History of Science Department
University of Aarhus

OLE KNUDSEN

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Hosta, No. 7, 2001
Work-in-Progress

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Publication is only made electronically on the web site of the Department (www.ifa.au.dk / ivh / hosta / home.dk.htm). The issues can freely be printed as pdf-documents. The web site also contains a full list of issues.

ISSN: 1600-7433

History of Science Department
University of Aarhus
Ny Munkegade, building 521
DK-8000 Aarhus C
Denmark

To be published in: J.Z.Buchwald and A.Warwick, eds.: Histories of the Electron: The Birth of Microphysics, MIT-Press, scheduled publication date: April 2001.

O. W. RICHARDSON AND THE ELECTRON THEORY OF MATTER, 1901-1916

Ole Knudsen

INTRODUCTION

To the generation of physicists who began their careers around the turn of the century the existence and characteristics of the electron were facts, the establishment of which constituted the latest triumph of physical science. The various determinations of the electron's charge to mass ratio, coming from optical measurements of the Zeeman effect and direct measurements on cathode rays agreed within ever diminishing margins of error, and in 1900 Planck could infer a very precise value for the electronic charge from his new theory of blackbody radiation. The electron was soon established as a universal constituent of all matter, some 2,000 times lighter than the smallest atom, and it lent a new sense of reality to microphysical theories and models of all kinds.

One important part of the early history of the electron, the development of models of the electron as part of the structure of atoms and molecules, ending with Niels Bohr's famous theory of 1913, has been well described in the historical literature.[1] In this paper I study a different aspect of the history of physics before 1916, one in which atomic structure was of little significance but in which physicists nevertheless relied heavily on the electron for the explanation of the macroscopic properties of matter. I do this by focusing on the career of one such physicist, Owen Willans Richardson. By following his career till about 1916 I hope to present some characteristic features of the electron theory of matter in the period when it was still dominated by classical dynamics and electrodynamics, even though the quantum theory was, so to speak, lurking in the background.

Richardson entered Trinity College, Cambridge, in 1897 and soon became one of a lively group of students, among them such luminaries as Ernest Rutherford, C. T. R. Wilson, and Paul Langevin, who were working at the Cavendish Laboratory to explore under J. J. Thomson's leadership the exciting new fields opened up by the discoveries of X rays, radioactivity, and the electron, known at the Cavendish as Thomson's subatomic corpuscle. Richardson's education followed the pattern which had become standard at Cambridge since the reform instigated by Thomson around 1890. The essential new element was that instead of taking the Mathematical Tripos physics students could now study for the Natural Sciences Tripos which had become a proper physics education combining a solid grounding in differential calculus and theoretical physics with practical laboratory training at the Cavendish.[2] Richardson passed the Tripos with first class honours in 1900 and thereafter worked full time at the Cavendish till 1906 when he was appointed professor of physics at Princeton. He was elected fellow of Trinity in 1902 and won a Maxwell Scholarship and a D.Sc. (London) in 1904.[3]

Richardson clearly belonged to the generation that grew up with the electron and whose scientific career centered on the physics of this new constituent of matter. He began his physics education in the year of the discovery of the electron and was trained as a researcher at the world's leading centre for experimental and theoretical work on the new physics. Moreover he stayed with the electron and did not stray much into such fields as radioactivity or x-rays; his research during the period dealt with in this paper was pretty much concentrated on one aspect of the electron theory of matter: the thermal emission of electrons. Furthermore, after about 15 years of research which brought him international fame (and eventually a Nobel Prize) he took time off to write a textbook which gave a comprehensive and critical survey of electron physics up to the time of writing, thus providing us with an insider's view of what the electron had meant for the development of microphysics during this period.

RICHARDSON'S RESEARCH, 1901-1916

Richardson's first piece of work as a new research student was a typical example of 'Cavendish physics' as characterised by I. Falconer.[4] It consisted in an attempt to look for a new effect the existence of which had been suggested to him by Thomson. The idea, inspired by Thomson's new conception of electric currents being carried by corpuscles[5], was that since in a wire carrying an alternating current of high frequency the moving corpuscles would be confined to a very thin layer near the surface, it would be reasonable to expect the wire to emit some kind of radiation, either in the form of emitted ions or corpuscles (like radioactive radiation) or of Röntgen radiation produced when the rapidly oscillating corpuscles collided with the atoms in the wire. Hence Richardson tried to detect such radiation, first by means of a photographic plate (which indeed showed a line of fogging when brought near to the wire; unfortunately this turned out to be due to a luminous discharge round the wire) and then by using a sensitive electrometer to look for ionisation in the gas near the wire in a pressure range from one atmosphere down to .01 mm of mercury. The results of numerous experiments of successively finer sensitivity with wires of different metals were all negative, but the young man learned to handle vacuum equipment and delicate measuring instruments, skills that he would soon put to good use.[6]

Richardson's next work which marked the beginning of his longlasting research on the thermal emission of electrons, was an almost direct continuation of his first: If rapidly alternating currents did not cause a wire to emit radiation, heating a wire was known to make it emit electricity. The researches of Elster and Geitel had shown that a heated wire would leak either positive or negative electricity, depending on the temperature and the nature of the surrounding gas, and McClelland had shown that at high temperatures a platinum wire would emit negative electricity and that the amount emitted increased with the temperature.[7] Richardson decided to concentrate on the effect at very low pressures where the influence of the surrounding gas could be assumed negligible, and to investigate the temperature dependence of the saturation current from the heated wire, *i.e.* of the number of electrons emitted per unit time.

The apparatus that he constructed for this investigation (fig. 2) was a modified version of one he had used in his earlier work (fig. 1) so that also with respect to equipment and experimental technique his study of the thermal emission of electrons was closely related to his failed attempt to detect radiation from alternating currents.

