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From aether impulse to QED: Sommerfeld and the Bremsstrahlen theory

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ABSTRACT

The radiation that is due to the braking of charged particles has been in the focus of theoretical physics since the discovery of X-rays by the end of the 19th century. The impact of cathode rays in the anticathode of an X-ray tube that resulted in the production of X-rays led to the view that X-rays are aether impulses spreading from the site of the impact. In 1909, Arnold Sommerfeld calculated from Maxwell's equations the angular distribution of electromagnetic radiation due to the braking of electrons. He thereby coined the notion of "Bremsstrahlen." In 1923, Hendrik A. Kramers provided a quantum theoretical explanation of this process by means of Bohr's correspondence principle. With the advent of quantum mechanics the theory of bremsstrahlung became a target of opportunity for theorists like Yoshikatsu Sugiura, Robert Oppenheimer, and–again–Sommerfeld, who presented in 1931 a comprehensive treatise on this subject. Throughout the 1930s, Sommerfeld's disciples in Munich and elsewhere extended and improved the bremsstrahlen theory. Hans Bethe and Walter Heitler, in particular, in 1934 presented a theory that was later regarded as "the most important achievement of QED in the 1930s" (Freeman Dyson). From a historical perspective the bremsstrahlen problem may be regarded as a probe for the evolution of theories in response to revolutionary changes in the underlying principles.

1. Introduction

In 2004, more than a hundred years after the dicovery of X-rays, the authors of a monograph on *The Elementary Process of Bremsstrahlung* introduced their subject by the following statement: "Apart from the interest in the nature of the process itself, there are a variety of reasons why the bremsstrahlung process occupies such an important place in physics. Firstly, the process is related to the fundamentals of the theory since it is a consequence of the general coupling of the electromagnetic field and matter fields. Therefore bremsstrahlung appears in nearly all branches of physics: atomic and nuclear, solid-state and elementary-particle physics. Moreover, bremsstrahlung is an important tool in many areas of experimental research, in the field of astrophysics, and it has a wide range of technical applications." (Haug & Nakel, 2004, p. 1)

Hence the theory of bremsstrahlung is regarded both as fundamental and as pertinent for a host of applications. It seems to belong to the "physics of principles" as well as to the "physics of problems" (Seth, 2003). From the perspective of contemporary physics it belongs to the realm of quantum electrodynamics (QED), but the bremsstrahlen problem dates back to the discovery of X-rays at the end of the 19th century. We may discern several periods in which different approaches to the bremsstrahlen problem prevailed: the classical era when the problem was regarded as a case for Maxwellian electrodynamics and electron theory; the period of the "old" quantum theory before 1925; the early years after the rise of quantum mechanics; and the 1930s with its early attempts to solve the riddles of QED. In the second half of the 20th century the bremsstrahlen problem was analyzed by new methods of quantum field theory.

In this study I follow the bremsstrahlen problem and the ways in which it has been analyzed with a particular focus on Sommerfeld and his school. This narrows the time period to the early decades of the 20th century. Some aspects of Sommerfeld's wave-

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Abbreviation: ASWB, Arnold Sommerfeld. Wissenschaftlicher Briefwechsel. vol. I: 1892–1918, vol. II: 1919–1951. Edited by Michael Eckert und Karl Märker. München, Berlin, Diepholz: Deutsches Museum und GNT-Verlag, 2000 und 2004; DMA, Deutsches Museum, Archiv. München; UAM, Universitätsarchiv, München; WPWB, Wolfgang Pauli. Wissenschaftlicher Briefwechsel. Edited by Karl von Meyenn. vol. I: 1919–1929, vol. II: 1930–1939. Springer: Berlin, Heidelberg, New York, Tokyo, 1979 and 1985

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mechanical bremsstrahlen theory received renewed interest in the theory of dark matter in the 21st century. Thus Sommerfeld's bremsstrahlen theory may also be regarded as a case-study for the persistence of problems in the light of revolutionary change with regard to the foundations of physics. From an epistemological and historical perspective, its persistence despite revolutionary changes in the foundations of physics is remarkable. Paradigm shifts did not render it obsolete nor reduce its pertinence for fundamental aspects of theoretical physics.

2. The aether impulse hypothesis

For at least a decade after the discovery of X-rays in 1895, the nature of this "new kind of rays" remained mysterious. In 1899, the Dutch physicists Hermanus Haga and Cornelis Wind had reported evidence for the wave nature of X-rays by diffraction experiments with narrowing slits. Arnold Sommerfeld, who had started his career five years before with a mathematical theory of diffraction, perceived these experiments as a challenge to derive the diffraction pattern of electromagnetic impulses.[1] Although the experimental data as well as Sommerfeld's theoretical analysis provided little evidence about the electromagnetic nature of X-rays, most physicists perceived them as electromagnetic aether impulses caused by the impingement of electrons in the anti-cathode of the X-ray tube (Wheaton, 1983, chapter 2). Hendrik Antoon Lorentz, the authority in all matters concerning electromagnetism and electron theory, in 1907 considered X-rays as light with a very short wavelength, emerging from "an irregular succession of impacts, each of which persists for a much shorter [time] than does one oscillation of the farthest ultraviolet light yet observed."[2]

By the same time, experiments by Charles Glover Barkla provided new evidence for the electromagnetic impulse hypothesis. He discerned two components of X-rays, an inhomogeneous "scattered radiation produced by the motion of electrons controlled by the electric force in the primary Röntgen pulses" and "a homogeneous radiation characteristic of the element emitting it, and produced by the motion of electrons uncontrolled by the electric force in the primary pulses."[3] In other words: X-rays come as a mixture of unpolarized pulses emitted isotropically with the same ("homogeneous") penetration power in all directions that is characteristic for the anti-cathode material, and polarized pulses (later called bremsstrahlen) with inhomogeneous penetration power dependent on their direction. Henceforth, the correlation between polarization and spatial distribution of X-ray intensity became a new goal for both experimental and theoretical researches on X-rays.

