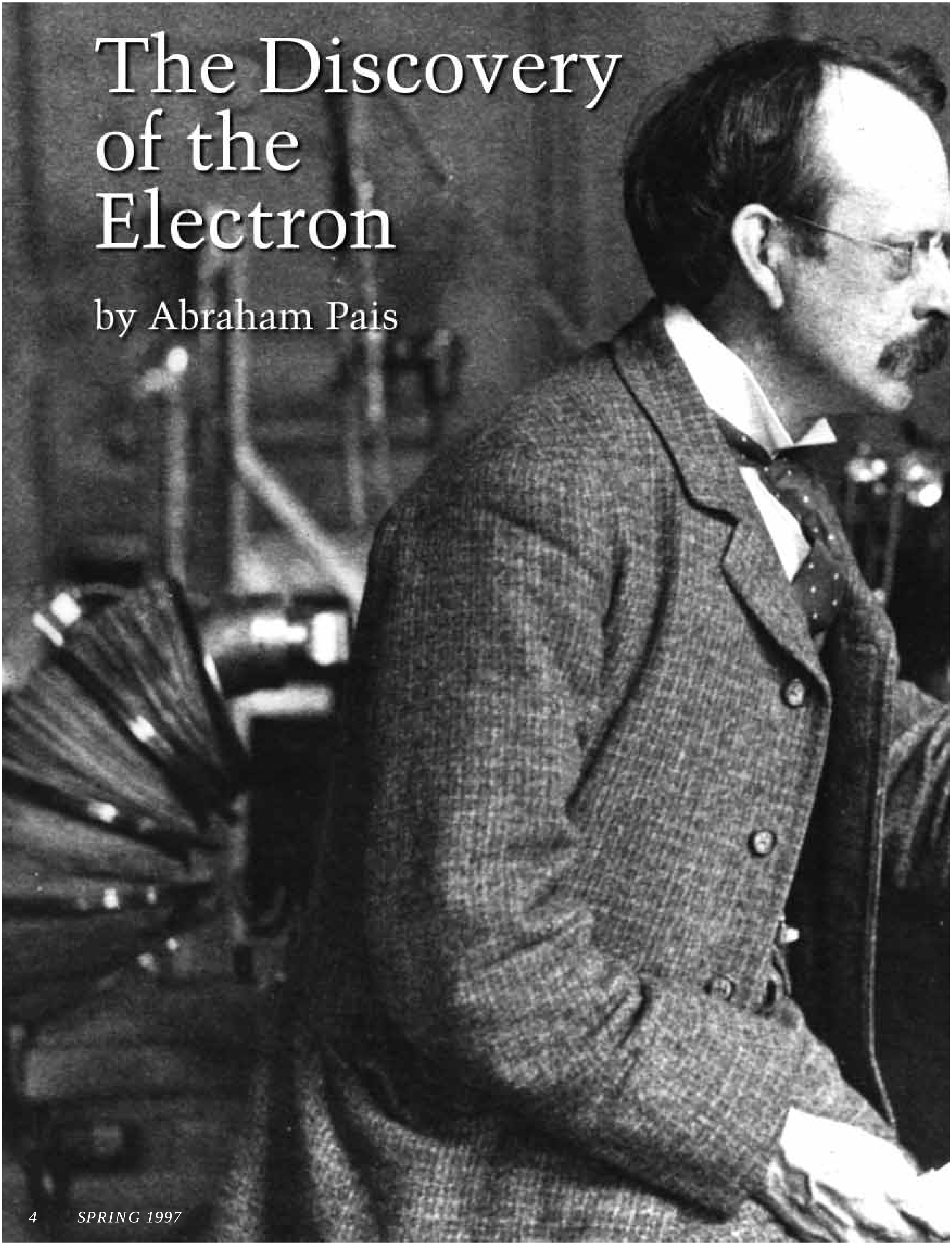
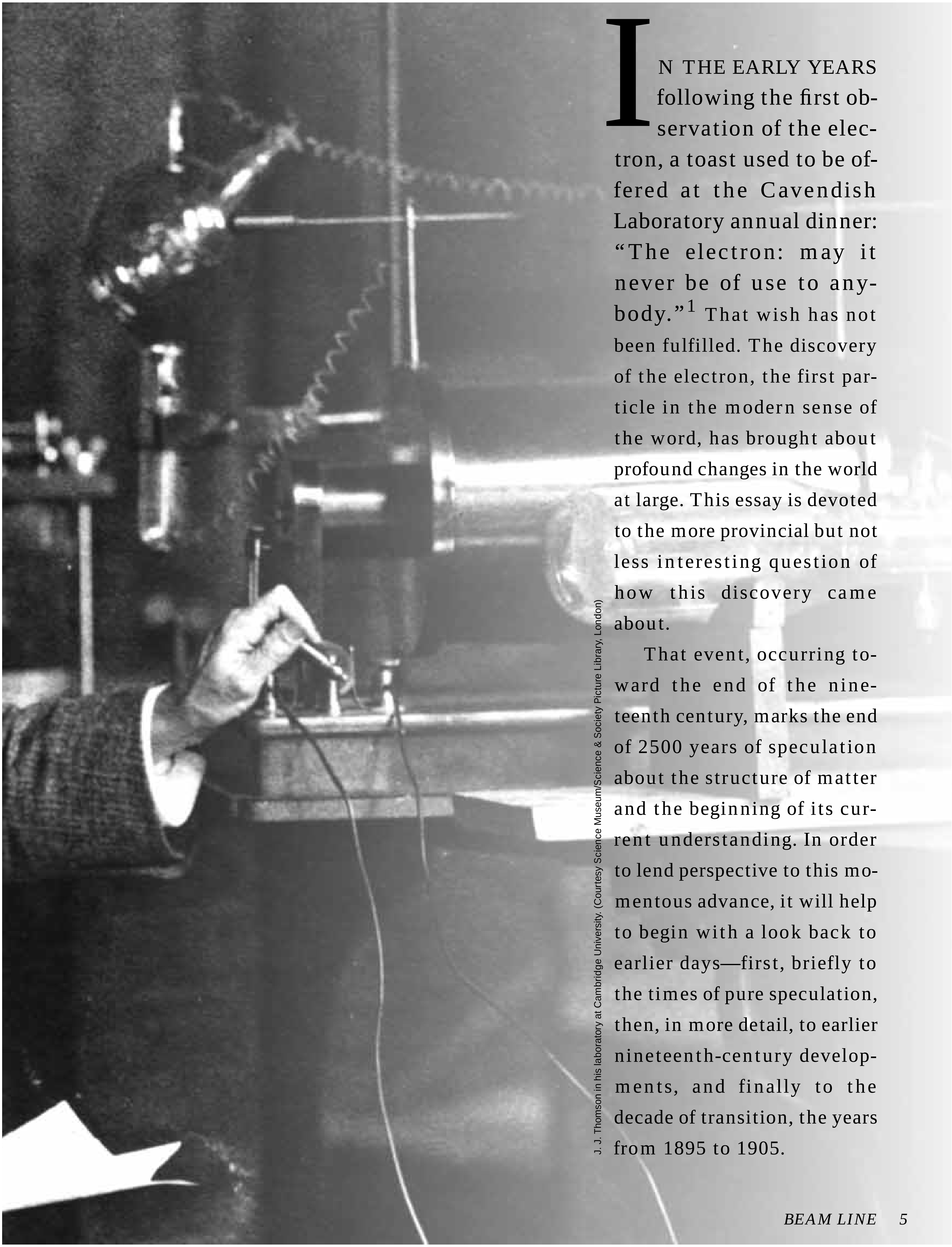
The Discovery of the Electron