Richardson published his results in a paper read to the Cambridge Philosophical Society in November 1901.[8] He began with a short theoretical consideration in which he reviewed the "corpuscular theory of conduction in metals"

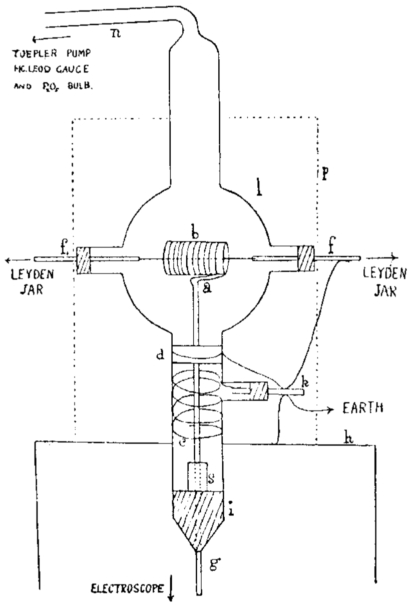

Fig. 1

Richardson's apparatus for detecting ionisation in the gas round a wire ff_1 carrying an alternating current. The spiral *b* was charged positively or negatively and connected to a sensitive electrometer. (Richardson, *op. cit.* n. 6, p. 175.)

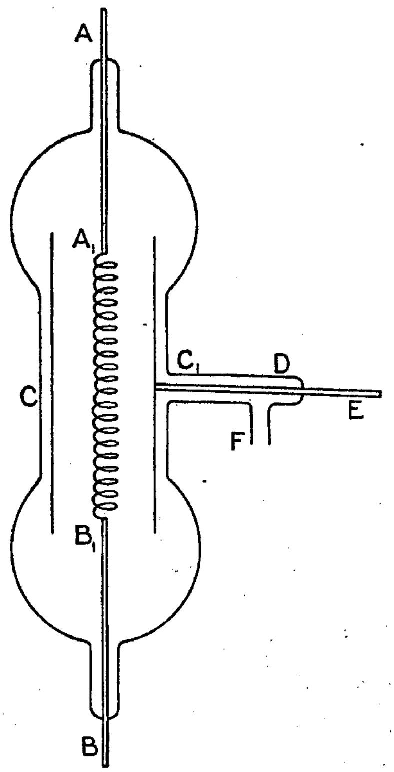

Fig. 2

Apparatus for measuring the saturation current from the hot platinum wire A_1B_1. The wire was surrounded by a metal cylinder *C* put to earth through a Thomson galvanometer measuring the current between the cylinder and the wire. (Richardson, *op. cit.* n. 11, p. 507). The purely verbal description in Richardson, *op. cit.* n. 8 ,pp. 287-8 seems to indicate that originally the wire was straight.

and used the Maxwell distribution of velocities to calculate the number of free corpuscles hitting unit area of the metal surface in unit time. Assuming that in order to penetrate the surface the corpuscles had to overcome a potential discontinuity *w*, he could then derive the first version of the expression that would later be known as Richardson’s law for the number N of electrons emitted from unit area of the metal surface in unit time:

$$N = N\sqrt{\frac{KT}{2M\pi}}\,E^{-w/kT} \qquad \textbf{(1)}$$

Here n is the number of free electrons in unit volume of the metal, k Boltzmann’s constant, T the absolute temperature, and m the mass of an electron.[9]

In the experimental part of the paper Richardson first established that the current between the wire and the cylinder was indeed caused by negative particles emitted from the wire; with a positive potential of 400 volts on the wire he obtained no current, while negative potentials resulted in quite large currents. Having made sure that the current reached saturation for a negative potential well below 80 volts, he proceeded to measure the saturation current as a function of temperature using a fixed potential of -120 volts on the wire and determining the temperature of the wire by measuring its resistance. In order to compare his results with eq. (1) he rewrote it in the form

$$N = i/\epsilon S = AT^{½}e^{-b/T} \qquad \textbf{(2)}$$

where i is the saturation current, ϵ the electronic charge, and S the surface area of the wire. In the temperature interval from 1300 K to 1600 K where the current increased three orders of magnitude from 2.5 x 10^{-9} to 4.0 x 10^{-6} ampères, he found a very good agreement between his measured values and eq. (2). Furthermore, from his measurements he could determine the constants A and b leading to the following values for n, the density of electrons in platinum, and $\delta\phi$, the discontinuity in the electric potential at the surface:

$$n = \left(\frac{2m\pi}{R}\right)^{\frac{1}{2}} A = 1.3\times10^{21}\ \mathrm{cm}^{-3} \qquad \textbf{(3)}$$

and

$$\delta\phi = \frac{w}{\epsilon} = \frac{b}{\epsilon k} = 4.1\ \text{volts} \qquad \textbf{(4)}$$

(The value of n was taken at a temperature of 1542 K while that of $\delta\phi$ represented an average between 1378 K and 1571 K). Both values seemed to be of the right order as compared, respectively, to the value $n = 1.37 \times 10^{22}$ cm^{-3} obtained from Patterson’s measurements of the change of resistance of platinum in a magnetic field using Thomson’s theory of conduction[10], and to contact emf’s between metals.

Fifteen months after reading this paper to the Cambridge Philosophical Society Richardson submitted to the Royal Society a lengthy article in which he brought his theoretical and experimental research on the thermal emission of electrons to a temporary completion.[11] In it he repeated the derivation of eq. (1) in a slightly more detailed manner and supplemented it by an alternative derivation using the ideal gas law and the first law of thermodynamics on unit mass of electrons passing from the inside to the outside of the metal. He ended the theoretical part with a veiled remark on the analogy between the emission of corpuscles and evaporation, thus supplementing the concept of the electron gas by that of the electron vapour.[12] In the experimental part a report of his results on platinum, taken almost verbatim from the earlier paper, was followed by descriptions of new experiments on carbon filaments and sodium. Because of its volatility and high photoelectric activity sodium posed particular difficulties which required the construction of a completely different type of apparatus and which even then made it impossible to achieve saturation, so that it was necessary to use the current at a fixed voltage to measure the number of emitted electrons per unit time as a function of temperature.The new results provided further confirmation of Richardson's law, but the values of n for both carbon and sodium turned out to be several orders of magnitude too high both from a theoretical point of view (they would correspond to pressures of millions of atmospheres) and compared to available experimental results. Richardson put this down to a slight temperature variation of w; this asumption also helped to improve the fit between differences in his values of $\delta\phi$ and known values of contact potentials between the three substances.

