Fréderic Joliot, Irène Curie and the early history of the positron (1932-33)

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Frédéric Joliot, Irène Curie, and the early history of positron (1932-33)

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Abstract
As it is well known, the positron was discovered in August 1932 by Carl Anderson while studying cloud chamber tracks left by cosmic rays. Far less known is the fact that a few months before Anderson's discovery, in April 1932, Frédéric Joliot and Irène Curie had missed an opportunity to discover the positron during a nuclear physics experiment. One year later, in April 1933, the French researchers eventually succeeded in discovering the mechanism of positron-electron pair production. The complex relationship between Anderson's discovery of the positron, Joliot and Curie's missed discovery, and their following work on the pair production is here discussed in detail.

1. Introduction

One of the most important developments of early thirties elementary particle physics was the experimental discovery of positron by Carl Anderson in August 1932. The circumstances surrounding the occurrence of Anderson's discovery and the subsequent conclusive confirmation by Patrick Maynard Stuart Blackett and Giuseppe Occhialini within the cosmic-rays physics field had been extensively discussed in the history of physics literature [e.g. 1-4], with an important exception, noted below, as regards the genesis of Anderson's discovery. Most importantly, little attention has been paid in literature to the experiments providing evidence for the existence of positron several months before Anderson's discovery carried out in early 1932 by Frédéric Joliot and Irène Curie at the Institut du Radium in Paris. The reasons behind Joliot and Curie's failure to discover the positron, or even consider the hypothesis of a positive electron, are identified and discussed in detail by means of primary sources. It is here analyzed also a notable consequence of Joliot and Curie's experimental approach, namely the discovery of the pair production mechanism (1933).

2. The missed discovery of positron

The history of Joliot and Curie's involvement in positron research started, with hindsight, with the discovery of neutron. In February 1932, James Chadwick discovered that the 'penetrating radiation' emitted by beryllium upon polonium alpha particles bombardment (Po+Be, onwards)[1] was found to consist of new particles of mass 1 and charge 0. Chadwick himself eventually named these new particles 'neutrons' [6]. Still in February 1932, independently of Chadwick's efforts, Joliot and Curie attempted to replicate by the Wilson cloud chamber technique a finding they had previously obtained by the ionization chamber method and that was of critical importance for the discovery of neutron, namely the observation that Po+Be radiation is able to project recoil protons out of hydrogenated substances [7]. While carrying out this experiment, however, Joliot and Curie obtained, besides the expected proton tracks, also 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

[1] This "penetrating radiation" was first observed by Walther Bothe and Herbert Becker in 1930 [5].

magnitude' [8, p. 709]. In March 1932, the same phenomenon, i.e. the cloud chamber observation of both protons and electrons out of Po+Be, was reported also by Pierre Auger in Paris [9].

In March and April 1932, Joliot and Curie repeated the cloud chamber experiment with a stronger, 1500 gauss, magnetic field and obtained as before a number of high energy electron tracks. What is especially noteworthy for the future developments, is that in these latest experiment the Po+Be radiation was filtered by a 2 cm shield of lead placed between the source and the cloud chamber [10]. This filter was chosen to ensure the absorption of the natural polonium gamma radiation whose presence, which was known to be negligible beyond a thickness of 15 mm of lead [11, p. 1413], might otherwise introduce a bias in the study of the Po+Be radiation.

In April 1932, with the goal of reconciling the observation of protons, that suggested that neutrons were involved, with the existence of the high energy electrons, that pointed instead to the effect of a 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 thickness of lead layers. As a consequence of these experiments, discussed in a note presented on April 11, 1932 to the Academy of Science in Paris, Joliot and Curie concluded that the Po+Be radiation is complex, and it consists of both neutrons and gamma rays, and that this latest component produces high energy electrons by Compton effect [12-13] (the same conclusion had been independently obtained by Franco Rasetti in Berlin [14] and Bothe and Becker in Giessen [15] by means of the counters in coincidence technique).

However, as reported in the same April 11 note, 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' [12, p. 1230] (see figure 1).

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 [16] (figure 2).

