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Electron: The Name of the Rose (**)

Abstract – The story of the electron is full of unexpected twists and turns of interest to historians, philosophers and physicists. The goal of this paper is to give a narrative biography of the electron from which we will try to draw some philosophical lessons on the question: What is an electron?

We will find that the electron's biography is a splendid example of all that is exciting and deep in history, philosophy and physics. This includes, how philosophical assumptions affect scientific research, the interplay between theory and data, transformations of such basic concepts as substance and visual representation, the electron's role in scientific discovery, as well as an excellent lesson in scientific realism.

As to their nature, physicists were divided along national lines:[1]

British (consensus): Cathode rays are comprised of negatively-charged particles. Among supporting evidence were speculations by C.F. Varley and William Crookes that cathode rays are due to ionisation of gas in the vacuum tube when the gas particles come into contact with the cathode (1871-1879); their deflection by a magnetic field observed by Julius Plücker (1858) and Heinrich Hertz (1883); J.J. Thomson's measurement of their velocity as less than that of light (1894); and Jean Perrin's measurement of their negative charge (1895).

Germans (almost universal): Cathode rays are pulsations in the ether that are converted into light upon striking gas molecules in the tube. Among the supporting evidence was the permeability of thin metal foils to the cathode rays; and Heinrich Hertz's erroneous results of 1883.

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[1] See E. Whittaker, *A History of Theories of Aether and Electricity: Volume 1, The Classical Theories* (New York: Humanities Press, 1973), esp. Chapter XI and A. Pais, *Inward Bound* (Oxford: Oxford University Press, 1986), esp. Chapter 4.

An exception to the Germanic opinion was Emil Wiechert who conjectured on the basis of preliminary experiments that the constituents of cathode rays are smaller than hydrogen atoms. He went on to measure their velocity to be of the order of c/10. In September 1897 Wiechert delivered a detailed report on his more accurate measurements on their velocity and charge-to-mass ratio. But this was too late, because J.J. Thomson announced his discovery of the electron in March 1897.

J.J. Thomson: Discoverer of the Electron

On 11 March 1897 J.J. Thomson, addressed the Philosophical Society in Cambridge with some results on his exploration of cathode rays; he developed these comments in his Friday evening lecture of 30 April 1897 at the Royal Institution (published in The Electrician, 21 May 1897); and then in full detail in an October 1897 paper in the Philosophical Magazine.[2] The electron's discovery dates from these papers, although others were hot on the trail. Briefly, Thomson's claim to fame rests on his determination of the electron's charge-to-mass ratio — the order of 10^7 emu/gm. But of equal importance is his assumption that cathode rays are not ethereal rays but are comprised of ions of electricity, which Thomson considered to be the true primordial atom of Prout. Thomson's reason for this atomistic assumption was simply that it was the most straightforward way to deal with his data.

During 1898-1899 Thomson performed a series of experiments that further clarified the nature of cathode rays. For example, he established their identity with the particles in the photoelectric effect, demonstrated their connection with Röntgen rays, and determined their charge to be on the order of 10^{-10} esu. This value would be further refined by Robert A. Millikan during 1911-1912 who claimed to demonstrate as well that it is the fundamental unit of electric charge.

With understatement Thomson pointed out that the value of e/m was the same as that found in spectroscopy by the Dutch physicist Pieter Zeeman at Leiden in 1896 and then deduced by Zeeman and his colleague H.A. Lorentz from Lorentz's electromagnetic theory. In other words, Thomson had discovered the elementary particle that Lorentz had postulated in 1892 for use in his electromagnetic theory.

But basic problems remained in 1899 because, as Thomson wrote, «We have no means yet of knowing whether or not the mass of the negative ion is of electrical origin». Because if this is the case, then the constancy of e/m could not be expected to persist for velocities approaching that of light. (Thomson established

[2] See A.I. Miller, *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905-1911)* (Reading, MA: Addison Wesley, 1981; reprinted, New York, Springer, 1998), Chapter 1.

the constancy of the ion's charge). Thomson's reasoning is based on results he had obtained in 1881 and 1889: owing to a self-induction effect, the mass of a moving charged particle ought to velocity dependent.