by Abraham Pais





J. J. Thomson in his laboratory at Cambridge University. (Courtesy Science Museum/Science & Society Picture Library, London)

IN THE EARLY YEARS following the first observation of the electron, a toast used to be offered at the Cavendish Laboratory annual dinner: "The electron: may it never be of use to anybody."[1] That wish has not been fulfilled. The discovery of the electron, the first particle in the modern sense of the word, has brought about profound changes in the world at large. This essay is devoted to the more provincial but not less interesting question of how this discovery came about.

That event, occurring toward the end of the nineteenth century, marks the end of 2500 years of speculation about the structure of matter and the beginning of its current understanding. In order to lend perspective to this momentous advance, it will help to begin with a look back to earlier days—first, briefly to the times of pure speculation, then, in more detail, to earlier nineteenth-century developments, and finally to the decade of transition, the years from 1895 to 1905.

THE ANCIENTS

THE TERM *atom*, derived from the Greek α, a privative, and *τεμειν*, to cut, appears first, I am told, in the writings of Greek philosophers of the fifth century BC. Democritus (late fifth century BC) taught that atoms are the smallest parts of matter, though in his view they were not necessarily minute. Empedocles (490–430 BC), physicist, physician, and statesman, held that there are four indestructible and unchangeable elements—fire, air, water and earth—eternally brought into union and eternally parted from each other by two divine forces, love and discord. Nothing new comes or can come into being. The only changes that can occur are those in the juxtaposition of element with element. Epicurus' (341–270 BC) opinion that atoms cannot be divided into smaller parts by physical means, yet that they have structure, was shared by prominent scientists well into the nineteenth century AD. The Roman poet Lucretius (98–55 BC) was an eloquent exponent of the theory that atoms, infinite in number but limited in their varieties, are, along with empty space, the only eternal and immutable entities of which our physical world is made. Today's scientist will not fail to note that in each of these speculative thinkers' considerations one finds elements that sound curiously modern.

