Who discovered positron annihilation?

Tim Dunker

(Dated: 31 December 2021)

In the early 1930s, the positron, pair production, and, at last, positron annihilation were discovered. Over the years, several scientists—commonly, Thibaud and Joliot—have been credited with the discovery of the annihilation radiation. A conversation between Werner Heisenberg and Theodor Heiting prompted me to examine relevant publications, when these were submitted and published, and how experimental results were interpreted in the relevant articles. I argue that it was Theodor Heiting—usually not mentioned at all in relevant publications—who discovered positron annihilation, and that he should receive proper credit.
I. INTRODUCTION

There is no doubt that the positron, the electron’s anti–particle, was discovered by Carl D. Anderson (e.g. Anderson, 1932; Hanson, 1961; Leone and Robotti, 2012) after its theoretical prediction by Paul A. M. Dirac (Dirac, 1928, 1931). Further, it is undoubted that Patrick M. S. Blackett and Giovanni P. S. Occhialini discovered pair production by taking photographs of electrons and positrons created from cosmic rays in a Wilson cloud chamber (Blackett and Occhialini, 1933). The answer to the question who experimentally discovered the reverse process—positron annihilation—has been less clear. Usually, Frédéric Joliot and Jean Thibaud receive credit for its discovery (e.g., Roqué, 1997, p. 110). Several of their contemporaries were engaged in similar research. In a letter correspondence with Werner Heisenberg (Heiting and Heisenberg, 1952), Theodor Heiting claimed that it was he who discovered positron annihilation.

To assess whether this claim has any merit, and find out who discovered positron annihilation, I investigate the literature on positron annihilation from the early 1930s. To be able to answer who should be credited for the discovery, I also evaluate the interpretation of the experimental results in the publications.

II. THE POSITRON, PAIR PRODUCTION, AND POSITRON ANNIHILATION

Before giving an overview of the relevant publications and assessing the physical interpretations, I briefly sketch a few concepts relevant to positron annihilation.

A. Theoretical prediction and experimental discovery of the positron

In his work “The quantum theory of the electron”, Dirac postulated the existence of vacant negative energy states regarding free electrons (Dirac, 1928, Eq. (9)). In a slightly altered form, that equation reads:

$$\frac{E^2}{c^2} - p_r^2 - (mc)^2 = 0,$$

where \( p_r = -i \hbar \frac{\partial}{\partial r} \) and \( E = i \hbar \frac{\partial}{\partial t} \). It has become known as the “Dirac equation”. As Dirac outlined in his speech when receiving the Nobel Prize in Physics in 1933 (Dirac, 1933), this equation can be satisfied either by particles of energy \( E > mc^2 \), or by particles of energy \( E < -mc^2 \). Such states of negative energy for the electrons correspond to particles with a positive elementary charge, the positive electron, or positron. Dirac interpreted unoccupied negative energy states as “holes”, which were short of negative energy, and therefore had positive energy. His theory (for a review, see e.g. Hill and Landshoff, 1938, especially § 23) is therefore often called “hole theory”. These “holes” could then be filled by ordinary electrons from higher shells, releasing energy as radiation—that is, positron annihilation. Dirac also mentioned the opposite process as a possibility (Dirac, 1928): transforming electromagnetic radiation into an electron and a positron, that is,

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1 See Appendix A for a rudimentary biography.
pair production\(^2\) Dirac was well aware that protons were far too heavy to be in agreement with his theory \(\text{\cite{Dirac1930}}\), but these were at the time the only known positively charged particles.

Not very long after Dirac’s postulation, \(\text{\cite{Anderson1932}}\) reported on the existence of “positives”, which were “comparable in mass and magnitude of charge” to electrons. His discovery confirmed Dirac’s theoretical postulation, and was based on observations of tracks of positively charged electrons in a Wilson cloud chamber \(\text{\cite{Anderson1932}}\). Protons could be ruled out from mass and energy considerations \(\text{\cite{Anderson1933b}}\). The new positively charged particle came to be known as a positron\(^1\).

Two processes in which a positron is involved, are pair production and positron annihilation. These are fascinating example of the transformation of light into matter and vice versa, respectively.