In 1906 Sommerfeld had been called to the university in Munich as a professor for theoretical physics. With Röntgen as a director of the neighboring institute for experimental physics, the investigation of X-rays became a major challenge. Eugen Bassler, a doctoral student of Röntgen, in his dissertation focused on the polarized fraction of X-rays emitted from different materials–and found that indeed the intensity of this component was not the same in all directions. Similar results were published in 1909 by Johannes Stark, then an aspiring experimental physicist at the Technische Hochschule Aachen. But Stark did not consider the anisotropy as evidence for the electromagnetic impulse hypothesis. He regarded X-rays as light quanta that carry momentum like particles; he imagined that the impact of the electrons in the cathode ray adds to the momentum of the isotropically emitted X-ray particles so that the resulting distribution of the X-ray intensity is no longer isotropic but shifted in the direction of the impinging cathode ray (Wheaton, 1983, pp. 120–126).

For Sommerfeld, however, the observed anisotropy was the long-sought evidence for the electromagnetic impulse hypothesis. A few years earlier he had even performed himself "some qualitative experiments with the help of my able assistant," as he wrote to a colleague in 1905, but they had found "practically no dependence of the intensity of X-ray actions on the angle between the X-ray and the direction of the cathode ray."[4] When Stark finally obtained the evidence for an anisotropic intensity distribution and claimed that the electromagnetic impulse theory was incompatible with this anisotropy, Sommerfeld responded immediately. Such anisotropy was a necessary consequence of the "Bremstheorie", he corrected Stark's erroneous view. "You will convince yourself, as I hope, that the Bremstheorie of X-rays leads by itself to all those consequences for which you resort to the (very hypothetical and uncertain) light quantum theory. Not that I am in doubt about the importance of the quantum of action. But your elaboration seems not only to me but also to Planck rather daring."[5]

The ensuing "Sommerfeld-Stark embroglio" (Wheaton, 1983, p. 126) has been the subject of detailed accounts.[6] It may suffice here to briefly review Sommerfeld's argument as published in the *Physikalische Zeitschrift* in December 1909 (Sommerfeld, 1909). Like in his letter to Stark, he made clear that he did not perceive his elaboration of the electrodynamic aether impulse hypothesis as a plea against quantum theory. The "aether", by that time, was no longer perceived as a material medium but merely as a substrate for Maxwell's equations. Furthermore, Sommerfeld restricted his analysis to the "Bremsanteil" only, and here Planck's quantum of action appeared to him irrelevant. The second component, the "Fluoreszenzanteil", involved in his view "an absorption and emission of energy in the atom. Here it is well possible that Planck's quantum of action plays a role."[7]

After this proviso Sommerfeld immediately presented a formula that explained the origin of the anisotropy of the "Bremsanteil". He referred to Max Abraham's classic textbook where a section was dedicated to the "Unstetige Bewegung des Electrons" (Abraham, 1905, Section 25) and the electromagnetic field resulting from a sudden stopping of an electron was calculated. The flux of energy (i.e., the Poynting vector), given by the product of the electric and magnetic field strengths, depended on both the velocity v of the electron and the angle ϕ between the direction of the impinging electron and the site at which the radiation was measured. Sommerfeld extended this case from an instantaneous braking to a constant deceleration over a short braking path along

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[1] For a biography of Sommerfeld see (Eckert, 2013).

[2] Quoted in Wheaton (1983, p. 48).

[3] Quoted in Wheaton (1983, p. 101).

[4] "Ich habe solche qualitativen Experimente mit Hilfe meines tüchtigen Assistenten selbst gemacht. Es ist so gut wie gar keine Abhängigkeit der Intensität der Röntgenwirkung von dem Richtungswinkel zwischen Röntgenstrahl und auffallendem Kathodenstrahl vorhanden…" Sommerfeld to W. Wien, 13 May 1905. DMA, NL 56, 010. Also in ASWB I, 242–244. Sommerfeld's assistant was Peter Debye, and since then the riddles of X-rays became almost a personal challenge for both of them.

[5] "Sie werden sich, wie ich hoffe, überzeugen, dass die Bremstheorie der Röntgenstrahlen alles das von selbst leistet, wozu Sie die (doch sehr hypothetische und unbestimmte) Lichtquantentheorie heranziehen. Nicht als ob ich an der Bedeutung des Wirkungsquantums zweifelte. Aber die Ausgestaltung, die Sie ihm geben, scheint nicht nur mir, sondern auch Planck sehr gewagt." Sommerfeld to Stark, 4 December 1909. Stark Papers, Staatsbibliothek zu Berlin – Preußischer Kulturbesitz, Handschriftenabteilung. Also in ASWB I, 365–366.

[6] Wheaton (1983, pp. 126–132) and Hermann (1968) also included the pertinent correspondence between Sommerfeld and Stark; see also ASWB I, pp. 365–375.

[7] "Bei dem zweiten 'Fluoreszenzanteil' der Strahlung findet eine Absorption und Emission im Atom statt. Es ist sehr wohl möglich, dass hierbei das Plancksche Wirkungsquantum eine Rolle spielt. (…) Mit dem ersten 'Bremsanteil' der Strahlung dagegen scheint mir das Wirkungsquantum nichts zu tun zu haben." (Sommerfeld, 1909, p. 970).