The opposite position, that matter is infinitely divisible and continuous, likewise had its early distinguished proponents, notably Anaxagoras (c 500–428 BC) and Aristotle (384–322 BC). The latter's prestige eclipsed the atomists' view until the seventeenth century. Even that late, Rene Descartes (1596–1650) pronounced that there cannot exist any atoms or parts of matter that are of their own nature indivisible; for though God had rendered a particle so small that it was not in the power of any creature to divide it, He could not, however, deprive Himself of the ability to do so.[2]

THE NINETEENTH CENTURY

REGARDING THE UNDERSTANDING of the basic structure of matter, very little had changed between the days of speculation by the ancient Greek philosophers and the beginning of the nineteenth century, when, in 1808, the British chemist and physicist John Dalton (1766–1844) commenced publication of his *New System of Chemical*

Philosophy. He had of course illustrious precursors, notably Antoine-Laurent Lavoisier (1743–1794). Yet his quantitative theory suddenly could explain or predict such a wealth of facts that he may properly be regarded as the founder of modern chemistry. In a sequel volume Dalton expressed the fundamental principle of the youngest of the sciences in these words:

> I should apprehend there are a considerable number of what may be properly called elementary principles, which can never be metamorphosed, one into another, by any power we can control. We ought, however, to avail ourselves of every means to reduce the number of bodies or principles of this appearance as much as possible; and after all we may not know what elements are absolutely indecomposable, and what are refractory, because we do not know the proper means of their reduction. All *atoms of the same kind*, whether simple or compound, must necessarily be conceived to be alike in shape, weight, and every other particular.

John Dalton, whose New System of Chemical Philosophy *resurrected the atomic theory of matter. (Courtesy A. L. Smyth,* John Dalton: 1766–1844, a Bibliography of Works By and About Him *and AIP Emilio Segrè Visual Archives)*

These superb lines ushered in the intense nineteenth century discussions on the nature of atoms and molecules. Perhaps the most remarkable fact about these debates is the great extent to which chemists and physicists spoke at cross purposes when they did not actually ignore each other. This is not to say that there existed one common view among chemists, another among physicists. Rather, in either camp there were many and often strongly diverging opinions. The principal point of debate among chemists was whether atoms were real objects or only mnemonic devices for coding chemical regularities and laws. The main issues for the physicists centered around the kinetic theory of gases, in particular around the meaning of the second law of thermodynamics.

An early illustration of the dichotomies between chemists and physicists is provided by the fact that Dalton did not accept the hypothesis put forward in 1811 by Amadeo Avogadro (1776–1856) that, for fixed temperature and pressure, equal volumes of gases contain equal numbers of molecules. Nor was Dalton's position held only by a single person for a brief time. The tardiness with which Avogadro's law came to be accepted clearly indicates the widespread resistance to the idea of molecular reality. As but one further illustration of this attitude I mention some revealing remarks by

Alexander Williamson (1824–1904), himself a convinced atomist. In his presidential address of 1869 to the London Chemical Society, he said:

> It sometimes happens that chemists of high authority refer publicly to the atomic theory as something they would be glad to dispense with, and which they are ashamed of using. They seem to look upon it as something distinct from the general facts of chemistry, and something which the science would gain by throwing off entirely. . . . On the one hand, all chemists use the atomic theory, and . . . on the other hand, a considerable number view it with mistrust, some with positive dislike.[3]

On the whole, molecular reality met with less early resistance in physics than it did in chemistry. That is not surprising. Physicists could already *do* things with molecules and atoms at a time when chemists could, for most purposes, take them to be real or leave them as coding devices.

The insight that gases are composed of discrete particles dates back at least to the eighteenth century. Daniel Bernoulli (1700–1782) may have been the first to state that gas pressure is caused by the collisions of particles with the walls that contain them. The nineteenth-century masters of kinetic theory were atomists—by definition, one might say. In Rudolf Clausius' (1822–1888) paper of 1857, entitled "On the kind of motion we call heat," the distinction between solids, liquids, and gases is related to different types of molecular motion. Ludwig Boltzmann (1844–1906) was less emphatic, but he could hardly have developed his theory of the second law of thermodynamics had he not believed in the particulate structure of matter.

Long before these learned fin-de-siecle discourses took place, in fact long before the laws of thermodynamics were formulated, theoretical attempts had begun to estimate the dimensions of molecules. As early as 1816, Thomas Young (1773–1829) noted that "the diameter or distance of the particles of water is between the two thousand and the ten thousand millionth of an inch."[4] In 1873 James Clerk Maxwell stated that the diameter of a hydrogen molecule is about 6×10^{-8} cm.[5] That same year Johannes Diderik van der Waals (1837–1923) reported similar results in his doctoral thesis.[6] By 1890 the spread in these values, and those obtained by others, had narrowed considerably. A review of the results up to the late 1880s placed the radii of hydrogen and air molecules between 1 and 2×10^{-8} cm,[7] a remarkably sensible range.