### B. Pair production

In pair production, electromagnetic radiation is transformed into matter, namely an electron–positron pair. As \(\text{\cite{OppenheimerPlesset1933}}\) have shown, if a photon has an energy of at least twice the rest mass of an electron \(E = 1.022 \text{ MeV}\), pair production becomes possible:

\[
\gamma \rightarrow e^- + e^+ \tag{2}
\]

Twice the rest mass of an electron is needed, because a positron has the same rest mass as an electron. The pair production cross–section is

\[
\sigma_{pp} \approx \alpha Z^2 r^2. \tag{3}
\]

Here, \(Z\) is the atomic number of the element in which pair production takes place, \(r = e^2 \left(4\pi\varepsilon_0 mc^2\right)^{-1}\) is the electron radius, and \(\alpha \approx 137^{-1}\) is the fine–structure constant.

The creation of electron and positron pairs was first observed by \(\text{\cite{BlackettOcchialini1933}}\) in a Wilson cloud chamber. Shortly after, \(\text{\cite{Chadwicketal1933}}\) argued that the positrons are most likely not created in the nucleus itself, but in the “electric field outside the nucleus” (that is, in the electron shells).

### C. Positron annihilation

The reverse process of pair production is called positron annihilation. This process has also been predicted by Dirac’s hole theory \(\text{\cite{Dirac1928}}\), although the positron had not been discovered yet, thus Dirac spoke of “protons” and acknowledged the problem of a large difference in mass between an electron and a proton \(\text{\cite{Dirac1930} p. 361 yo 362}\). When a positron combines with an electron, two \(\gamma\)–rays are emitted:

\[
e^- + e^+ \rightarrow \gamma + \gamma \tag{4}
\]

\(^2\) In fact, pair production is not strictly the opposite process, because in pair production, one photon is transformed into two particles, while positron annihilation transforms two particles into at least two photons. One–photon annihilation is practically irrelevant, as \(\text{\cite{FermiUhlenbeck1933}}\) calculated.

\(^3\) According to Carl Anderson, the name “positron” was not suggested by him, but by Watson Davis, the then–editor of the journal Science \(\text{\cite{AndersonWeiner1966}}\).
Although the probability of annihilation was deemed low (Fermi and Uhlenbeck, 1933) from a theoretical point of view, this process of annihilation does in fact occur. Before it occurs, a positron and an electron may form a positronium atom: This is a hydrogen–like atom, but with a positron instead of a proton (Deutsch, 1951). The singlet state of the positronium atom, so–called parapositronium, decays by emitting two photons of equal energy.\(^4\) Parapositronium has a lifetime of \(\sim 142 \times 10^{-9}\) s in vacuum (Al–Ramadhan and Gidley, 1994).

The emitted \(\gamma\)–rays in the annihilation process have energies of 511 keV each, corresponding to the electron rest mass. These \(\gamma\)–rays are emitted in opposite direction to each other to satisfy the conservation of total momentum. These two quanta are also polarized perpendicularly to each other. In many of the early articles, especially in the 1930s, the wavelength that corresponded to the quantum’s kinetic energy was commonly expressed in the “X–unit/xu”, or “X.E.” for “Röntgeneinheit” in German, or “UX/unité x” in French. Bearden (1965) has determined the wavelength conversion factor \(\Lambda\) to be

\[
\Lambda = (1.002076 \pm 0.000005) \times 10^{-13} \text{ m xu}^{-1}.
\]

For some of the articles cited below, I use this conversion factor to transform the outdated units to today’s SI units.

III. WHO DISCOVERED POSITRON ANNIHILATION?

In the early 1930s, many different scientists in France, Germany, and Great Britain worked on the interaction of hard \(\gamma\)–rays and different metal absorbers. Results were, accordingly, published in English, French, and German. Nomenclature was not yet well–developed, because both the underlying theory (Dirac, 1928) and many experimental effects were quite new and sometimes uncertain, or at least subject to interpretation. It was a very vibrant field and publications arrived at the scientific journals in very short intervals, and, occasionally, different scientists published their results in the same issue of a journal. In the following, I take the Nobel Prize in Physics in 1948 as a starting point. My goal is to answer the question who first discovered the annihilation radiation. Table I gives an overview over relevant publications, when these were submitted, and when these were finally published.

In his presentation speech of the Nobel Prize in Physics in 1948, which was awarded to P. M. S. Blackett, G. Ising of the Nobel Committee for Physics said the following (Ising, 1964, p. 95):

“[..] Reversely, the meeting of two slow electrons, opposite in sign, results in their fusion and annihilation as material particles; in this process two light quanta, each of 1/2 million electron volts, are formed; these fly out from the point of encounter in opposite directions, so that the total momentum remains about zero (for even light possesses a momentum directed along the ray). Blackett and Occhialini immediately drew these conclusions from their experiments.