To summarise thus far: By 1901 the ion of electricity in cathode rays was referred to as an «electron», a term coined in 1891 by George Johnston Stoney. In 1902 Lorentz and Zeeman were awarded the Nobel Prize for their work on the Zeeman effect. Thomson was awarded the Nobel in 1906 for his research on the «investigation of the conduction of electricity by gases», not specifically for the electron's discovery. Philip Lenard had been awarded the 1905 Nobel for «his work on cathode rays», in the words of the Nobel committee. In the end, no one received a Nobel Prize directed at the electron's discovery. May it be that we are guilty of some sort of Whig history when we project backward from a more modern time when discovering new particles was focused on? Perhaps. In this case, however, perhaps some Whiggism is acceptable, particularly so in an (invented?) centennial for the electron.

Some historians have questioned whether Wiechert ought to share the accolades with Thomson for discovering the electron.[3] Needless to say, Thomson had competitors who were close on the trail, such as Walter Kaufmann (more in a moment) and Wiechert (although unknown to Thomson). Nevertheless, it was Thomson who did the most complete set of experiments, drew the proper conclusion and published it first. Is this not science in the making? I believe that nothing more need be said on this issue.

Walter Kaufmann: The First High Energy Experimenter

This brings us to the experimentalist Walter Kaufmann working in Berlin during 1897-1899. Simultaneously and independently Kaufmann was engaged in the same sort of experiments as Thomson, only with much more accurate equipment. Yet being a follower of the positivist philosopher Ernst Mach, Kaufmann could not bring himself to the conclusion that cathode rays were comprised of submicroscopic particles. For this omission he missed out on the accolades for the electron's discovery. Eager not to be left out again, in 1901 Kaufmann, now at Göttingen, embarked on exploring the characteristics of high velocity electrons. Thus Kaufmann became the first high energy experimentalist. Using electrons from radium bromide salts, Kaufmann demonstrated that their mass does indeed increase without limit as their velocity approaches that of light. Why was Kaufmann carrying out these sorts of experiments?

The answer is contained in the very first presentation of his stunning results in September 1901 where he pointed out the central role played by the electron in

[3] I believe that Pais was the first to do so, see PAIS, *Inward Bound*, Chapter 4.

such wide ranging fields as dispersion, stellar aberration, electrolysis, the electron theory of metals, the decay of Uranium compounds, and that the electron charge calculated from Max Planck's theory of cavity radiation was almost identical to that obtained from electrical experiments. Modern philosophers of science call this phenomenon convergence — in this case it means that electrons really exist. To Kaufmann and many other physicists in 1901, convergence also meant the possibility of unification of the then known forces, electromagnetism and gravitation within a single theory — namely, H.A. Lorentz's electromagnetic theory. This research programme was referred to as the electromagnetic world-picture. It was the Theory of Everything of its day and so was the cutting edge of physics in the first decade of the 20th century. One of its first predictions was that the electron's mass is generated by its own electric and magnetic fields and so should be a velocity — dependent quantity. Thomson had shown this to be the case for macroscopic charges and had intimated that this situation should hold for ions as well. Kaufmann had verified it.

Kaufmann's experimental arrangement differed drastically from ones used by Thomson and the ones he himself had used in 1897. Instead of perpendicular electric and magnetic fields, Kaufmann used parallel ones. The data analysis becomes much more difficult because instead of a spot on a photographic plate or a cathode ray tube, he had to calculate the electron's charge-to-mass ratio from delicate measurements made off a fuzzy gull-winged shaped curve. Each wing of the curve took 24 hours of exposure which meant, among other variables, maintaining a vacuum for 48 hours. Nevertheless, Kaufmann's 5 data points per run were deemed state of the art. Theories were called for to produce analytical expressions for the electron's mass that could fit Kaufmann's data. The procedure was to add hypotheses to Lorentz's electromagnetic theory that concerned the shape of moving electrons.

By the end of 1904 there were three viable theories of the electron: Max Abraham's rigid electron theory; Lorentz's electron theory in which the moving electron underwent a Lorentz contraction; and one due to Alfred Bucherer and Paul Langevin (separately) in which the moving electron becomes deformed in such a way that its volume remains unchanged. By this time that man for all seasons Henri Poincaré had become involved and proved that only Lorentz's preserves a principle of relativity. The stakes, therefore, were high because Abraham's theory seemed to fit Kaufmann's data the best.

In September 1905 a paper appeared in the *Annalen der Physik* that seemed of some importance — «On the Electrodynamics of Moving Bodies» — only because in its final section the little known author in Bern, Switzerland, Albert Einstein, was able to derive with no approximations certain results concerning the electron's mass for which Lorentz was forced to use suspect methods. In November 1905 and January 1906 Kaufmann published his ultimate experimental runs in which he now referred to Lorentz's theory as the Lorentz-Einstein theory of the electron. The Patent Clerk Albert Einstein did not demur at the reverse alphabetical order. Kaufmann's results agreed only with Abraham's theory. What happened next I can only sketch out.