Until the very last years of the nineteenth century, most if not all scientists who believed in the reality of atoms shared the view that these particles cannot be decomposed further, as was eloquently expressed by Maxwell in 1873:

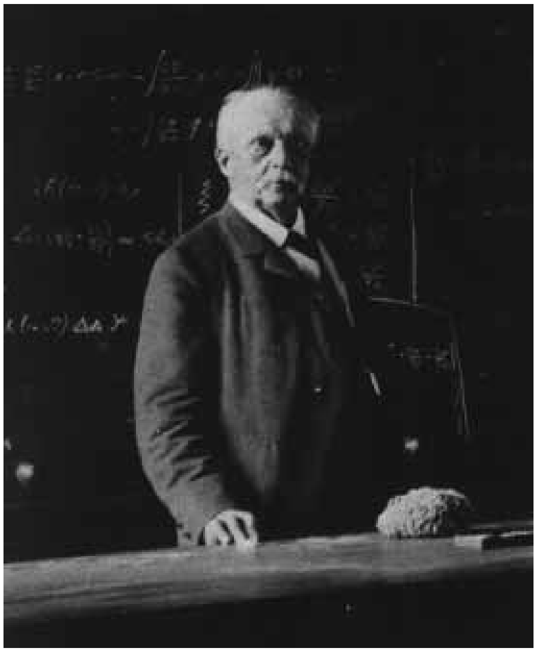
> Though in the course of ages catastrophes have occurred and may yet occur in the heavens, though ancient systems may be dissolved and new systems evolved out of their ruins, the molecules [i.e., atoms!] out of which these systems [the Earth and the whole solar system] are built—the foundation stones of the material universe—remain unbroken and unworn. They continue this day as they were created—perfect in number and measure and weight.[8]

THE ATOMICITY OF CHARGE

ELECTROMAGNETISM BECAME A PART of science in the eighteenth century, largely due to rapid progress in the invention of new instruments: the first condenser (the Leiden jar), the lightning rod, the first battery (the Voltaic pile), the first solenoid. These advances led, in turn, to the formulation of phenomenological laws based on new experiments. Of interest here is the law of electrolysis, formulated in the 1830s by Michael Faraday (1791–1867), one of the great experimentalists of all time, who coined terms of lasting use: electrode, anode, cathode, electrolysis, ion, anion, cation. In modern language, his law can be stated like this:

The amount of electricity deposited at the anode by a gram mole of monovalent ions is a universal constant, the farad (F), given by $F = Ne$, where N, Avogadro's number, is the number of molecules per mole, and e is a universal unit of charge.

What does this e signify? In 1881 Herman von Helmholtz (1821–1894) put it like this in his Faraday lecture: "The most startling result of Faraday's law is perhaps this. If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity."[9] This statement explains why in subsequent years the quantity e was occasionally referred to in the German literature as "das Helmholtzsche Elementarquantum."



Hermann von Helmholtz, who in 1881 speculated on the atomicity of charge. (Courtesy AIP Emilio Segrè Visual Archives)

March of Discovery

1895
- Wilhelm Roentgen (1845–1923) discovers X rays, for which he would receive the first Nobel Prize in physics, in 1901.

1896
- Antoine Henri Becquerel (1852–1908) observes what he called “uranic rays,” the first phenomenon that opens a new field later called radioactivity.
- Wilhelm Wien (1864–1928) publishes his exponential law for black-body radiation, the first quantum law ever written down.
- Pieter Zeeman’s (1865–1934) first paper appears on the influence of magnetic fields on spectral lines.

1897
- Determination of e/m for cathode rays by J. J. Thomson and others.
- First mention of a particle lighter than hydrogen.

1898
- Ernest Rutherford discovers there are two species of radioactive radiations: α-rays and β-rays.

1899
- Thomson measures the electric charge of free electrons and realizes that atoms are split in ionization processes.

1900
- Paul Villard (1860–1934) discovers γ-rays.
- First determination of a half-life for radioactive decay.
- Max Planck discovers the quantum theory.

1905
- Albert Einstein postulates the light quantum (March).
- Einstein’s first paper on special relativity is published (June).

Even before Helmholtz’s memorable address, the Irish physicist George Johnstone Stoney (1826–1911) had reported to the 1874 meeting of the British Association for the Advancement of Science an estimate of e, the first of its kind, based on $F = Ne$. Values for F and N were reasonably well known by then. Stoney obtained $e \sim 3\times10^{-11}$ esu, too small by a factor of about 20, yet not all that bad for a first and very early try.[10] In 1891 he baptized the fundamental unit of charge, giving it the name “electron.”[11] Thus the term was coined prior to the discovery of the quantum of electricity and matter that now goes by this name.