\(^4\) The probability of the emission of a higher (even) number of photons is not zero, but much smaller than that of the two–photon decay.
and were guided in so doing by the earlier mathematical electron theory elaborated by Dirac on the quantum basis. The existence of the ‘annihilation radiation’ was shortly afterwards established experimentally by Thibaud and Joliot. [...]”,

referring to the works of Thibaud (1933) and Joliot (1933).

In December 1933, Joliot published his results on positron annihilation (Joliot, 1933). Five months later, he submitted a more detailed version of those experimental results, which were published in July 1934 (Joliot, 1934a).

Thibaud (1933, p. 1631, “6.”) claimed to have published the first experimental proof of positron annihilation radiation. Shortly after, Gentner (1934b) mentioned that the experimental proof for positron annihilation, i.e. the detection of a $\sim 500$ keV radiation component, was achieved simultaneously by Joliot (1933) and Thibaud (1933). Joliot (1933) and Thibaud (1933) published their results in the same issue of Comptes Rendus, dated 18 December 1933.
Thibaud (1934a) subsequently published a more detailed version in English. He comments on Joliot’s results (Joliot, 1933), stating that 86% of Joliot’s results obtained with a Geiger–Müller counter were due to “parasitic effects”, while his own method (film exposure) was exempt from such contamination (see also Thibaud, 1934b).

Results similar to Joliot and Thibaud have been obtained by Gray and Tarrant (1934a), namely, that much of the secondary $\gamma$–radiation occurred with energies $0.5 \times 10^6 \text{eV} \leq E_{\text{kin}} \leq 1.0 \times 10^6 \text{eV}$, regardless of the scattering angles observed. They used various absorber materials (Gray and Tarrant, 1934a). They interpreted their results in a companion article (Gray and Tarrant, 1934b), but did not relate their results to Dirac’s theory.

Williams (1934) detected backscattered particles, resulting from hard $\gamma$–rays incident on a Pb plate. The backscattered particles were detected by an ionisation chamber at an angle of 140° relative to the Pb plate. He performed two different experiments: one without an additional absorber, and one with an Al plate as absorber between the Pb plate and the ionisation chamber. He interpreted the results such that, when the Al plate was present, most positrons emitted by the Pb plate were absorbed by the Al plate, while the positrons without the absorber would be annihilated in greater distance from their source. However, Williams could only speculate about the particles being positrons, and the experiments did not yield information on the particles’ energy or charge, or energy of the annihilation radiation.

Klemperer (1934) has also provided proof of the annihilation radiation, using a Geiger–Müller counter in his experiments. His report was received by the Cambridge Philosophical Society on 20 May 1934.

Gentner (1934b) tried to clarify the differences between theoretical expectations according to the Klein–Nishina formula and the spectral dependence of absorption coefficients found experimentally. Gentner interpreted his own results as Compton electrons, and to lesser extent as electrons from a photoeffect in the absorber which were backscattered towards the filter. He concluded that, because the bremsstrahlung spectrum consists of energies up to $10^6 \text{eV}$, many of the characteristics of secondary radiation might be explained by backscattered electrons (Gentner, 1934b).

In their review article, Fleischmann and Bothe (1934, §23, pp. 37 to 40) credit Joliot (1934b), Thibaud (1933, 1934b), and Crane and Lauritsen (1934) with the experimental discovery of positron annihilation. Heiting’s work (Heiting, 1934) is mentioned, too, in connection with the secondary radiation observations made with hard $\gamma$–rays. Amaldi (1934, p. 67) also credits Joliot (1933, 1934a) and Thibaud (1933) with the discovery, while Hill and Landshoff (1938, footnote 56a, p. 121) attribute the experimental proof to Klemperer (1934) and Crane and Lauritsen (1934). More recently, Guerra et al. (2012) indirectly credited Joliot with the discovery of positron annihilation, writing that

“[...] between the middle of December 1933 and early January 1934, [Joliot] studied positron–electron annihilation, finding results in complete agreement with Dirac’s theory, which he published in the Comptes rendus”.

5 I have not been able to determine which article of Thibaud their footnote 177 refers to.
referring to Joliot (1933) and Joliot (1934b). Evidently, all of the works cited in this paragraph have been published after Heiting’s first two articles (cf. Table I).