Like a good Popperian, on 8 March 1906 Lorentz wrote to Poincaré that he would have to abandon his electron theory in the face of the redoubtable Kaufmann's disconfirming data. Poincaré urged him to hang on. The Patent Clerk was pretty much unfazed because the goal of his 1905 paper was to offer a new theory of space and time, and not a new method to derive the electron's mass in Lorentz's theory. Planck, among others, looked deeply into Kaufmann's method for data analysis and his experimental set up. They found possible inconsistencies. In 1908 Bucherer, at Bonn where Kaufmann was now his colleague, began a new series of high velocity electron deflection experiments using Thomson's crossed field method. His data weighed heavily in favour of the Lorentz-Einstein theory. Exit Kaufmann who had a penche for complications that, as it turned out, resulted in such problems as vacuum breakdowns.

By 1916 more precise versions of Bucherer's experiment were carried out and the question of the velocity-dependence of the electron's mass seemed settled. By this time the electromagnetic world-picture had been abandoned owing to another result of the Patent Clerk's Annus Mirabilis of 1905, namely, light quanta which indicated severe shortcomings in Lorentz's electromagnetic theory.

In summary thus far, Lorentz's electron seemed the proper one because experiment supported it. That is, it seemed that way until 1938. In that year two American experimentalists were carrying out electron deflection experiments using electrons from radioactive sources. Their goal was to ascertain whether the electrons emerging from nuclei were really Lorentz electrons and not ones whose mass had some weird velocity dependence so that neutrinos were unnecessary. Knowing their history of physics they realised that they were repeating, with improved apparatus, the old electron deflection experiments of Bucherer and successors. Upon looking into those papers from 20 odd years before they ascertained that all of these physicists used velocity filters whose geometry caused severe loss of accuracy when the electrons' velocities exceeded .7c, just the region where mass variation becomes increasingly evident. Consequently, the only result that any of the old electron deflection experiments demonstrated was that the electron's mass increased with its velocity. By 1938 the problem of the proper expression for the electron's mass had become moot. Nevertheless the interesting problem arises of when should one stop experimenting? As Einstein put it in 1946, comparison between experiment and theory can be «quite delicate».

Atomic Physics and the Electron

In 1913 the frontier of physics shifted to Niels Bohr's atomic theory with its splendidly visualisable atom. The Lorentz electron had now to be endowed with other properties such as only radiating when it dropped from a higher to a lower allowed orbit, and not falling any lower than the atom's ground state. During a transition it was unvisualisable. It disappeared and appeared like the Cheshire cat.

By 1923, however, dispersion data indicated that atoms don't really respond to light as if they were minuscule solar systems. Atomic electrons were replaced by as many oscillators as there were transitions to and from a particular stationary state: the atomic electron became unvisualisable.

In 1924, Bohr along with Hendrik Kramers and John C. Slater, reformulated the Bohr theory in such a way as to avoid any inclusion of light quanta, which Bohr and most other physicists wanted to avoid on purely conceptual grounds. Basically in the BKS theory the atomic electron responds to incident radiation by emitting electromagnetic radiation as well as a field of probability, thereby endowing the electron with yet more characteristics.

By mid-1925 the Bohr theory had withered away, electrons had become indistinguishable (owing to results of Bose and Einstein), and a new atomic physics called quantum mechanics was formulated by Werner Heisenberg. By mid-1926 another form of atomic physics called wave mechanics was proposed by Erwin Schrödinger. Whereas in Heisenberg's quantum mechanics electrons are represented as nonvisualisable particles, in Schrödinger's mechanics they are waves. This dichotomy was not surprising in light of the wave/particle duality of electrons that had been proposed in 1923 by Louis de Broglie.

Not only were electrons indistinguishable, but they were wave and particle simultaneously, and did not like to be near one another as the then mysterious Pauli Exclusion Principle dictated.

Bohr's complementarity principle of September 1927 served to put physicists on notice that when certain fundamental constants that are essential to correspondence principles come into play, we must be prepared for surprises. Consequently when the small but nonzero Planck's constant is taken seriously, we enter a world in which our intuitivity must be redefined in order that something like the wave/particle duality is not taken as paradoxical.