DECADE OF TRANSITION

IN MARCH 1905 Ernest Rutherford (1871–1937) delivered the Silliman lectures at Yale. He began the first of his talks as follows:

> The last decade has been a very fruitful period in physical science, and discoveries of the most striking interest and importance have followed one another in rapid succession. . . . The march of discovery has been so rapid that it has been difficult even for those directly engaged in the investigations to grasp at once the full significance of the facts that have been brought to light. . . . The rapidity of this advance has seldom, if ever, been equaled in the history of science.[12]

The speed with which one important discovery followed another (see box at left) was indeed breathtaking. It is natural to ask but not easy to answer why so much novelty should be discovered in so short a time span. It is clear, however, that a culmination of advances in instrumentation was crucial. They include:

- *Higher voltages*. Higher voltages were the result of Heinrich Ruhmkoff’s (1803–1874) work, beginning in the 1850s, on an improved version of the induction coil. These were the coils that in 1860 served Gustav Kirchhoff (1824–1887) and Robert Bunsen (1811–1899) in their analysis of spark spectra; Heinrich Hertz (1857–1894) in 1886–1888 in his demonstration of electromagnetic waves and his discovery of the photoelectric effect; Wilhelm Roentgen in his discovery of X rays; Guglielmo Marconi (1874–1937) in his transmission of telegraph signals without wires; Pieter Zeeman in his discovery of the Zeeman effect; and Thomson in his determination of e/m for electrons. By the turn of the century, voltages of the order of 100,000 volts could be generated by these coils.

J. J. Thomson and Ernest Rutherford (right) at the Cavendish Lab in 1934. (Courtesy AIP Emilio Segrè Visual Archives Bainbridge Collection)

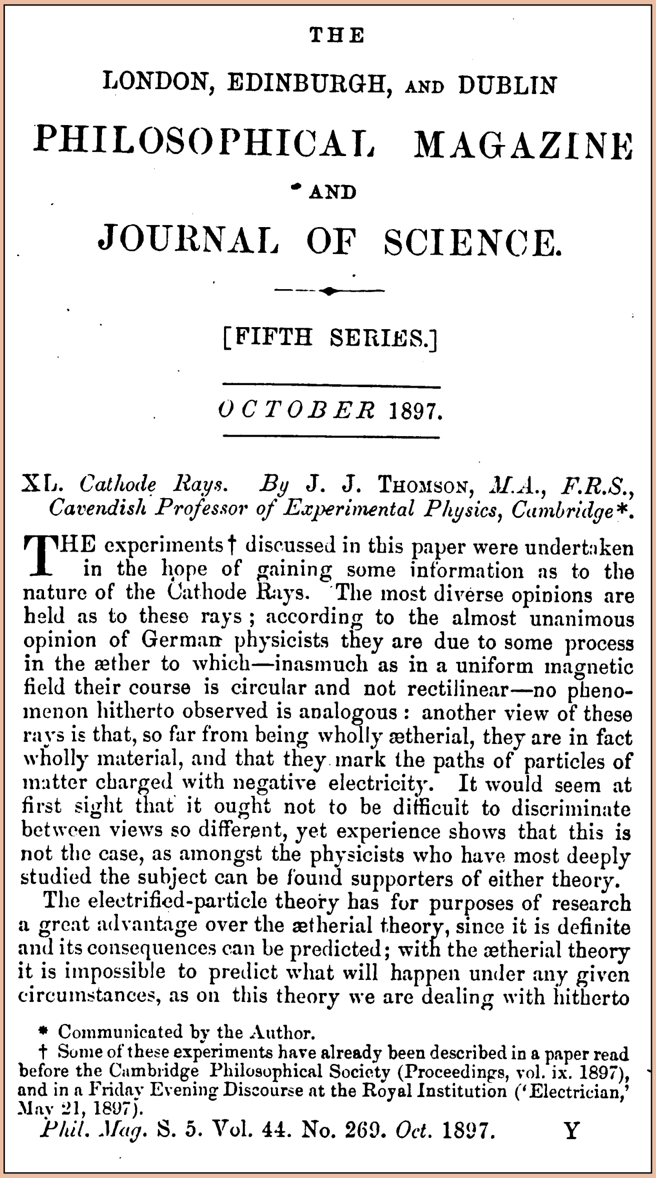
- *Improved vacua.* Improved vacua were achieved in the 1850s, when Johann Geissler (1815–1879) began developing the tubes now named after him. Soon he was able to reach and maintain pressures of 0.1 mm of mercury. Refined versions of this tube were crucial to the discoveries of Roentgen and Thomson.
- *Ionization chambers.* Early versions of the parallel-plate ionization chamber were developed in Cambridge during the 1890s. They were used by Rutherford and the Curies in the earliest quantitative measurements of radioactivity.
- *Concave spectral gratings.* Concave spectral gratings were developed starting in the 1880s by Henry Rowland (1848–1901) at the Johns Hopkins University. Their resolving power made Zeeman's discovery possible.
- *Cloud chambers.* Work on the development of a cloud chamber was begun in Cambridge in 1895 by Charles T. R. Wilson (1869–1959). This instrument enabled Thomson to measure the electron's charge.