Let us return to the contents of the Nobel Prize speech: in 1951, Physikalische Blätter published articles on recently awarded Nobel Prizes in Physics. Among them was the Nobel Prize 1948, awarded to P. M. S. Blackett. This prompted a comment by Theodor Heiting and a reply by Werner Heisenberg (Heiting and Heisenberg, 1952). Heiting claimed that he had discovered positron annihilation even earlier than Joliot and Thibaud. Heisenberg, whom Heiting thanked in his publications for his counselling and persistent interest in his work, replied that he could dimly remember a conversation with Heiting and a Mr Messerschmidt and that he was happy about Heiting’s confirmation of Dirac’s theory (Heiting and Heisenberg, 1952). Heisenberg remarked that it might have been possible that also other physicists before Heiting mentioned positron annihilation radiation, or made it experimentally probable. However, he could not find any evidence for that, and subsequently Heiting should be named as the discoverer of positron annihilation radiation.

Heiting was a doctoral student with Gerhard Hoffmann at the Institut für Experimentalphysik in Halle an der Saale, Germany. Three articles were published by Heiting, submitted on 7 August 1933 (Heiting, 1933a), 28 September 1933 (Heiting, 1933b), and the third one received by the journal on 2 November 1933 (Heiting, 1934). This is six weeks earlier than Joliot’s and Thibaud’s publications (Joliot, 1933; Thibaud, 1933).

In his experiments, Heiting used $\gamma$–rays from a RaTh source, which was equivalent to 28 mg of radium (Heiting, 1934). This material emits electromagnetic radiation with a wavelength of $4.7\times 10^{-8}$ m, which equals

$$\lambda = 4.7\times 10^{-8} \Rightarrow E_{\text{kin}} = 2.63 \times 10^6 \text{ eV} \approx 5.2 \cdot m_e c^2,$$

corresponding to the radioactive decay ThC”, that is, the transition $^{208}\text{Th} \rightarrow ^{208}\text{Pb}$. This kinetic energy is sufficient to create electron–positron pairs.

The $\gamma$–rays were incident on aluminium, iron, copper, and lead absorbers, respectively. An ionization chamber was used to detect the penetrating radiation. Heiting measured the attenuation coefficients for all the absorber materials, and reported the first results in August 1933 (Heiting, 1933a). Heiting discovered that all the mentioned absorbers emitted a type of secondary radiation, which was independent of the absorber element (Heiting, 1933a,b). Using Chao’s method, who found that the attenuation coefficient

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6 For three articles, I have been unable to find the date of submission or reception by the journal “Comptes rendus”. Judging from the publication date, though, it seems certain that these articles were submitted after Heiting had submitted his two first articles. It seems very likely—given the rapid nature of publication at “Comptes rendus” with its two–week cycle between issues—that these were submitted after the publication of Heiting’s first two articles.

7 This was the journal of the Verband Deutscher Physikalischer Gesellschaften, at that time the intermediate organization of the Deutsche Physikalische Gesellschaft.

8 This was almost certainly Wilhelm Messerschmidt (see also Brüche et al., 1966), who, like Heiting, was a member of Gerhard Hoffmann’s group in Halle in the early 1930s.

9 Apparently, Heiting got a private lecture by Werner Heisenberg on Dirac’s “hole” theory. I have not found other sources regarding the communication between Heiting and Heisenberg.

10 At that time, the university was still called Vereinigte Friedrichs–Universität Halle–Wittenberg. On 10 November 1933, the university got today’s name “Martin–Luther–Universität Halle–Wittenberg”. The university’s official name includes Wittenberg, but the actual location is Halle. There has not been any university activity in Wittenberg, approximately 60 km from Halle, for a long time (Reinhard Krause–Rehberg, pers. comm., 2018).
is a function of wavelength \( \text{(Chao, 1930)} \). Heiting determined the mean wavelength from the measured 
attenuation coefficients to be

\[
\lambda = (23.8 \pm 1.0) \text{xu} \cdot \Lambda = 2.385 \times 10^{-12} \text{m}.
\]

With today’s values of the Planck constant and the speed of light, this wavelength corresponds to a photon
energy of \( E_{\text{kin}} = (0.52 \pm 0.02) \times 10^{6} \text{eV} \). Well within the measurement uncertainty, this energy equals
an electron’s rest mass. This finding was pointed out by Heiting in his second publication on the topic
\( \text{(Heiting, 1933a)} \), and he also interpreted that secondary radiation as recombination radiation (“Rekombina-
tionsstrahlung”) of an electron with a positron\(^{11}\) positron annihilation radiation.

