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THEORY VS. EXPERIMENT: THE CASE OF THE POSITRON

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Abstract

The history of positron discovery is an interesting case-study of complex relationship between theory and experiment, and therefore could promote understanding of a key issue on the nature of science (NoS) within a learning environment. As it is well known we had indeed a theory, P.A.M. Dirac's theory of the anti-electron (1931), before the beginning of the experiments leading to the experimental discovery of the positive electron (Anderson, 1932). Yet, this case is not merely an instance of successful corroboration of a theoretical prediction since, as it will be shown, the man who made the discovery, Anderson, actually did not know from the start what to look for.

1. Introduction

Over the years many researchers argued for the usefulness of history and philosophy of science (HPS) in science teaching. Among the main reasons for using HPS are its power to promote understanding the nature of science (NoS) by making it concrete and meaningful (e.g. Kipnis 1998, Matthews 2000, McComas 2008, National Research Council 2011); to provide scientific clarification of the concept to be taught (Duit et al, 2005); to overcome conceptual difficulties by drawing on the similarity between philo- and onto-genesis of knowledge (e.g. McCloskey 1983, Halloun & Hestenes 1985, Galili & Hazan 2000). Despite the intensive support for using the HPS in science teaching, however, "the issue continues to be complex and controversial" (Galili 2011; see also Galili & Hazan 2001, Monk & Osborne 1997).

This paper is essentially a case study in the history of particle physics that could likely promote understanding a NoS key issue, namely the relationship between theory and experiment.[1] The starting point will be an interesting remark originally put forward by Kuhn, of *Structure of Scientific Revolutions* fame. According to Kuhn (1962) there are two classes of scientific discoveries, namely those discoveries which "could not be predicted from accepted theory in advance and which therefore caught the assembled profession by surprise" (e.g. the oxygen, the electric current, x-rays, and the electron), and those that had been "predicted from theory before they were discovered, and the man who made the discoveries therefore knew from the start what to look for" (e.g. the neutrino, the radio waves, and the elements which filled empty spaces in the

[1] The U.S. National Research Council committee for K-12 education recently advocated the view that using HPS materials might promote understanding NoS. In the section "Practice 7: Engaging in Argument from Evidence" of their recent recommendation, it is indeed emphasized that the "Exploration of historical episodes in science can provide opportunities for students to identify the ideas, evidence, and arguments of professional scientists. In so doing, they should be encouraged to recognize the criteria used to judge claims for new knowledge and the formal means by which scientific ideas are evaluated today." (National Research Council 2011, 3-19)

periodic table). As emphasized by Kuhn, however, “not all discoveries fall neatly into one of the two classes,” and one notable example of such an occurrence had been the discovery of positron by Carl Anderson in 1932. The positron is therefore especially suitable to show the complexity of theory-experiment relationship within a learning environment.

2. Theory vs experiment in the positron discovery

The standard history of positron discovery is well known (Hanson 1961,1963; De Maria and Russo 1985; Roqué 1997; Leone and Robotti 2008). In May 1931 P.A.M. Dirac brought up the hypothesis of the anti-electron from his relativistic quantum theory of the electron. According to Dirac (1931), “an encounter between two hard γ-rays (of energy at least half a million volts) could lead to the creation simultaneously of an electron and anti-electron”. In October 1931, during a Princeton lecture, the soon to be appointed Lucasian Professor of Mathematics stated that “this idea of the anti-electrons doesn’t seem to be capable of experimental test at the moment; it could be settled by experiment if we could obtain two beams of high frequency radiation of a sufficiently great intensity and let them interact” (Dirac, as excerpted by Kragh 1990).

Within a completely different context, on September 1, 1932, Carl Anderson reported about a discovery obtained during a cosmic radiation research program at the Caltech Laboratory in Pasadena, under the directorship of Robert Millikan. By means of a vertical cloud chamber operating in a strong magnetic field, Anderson photographed indeed the passage through the cloud chamber volume of “a positively charged particle having a mass comparable with that of an electron” (Anderson 1932b) eventually named “positron”.

The connection between Dirac’s anti-electron and Anderson’s positron occurred in February 1933 at the Cavendish Laboratory in Cambridge thanks to P.M.S. Blackett and G. Occhialini. By means of their recently developed triggered cloud chamber (Blackett and Occhialini 1932), the Cavendish researchers succeeded indeed in collecting many photographs showing positron tracks that they interpreted through the theoretical framework provided by Dirac (Blackett and Occhialini 1933).