THE DISCOVERY

ALL RESEARCH THAT LED to the discovery of the electron deals with studies of cathode rays, a subject that had already engaged Faraday, who in 1838 made this prophetic remark on its future: "The results connected with the different conditions of positive and negative discharge will have a far greater influence on the philosophy of electrical science than we at present imagine."[13]

J. J. Thomson discovered the electron. Numerous are the books and articles in which one finds it said that he did so in 1897. I cannot quite agree. It is true that in that year Thomson made a good determination of e/m for cathode rays, an indispensable step toward the identification of the electron, but he was not the only one to do so. It is also true that in 1897 Thomson correctly conjectured that the large value for e/m he had measured indicated the existence

Thomson's Two Experimental Papers



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

OCTOBER 1897.

XL. *Cathode Rays.* *By* J. J. Thomson, *M.A., F.R.S., Cavendish Professor of Experimental Physics, Cambridge**.

THE experiments† discussed in this paper were undertaken in the hope of gaining some information as to the nature of the Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the æther to which—inasmuch as in a uniform magnetic field their course is circular and not rectilinear—no phenomenon hitherto observed is analogous: another view of these rays is that, so far from being wholly ætherial, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity. It would seem at first sight that it ought not to be difficult to discriminate between views so different, yet experience shows that this is not the case, as amongst the physicists who have most deeply studied the subject can be found supporters of either theory.

The electrified-particle theory has for purposes of research a great advantage over the ætherial theory, since it is definite and its consequences can be predicted; with the ætherial theory it is impossible to predict what will happen under any given circumstances, as on this theory we are dealing with hitherto

* Communicated by the Author.

† Some of these experiments have already been described in a paper read before the Cambridge Philosophical Society (Proceedings, vol. ix. 1897), and in a Friday Evening Discourse at the Royal Institution ('Electrician,' May 21, 1897).

Phil. Mag. S. 5. Vol. 44. No. 269. *Oct.* 1897. Y

WHEN J. J. THOMSON began his research on the cathode rays during the 1890s, there was great confusion about their exact nature. As he noted in the introduction to his paper, "On Cathode Rays," [*Phil. Mag.*, Ser. 5, Vol. 44, No. 269 (1897), p. 293]:

> The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the æther to which . . . no phenomenon hitherto observed is analogous; another view of these rays is that, so far from being wholly ætherial, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity.

Following the lead of French physicist Jean Perrin, Thomson first satisfied himself that the rays were negatively charged, then addressed a quandary that had been puzzling scientists on both sides of the Channel for years. Although the rays were easily deflected by a magnetic field, they were apparently *not* deflected by an electric field between two plates. The absence of this deflection, he showed, was due to the ionization of the gas remaining in a cathode-ray tube, which permitted a current to flow between the plates and drastically reduced the field. This did not occur at high vacuum, however, and the rays were indeed deflected as expected for negatively charged particles. Thus he noted:

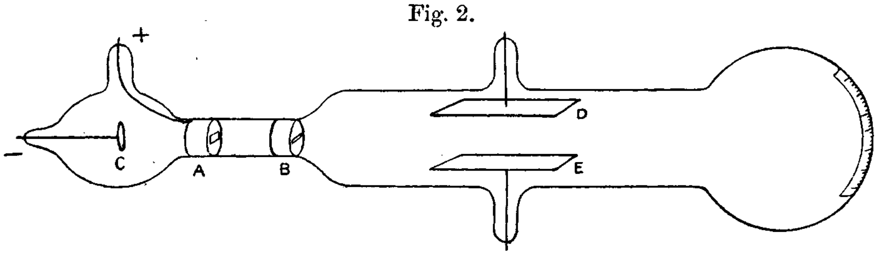
> I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. The question next arises, What are these particles? [A]re they atoms, or molecules, or matter in a still finer state of subdivision?

By simultaneously deflecting the rays in *both* electric and magnetic fields, Thomson was able to determine their velocity and the ratio m/e of the mass m to the electric charge e carried by these (then) hypothetical particles. His result was startling:

> From these determinations we see that the value of m/e is independent of the nature of the gas, and that its value 10^{-7} [gram per emu] is very small compared with the value 10^{-4}, which is the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis.

But he could not conclude from these data that m itself therefore had to be very small. "The smallness of m/e may be due to the smallness of m or the largeness of e," Thomson wrote. Because the values of m/e were independent of the nature and pressure of the gas, he began

Fig. 2.



The rays from the cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminium plates about 5 cm. long by 2 broad and at a distance of 1·5 cm. apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflexion of this patch.

Figure from Thomson's first paper (together with explanatory text) illustrating the apparatus he used to measure e/m.

to envision atoms as made of "primordial atoms, which we shall for brevity call corpuscles." He went on:

> The smallness of the value of *m/e* is, I think, due to the largeness of *e* as well as the smallness of *m*. There seems to me to be some evidence that the charges carried by the corpuscles in the atom are large compared with those carried by the ions of an electrolyte.

