Secondary Literature

29. R. Loudon: *The quantum theory of light* (Oxford University Press, Oxford 2000)
30. *The Feynman Lectures on Physics* (Addison-Wesley 2005, Vol. 3)
31. J.C.H. Spence: Lensless (Diffractive) Imaging, in: *Science of Microscopy*. P. Hawkes, J.C.H. Spence Eds. (Springer, Berlin 2007, Ch. 19)

Electrons

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The discovery of the electron was a complex and extended process, stretching from Faraday's investigation of electrolysis to Millikan's oil-drop experiments [18]. The results of four different fields (electrochemistry, electromagnetic theory, ► spectroscopy, and ► cathode rays) converged to support the existence of a novel subatomic constituent of matter. Faraday's experiments on electrolysis, interpreted from the perspective of the atomic theory of matter, implied that electricity has an atomic structure [4]. That is, electricity appears in naturally occurring units. In 1891 George Johnstone Stoney (1826–1911) named those units "electrons" ([13], p. 583, [30]).

In 1894 Stoney's electrons were appropriated by Joseph Larmor (1857–1942) to overcome certain empirical and conceptual problems faced by Maxwell's electromagnetic theory ([6], pp. 806 ff.). Larmor's electrons were supposed to be universal constituents of matter and were represented as structures in the all-pervading ether. On the continent a similar electromagnetic theory had been proposed by Hendrik Antoon Lorentz (1853–1928), who developed a synthesis of British and Continental traditions in electromagnetism [7]. Lorentz's theory incorporated Maxwell's suggestion that electromagnetic phenomena are wave processes in the ether and the suggestion of continental theorists (e.g., Wilhelm Weber) that these phenomena are due to the action of charged particles. Lorentz named those particles "ions", in analogy with the ions of electrolysis.

A crucial event for the development of Larmor's and Lorentz's theories was an experimentally discovery by Pieter Zeeman (1865–1943). In 1896 Zeeman observed that the spectral lines of sodium widen under the influence of a magnetic field (► Zeeman effect). Drawing on Lorentz's theory, he attributed the modification of the sodium spectrum to the influence of magnetism on the mode of vibration of the "ions". From the observed widening he was able to calculate their charge to mass ratio, which to everyone's surprise turned out to be three orders of magnitude larger than that of the electrolytic ions [17]. That was the first indication that Lorentz's ions, as well as Larmor's electrons, were much smaller than ordinary ions. In 1899 Lorentz changed the name of his "ions" to "electrons" [18].

Electron theories received additional support by the theoretical and experimental investigation of ► cathode rays. The nature of those rays had been the subject of considerable debate. The controversy subsided in 1897, when J. J. Thomson (1856–1940) showed that they were composed of “corpuscles”, minute charged particles. From the electric and magnetic deflections of those particles he calculated their mass to charge ratio (m/e). It turned out that the value of m/e was three orders of magnitude smaller than “the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis” ([15], p. 310).

In 1899 Thomson reported measurements of the mass to charge ratio of the particles produced in the ► photoelectric effect as well as by thermionic emission. Those measurements indicated that the particles in question were identical with the constituents of cathode rays [16]. Henri Becquerel (1852–1908) reached a similar conclusion about the identity of the recently discovered β-rays, which were shown to be “entirely comparable to . . . cathode rays, or masses of negative electricity transported with great speed” ([1], p. 210). Thus, by the end of the nineteenth century the electron had surfaced in a variety of theoretical and experimental contexts.

In the beginning of the twentieth century, β-rays were employed as a tool to adjudicate between contemporary electromagnetic theories, which gave different accounts of the electron’s shape and structure. First, the theory developed by Max Abraham (1875–1922) implied that the electron was a rigid sphere with a uniform (surface or volume) distribution of charge, whose shape was not affected by its motion through the ether. Second, according to H. A. Lorentz’s theory of electrons and Albert Einstein’s relativity theory, the electron was deformable and contracted in the direction of its motion. Third, Alfred Bucherer (1863–1927) and Paul Langevin (1872–1946) suggested that a moving electron would be deformed but its volume would remain constant. All of those theories implied that the mass of the electron depended on its velocity. However, their quantitative predictions about that dependence differed. Walter Kaufmann (1871–1947) undertook an experimental research program that aimed at elucidating the nature of the electron’s mass and its variation with velocity. He determined the velocity dependence of the charge to mass ratio of β-rays, on the basis of their electric and magnetic deflections. His results seemed to contradict the predictions of the “Lorentz–Einstein” theory and to favor the theories of Abraham, Bucherer, and Langevin [5]. Lorentz, for one, thought “very likely that we shall have to relinquish this idea [of a deformable electron] altogether” ([8], p. 213). His pessimism, however, was not vindicated by subsequent developments. By the mid-1910s the combined efforts of theoreticians and experimentalists had shown that Kaufmann’s results were erroneous [20, 24–26].