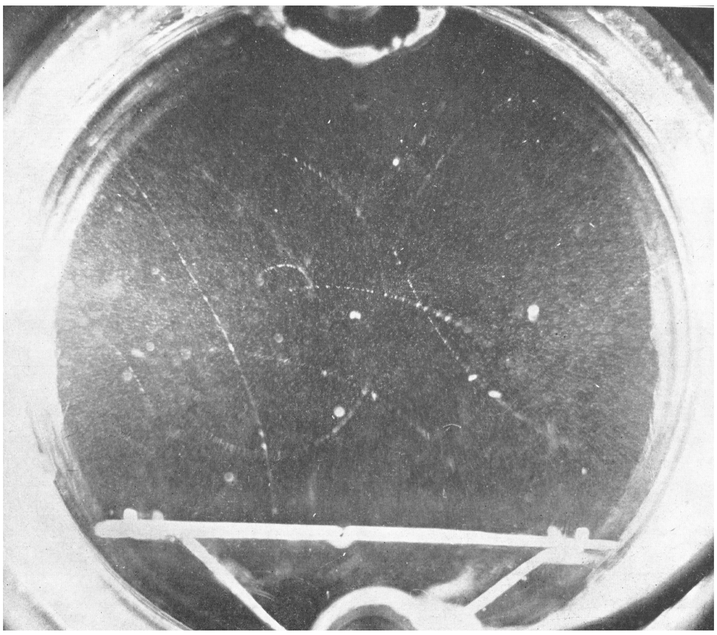

Figure 1. Joliot and Curie's photograph showing electron tracks of curvature opposite to that of others. The horizontal white band in the lower section is the paraffin screen [13, p. 12, tav. 3].

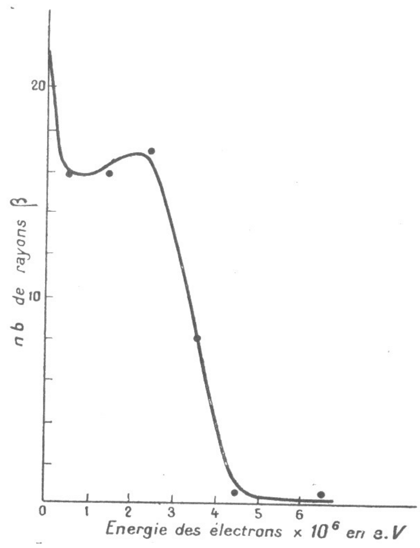

Figure 2. Spectrum of energy of Compton electrons produced by Po+Be gamma radiation [16, p. 24].

Soon after the Academy of Science note, Joliot and Curie asked the advice of Ernest Rutherford, the undisputed leader of experimental nuclear physics, and Niels Bohr, one of the most authoritative theoretical physicists abroad. As for Rutherford, unfortunately, we have not been able to find the letter the French researchers sent to him jointly with a sample of photographs. Anyhow, we have located Rutherford's April 26 reply, where the author, however, avoided to make specific comments about the contents of the photographs. In his letter, Rutherford remarked only that the photographs 'are very good and I can guess what they represent' and observed that 'the photographs of the circular tracks of the β-particles are very clear and distinct' [17]. The correspondence with Bohr was, on the contrary, much more to the point since it was devoted to the mechanism underlying the production of the backwards tracks. On April 26, Joliot and Curie sent to Bohr a photograph (figure 1) showing 'several electrons [that] are born far from the source and move toward it' [18]. On the lower side of the photograph, they sketched the experimental set-up outside the chamber (Po+Be source and lead layer) and, in particular, 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 toward the source (figure 3). 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 a scattered Po+Be gamma radiation, since, as later emphasized, 'this would led to assign to this radiation an extremely high quantum energy' [16, p. 31].

The presence of these opposite curvature electrons raised a further possibility, namely that these electrons resulted out of a 'disintegration phenomenon induced by the neutrons on the traversed medium' (lead) [18]. This disintegration might therefore be responsible, in Joliot and Curie's view, for the creation of a secondary radiation within the lead absorber that, in turn, might be responsible of the electrons moving toward the source. The disintegration hypothesis explained by Joliot and Curie in their letter to Bohr 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. According to Joliot and Curie, the shapes of these absorption curves seemed indeed 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' [12, p. 1231].