Over the next two years, Thomson determined the mass and charge of his corpuscles, but it took additional experiments culminating in a second paper, "On the Masses of the Ions in Gases at Low Pressures," [*Phil. Mag.,* Ser. 5, Vol. 48, No. 295 (1899), p. 547]. Using a novel technique developed by his student C. T. R. Wilson, he measured both *m/e* and *e* for the negatively charged particles created by dissociation of atoms in ultraviolet light. He found *m/e* to be the same as for cathode rays and *e* to have the same absolute value as the hydrogen ion in electrolysis. Thus he concluded:

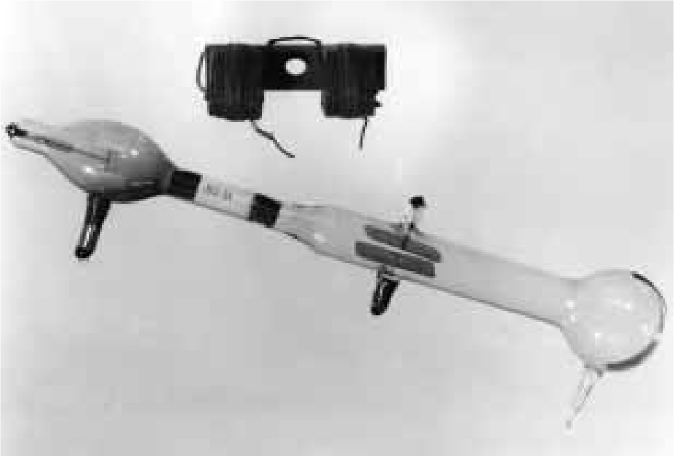
> The experiments just described, taken in conjunction with the previous ones on the value of *m/e* for the cathode rays . . . show that in gases at low pressures negative electrification, though it may be produced by very different means, is made up of units each having a charge of electricity of a definite size; the magnitude of this negative charge is about 6 x 10^{-10} electrostatic units, and is equal to the positive charge carried by the hydrogen atom in the electrolysis of solutions.
>
> In gases at low pressures these units of negative electric charge are always associated with carriers of a definite mass. This mass is exceedingly small, being only about 1.4 x 10^{-3} of that of the hydrogen ion, the smallest mass hitherto recognized as capable of a separate existence. The production of negative electrification thus involves the splitting up of an atom, as from a collection of atoms something is detached whose mass is less than that of a single atom.

Thus was the first elementary particle finally discovered and the field of particle physics born. Educated at Cambridge as a mathematical physicist, Thomson seems to have grasped the importance of his breakthrough almost immediately. For he ended his second paper with some bold speculations about its ultimate significance:

> From what we have seen, this negative ion must be a quantity of fundamental importance in any theory of electrical action; indeed, it seems not improbable that it is the fundamental quantity in terms of which all electrical processes can be expressed. For, as we have seen, its mass and its charge are invariable, independent both of the processes by which the electrification is produced and of the gas from which the ions are set free. It thus possesses the characteristics of being a fundamental conception in electricity; and it seems desirable to adopt some view of electrical action which brings this conception into prominence.

Within a few years most physicists recognized Thomson's new particle by the name "electron," the term George Stoney had coined for the fundamental unit of charge (see main text). But Thomson stuck resolutely by his beloved "corpuscle" and still refused to call it anything else upon receiving the 1906 Nobel Prize in Physics "in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases."

—M.R.



The vacuum tube used by Thomson in his discovery of the electron. (Courtesy Science Museum/Science & Society Picture Library, London)

of a new particle with a very small mass on the atomic scale. However, he was not the first to make that guess. In order to explain, I need to introduce two other players in the field.

The first is Emil Wiechert (1861–1928), then a Privatdozent at the University of Konigsberg. In the course of a lecture before Konigsberg's Physical Economical Society, on January 7, 1897, he stated his conclusion about cathode rays[14] to which his experiments had led him: "It showed that we are not dealing with the atoms known from chemistry, because the mass of the moving particles turned out to be 2000–4000 times smaller than the one of hydrogen atoms, the lightest of the known chemical atoms." It was the first time ever that a subatomic particle is mentioned in print and sensible bounds for its mass are given. However, these conclusions depended crucially on his assumption about the charge. "Als Ladung ist 1 Elektron angenommen" (the charge is assumed to be one electron) he stated, using Stoney's terminology.

The second person is Walter Kaufmann (1871–1947), then Assistent at the University of Berlin, whose cathode-ray experiments had taught him two crucial points.[15] First, e/m for his rays was a *constant*, the same for whatever residual gas remained in his Geissler tube. That greatly puzzled him: "This assumption [of constant e/m] is physically hard to interpret; for if one makes the most plausible assumption that the moving particles are ions [in the electrolytic sense] then e/m should have a different value for each gas." Furthermore there was, as he perceived it, a second difficulty. Assuming e/m to be a constant, his measurements gave him about 10^7 emu/g for the value of e/m, "while for a hydrogen ion [e/m] equals only 10^4." Thus, he stated, "I believe to be justified in concluding that the hypothesis of cathode rays as emitted particles is by itself inadequate for a satisfactory explanation of the regularities I have observed."

