looking for positive electrons or influenced by Dirac's prediction. As for Blackett and Occhialini, although they were aware of Dirac's anti-electron, their research program did not have it as a goal and, as reported by Rutherford, they "did everything possible not to be influenced by the [Dirac] theory." Yet, the discovery of positron was inevitable since it was rooted in the intrinsic nature of the technology and experimental apparatuses used by the early 1930s physicists working on penetrating radiation, whether of cosmic-ray or polonium-beryllium nature. As for the reasons why Anderson arrives first at the "discovery" of the positron, as we have seen it was just a matter of contingency, depending on lead plates, temperamental instruments, and a certain reluctance to pursue further the issue of oddly behaving electrons.

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FIGURE CAPTIONS

Fig. 1. Photograph of a particle "of uncertain sign of charge" traversing a 6-mm thick lead plate (12 000 gauss magnetic field) obtained by Anderson in the effort to study the scattering of cosmic rays. According to Anderson the particle energy exceeds 200 MeV if a proton is assumed and exceeds 600 MeV if an electron is assumed. The particle suffers a deflection of 0.5 degrees as measured in the plane of the chamber. Source: Ref. 4, p. 417. Copyright 1932 by The American Physical Society.

Fig. 2. The much-celebrated photograph of the discovery of the positron. As in Fig. 1, it shows a particle crossing a lead screen where the curvature of the track is easily measurable. As reported by Anderson it shows a 63-MeV positron passing through the 6-mm lead plate and emerging as a 23-MeV positron. The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature. Source: Ref. 7, p. 492. Copyright 1933 by The American Physical Society.

Fig. 3. Another photograph supporting the positron hypothesis obtained by experiments with plates of lead within the cloud chamber. It shows two tracks of opposite curvature below the lead: a 20-MeV positron and a 30-MeV electron. As reported by Anderson, the range of the positive particle precludes

the possibility of ascribing it to a proton of the observed curvature. Source: Ref. 7, p. 493. Copyright 1933 by The American Physical Society.

Fig. 4. Apparatus devised by Blackett and Occhialini in 1932. The coincident discharge of two Geiger-Muller counters (B_1 and B_2) triggers a photograph of a cloud chamber placed between the counters. Source: Ref. 15, p. 717. Reprinted with permission from the Royal Society.

Fig. 5. Photograph and sketch sent by Joliot and Curie to Bohr on April 26, 1932 (Archives for the History of Quantum Physics). While the poor quality of the photograph prevents us from seeing the tracks allegedly left by electrons moving toward the source, a clearer version of this same photograph was eventually published by Joliot and Curie in Ref. 25, table I. From the library of the "Accademia Nazionale delle Scienze detta dei XL" in Rome, repository of Source for History of Quantum Physics.

Fig. 6. Schematic representation of Joliot and Curie's model describing the interaction of the complex Po+Be radiation with the gas inside a cloud chamber.

Fig. 7. Methods for recognizing in which direction a particle was moving as explained by Occhialini to his father on March 9, 1933 (Ref. 36). Image

supplied by the Occhialini-Dilworth Archives (Dipartimento di Fisica, Università degli Studi di Milano).