In fact, (Dirac’s) theory preceded (Anderson’s) experiment. In this respect, during the 1933 Solvay Conference, Ernest Rutherford expressed his regret at the way the history of positron discovery occurred, since “we had a theory of the positive electron before the beginning of the experiments. […] I would have liked it better if the theory had arrived after the experimental facts had been established”(Institut International de Physique Solvay 1934).

3. Anderson’s experiment

According to Anderson, his celebrated photograph (Figure 1) showing a positron traversing a 6 mm lead plate upwards was obtained on August 2, 1932 (Anderson 1933). The change of curvature below and above the plate showed that the particle went upwards and lost energy while crossing the lead shield. Since the 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.

Anderson's original papers devoted to the positron (Anderson 1932b, 1933) do not report about the actual circumstances leading to the discovery. The first details date back to his 1936 Nobel Lecture, where Anderson explained that the plate was inserted "to determine without ambiguity [the particles'] direction of motion", 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" (Anderson 1936). As regards the theoretical framework, many years elapsed before Anderson explained that the Dirac's theory "played no part whatsoever in the discovery of the positron" (Anderson 1961).

The primary historical sources, however, tell quite different a history. As for the experimental setup, in all likelihood the 6 mm lead plate had a different goal than later recollected by Anderson. Two months before his discovery, he had indeed reported that the goal of distinguishing between positive and negative particles was pursued by collecting "precise data on the specific ionization of the low-energy positives" rather than with a lead plate. Since at low energy protons and electrons ionize very differently, measures of specific ionization will indeed "distinguish […] between downward positives and upward negatives" (Anderson 1932a). But what is most significant here is that plates of lead were used by Anderson two months before his discovery (Figure 2), with the reported goal of pursuing the study of the "scattering of the cosmic particles" (Anderson 1932a, 410). For some reasons, aims and methods change as of the later recollections. What if the discovery of positron was an entirely accidental and unplanned issue?

The primary sources offer a new perspective also for what concerns the theoretical framework. While no grounds exist to support the view that Dirac's theory influenced Anderson's experiment, another theory actually played a relevant part. It is worth to recollect that Anderson worked under Millikan's directorship, and that according to Millikan's "atom-building" theory, cosmic-rays are γ-rays. Central to this theory is the idea that cosmic rays band spectrum is due to the absorption of photons emitted in the atom-building, "in the depths of space", of abundant elements like helium, oxygen, silicon and iron, out of hydrogen. The appearance of positive charges in the cloud chamber photographs, detected since late 1931, could be explained within Millikan's framework by suggesting the ejection of protons following the "disintegration of the nucleus" (Millikan and Anderson 1932). Thus, Anderson was clearly thinking in terms of Millikan's theory when he wrote in his first paper devoted to the discovery of the positron that one of the possible ways to explain the photographs was that a negative and positive electrons "are simultaneously *ejected* from the lead [emphasis added]" (Anderson 1932, 238) according to a process similar to that formerly suggested by Millikan to explain the alleged proton tracks. In 1934, Anderson was still moving within Millikan's theoretical framework when he wrote that "the simplest interpretation of the nature of the interaction of cosmic rays with the nuclei of atoms, lies in the assumption that when a cosmic-ray photon impinges upon a heavy nucleus, electrons of both sign are *ejected* from the nucleus […]. [The photographs] point strongly to the existence of nuclear reactions of a type in which the nucleus plays a more active role than merely that of the catalyst [emphasis added]"

(Anderson et al 1934).

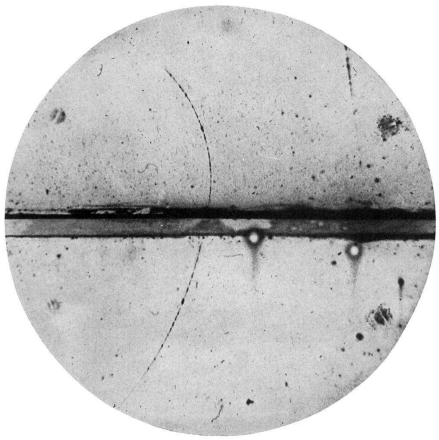

Figure 1. Anderson's cloud chamber photograph of a positron traversing the 6 mm lead plate upwards, discussed in September 1932 in Science *(Anderson 1932b) and submitted in February 1933 to* Physical Review *(Anderson 1933)*