Richardson's early work on thermal emission established his reputation as a physicist and was instrumental for his appointment at Princeton in 1906. However, the phenomenon turned out to be very complicated, if not to say messy, and it continued to take up a large proportion of his efforts, both during his time in America and after his return to England in 1914 as a newly elected FRS and Wheatstone professor of physics at King's College, London. Before the outbreak of WW I he had published some thirty papers on many different aspects of "thermionics" as he dubbed the phenomenon in 1909,[13] and the subject had developed into a flourishing research field with many contributors, as is amply demonstrated by Richardson's monograph of 1916.[14] The interest in this field was due partly to its relevance for the important progress of radio technology[15], partly to its theoretical implications for the electron theory of metals, in particular with respect to their thermoelectric properties.[16]

To follow Richardson's later work in detail would take us too far afield, but a few points may be mentioned:[17]

1) In collaboration with his student F. C. Brown, Richardson demonstrated experimentally that the electrons emitted by a hot strip of platinum have velocities that agree with the Maxwell distribution, thus providing the first direct experimental verification of that distribution for any gas. The authors interpreted this result as a support for Richardson's original theory of the electronic emission, in particular for the assumption that the Maxwell distribution held for the conduction electrons inside the metal as well. Thus they saw their work as confirming the electron gas theory of metals.[18]

2) Richardson's original derivation of his law relied on the kinetic theory of the electron gas in metals. As the difficulties of this theory with respect to specific heats and in relation to radiation theory became more and more evident[19], Richardson came to

rely more on purely thermodynamical arguments. In two theoretical papers he in 1912 developed a new theory which brought electron emission into relation with thermoelectric phenomena and which also led to a modified form of his law. Instead of the formula

$$i = AT^{1/2}e^{-w/kT} \qquad \textbf{(5)}$$

which follows from eq. (1) he now found

$$i = AT^{2}e^{-w/kT} \qquad \textbf{(6)}$$

where i is the saturation current, w is the work function (the work an electron has to perform to pass from inside the metal to the outside), and A denotes different constants in the two formulas. Because the variation with temperature was dominated by the exponential function the difference between the two expressions could not be detected experimentally. A further elaboration of the thermodynamical relations between the work function and thermoelectric properties showed that the relation

$$w = w_0 + \frac{3}{2}kT \qquad \textbf{(7)}$$

would be a good approximation for substances having a small Thomson effect, *i. e.* for most metals.[20]

3) The basic assumption underlying the whole of Richardson's work was that the thermionic currents consisted of conduction electrons evaporating out through the surface of the metal. The currents were however greatly influenced by residual gases, gases occluded in the metal, impurities in the hot filament, etc. Already in 1903 H. A. Wilson had found results indicating that the main part of the current from platinum was due to occluded hydrogen,[21] and by 1912 Richardson's results on carbon and sodium had also been cast in doubt, so that there was a real possibility that the emission of electrons was in all cases a secondary effect accompanying some chemical or other process at the surface of the hot filament. In 1913 I. Langmuir of General Electric provided Richardson with specimens of ductile tungsten and taught him the best way of removing gas from his apparatus; this enabled him to prove conclusively that at least in the case of tungsten the overwhelming part of the current came from the conduction electrons. The tungsten filaments could stand a very high temperature for a very long time, so Richardson could show that in some of his experiments the total number of electrons emitted was 10^4-10^8 times the number of gas molecules liberated from the filament or impinging on it. In another experiment the total mass of emitted electrons was close to three times the mass of tungsten lost by evaporation or sputtering from the hot filament. Thus the only possible source for the thermionic electrons was that they must have flowed into the filament from outside the tube, *i.e.* by conduction.[22]

4) Another disturbing influence was the photoelectric effect. Already in his

1903 experiments on sodium Richardson had had to take special precautions to protect the emitting surface from light in order to remove the photoelectric emission which for this very electropositive metal was considerable even at ordinary temperatures.[23] In 1912 he began a thorough study of the photoelectric effect both theoretically and experimentally, the latter in collaboration with his student Karl T. Compton. In his theory Richardson used statistical and thermodynamical arguments, similar to those used in his thermionic theory, to establish equilibrium conditions for the electron vapour near a metal surface subject to blackbody radiation described by Wien's radiation law (the high frequency limit of Planck's law). The result was an integral equation for the number $F(\nu)$ of electrons emitted by a unit of incoming radiative energy of frequency ν, and a second integral equation containing $F(\nu)$ and the maximum kinetic energy T_ν of the electrons emitted by radiation of frequency ν. A solution to the first integral equation was

$$\begin{aligned} F(\nu) &= 0 && \text{when} \quad 0 < h\nu < w_0 \\ F(\nu) &= A_1 \frac{h}{k^2\nu^2}\left(1 - \frac{w_0}{h\nu}\right) && \text{when} \quad w_0 < h\nu < \infty \end{aligned} \qquad \textbf{(8)}$$

where A_1 is a constant characteristic of the metal, h is Planck's constant and w_0 is the constant part of the work function, cf. eq. (3). With $F(\nu)$ given by eq. (4) the second integral equation had the solution

$$T_\nu = h\nu - w_0 \qquad \textbf{(9)}$$

These results were not very surprising since Einstein had derived eq. (9) already in 1905, but Richardson emphasized that in his derivation he had used only Planck's radiation law, not Einstein's lightquantum hypothesis or, as he also called it, the "unitary" hypothesis. Hence experimental confirmation of eqs. (8) and (9) did not constitute compelling evidence for Einstein's theory.[24]