The 1910s saw the culmination of a research program that aimed at measuring the charge of the electron. Its origins go back to the late nineteenth century and the experimental method devised by C. T. R. Wilson (1869–1959) to obtain artificial clouds and raindrops. J. J. Thomson employed Wilson’s method to measure the charge of the “ions” (i.e., electrons) liberated “when a negatively electrified metal plate . . . is illuminated by ultra-violet light” ([16], p. 548). Thomson’s work, as well as subsequent efforts along similar lines, were beset by many uncertainties (e.g., due to the evaporation of cloud droplets). Their main limitation was that they provided information about the statistical average of a great number of individual charges. Those difficulties were met by Robert Millikan (1868–1953). From 1909 onwards Millikan was able to get a grip on individual electrons. His meticulous observations of charged oil drops, moving under the simultaneous action of gravity and an electric field, enabled him to measure the charge of individual electrons [9]. Those measurements established that electricity has an atomic structure and eliminated the possibility of the electron being "a *statistical* mean of charges which are themselves greatly divergent" ([11], p. 58; cf. [23]). Thus, they provided "[t]he most direct and unambiguous proof of the existence of the electron" ([10], p. 55].

The electron also played a key role in the development of ► atomic models [22]. From 1913 to 1928 a quantum physics of the electron was gradually developed. Niels Bohr (1885–1962) and Arnold Sommerfeld (1868–1951) imposed restrictive conditions on the size, shape, and direction in space of the orbit of electrons bound within the atom. Those conditions were expressed as ► quantum numbers, which "denote the state of the electron in question" ([12], p. 150). In 1924 Wolfgang Pauli (1900–1958) attributed a fourth quantum number to the electron in an attempt to come to terms with the complexities of the anomalous Zeeman effect and the regularities of the periodic table. Furthermore, Pauli formulated an ► exclusion principle, which prohibited the coexistence of identical electrons (i.e., with the same quantum numbers) in the same atom. In 1925 Samuel Goudsmit (1902–1978) and George Uhlenbeck (1900–1988) proposed a semi-classical interpretation of the fourth quantum number as a manifestation of ► spin, that is, as a self-rotation of the electron. This interpretation led to several paradoxes (► errors and paradoxes in quantum mechanics) and was subsequently abandoned [18]. Spin was reconceptualized as a quantum mechanical property with no classical correlate. However, the incorporation of spin into the new quantum mechanics encountered difficulties, until P. A. M. Dirac (1902–1984) showed in 1928 that spin could be derived from his relativistic wave equation [27].

During the 1920s the wave character of the electron was also established. In 1923 Louis de Broglie (1892–1987) developed a synthesis of particle and wave conceptions of matter. The wave properties of matter implied that "[a] group of electrons that traverses a sufficiently small aperture will exhibit diffraction effects" ([2], p. 549; transl. in [29], p. 263; ► matter waves; ► de Broglie wavelength). De Broglie's suggestion was confirmed in 1927–28, when Clinton Davisson (1881–1958) and Lester Germer (1896–1971) in the US and George Paget Thomson (1892–1975) in England discovered experimentally electron diffraction [3, 14, 28] ► Davisson–Germer experiment.

Primary Literature

1. H. Becquerel, Contribution à l'ètude du rayonnement du radium, Comptes Rendus **130**, 206–211 (1900).
2. L. de Broglie, Quanta de lumière, diffraction et interférences, Comptes Rendus **177**, 548–550 (1923).

3. C. J. Davisson and L. Germer, Diffraction of electrons by a crystal of nickel, Physical Review **30**, 705–740 (1927).
4. H. Helmholtz, On the modern development of Faraday's conception of electricity, Journal of the Chemical Society **39**, 277–304 (1881).
5. W. Kaufmann, Über die Konstitution des Elektrons, Annalen der Physik **19**, 487–553 (1906).
6. J. Larmor, A dynamical theory of the electric and luminiferous medium, Philosophical Transactions of the Royal Society of London A **185**, 719–822 (1895).
7. H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (Leiden: E. J. Brill, 1895).
8. H. A. Lorentz, *The Theory of Electrons* (New York: The Columbia University Press, 1909).
9. R. Millikan, On the elementary electrical charge and the Avogadro constant, Physical Review **2**, 109–143 (1913).
10. R. A. Millikan, The electron and the light-quant from the experimental point of view, Nobel Lecture, May 23, 1924, in *Nobel Lectures: Physics, 1922–1941* (Amsterdam: Elsevier, 1965), pp. 54–66.
11. R. A. Millikan, *The Electron: Its Isolation and Measurement and the Determination of some of its Properties* (Chicago: The University of Chicago Press, 2nd ed., 1924; 1st ed., 1917).
12. A. Sommerfeld, *Atomic Structure and Spectral Lines* (London: Methuen, 3rd rev. ed., 1934).
13. G. J. Stoney, On the Cause of Double Lines and of Equidistant Satellites in the Spectra of Gases, The Scientific Transactions of the Royal Dublin Society (2nd ser.) **4**, 563–608 (1888–1892).
14. G. P. Thomson, Experiments on the diffraction of cathode rays, *Proceedings of the Royal Society* **117A**, 600–609 (1928). This article was published in February 1928.
15. J. J. Thomson, Cathode Rays, Philosophical Magazine (5th ser.) **44**, 293–316 (1897).
16. J. J. Thomson, On the Masses of the Ions in Gases at Low Pressures, Philosophical Magazine (5th ser.) **48**, 547–567 (1899).
17. P. Zeeman, Doublets and Triplets in the Spectrum produced by External Magnetic Forces, Philosophical Magazine (5th ser.) **44**, 55–60, 255–259 (1897).