Quantum Electrodynamics and the Electron

The year 1928 saw the first attempt to combine the new quantum mechanics with relativity; this is P.A.M. Dirac's theory of the electron from which the electron's spin emerged naturally. Yet a price was paid, namely, negative energy states which, at first, were considered to be «physically meaningless», and yet they are essential for obtaining certain classical limits of Dirac's theory. In 1928 Heisenberg referred to Dirac's theory as the «saddest chapter in theoretical physics». Yet it had to be dealt with simply because it was the only game in town.

What followed was a complex succession of events in which Dirac, Heisenberg and Wolfgang Pauli, among others, attempted to produce a relativistic field theory of the interaction between light and electrons, a quantum electrodynamics.[4] Their work included considering the negative states as holes in the vacuum and then as positrons, the electron's antiparticle, which was found experimentally in 1931. Their Holy Grail was a field-theoretical description of electrons and photons in coordinate space that contained no infinite quantities such as an infinite mass and charge. The finite quantities that emerged such as vacuum polarisation did so in an unsatisfactory manner. Basically the appropriate field equations or Hamiltonians never emerged.

Interestingly a route to success lay elsewhere, namely, in research into the nucleus initiated by Heisenberg in 1932. The discovery of the neutron by James Chadwick earlier that year permitted a representation of molecules and nuclei in agreement with the proper quantum statistics. The problem arose, however, to explain the attractive force between a charged proton and neutral neutron. This was anything but classical. Neither was the problem of nuclear β-decay which was essentially this: How do electrons emerge from nuclei when they are not supposed to be there in the first place?

Heisenberg resorted to a theoretical free-for-all in his 1932 formulation of a theory for the nuclear force that took account of β-decay, too.[5] In modern parlance we would say that Heisenberg tried to formulate a unified theory of the strong and weak interactions. Briefly Heisenberg's strategy was to assume that, for this purpose, the neutron is a composite of a proton and electron, which dissociates within the nucleus. In this case, the electron acts like a Bose particle. In Heisenberg's view this was permissible because quantum mechanics may well not be valid within the nucleus. Two things can happen: (1) the Bose electron can migrate over to a fundamental proton to form another composite neutron — in this way the electron carries the attractive nuclear force; (2) the electron can leave the nucleus as in β-decay upon which it becomes a Fermi-Dirac particle. The concept of particles carrying forces would be crucial in Hideki Yukawa's more correct 1934 theory of the nuclear force whose basis is Heisenberg's Hamiltonian rewritten in such a way that the nuclear force is carried by a proper Bose particle. This line of thought would be important to Richard Feynman in 1948.[6]

[4] See A.I. Miller, *Early Quantum Electrodynamics: A Source Book* (Cambridge: Cambridge University Press, 1994), Chapter 4.

[5] See Miller, *Early Quantum Electrodynamics*, Chapter 5.

[6] See Miller, *Early Quantum Electrodynamics*, Chapter 5 and S.S. Schweber, *QED and the Men Who Made: Dyson, Feynman, Schwinger and Tomonaga* (Princeton: Princeton University Press, 1994).

Feynman Diagrams and the Electron

In the modern-day quantum electrodynamics of Feynman, Julian Schwinger and Sin-itoro Tomonaga, the electron is a bare charge surrounded by a quantised electromagnetic field and a cloud of virtual electron-positron pairs. All infinite quantities are eliminated in a properly Lorentz covariant manner. Agreement between theory and experiment is astronomical.

But even more than that, the fertility of quantum electrodynamics is clearly demonstrated by its visual representation in terms of Feynman diagrams. In turn, these diagrams have served as a guide toward a theory for unifying the electromagnetic and weak interactions, which is the Electroweak Theory or Standard Model of Weinberg, Salam and Glashow.[7] In this theory the electron is one of six leptons along with six quarks that are taken as fundamental building blocks.

Physicists consider this theory to be another touchstone on the way toward higher unifications. That this is the case may already have been demonstrated by recent data from the HERA particle accelerator ring near Hamburg which indicate the possibility of a bound state comprised of an electron and a quark, a so-called leptoquark. If the leptoquark actually exists then there is a fifth force in nature capable of holding together an electron and a quark. Another explanation for current data is that the occasional violent scatterings of positrons may result from the positron striking a constituent of an electron or quark, indicating that electrons and quarks may not be fundamental after all.

What is an Electron?

So, what does all this mean with respect to the problem: What is an electron?