Compton's and Richardson's experiments confirmed the general features of the theory, particularly the linear relation between T_ν and ν as well as the existence of a threshold frequency below which photoelectric emission ceased, and they provided two independent methods of determining the value of Planck's constant: from the slope of the experimental (T_ν,ν)-curves or from the experimental values of the threshold frequency $\nu_0 = w_0/h$, using values of w_0 from thermionic and thermoelectric data. The first method yielded a value some 20% smaller than the well established radiation value $h = 6.55\times10^{-27}$ erg sec, while the second gave a value almost as much in excess. A fairly thorough discussion of possible sources of error did not enable the authors to reach a firm conclusion about the reasons for these deviations[25].

The problem which originally had turned Richardson's attention to the photoelectric effect was that of distinguishing it from the thermionic emission, or in other words to prove that the latter was a genuine effect and not simply photoemission due to the ubiquitous blackbody radiation. However, his theory showed that the temperature variation of photoemission caused by blackbody radiation at the temperature of the hot filament was given by the same expression that governed thermionic emission (eq. (2)), and his theoretical expression (8) for the number of emitted electrons as a function of the frequency of the radiation turned out to agree rather badly with experimental results. It was only in 1916 that Richardson had enough theoretical results and experimental data to be able to conclude with some certainty that blackbody photoemission could account for only an insignificant fraction (less than 1/5,000 in the worst case) of the observed thermionic current from platinum at 2,000 K.[26]

Richardson's impressive research activity during the 15 years we have been considering clearly showed the influence of his Cavendish education. The most characteristic feature of his work was the integration of experiment with theory. Almost all his experimental papers were introduced by a theoretical section in which fundamental theory, usually statistical mechanics or thermodynamics, was combined with microphysical assumptions to yield reults that were then tested in experiments in which ever improved vacuum technique went hand in hand with manipulation of electrons or ions by electric fields and measurements of currents by sensitive galvanometers or electrometers. An example of Cavendish ingenuity in solving an experimental problem by inexpensive means may be seen in his and Compton's method of obtaining a fresh sodium surface free of oxidation by furnishing their vacuum tube with an additional bulb containing a small electrically heated furnace by means of which they could evaporate sodium on to their target. An external magnet acting on a piece of soft iron connected with the target allowed them to then hoist the target back into position in the measuring bulb without breaking the vacuum.[27] On the other hand the influence of Richardson's exposure to a different American laboratory practice with ties to the affluent industrial laboratories may perhaps be discerned in the apparatus he built for his 1908 determination of the specific charge of thermionic particles.[28] With its precisely machined moving parts this complicated piece of equipment was a long way from the Cavendish "string and sealing wax" approach, strikingly illustrated by Richardson himself during his Cavendish days in a paper on electroscopes.[29]

When Richardson in 1916 published his monograph *The Emission of Electricity from Hot Bodies*, summing up his own and others' work on thermionics, he was hailed by an anonymous reviewer in *Nature* as the acknowledged master of his field:

> " The author was one of the first workers in this new field of work... A large part of our knowledge of this subject is due to his investigations.
>
> As a consequence, we have a first-hand account of this interesting subject, written by one who has a full appreciation of the experimental difficulties and the adequacy of the theories proposed."[30]

RICHARDSON'S TEXTBOOK

In 1914 Richardson published a textbook called *The Electron Theory of Matter*, a second revised edition of which appeared in 1916.[31] Based on a course of lectures he had been giving to his graduate students at Princeton this was an advanced textbook aiming at bringing the students rapidly up to the research front in electron physics in general. Thus it had a much wider scope than his later monograph and it was praised for this by Niels Bohr in a review in *Nature:*

> It will be seen that the book covers a very extensive field. To give an adequate representation of the entire electron theory is naturally a task of the greatest difficulty, but the author appears to have done this in an admirable manner.[32]

The value of *ETM* as a historical source for the first phase of the electron theory lies not only in its being probably the most comprehensive survey available, but also in the fact that it was published at a particularly interesting point in time. Again it is appropriate to quote *Nature*, this time from an editorial note reporting the award of the Nobel prize to Richardson:

> Richardson's "Electron Theory of Matter" is also well known to students of electricity and atomic physics, and although published between the advent of the Bohr and the Wilson-Sommerfeld theories of the atom and with a strong classical bias, is still much used.[33]

There is indeed a world of difference between *ETM*^{2} and, say, Arnold Sommerfeld's *Atombau und Spektrallinien*, published only three years later. A comparison makes the former stand out as perhaps the last important book on the constitution of matter written "with a strong classical bias" by an acknowledged master of electron physics in general. In the following I describe some characteristic features of the book with respect to three main points: electromagnetic principles, electrons in matter, and quantum theory.

FUNDAMENTAL PRINCIPLES OF ELECTROMAGNETISM

It is interesting to compare *ETM* with two other surveys of the electron theory, H. A. Lorentz's *Theory of Electrons* and Niels Bohr's *Metallernes Elektrontheori*[34], both strongly theoretical with little concern for experiment; not surprisingly, Richardson showed more appreciation of experimental work and reported much more fully on experimental results. Both works were written for specialists who were tacitly assumed to accept a standard version (Lorentz's) of the general principles of the electromagnetic theory. Bohr plunged directly into his investigation of the extent to which the behaviour of electrons in metals could be accounted for by these principles combined with statistical mechanics and reasonable assumptions about the interactions betweeen electrons and metal atoms, while Lorentz began his book with a succinct account of his own theory including the concept of electromagnetic mass and the electromagnetic world view.