The two major conclusions, out of a total of four, in his most comprehensive article \( \text{(Heiting, 1934, p. 137)} \) are:

V. Summary and interpretation

1. The examined elements Al, Fe, Cu, Pb all emit the same wavelength \( \lambda = (23.8 \pm 1.0) \text{xu} \).

   This effect can be interpreted according to Dirac’s theory. As L. Meitner and K. Philipp, as well
   as others (using a cloud chamber), showed, positive electrons occur if hard ThC\textsuperscript{–}–\( \gamma \)
   radiation is absorbed, especially in the case of heavy atoms. According to Dirac, the positron
   is only short-lived (\( \sim 10^{-10} \text{s} \)), because it seeks to recombine with a negative electron, emitting
   the energy of \( 2m_0c^2 \) during this process. This energy is emitted as two quanta \( h\nu = m_0c^2 \),
   that is, the wavelength \( \Lambda = 24.2 \text{xu} \) will be observed.

2. The intensity of this “recombination radiation” per nuclues scales with the square of the
   atomic number. This observation, too, is in accord with the theory. […]"

In the months following the publication, Heiting’s findings were criticized by Bothe and Horn \( \text{(1934a)} \),
who doubted that the results of Gray and Tarrant \( \text{(1932)} \) and Heiting \( \text{(1934)} \) were proof of a real secondary
radiation of 500 keV, but they did not rule out the possibility entirely. Bothe and Horn \( \text{(1934a)} \) concluded
that processes assumed by Meitner and Hupfeld \( \text{(1931)} \), Gray and Tarrant \( \text{(1932)} \), and Heiting \( \text{(1934)} \) could
only play a subordinate role, even though their experimental results were in good agreement with the
aforementioned authors’ works. What is more, Bothe and Horn \( \text{(1934a)} \) attributed the additional radiative
component to bremsstrahlung, or to anomalies of the Compton effect. They also hypothesized that the
deceleration and annihilation of a positron occurs in one single radiative process \( \text{(Bothe and Horn, 1934a)} \).
However, Bothe and Horn’s results are not spectrally resolved \( \text{(Bothe and Horn, 1934a)} \). It appears their
measurements do not contradict the results of Heiting \( \text{(1934)} \).

\(^{11}\) “The fact that the wavelength \( \lambda = 24 \text{xu} \) occurs, requires special attention, because this wavelength corresponds to
the energy \( h\nu = m_0c^2 \). Recently, with a Wilson cloud chamber, it was found \( \text{(Anderson, 1933a)} \) that positrons can
come in heavy elements when these are hit by hard Th C\textsuperscript{–}–\( \gamma \) rays. According to Dirac’s view, the positive electron
only has a short lifetime, because it seeks to recombine with a negative electron, emitting the energy \( 2m_0c^2 \) as
two quanta \( h\nu = m_0c^2 (\lambda = 24.2 \text{xu}) \). The observed secondary radiation can thus be interpreted as recombination
radiation, and the nuclear absorption can be interpreted as splitting of the primary \( \gamma \) rays in the nucleus into
positive and negative electrons. […]”
Neither in Amaldi (1984) nor in a recent overview article by Goworek (2014) are Heiting’s articles mentioned. Neither were Heiting’s articles cited by Joliot nor Thibaud, which might be due to the fact that Heiting published in German, and also because—in retrospect—the titles of his publications were not ideal. That is, Heiting never used a term like “positron annihilation” or similar as part of the title, even though Heiting quite clearly concluded that his results were proof of Dirac’s theory regarding positron annihilation radiation (Heiting, 1934, “Rekombinationsstrahlung”). One may argue that because the publications cited here were in English, French, and German, it may be possible that the authors were unaware of each other’s findings. This does not seem to be the case, though. They frequently cited each other’s articles for various reasons, regardless of the language.

IV. CONCLUSION

After inspecting the chronology of submissions and the interpretation of results in these submitted manuscripts, I conclude that Heiting’s claim (Heiting and Heisenberg, 1952) seems justified. Indeed, Theodor Heiting should receive credit for the experimental discovery of positron annihilation radiation. Heiting submitted his first results on 7 August 1933, and these were published shortly after (Heiting, 1933a). The interpretation of those results followed in a publication submitted on 28 September 1933 (Heiting, 1933b), where he attributed the secondary radiation to positron annihilation—recombination radiation, as Heiting put it at the time. His final publication on the topic was received by the Zeitschrift für Physik on 2 November 1933, which contained a more detailed description of the method and comprehensive experimental results (Heiting, 1934). The interpretation of his results remained the same. Joliot (1933), Thibaud (1933), and Klemperer (1934) published their results after Heiting published his discovery. Heiting’s remark that he was the first to experimentally discover positron annihilation radiation (Heiting and Heisenberg, 1952) seems justified.