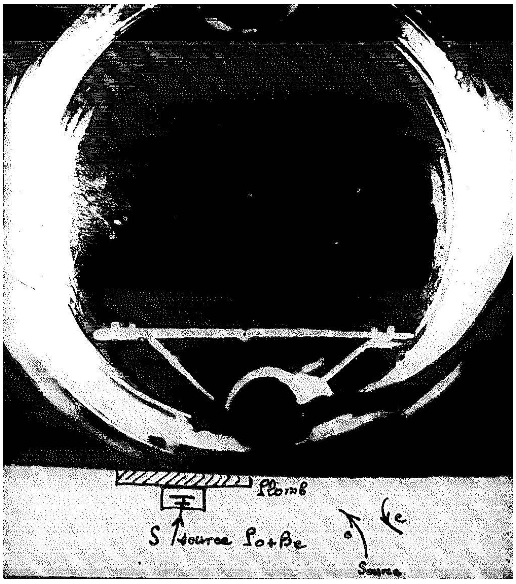

Figure 3. Photograph sent to Bohr on April 26, 1932 by Joliot and Curie [18]. This photograph is preserved by Bohr Scientific Correspondence at the Archives for History of Quantum Physics (AHQP) together with Joliot and Curie's April 26 letter (this letter is wrongly dated to August 26 in AHQP archives because of an erroneous decoding of Joliot's handwriting). Although the poor resolution of the AHQP digital image prevents a definite conclusion, in all likelihood this photograph is the same one shown in figure 1 (referred to earlier in the text) and published in Joliot and Curie's *L'existence du neutron* monograph [13]. As it is visible in the lower side of the AHQP image, the photograph sent to Bohr, unlike the published one, was accompanied by a sketch of the behaviour of the backwards electrons.

On April 30, Bohr expressed scepticism about Joliot and Curie's hypothesis that 'the electron tracks cannot all be due to Compton recoil' produced by Po+Be gamma rays. Rather than originating within the gas inside the cloud chamber, 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 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' [19]. The same hypothesis was reiterated by Bohr in a May 2 letter to Rutherford, where the Danish physicist reaffirmed his conclusion that the electrons do not originate within the chamber but rather in the walls [20]. This letter demonstrates that the issue of the electrons moving toward the source, communicated by Joliot and Curie, was felt to be important enough to make Bohr writing about it in a letter to Rutherford.[2]

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 [21]. According to the Danish physicist's final May 19 reply, the high speed electrons tracks might be portion 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 [22].

Apparently, the exchange with Bohr did not stimulate Joliot and Curie to pursue further the issue of backwards 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 [23]. Several months elapsed before Joliot and Curie attempted again to study this issue. In the meantime, a young CalTech physicist – which was working on a completely different subject, the cosmic radiation physics – reported having collected three cloud chamber photographs of electron-like tracks whose curvature was opposite to that expected if electrons

[2] However, it was not felt by Rutherford important enough to be addressed in his May 26 reply to Bohr (AHQP/BSC).

were actually involved. As a matter of fact, this is just what Joliot and Curie had earlier observed, although operating in a completely different field.

3. The actual discovery of positron

The discovery of positron has been extensively discussed in the history of physics literature. For sake of completeness, here we give a brief description of the major points and we emphasize an issue that has not emerged so far in the historiographical analyses, namely the fact that the positron was discovered by an experimental setup devised with the goal of studying the scattering of cosmic rays by matter, and in which the presence of a lead screen was of fundamental importance.