By contrast, *ETM* was composed as a textbook for beginning graduate students who could be assumed to have from the outset only an elementary knowledge of electromagnetic phenomena. Thus its account of electromagnetic principles was much more detailed than Lorentz's; but, more significantly, it presented different theoretical points of view without explicitly preferring one over the other. An example is the discussion of the Ampère law and the Faraday law (which Richardson called the First and Second Law of Electrodynamics) where a Maxwellian conception of the ether was compared to the more axiomatic view inherent in the electromagnetic world view:

> The Second Law of Electromagnetism may be looked upon from two different standpoints according to the attitude we take towards electrical science. If we regard electrodynamics as more fundamenal than dynamics proper, then we must regard the Second Law as a fundamental law of nature empirically given. We may however take the standpoint that the aether, which we postulate as a medium in which all electrical actions occur, will in the last analysis prove to be a mechanical system subject to the basic laws of dynamics. ... The view that electrical actions are ultimately dynamical is one whose development in the hands of Maxwell led to notable advances in the science, and it is the view towards which, at any rate until quite recently, most authorities have leaned. Nevertheless it is equally logical to accept the Second Law as an ultimate fact and then, later on, to consider what we can make of the laws of dynamics from the standpoint thus adopted. (*ETM*^{2}, p. 102)

This comment introduced seven pages explaining the analytical dynamics of the ether and the deduction of the Second Law from the First, so that the late Maxwellian views with which Richardson must have been thoroughly familiar from his Cambridge education were faithfully transmitted to his readers.[35]

The electromagnetic world view was no less fully represented. In a chapter headed "The Fundamental Equations" the four microscopic Maxwell equations and the Lorentz force expression were presented as the equations "associated with the name of Lorentz", and a later chapter entitled "The Aether" gave a detailed account of Lorentz's theory of the electrodynamics of moving media. Furthermore the concept of electromagnetic mass was introduced as a foundation for the electromagnetic world view:

> The idea of electromagnetic inertia, which is due to J. J. Thomson, is fundamental to the electron theory of matter. For it opens up the possibility that the mass of all matter is nothing else than the electromagnetic mass of the electrons which certainly form part, and perhaps form the whole, of its structure. It obviously opens up the possibility of an electrical foundation for dynamics. (*ETM*^{2}, p. 229)

In the very beginning of the book Richardson defined the electron as a particle consisting "of a geometrical configuration of electricity and nothing else, whose mass, that is, is all electromagnetic" (*ETM*^{2}, p. 8). This was followed up at the end of the book by a detailed discussion of the unsuccessful attempts to account for gravitation on an electromagnetic basis, concluding that

> ... the electron theory is not in a position to make very definite assertions about the nature of gravitational attraction. (*ETM*^{2}, p.619).

Having mastered the technical and conceptual complications of understanding first the Maxwellian derivation of electrodynamics from ether mechanics, then Lorentz's electrodynamics of systems of charged particles moving through the ether and its associated hope of an electrical foundation for dynamics, Richardson's students must have felt slightly dizzy upon encountering, immediately after the chapter on "The Aether", yet a third world view which denied the existence of the ether. Richardson's chapter on "The Principle of Relativity" was taken almost verbatim (with due reference) from Einstein's 1907 review in Stark's *Jahrbuch.* Einstein had taken great pains to make his review as clear as possible and Richardson must have appreciated this for he made no substantial changes in the presentation.[36] However, he showed his sympathy with the reader's difficulties (perhaps his own as well) in accepting the consequences of the theory by a remark following the derivation of the Lorentz contraction, the time dilation, and the addition of velocities:

> Some of the preceding results differ so considerably from those which follow from the generally accepted notions of space and time that many readers will probably regard them as serious objections to the views here developed. If, however, the principle of relativity is accepted they appear to follow with logical certainty. (*ETM*^{2}, p. 303)

The chapter ended with a section entitled "The Principle of Relativity and the Aether" which stated that Lorentz's theory could explain all the known facts, but that the principle of relativity "describes them in a simpler and more symmetrical manner", and that, by denying the possibility of determining the motion of the ether it "finds the aether a superfluous hypothesis" (*ETM*^{2}, pp. 323-325).

Clearly, Richardson's approach to the fundamental principles must be characterized as pluralistic. He made an effort to present each of the three paradigms in its own terms and on its own premises, emphasizing the strength of each and to a great extent letting his readers form their own judgement on their relative merits. This attitude may of course be put down to the pragmatism of a working physicist to whom debates on fundamental theory mattered little, either for his own research or for the main chapters of his textbook; this will be discussed more fully in the conclusion.

THE CLASSICAL ELECTRON THEORY OF MATTER

The main part of Richardson's book consisted of a number of chapters on electron-theoretic explanations of specific groups of physical phenomena. These chapters usually began with a short description of the main features of the phenomena in question. Then a microphysical model involving the electron was sketched and subjected to a detailed and rigorous treatment using electromagnetic theory, classical dynamics and, if necessary, statistical mechanics or thermodynamics. The resulting formulas and constants were compared with the best established empirical laws and experimental measurements, and the free parameters of the model were adjusted so as to give the best possible fit between theory and experiment. Sometimes the original model proved unable to accommodate all the data; an attempt was then made to generalize the model by dropping some too specific assumptions. As an example consider the chapter on "Dispersion, Absorption and Selective Reflection". First "an ideal substance" was described "which in all probability is somewhat simpler in its constitution than any real substance occurring in nature" (*ETM*^{2}, p. 142). It consisted of molecules, each of which contained a number of electrons having fixed positions of equilibrium around which they could oscillate under the combined influence of forces of restitution obeying Hooke's law, velocity-proportional damping forces, and external electric and magnetic fields. The description included a comment to the effect that the damping forces were badly understood - attempted explanations in terms of radiation damping or molecular collisions having resulted in absorption coefficients much smaller than those actually observed - and that generally the absorption process was still mysterious. Next the consequences of the model were worked out and compared with an extensive amount of optical data, and finally it was shown how by means of Lagrangian dynamics a generalized theory might be obtained that was free of unfounded assumptions about the unknown details of atomic structure and at the same time could be adapted to fit a wider range of experimental data, but at the cost of formulas so unwieldy as to be of limited practical use.