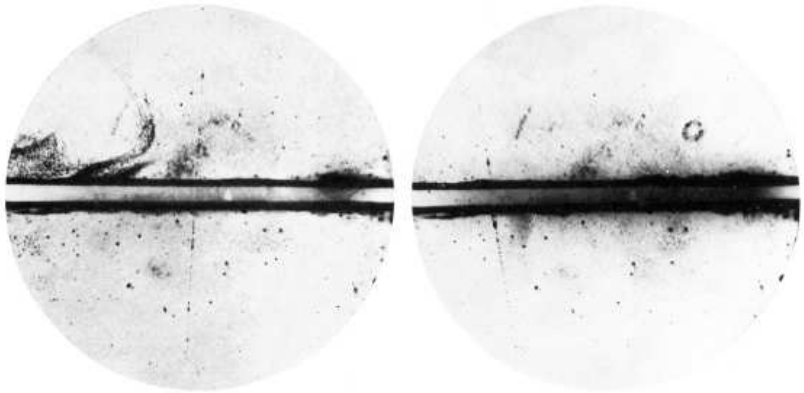

Figure 2. Anderson's cloud chamber photographs, submitted in June 1932 to Physical Review *(Anderson 1932a), showing a particle of uncertain sign of charge that suffers a deflection of 0.5 degrees in traversing the 6 mm lead plate.*

4. Blackett and Occhialini' synthesis

By their discovery of plenty of electron-positron pairs within the new phenomenon of cosmic-ray "showers" (Figure 3), made possible by their efficient triggered cloud chamber (Leone 2011), Blackett & Occhialini's "constructed a forceful case" (Kuhn 1962) for the existence of positron. Furthermore, they grasped that Anderson's positive electron and Dirac's anti-electron were the

same particle, a view supported by the fact that Dirac's theory predicted the successful detection of a positron by the cloud chamber method. As reported by Blackett and Occhialini, Dirac's calculation of probability of electron/positron annihilation process led to a positron mean life in water close to 3.6 x 10^{-10} s. Thus, the Cavendish researchers concluded, "in [Dirac's theory] favour is the fact that it predicts a time of life for the positive electron that 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" (Blackett and Occhialini 1933, 716).

Notwithstanding their support to Dirac's theory, Blackett and Occhialini's original paper provides reasons to believe that, in some respects, they departed from Dirac's pair production mechanism. In one instance, they suggest indeed that electron and positron "may be born in pairs during the *disintegration of light nuclei* [emphasis added]" since the showers had been observed to arise in air, glass, aluminum and copper" (Blackett and Occhialini 1933, 713). Within another context, namely F. Joliot and I. Curie's April 1932 observation of electrons moving towards a polonium-beryllium neutron source (Leone and Robotti 2010), they concluded that Joliot and Curie's electrons were actually positrons arising from the action of neutrons (as opposed to γ rays). Both instances reveal a production mechanism dissimilar of the one originally put forward by Dirac.

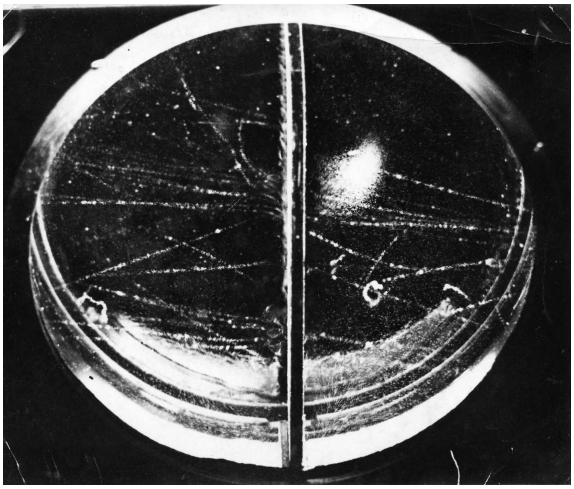

Figure 3. Photographs of electron-positron showers captured by Blackett and Occhialini via their triggered cloud chamber technique (Blackett and Occhialini 1933).

5. Concluding remarks

As pointed out by Kuhn, it might be safely concluded that Dirac's theory preceded positron discovery (to Rutherford's regret); that Anderson's experiment was done in complete ignorance of Dirac's theory; and that Blackett and Occhialini made use of Dirac's theory to corroborate the positron existence. However, as we have evidenced above, on the one hand a "wrong" theory

(Millikan's one) guided Anderson's discovery of the positron and interpretation of the tracks. And on the other hand, a "correct" theory (Dirac's one) was not fully exploited by Blackett and Occhialini in interpreting the positron production mechanism.

This case study raises therefore a number of relevant issues about NoS. Firstly, that the theory vs. experiment relationship is not always a two-poles one (often in actual science, as in the actual discovery of positron, more theories and more experiments are involved). Secondly, that sometimes "wrong" theories led to "correct" discoveries. And, finally, that original historical sources tell histories in some respects at odds with textbooks histories or with later recollections by the protagonists themselves.

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