In 1931, in order to get a direct measurement of the energy spectrum of the secondary electrons produced in the atmosphere by the incoming cosmic radiation, an important research program was started by Carl Anderson, under the directorship of Robert Millikan, at the Caltech Laboratory in Pasadena. This program made use of a vertical cloud chamber operating in a strong magnetic field. By this set-up, Millikan and Anderson were confident to be able to capture photographs and measure the energy of the expected secondary electrons emitted by the energetic primary cosmic radiation, which according to the contemporary standard view was of electromagnetic nature. As Millikan and Anderson reported on April 12, 1932, i.e. just the day after Joliot and Curie's note to the Academy of Science, by the use of a 17,000 gauss magnetic field they had recorded several tracks left by 'positive particles' [24].

The detection of positive particles was stated again on June 28, when Anderson reported about the analysis of 3000 photographs. By assuming that the particles were travelling downward through the vertical cloud chamber, followed that 'the tracks are deviated in a sense to indicate the presence of positively charged particles as well as electrons' [25, p. 406]. Since 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', i.e. the only known light positively charged particles beyond the alpha particles. With the goal of pursuing the study of the scattering of cosmic rays, and owing to his experimental observation that certain of the tracks showed 'sudden though very small deflections, within the gas or from the walls of the chamber', Anderson planned to collect data on the scattering of cosmic particles in lead by introducing in the middle of the chamber a plate of lead. Preliminary results of this 'in progress' work had led to no less than three photographs showing very small deflections of particles traversing a plate of lead 6 mm thick (figure 4) [25, p. 410, 417].

In a few weeks, it was just by the study of the scattering in lead that effects were discovered for the interpretations of which it seemed necessary to Anderson 'to call upon a positively charged particle having a mass comparable with that of an electron' [26, p. 239]. The main evidence for this statement was found in a much celebrated photograph, collected while studying the scattering in lead, showing the tracks of a particle on both sides of the lead plate (figure 5). The change of curvature below and above the plate showed that the particle went upward and lost energy while crossing the lead shield. Since the sign of curvature indicated that the particle has 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. This particle was eventually named positron [27].

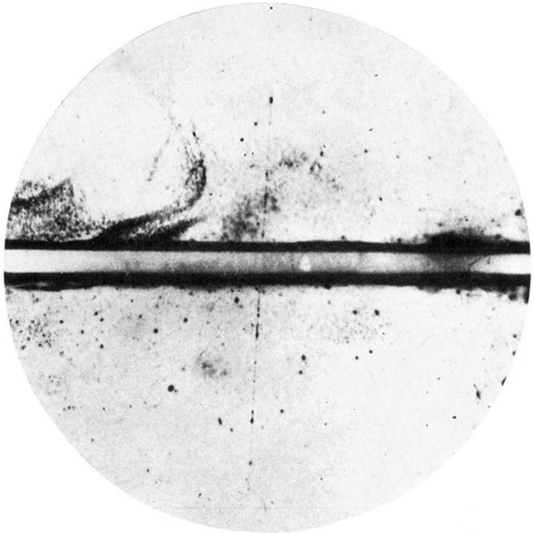

Figure 4. Anderson's cloud chamber photograph, submitted in June 1932 to *Physical Review*, showing a particle of uncertain sign of charge that suffers a deflection of 0.5 degrees in traversing the 6 mm lead plate [25].

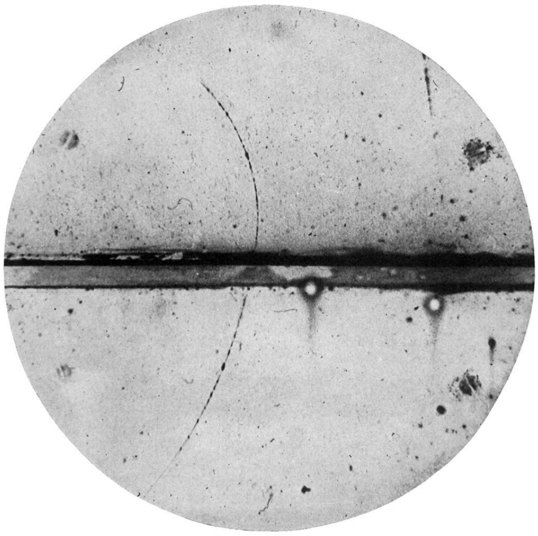

Figure 5. Anderson's cloud chamber photograph of a positron traversing upward the 6 mm lead plate, discussed in September 1932 on *Science* and submitted in February 1933 to *Physical Review* [27].