Richardson devoted two chapters entitled "The Kinetic Theory of Electronic Conduction" and "The Equilibrium Theory of Electronic Conductors" to the electron gas theory of metals, including his own specialty of thermionics. In the first of these he applied Boltzmann's kinetic theory, taken from Jeans's textbook,[37] as a foundation for a thorough theoretical and experimental discussion of electrical and thermal conductivities, and for the theory of thermoelectricity, deriving relations between the thermoelectromotive force, the Peltier coefficient, and the Thomson coefficient. He also discussed galvanomagnetic phenomena emphasizing the difficulties with understanding the negative Hall effect. In the second chapter he gave a full account of his own 1912 thermodynamical treatment of thermionic emission and its relations to thermoelectricity, and repeated his theory of the photoelectric effect.

In these two chapters, as in several others, much discussion was given to various models of the structure of atoms and the behaviour of electrons in matter. We have already met one such: electrons oscillating around fixed positions of equilibrium. In his chapter on magnetism Richardson needed atoms to possess magnetic dipole moments and so introduced orbiting electrons. In the kinetic theory of the electron gas electrons were originally regarded as free, except for brief hard-sphere collisions with atoms, but Richardson showed that if the electrons were supposed to move under the influence of a force from the rest of the atom, proportional to the inverse cube of the distance to the center of the atom, this would make the constant in the so-called Wiedemann-Franz law for the ratio between the thermal and electrical conductivities of a metal agree better with experimental measurements (*ETM*^{2}, pp. 413-422).[38] At this point Richardson gave his readers a glimpse of a possible unification: an atom might have a core containing strongly bound, oscillating electrons. This core would constitute an atomic dipole with an oscillating electric moment. In the r^{-3}-field from these dipoles other, more loosely bound electrons might describe orbits and thus give the atom a net magnetic moment. Some of these orbiting electrons might be so weakly bound that they could become "free" from time to time in the sense that they might be able to move from one atom to the next under the influence of an external field and thus produce an electric current. Richardson listed a number of uses of this dipole model, as I shall call it (*ETM*^{2}, pp. 422-425; 461-468):

1°. A model of this type had been used by J. J. Thomson to explain the photoelectric effect.[39]

2°. The magnetic moment of the orbiting electrons would be proportional to the electrical moments of the cores and since one could infer from the "universality of the law connecting radiation and temperature" that the latter were matter-independent one would have an explanation of Weiss's magnetons.

3°. One might identify the oscillating cores with the vibrators in Einstein's theory of specific heats. The amplitudes of their dipole moments would then tend exponentially to zero as the temperature approached absolute zero; by making the "free" electrons "more free" this would explain the increase of conductivity at low temperatures. Even superconductivity, recently discovered by Kamerlingh Onnes, had been explained by J. J. Thomson using the dipole model.[40]

4°. On the simple kinetic theory of the electron gas the conductivity of a metal would be proportional to the number of free electrons per unit volume, while the Peltier effect at a junction between two metals would be proportional to the logarithm of the ratio between these numbers for the two metals. Hence there ought to be a large Peltier effect at the junction between a good and a bad conductor. This was not borne out by experiments; in some cases the Peltier effect even went in the direction opposite to the expected. The dipole model removed this difficulty by making the conductivity proportional to the mean number of electrons actually free at a given moment, while making the Peltier effect depend on the mean potential energy of the electrons which might become free from time to time. In a bad conductor there might be many more of the latter than of the former type of electrons. The same feature of the model might also help explaining the relation between conductivity and thermoelectric power in alloys.

The dipole model was partly inspired by J. J. Thomson and was in general agreement with Thomson's views on atomic structure. Though Richardson was impressed by the number of phenomena for which this model furnished a qualitative (and sometimes quantitative) explanation, he was aware of the recent doubts cast on the Thomson atom. In a discussion of the scattering of α and β rays, for instance, he compared Thomson's theory of multiple scattering with Rutherford's theory of single scattering against atomic nuclei. "Reviewing the whole evidence broadly" he concluded that the phenomena were "quite decisively in favour of Rutherford's view" (*ETM*[2], pp. 490-496), and he then gave a veiled reference to Bohr's theory of the atom, but he did not take the opportunity to discuss the consequences of this new theory for the dipole model.

THE QUANTUM THEORY

On p. 347 of *ETM*[2], more than halfway through the book, Richardson's readers made their first acquaintance with Planck's quantum. This happened in the middle of a chapter on "Radiation and Temperature" after a 20-page discussion of blackbody radiation ending with a demonstration that any theory in which the emission and absorption of radiation by matter was assumed to be a continuous process, subject to the laws of dynamics and electrodynamics, would inevitably lead to the radiation formula of Rayleigh and Jeans, a formula that, except for long wavelengths, went against all experimental evidence. "Although it may appear revolutionary to some", Richardson continued, "it seems to the writer that the only logical way out is to deny the adequacy of dynamics and electrodynamics for the explanation of the emission and absorption of radiation of energy by matter." He then went on to recount Planck's latest (1912) version of his theory in which the only discontinuous feature was that an atomic oscillator was assumed to emit all its energy, with a certain probability dependent on the radiation density, whenever its energy reached an integral multiple of Planck's constant h times its frequency ν, while absorption was treated as a completely continuous and classical process.

After deriving Planck's radiation formula and emphasizing that the experimental determination of Boltzmann's constant from measurements on blackbody radiation had led to values for Loschmidt's number and the electronic charge in excellent agreement with those found independently by more direct methods, Richardson stated that Planck's theory had recently received "unexpected support" in other directions. One of these was Einstein's theory of specific heats (1907) and Debye's modification of it (1912), another was Richardson's own theory of the photoelectric effect, and yet another was Bohr's theory of atoms and molecules. All of these he described not as essentially new theories, but rather as natural extensions of Plancks quantum theory of the interaction between radiation and matter.