Secondary Literature

18. T. Arabatzis, *Representing Electrons: A Biographical Approach to Theoretical Entities* (Chicago: The University of Chicago Press, 2006).
19. J. Z. Buchwald and A. Warwick (eds.), *Histories of the Electron: The Birth of Microphysics* (Cambridge, MA: MIT, 2001).
20. J. T. Cushing, Electromagnetic Mass, Relativity, and the Kaufmann Experiments, American Journal of Physics **49**, 1133–1149 (1981).
21. S. Goldberg, The Abraham Theory of the Electron: The Symbiosis of Experiment and Theory, Archive for History of Exact Sciences **7**, 7–25 (1970).
22. J. L. Heilbron, *Historical Studies in the Theory of Atomic Structure* (New York: Arno Press, 1981).
23. G. Holton, Subelectrons, Presuppositions and the Millikan-Ehrenhaft Dispute, in Holton, *Scientific Imagination: Case Studies* (Cambridge: Cambridge University Press, 1978), pp. 25–83.
24. G. Hon, Is the Identification of Experimental Error Contextually Dependent? The Case of Kaufmann's Experiment and Its Varied Reception, in J. Z. Buchwald (ed.), *Scientific Practice: Theories and Stories of Doing Physics* (Chicago: The University of Chicago Press, 1995), pp. 170–223.
25. M. Janssen and M. Mecklenburg, From Classical to Relativistic Mechanics: Electromagnetic Models of the Electron, in V. F. Hendricks, K. F. Jørgensen, J. Lützen and S.A. Pedersen (eds.), *Interactions: Mathematics, Physics and Philosophy, 1860–1930* (Dordrecht: Springer, 2006), pp. 65–134.
26. A. I. Miller, *Albert Einstein's Special Theory of Relativity, Emergence (1905) and Early Interpretation (1905–1911)* (New York: Springer, 1998).

27. M. Morrison, Spin: All is not What it Seems, Studies in History and Philosophy of Modern Physics **38**, 529–557 (2007).
28. A. Russo, Fundamental Research at Bell Laboratories: The Discovery of Electron Diffraction, Historical Studies in the Physical Sciences **12**, 117–160 (1981).
29. B. R. Wheaton, *The Tiger and the Shark: Empirical Roots of Wave-Particle Dualism* (Cambridge: Cambridge University Press, 1983).
30. J. G. O'Hara: George Johnstone Stoney, F.R.S., and the Concept of the Electron, Notes and Records of the Royal Society of London **29** (2), 265–276 (1975).

Ensembles in Quantum Mechanics

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> The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which immediately become unnecessary if one accepts the interpretation that the description refers to *ensembles* of systems and not to individual systems.
> – Albert Einstein (1879–1955) [1], p. 671.

This quotation is perhaps the most famous statement of the *ensemble* interpretation of quantum mechanics. The role of the ensemble in quantum mechanics ranges from innocuous to profound, and even controversial.

The innocuous role of the ensemble stems from the fact that quantum mechanics does not predict the actual events, but only the probabilities of the various possible outcomes (► *probability in quantum mechanics*) of the various possible events. In order to compare the predictions of quantum mechanics with experiment, one must prepare a ► state and measure some dynamical variable, and repeat this preparation–measurement sequence many times. The relative frequencies of the various outcomes in this ensemble of results can then be compared with the theoretical probabilities predicted by quantum mechanics. Thus it is natural to say that quantum mechanics describes the statistics of an ensemble of similarly prepared systems.

Here, as in classical statistical mechanics, one should not confuse the *ensemble* of systems with an *assembly* of systems into a composite. For example, if the system is a single particle, then the ensemble is a conceptual set of replicas of it, each in its own environment, whereas the assembly would be a many-particle system. The role of the ensemble is to enable statistical analysis; its members do not interact with or influence each other.

The more significant role of the ensemble interpretation is exemplified by ► *Schrödinger's cat paradox* [2], which involves an unstable atom, a cat, and a mechanism that releases a poison to kill the cat when the atom decays. The initial state vector of the system, $|\phi_1\rangle|live\rangle$, describes an atom in an excited state and a live cat. The final state vector, after the atom has decayed and the cat is dead, will