Anderson's discovery apparently went unnoticed in Paris. In alternative, we may think that this discovery was not connected by Joliot and Curie with the detection, within a completely different research field, of their backward electrons tracks.[3] As a matter of fact in November 1932, i.e. two months after the publication of Anderson's report, Joliot and Curie wrote a paper on the experimental evidence for the existence of neutron where no mention is made of the positron discovery and of the possibility of connecting it with their backward tracks. In a brief paragraph of the paper, devoted to the 'electrons […] going toward the source' [16, p. 31], they concluded that the backwards electrons likely originated out of the medium inside the cloud chamber. According to the French researchers, these electrons were Compton electrons and, as earlier reported to Bohr, rather than being produced by Po+Be gamma rays, they were produced by a new gamma radiation

[3] Anderson later declared that Joliot 'was very angry with me – I never met him – for publishing in *Science*, which he didn't read, instead of the *Physical Review*, because my paper might have helped him with his work' [28, p. 37].

emitted in a nuclear transmutation induced by the neutrons on the traversed medium [16]. Still in January 1933, i.e. four months after Anderson's report, the same hypothesis on this new gamma radiation was proposed by Pierre Auger who, as Joliot and Curie, had allegedly observed cloud chamber tracks of 'high energy beta rays [i.e. electrons] distributed in all directions and even toward the neutron and gamma ray source' while studying the problem of neutron diffusion with a cloud chamber [29, p. 172].

As for Bohr, for a long time after the positron discovery the Danish physicist expressed scepticism about its existence. By early 1933, as it will be discussed in the following section, a lot of corroborating evidence for the positron, as well as for its interpretation within Dirac theory, had surfaced. Yet, this evidence did not persuade Bohr to change his doubtful attitude. Still in April 1933, he wrote to his colleague and friend Oskar Klein that 'it will take a long time before we can have any certain knowledge about the existence or non-existence of the new particle' [30]. It is no wonder that in April 1932 he had failed to see evidence of positrons in Joliot-Curie photographs.

4. Toward the pair production

A few months after Anderson's observation, the existence of positron in the cosmic radiation was fully confirmed by Patrick Blackett and Giuseppe Occhialini at the Cavendish Laboratory in Cambridge. By means of their recently developed counter-controlled cloud chamber [31] – a device of greater efficiency than the standard automatic cloud chamber (80% vs. 2%) where the coincidence discharge in two Geiger-Müller counters placed above and below the cloud chamber triggered the expansion apparatus of the chamber – the Cavendish researchers succeeded in collecting many photographs showing positron tracks. Sometimes these positrons were detected as electron-positron pairs and sometimes as electron-positron groups, i.e. the multiple tracks, later to be called 'showers', the majority of whom originated in the copper solenoid surrounding the chamber [32-33].

Beyond confirming Anderson's observation, Blackett and Occhialini provided also 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 [e.g. see 4]. Dirac's anti-electron hypothesis, as reported by Blackett and Occhialini, was supported by the fact that it predicted 'a time of life for the positive electron that is long enough for it to be observed in a cloud chamber but short enough to explain why it had not been discovered by other methods' [33, p. 716]. As regards the mechanism of positive and negative electron production, the Cavendish researchers suggested that these particles 'may be born in pairs during the *disintegration of light nuclei* [emphasis added]', since the showers had been observed to arise in air, glass, aluminium and copper. [33, p. 713].

Thus, as of February 1933, the positron was closely connected with physical processes involving the cosmic radiation. Yet, Blackett and Occhialini were confident that 'positive electrons may be produced otherwise than in association with the penetrating radiation' of cosmic origin [33, p. 716]. In particular, they referred to the possibility that the positrons may be produced by neutrons. According to Blackett and Occhialini this hypothesis was held to be legitimate largely because of Joliot and Curie's April 1932 experiment on neutrons, and in particular by their observation reported above, i.e. 'the curious fact […] that fast electron tracks are found with a curvature indicating a negative electron moving *towards* [a] neutron source [emphasis in the original]' [33, p. 716]. This curious fact which was neglected by Bohr and also by Rutherford, and which was not fully appreciated by Joliot and Curie themselves, might be indeed re-examined and reinterpreted in the light of Anderson's discovery, namely by assuming that positrons were actually involved in Joliot and Curie's experiments.