On the whole, despite his use of the word "revolutionary" in the quotation above, Richardson seems to have regarded the quantum as signifying a new, mysterious property of atoms rather than as the beginning of a new fundamental theory. Thus he justified his preference for Planck's latest theory by saying:

> In his earlier papers the assumptions made were equivalent to postulating that the energy itself had a discontinuous structure, but Planck has now shown that equivalent results may be obtained by merely supposing that the radiant energy is emitted by jumps, the absorption taking place continuously. As the emission of radiant energy might be expected to be conditioned by the breaking up of some structure present in the matter, this seems a very natural hypothesis. (*ETM*^{2}, p. 350)

Two pages earlier he had characterised the theory as "free from self-contradiction and from assumptions, such as that of the discontinuous nature of energy, which appear to do violence to the fundamental ideas of physics. So much could not be said of the earlier forms". One of the violators against the "fundamental ideas of physics" was no doubt Einstein's lightquantum hypothesis. In their first report in the May 17, 1912 issue of *Science* on their photoelectric experiments Richardson and Compton said that their results were "favorable to a theory ... of the type of Einstein's ..." [41], but in the July 12 issue Richardson published a note in which he argued that Planck's new derivation of the blackbody radiation law and his own derivation of the photoelectric equation (9) had shown that "the unitary theory of light" was unnecessary to account for either of these laws.[42] In *ETM*, after repeating his derivation of eq. (9), he said that a similar equation "was first given by Einstein as a consequence of the view that the energy of light waves was distributed in discrete quanta" (*ETM*^{2}, pp. 473-474). This laconic statement is the only direct mention of the lightquantum in the whole book.

In his book on the wave-particle dualism Wheaton has shown both the widespread use of the "triggering hypothesis" as an explanation for the observed particle features of x-rays and visible light, and the relation between this hypothesis and Planck's 1912 theory, clearly exemplified in Richardson's "breaking up" hypothesis in the above quotation.[43] Wheaton has also demonstrated the growing recognition after 1911 of the similarity between the photoelectric effect and the emission of secondary electrons by x-rays, and its significance for the discussions of the nature of x-rays and light.[44] Richardson was clearly aware of these problems. In his discussion of x-rays he pointed out the similarity between W. H. Bragg's experiments showing a preponderance in the forward direction of secondary electrons produced by x-rays and the similar experiments of O. Stuhlmann and R. D. Kleeman on photoelectrons from ultraviolet light.[45] These experiments, he said, could not be reproduced by the simple view that the kinetic energy of the electrons derived from the work done as the electromagnetic pulse passed over them; this view would in any case lead to far too small values of the kinetic energy. He then referred to Planck's 1912 theory and his own photoelectric theory as having led to the view that "when radiant energy causes the disruption of an electron from a material system, the electron acquires an amount $h\nu$ of energy" and then gave a long and involved statistical argument about the exchange of momentum between radiation and the electrons in a thin slab of material to prove that the Bragg and Stuhlmann effects could be brought out "without supposing the primary radiations which exhibit them to be of a material nature" (*ETM*^{2}, pp. 478-481). After surveying many more phenomena relating to x-, γ-, and β-rays, among them the fact that the maximum energy of secondary electrons produced by a characteristic x-ray was equal to the minimum energy of the primary electrons required to produce that ray, he admitted that these facts "receive a simple and obvious explanation on the view that the X rays and light consist of showers of material particles or of bundles of energy". However, he immediately rejected this view as unable to account for interference phenomena and deemed it "a little safer" to adopt the triggering hypothesis which he now described as a condition "of a very general character and necessarily inherent in all types of matter". This condition would determine the disruption of matter under the stimulus of a given radiation in such a way that the energy of the disrupted electrons would be equal to $h\nu$, or an integral multiple of this quantity. He ended this discussion with an aside, put between square brackets, which shows a very clear appreciation of the paradoxical, dualistic character of the evidence that existed on the nature of light and x-rays, that is of radiation in general:

> [It is difficult, in fact it is not too much to say that at present it appears impossible, to reconcile the divergent claims of the photoelectric and the interference groups of phenomena. The energy of the radiation behaves as though it possessed at the same time the opposite properties of extension and localization. At present there seems no obvious escape from the conclusion that the ordinary formulation of the geometrical propagation involves a logical contradiction, and it may be that it is impossible consistently to describe the spacial distribution of radiation in terms of three dimensional geometry.] (*ETM*^{2}, pp. 507-508)

Although Richardson left no doubt of his preference for an approach that, like Planck's and his own, combined a vaguely expressed version of the triggering hypothesis with the wave theory of light and x-rays, using general statistical and thermodynamical methods, the final period of this quote seems to express an uneasiness that this might not suffice and that more radical measures might turn out to be required. Hence perhaps the square brackets.