Regarding a rose by any other name — any entity called an electron is necessarily a Lorentz electron to which a succession of scientific theories have revealed more of its properties. This is the view of scientific realism, as it can be developed within the causal theory of reference. Scientific theories add to the electron's stereotypes (Figures 1-3).[8]

Perhaps the very notion that has become intuitive of the electron — that is, being a wave and particle, but usually thought of as a particle — may have to be transformed as the Standard Model assumes its role as another effective field theory valid within a certain energy range. Above this range perhaps higher modes of vibration are excited in a superstring theory.

[7] See A.I. MILLER, *Insights of Genius: Imagery and Creativity in Science and Art* (New York: Springer, 1996), Chapter 7.

[8] See MILLER, *Insights*, Chapter 7.

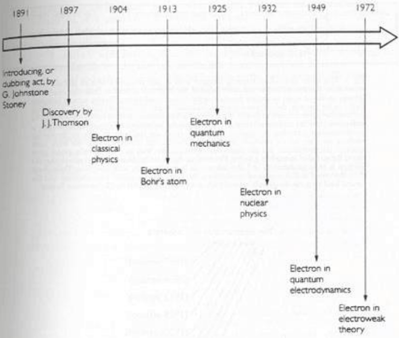

Fig. 1. The development of the electron from 1891 to 1972. It was dubbed by the English scientist G. Johnstone Stoney on the basis of experimental and theoretical results implying such an entity's existence.

Might it turn out that the natural-kind term electron refers to nothing at all, along with all the other particles taken as elementary in the Standard Theory? Might we imagine that the natural-kind terms of today's elementary particle physics will suffer the same fate as phlogiston, caloric and the ether? Hilary Putnam has referred to this as the disastrous «meta-induction». Antirealists take this as part of an argument against scientific realism. But, as we all know, antirealism is strictly a philosopher's game.

The realist does not commit the inductive fallacies of predicting what science

Classical theory	Quantum mechanics	Quantum electrodynamics	Electroweak theory
— charge — mass — radius	— spin — radius is ambiguous — indistinguishability	— anomalous g-factor	— electron is fundamental — interactions with neutrinos

Fig. 2. This figure shows how scientific research adds to and sets restrictions on the electron's stereotypes, thereby adding to our knowledge of the electron's structure. Quantum mechanics informs us that in order to explain certain empirical data, in addition to having a more complete theory of the electron, the electron has a nonvisualisable degree of freedom called spin. According to Heisenberg's uncertainty principle, the notion of a well-defined electron radius turns out to be ambiguous. Another surprise of quantum mechanics is the indistinguishability of electrons. This is counterintuitive according to classical physics in which we ought to be able to distinguish anything we want by, for example, painting certain molecules different colors. We learn from quantum electrodynamics that the interaction of the electron with its cloud of light quanta gives rise to the so-called anomalous g-factor. Electroweak theory (to be discussed later) reveals that the electron is truly fundamental and also informs us how it interacts with neutrinos. Throughout these theoretical and experimental explorations, the electron's charge and mass reappear, and the natural kind term can be causally related back to its dubbing in 1891 by G. Johnstone Stoney.

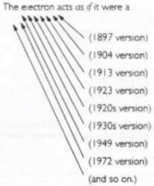

Fig. 3. According to the casual theory of reference and metaphors, the natural kind «electron» is explored by successive scientific theories. The theories themselves emerged from metaphors. The 1897 version that probed the electron is classical electromagnetic theory applied to the electron *as if* it were a charged billiard ball. The 1904 version is Lorentz's theory of the deformable electron. The 1913 version is Bohr's atomic theory in which the electron became further removed from classical physics. The 1923 version is the harmonic oscillator one. The 1920s version was the one proposed by Heisenberg and Schrödinger attributing certain quantum mechanical properties to electrons. The 1930s and 1949 versions probed the electron as a primitively bare object surrounded by its covering of light quanta. The 1972 version explores the natural kind term «electron» with the electroweak theory. Other theories, yet to be formulated adequately, will further explore the electron.

will be like in the far future based on what it is now. Rather the history of science informs us of a continuity of theoretical concepts, with fertile ones such as phlogiston, caloric, ether and possibly electron, serving as beacons on the high road of scientific discovery.

I conclude with mention of an area in which the electron affects not only our everyday life but the very core of scientific research, too. It is an area where science and technology interface with an intensity pretty much unimaginable even 30 years ago, and in which the electron will be considered as fundamental for some time to come: computer architectures. The electron jumping from chip to chip is presently the fundamental transporter of information. In this era where the term «information warfare» or better «computer warfare» has taken on new meaning, the electron turns out to be the ultimate guided missile.