A few weeks later, in March 1933, independent confirmations of Blackett and Occhialini' 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' [34, 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' 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', [35, p. 473] that they identified as positrons. The main reason supporting the positron hypothesis was acquired by them by 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' [35, p. 473]. This result had been anticipated by Occhialini to his father, the physicist Raffaele Augusto (Professor of experimental physics at the University of Genoa), in a March 9 letter on the status of the cosmic-ray researches at the Cavendish laboratory. Occhialini concluded indeed his letter by remarking with emphasis that 'it seems that also the neutron source emits positive electrons, however, please, do not tell this to anyone' [36].

Notwithstanding this major accomplishment, both the Berlin group and the Cavendish one agreed on the existence of a still unsettled issue, i.e. whether these positrons arose from the action of the neutrons emitted by the beryllium or from the action of the accompanying γ-radiation. Although Chadwick, Blackett and Occhialini did not make this clear, this second hypothesis was supported by Dirac theory. In his 1931 paper, Dirac had indeed suggested that '*an encounter between two hard gamma rays* (of an energy at least half a million volts) could lead to the creation simultaneously of an electron and anti-electron [emphasis added]' [37, p. 61].

The origins of the positrons was conclusively established, a few days after the Berlin and Cavendish papers, by Curie and Joliot, who managed to repeat their April 1932 experiment with some changes, i.e. by placing the Po+Be source against a 1.8 cm thick lead screen within the glass wall of the cloud chamber. By this arrangement, Joliot and Curie discovered that while with the above set-up both negative and positive electrons were readily observed, if the lead screen was substituted by an aluminium layer the number of positive electrons sharply falls with respect to the number of negative electrons. This demonstrated, Joliot and Curie wrote, that the positive electrons 'are just emitted by the lead' [38, p. 1106]. By placing another, 2 cm thick, lead absorber between the source and the above lead screen, they observed a conspicuous reduction in the number of positrons ejected from the matter beyond the absorber. According to Joliot and Curie, this result meant that these positrons were due to the relatively absorbable γ-rays rather than to the much more highly penetrating neutrons.

Soon after the demonstration that positrons were ejected from lead by γ-rays, a number of researchers attempted to get positrons out of other γ-rays emitters, notably the thorium active deposit ThC" (^{208}Tl). In May 1933, independent reports about the production of positrons out of ThC" came from Caltech [39], Kaiser Wilhelm-Institut [40], Institut du Radium [41] (see figure 6), and Cavendish Lab [42].

The results of all these experiments were soon explained by Joliot and Curie with the simultaneous creation of a positive and negative electron pair out of the interaction between an high-energy photon and a heavy nucleus. To underscore the origins of these positive and negative electrons, Joliot and Curie followed a suggestion of Madame Curie's and labelled them 'materialization electrons'. These two positive and negative electrons required an energy of 1.02 MeV. The energetic surplus, hν-1.02 MeV, where hν is the energy of the radiation, was shared between the kinetic energies of the electrons and, possibly, the energy of the scattered quantum [43, p. 494]. No positive electron, therefore, could have an energy higher than hν-1.02 MeV. This physical requirement was met with the measurements of positron energies carried out by Joliot and Curie, both with the Po+Be Radiation (5 MeV) and the ThC" radiation (2.65 MeV). These measurements supported the validity of the pair production mechanism and, as later emphasized by Joliot and Curie, demonstrated that 'we have here for the first time the transformation of electromagnetic radiation into matter' [44, p. 150]. In spite of its importance, Joliot and Curie's explanation of the pair production was poorly acknowledged within the history of physics. This lack of acknowledgement dates back to the presentation speech for Blackett's Nobel Prize in Physics (1948), where the member of the Nobel Committee for Physics went so far as to say that, contrary to what our analysis has shown, Blackett and Occhialini 'established, in collaboration with Chadwick, that electron pairs are also produced by hard gamma rays' [45, p. 95].