ACKNOWLEDGMENTS

I am very grateful to Karin Keller, Universitätsarchiv der Universitätsbibliothek, and Reinhard Krause–Rehberg, Institut für Exeprimentalphysik, both of Martin–Luther–Universität Halle–Wittenberg, for their kind help in finding information on Theodor Heiting and sharing these with me, as well as for comments on a draft version. Isabelle Maurin–Joffre kindly provided me with information on the submission and publication procedures in Comptes Rendus. I also thank Eirik Malinen of the Department of Physics, University of Oslo, for helpful discussions and comments on an earlier version of this manuscript.
Appendix A: Rudimentary biographical notes on Theodor Heiting

The following notes are mostly based on archived information at Universitätsarchiv der Universitätsbibliothek, Martin–Luther–Universität Halle–Wittenberg, Germany.

Theodor Fritz Heiting was born in Wuppertal–Elberfeld on 14 July 1908. His parents were Heinrich and Maria Heiting. He went to the Volksschule in Elberfeld from 1914 until 1918, and went on with a humanistic secondary school education (LMU München 1928), at first in Elberfeld until 1919, then eight more years in Halle an der Saale, where he passed his “A–levels” in 1927. He went on to study Physics, Mathematics, and Chemistry in Halle with a short intermezzo in Munich. At least in early 1934, he lived at Johannesplatz 14 in Halle.

In Munich, he was a student at Philosophische Fakultät, Ludwig–Maximilians–Universität München, in winter semester 1928/1929 and summer semester 1929. He lived in Augustenstraße 50/4 (LMU München 1928) and Leopoldstraße 60/2 (LMU München 1929). At Ludwig–Maximilians–Universität, he took the following courses (teacher in parentheses): introduction to theoretical physics I and II (Graetz), theory of electricity and magnetism (Graetz), thermodynamics and statistical gas theory (Ott), lab course in physics (Kirchner), and differential equations (Perron).

He then continued his studies at Halle–Wittenberg. From September 1931 until July 1933, he was a doctoral candidate with Gerhard Hoffmann. From his early doctoral work, there is an abstract published in Chemisches Zentralblatt Heiting (1932). On 6 January 1934, he applied for his doctoral defence, majoring in physics. His two minors were mathematics and chemistry. Together with his application, he submitted an abstract of his dissertation to the university. I have translated the German abstract, also dated 6 January 1934, as follows:

“An anomalous absorption is observed as hard $\gamma$ rays pass through heavy atoms. This anomalous absorption cannot be explained by photoelectric nor by Compton scattering processes. Simultaneously, there is a secondary radiation emitted by the irradiated materials which is different from Compton scattering radiation. The investigation of this secondary radiation by C. Y. Chao, L. H. Gray und G. T. P. Tarrant, L. Meitner and H. H. Hupfeld has led to contradictory results.

The purpose of my work was the resolve these contradictions. The secondary radiation of aluminium, iron, copper, and lead was investigated. The radiation of these metals proved to be homogeneous, with the wavelength $(23.8 \pm 1.0) \times 10^{-11}$ cm being independent of the material (within the measurement uncertainties), and the intensity of the radiation increased with the square of the atomic number. (Only in lead a second component was found, with a wavelength of $6.6 \times 10^{-11}$ cm)

This finding was interpreted as follows: If hard $\gamma$ rays interact with matter, a split of the $\gamma$ rays in pairs of positive and negative electrons is possible, and the scattering cross section increases with the square of the atomic number. According to Dirac, the positron is an
unstable particle analogous to the photon, it “recombines”, after it has lost its kinetic energy, with a negative electron, thereby emitting the energy $1.02 \times 10^6 \text{ eV}$. From the conservation of momentum, it follows that this energy has two be emitted as two quanta $h\nu = 0.51 \times 10^6 \text{ eV}$, which corresponds to the wavelength $24.2 \times 10^{-11} \text{ cm}$.

On 28 February 1934, he passed the doctoral examination at Martin–Luther–Universität Halle–Wittenberg (see footnote [10] on page [7]), and was awarded a doctoral degree in science (Dr. rer. nat.) on 8 March 1934 for his dissertation entitled “Untersuchungen über die durch harte $\gamma$-Strahlung hervorgerufene Sekundärstrahlung” [12].

[12] Translated as “Investigations of the secondary radiation due to hard $\gamma$ rays”
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