Clearly Kaufmann was a fine experimentalist who, however, lacked the chutzpah of Thomson, who on August 7, 1897, submitted his memoir on cathode rays.[16] His first determination of e/m yielded a value 770 times that of hydrogen. He observed (see box on pages 12 and 13) that, “The smallness of m/e may be due to the smallness of m or the largeness of e, or to a combination of these two.” He went on to argue in favor of the smallness of m, “Thus on this view we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter . . . is of one and the same kind; this matter being the substance from which all the chemical elements are built up.”

As I see it, Thomson’s finest hour as an experimentalist came in 1899 when he applied the methods just described to photoelectrically produced particles and concluded—he was the first to do so!—that these particles were electrons: “The value of m/e in the case of ultraviolet light . . . is the same as for cathode rays.”[17] In the same paper he announced his experimental results for the value of e, obtained by a method recently discovered by his student C. T. R. Wilson, who had found that charged particles can form nuclei around which supersaturated water vapor condenses. Thomson’s measurement of e is one of the earliest applications of this cloud-chamber technique. He determined the number of charged particles by droplet counting, and their overall charge by electrometric methods, arriving at $e \sim 6.8\times10^{-10}$ esu, a very respectable result in view of the novelty of the method. And that is why Thomson is the discoverer of the electron.

When Thomson addressed a joint meeting of British and French scientists in Dover in 1899, most doubts had been resolved. He quoted a mass of 3×10^{-26} g for the electron, the right order of magnitude. The atom had been split. “Electrification essentially involves the splitting up of the atom, a part of the mass of the atom getting free and becoming detached from the original atom.”[18]

ENVOI

TO DEFINE the “birth of an era” is perhaps best left for parlor games. Let me write of the birth of particle physics nevertheless, define it to take place in 1897, and appoint Wiechert, Kaufmann and Thomson as keepers at the gate. Their respective experimental arrangements are of comparable quality, their experimental results equally good. Kaufmann’s observation that certain properties of cathode rays are independent of the nature of the gas they traverse is, we would say, a clear indication the universality of the constitution of these rays. The value for e/m he obtained is a good one. Had he added one conjectural line to his paper, something like, "If we assume e to be the fundamental unit of charge identified in electrolysis, then cathode rays must be considered to be a new form of matter," he would have shared equal honors with Thomson for advances made in 1897. Perhaps the thought never struck him, perhaps it did but was rejected as too wild. Perhaps also the Berlin environment was not conducive to uttering speculations of this kind, as is evidenced by a recollection about the year 1897: "I heard John Zeleny say that he was in Berlin at that time, working in the laboratory of Warburg. When the discovery of the electron was announced, nobody in Berlin would believe in it."[19] It may not have been known at that time what went through Kaufmann's mind; it certainly is not known now.

It is fitting to conclude with a line from one of my favorite essays: "On History," by Thomas Carlyle[20]: "No hammer in the Horologe of Time peals through the universe when there is a change from Era to Era. Men understand not what is among their hands."

NOTES

[1] E. N. da C. Andrade, *Rutherford and the Nature of the Atom* (New York: Doubleday, 1964), p. 48.
[2] R. Descartes, *Principles of Philosophy*, Part 2, Principle 20. Translated by E. Haldane and G. Ross (New York: Dover, 1955).
[3] A. Williamson, *J. Chem. Soc.* 22 (1869), 328.
[4] T. Young, *Miscellaneous Works*, Vol. 9, (New York: Johnson Reprint, 1972), p. 461.
[5] J. C. Maxwell, *Collected Works*, Vol. 2, (New York: Dover, 1952), p. 361.
[6] J. D. van der Waals, (Ph.D. diss., Sythoff, Leiden 1873).
[7] A. W. Rucker, *J. Chem. Soc.* 53 (1888), 222.
[8] Maxwell, *Collected Works*, pp. 376–77.
[9] H. von Helmholtz, in *Selected Writings by Hermann von Helmholtz*, ed. R.Kahl (Wesleyan Univ. Press, 1971), p. 409.
[10] G. J. Stoney, *Phil. Mag.* 11 (1881), 381.
[11] ———, *Trans. Roy. Dublin Soc.* 4 (1888–92), 563.
[12] E. Rutherford, *Radioactive Transformations* (London: Constable, 1906), pp. 1, 16.
[13] M. Faraday, *Philos. Trans. Roy. Soc.* 128 (1838), 125.
[14] E. Wiechert, *Schriften der Phys.-Okon. Ges. zu Konigsberg* 38 (1897), 3.
[15] W. Kaufmann, *Ann. der Phys. und Chem.* 61 (1897), 544.
[16] J. J. Thomson, *Phil. Mag.* 44 (1897), 310–12.
[17] ———, *Phil. Mag.* 48 (1899), 547.
[18] Ibid., p. 565.
[19] G. Jaffe, *J. Chem. Educ.* 29 (1952), 230.
[20] T. Carlyle, "On History," in *The Varieties of History*, ed. F. Stern (New York: Vintage, 1973).