Joliot and Curie's discovery that the pair production was caused by gamma rays closed the circle started one year before by their photographs showing 'tracks, likely due to swift electrons, of curvature opposite to that of others' [13, p. 12]. On one hand these photographs are only a footnote in the history of the discovery of positron, since Joliot and Curie failed to see in them evidence for positron in April 1932, albeit with good reasons given the fact that the anomalous tracks were electron-like in all respects, and that, therefore, no need for other experiments like e.g. scattering experiments was apparent. On the other hand, as we have seen, these very same photographs suggested the possibility that positrons are not restricted to the cosmic-rays physics field and, as a consequence of this, acquired a prominent place in the history of electron-positron pair production.

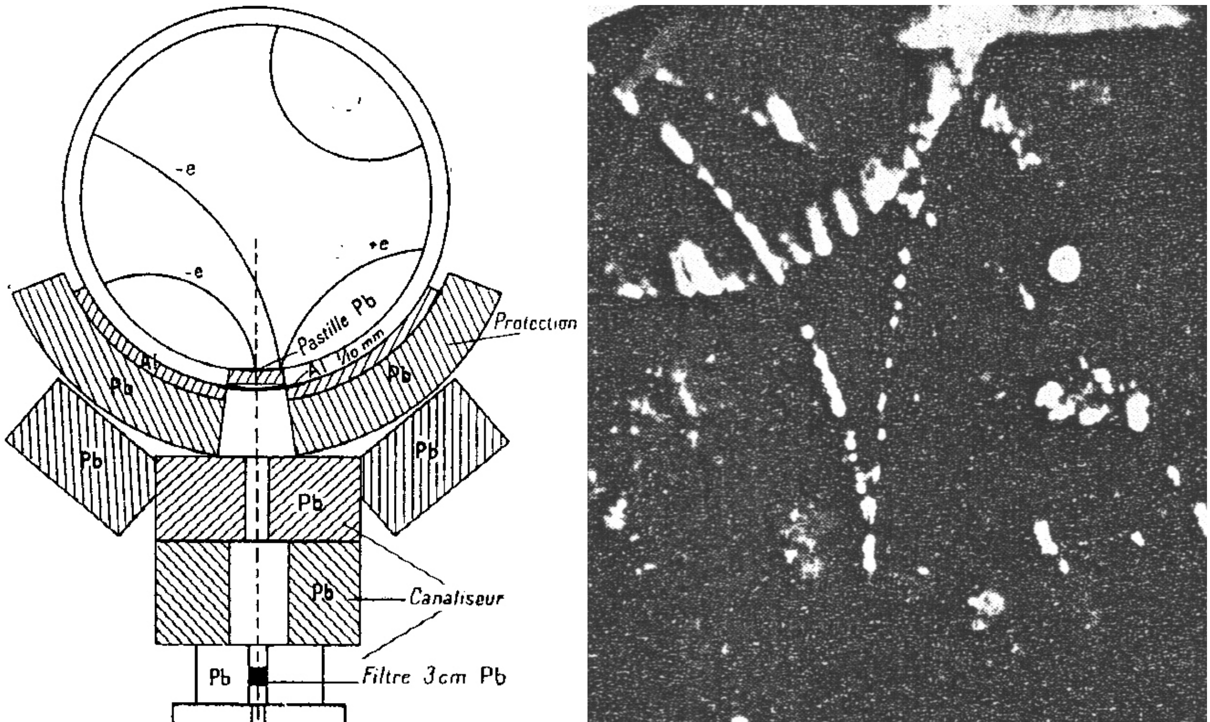

Figure 6. Schematics of Joliot-Curie apparatus for the visualization of ThC" positrons (*left*) and the first Joliot-Curie's cloud chamber photograph showing an electron-positron pair out of γ radiation (*right*) [43, tav. 1].

5. Conclusion

The analysis of Joliot and Curie's work in 1932-33 provides new insight into the role of chance in the discovery of positron. With the goal of studying the radiation emitted by beryllium upon alpha particle bombardment, Joliot and Curie inadvertently set-up in April 1932 an experiment ideal to *yield* the production of positrons. Four months later, with the goal of studying the scattering of cosmic radiation, Anderson inadvertently set-up an optimal experiment to *detect* positrons. As it was shown above, the yielding vs. detecting positrons opposition resolved itself in favour of Anderson's approach, as far as the issue of discovering the positron is concerned. This outcome was rooted in Anderson's choice of inserting a lead shield within the cloud chamber that made his apparatus more apt to distinguish negative from positive electrons than Joliot and Curie's one.

Nonetheless, our analysis shows that also Joliot and Curie's approach bore fruits. One more time, the use of a thickness of lead had dramatic consequences. It was indeed just by a lead absorber – aimed at filtering out the natural polonium gamma radiation – placed between a Po+Be source and a cloud chamber, that they observed a number of electronic tracks bent in the wrong way with respect to the direction of the magnetic field established within the chamber. Backed-up by Bohr's authoritative opinion, they concluded that these tracks were left by Compton backward electrons generated by a secondary radiation produced by the interaction of neutrons with matter. While not succeeding in identifying the positron by their backward tracks, Joliot and Curie set the stage for the discovery that positrons are not just a cosmic radiation phenomenon since they might be produced in laboratory, as it was eventually discovered by Blackett and Occhialini. One month later, the Cavendish researchers themselves admitted that it was not yet known whether these positrons were actually produced by neutrons or the accompanying gamma radiation. This issue was solved a few days later by Joliot and Curie who demonstrated that the positron was produced by a pair production effect due to the interaction between a beryllium high-energy photon and a heavy nucleus, such as those of the lead absorber. In some respect, the history of the experimental discovery of positron boils down therefore to the history of an ordinary piece of lead and its arrangement within or without a cloud chamber.

Another lesson of this analysis concerns the complex relationship between theory and experiment. At the October 1933 Solvay conference, Rutherford expressed his regret at the way the history of positron discovery actually occurred:

> [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' [44, pp. 177-178].

Rutherford's remark about the possible influence the Dirac theory had upon Blackett and Occhialini's experiments is fully justified for what concern the identification of Anderson's positron with Dirac's anti-electron. It is indeed worth to remember that at that time Dirac was Lucasian professor of Mathematics at St. John's College in Cambridge, a few hundreds of meters away from the Cavendish Laboratory, and that Blackett and Occhialini acknowledged Dirac's help 'not only for most valuable discussions […] but also for allowing us to quote the result of a calculation made by him of the actual probability of [the] annihilation process' [33, p. 715]. As a matter of fact, however, neither Joliot and Curie's missed discovery of positron nor Anderson's actual discovery were in any way prompted by Dirac's anti-electron hypothesis (1931). As we have seen, in early 1932 the positrons were observed but not identified by Joliot-Curie. Even Bohr and Rutherford, questioned about this issue, did not consider the anti-electron hypothesis. In august 1932, the positrons were finally observed and understood by Anderson, without making recourse to Dirac's conjecture. On the contrary, Blackett and Occhialini later supported the existence of positron and connected it for the first time with the anti-electron hypothesis. Yet, at the same time, while having observed plenty of electron-positron pairs, they failed to make the connection with Dirac's hypothesis since they believed that the Po+Be positrons arose from the action of neutrons! The mechanism of positron-electron production out of the interaction between high energy photons and heavy nuclei was understood only after Joliot and Curie's April 1933 measurements of positron energies compared with the energy of the gamma radiation emitted by Po+Be and ThC". It is somewhat ironic that Joliot and Curie succeeded in fully understanding the mechanism of positron-electron pair production by working, more or less unaware, along the lines suggested by Dirac, while Dirac's neighbours in Cambridge had failed to do so.

Acknowledgments

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