Richardson's penultimate chapter was headed "The Structure of the Atom". Two thirds of its pages were devoted to J. J. Thomson's atom, chiefly emphasizing Thomson's explanation of the periodic system of the elements and his theory of chemical combination. In keeping with the pluralistic character of the book, this was followed by a brief review of Rutherford's arguments for the nuclear atom, and then by a full treatment of Bohr's 1913 theory of the atom, one of the earliest, if not the earliest such treatment in a regular textbook[46]. In the preface to the second edition Richardson said that this treatment was considerably expanded relative to the first edition and wrote about the "remarkable successes of this theory" (*ETM*^{2}, p. vii). In the chapter he detailed Bohr's explanation of spectra and Moseley's and Kossel's work on x-rays as instances of these successes. Interestingly he described Bohr's postulates as "closely related to those underlying Planck's theory of Radiation", and he ended the chapter by emphasizing that although Bohr's theory was "non-mechanistic" it preserved "continuity with the ordinary dynamics in the region of slow vibrations" (*ETM*^{2}, p. 606). Thus Bohr's theory was characterized rather as a natural extension of Planck's than as a radical departure from previous theory. In view of his express preference for the triggering hypothesis and Planck's second theory it is surprising that Richardson did not mention the fact that Bohr diverged from Planck in making the absorption of radiation as discontinuous a process as emission. Neither did he discuss the implications of Bohr's theory for the dipole model or other models of atomic structure used in previous parts of the book. However he did remark that the kinetic energy of an electron liberated by radiation of frequency ν from a Bohr orbit of energy $-W_D$ would be given by

$$\frac{1}{2}mv^2 = h\nu - W_D \qquad \textbf{(10)}$$

and that this result agreed with that of his own photoelectric theory.

CONCLUSION

In a recent work A. Warwick has introduced the term theoretical technology to distinguish "the pieces of theoretical work ... which are used to solve particular problems" from "the idealized conceptual schema of a general theory", and has employed this concept to analyze the reception of the theory of relativity by physicists at Cambridge.[47] Although Warwick in his introduction of this term seems to define it as a sociological concept characterising a theoretical school or group of physicists, I would suggest that it might be useful also to apply it to the case of an individual physicist. As an example it is evident that even if Richardson in his textbook gave an excellent account of the fundamental concepts and theorems of the theory of relativity (taken almost verbatim from Einstein himself) that theory was not a part of the theoretical technology that he employed either in his research papers or elsewhere in his book.

The example indicates that by adopting Warwick's point of view we might as it were get behind the apparent pluralism of Richardson's book and obtain a deeper understanding of his view of physics. I have characterized Richardson's account of the fundamentals of electromagnetic theory as pluralistic, one might say indifferent, with respect to the three world views: the mechanistic, the electromagnetic, and the relativistic. However, his research papers as well as the 'applied' chapters of his book (dealing with optical effects, radiation, magnetism, properties of metals, etc.) give a different impression. The theoretical technology that Richardson applied came from electromagnetic theory, statistical mechanics and thermodynamics, classical mechanics, and Planck's quantum theory of radiation. I have already noted the absence of any use of relativistic concepts or arguments. Likewise we find no use of ideas that can be referred to the mechanistic view of the ether. On the other hand, the Lorentz force expression was used without comment whenever appropriate, but even more revealing is Richardson's explicit definition of the electron as "a geometrical configuration of electricity and nothing else" as well as a remark in his discussion of the Thomson atom to the effect that the electromagnetic inertia of its positive sphere "is negligible compared with that of a single electron, so that the greater part of the mass is entirely unaccounted for by this theory"(*ETM*^{2}, pp. 586-587), a remark that only makes sense within the electromagnetic world view. We may safely conclude that despite the disinterestedness displayed in his chapters on the three paradigms, Richardson thought and worked within the electromagnetic world view.

As regards Richardson's views on atomic structure it should first be noted that in his research he had not had much use for detailed models of atomic structure, and he had never taken active part in the work of the 'atom builders', to use J. L. Heilbron's phrase for the constructors of atomic models before 1913.[48] He had used few specific properties of the dipole model, such as the r^{-3}-field, otherwise he had needed only more general features, such as the distinction between bound and free electrons in a metal and the existence of a characteristic potential energy jump or work function for an electron passing out through the surface of a metal. In his work on the photoelectric effect he had used the quantum theory, but only in the form of Planck's radiation law as a condition for statistical equilibrium; in his derivation of the photoelectric equation he had completely bypassed Einstein's lightquantum as indeed any detailed consideration of the process by which a single electron was forced out of a metal by radiation.

In his textbook one finds more extensive use of models of specific atomic properties. At first glance it seems as if Richardson postulated different such properties according to the phenomenon under discussion: fixed electrons for dispersion, orbiting electrons for magnetism, free electrons for conduction. However, as I have emphasized above, the dipole model appeared to him to unify these structures. It was precise enough to serve as a basis for calculations, on the other hand it was sufficiently flexible to allow for the different types of electronic motions that were needed for the explanations of the many and varied types of properties of matter. It is worth noting that the atomic models of Thomson and Bohr both contained orbiting electrons of which some were strongly bound, while others, e.g. the valency electrons in the alkali metals, were easily removed. For this reason either of them may have seemed to Richardson as a particular version of the dipole model. There is certainly no indication of his being aware that Bohr's theory might require profound revisions of the theories propounded in earlier parts of the book, though he did note that it could furnish an explanation of Weiss's magneton (*ETM*[2], pp. 395 and 592).

In order to grasp Richardson's understanding of Bohr's theory it is instructive to consider the dispersion theory that was put forward by Debye and Sommerfeld in 1915. Using Bohr's models for the molecules of hydrogen, oxygen and nitrogen they evaluated the perturbations caused by an electromagnetic wave in the orbit of a molecular electron, calculated the mean dipole moments corresponding to the proper vibrations into which the perturbations could be resolved, and then used these oscillating dipole moments in the formulas of Lorentz's dispersion theory. Thus the interaction between radiation and the orbiting electron was described in completely classical terms. The resulting dispersion formula contained the frequency of revolution in the unperturbed orbit as a free parameter, and the whole exercise consisted in determining this frequency from the best dispersion measurements and comparing it with that determined by Bohr's quantisation of angular momentum in the ground state of the molecule. In other words, they accepted Bohr's quantum condition for the ground state, but rejected his quantum postulate for the emission and absorption of radiation in favour of a classical treatment of the interaction between light and the orbiting electron. Not surprisingly, this hybrid theory found little favour in Copenhagen and was criticised in public by C. W. Oseen, nevertheless it lived on in the literature till about 1919.[49] My point in bringing it up here is to suggest that Richardson's conception of Bohr's theory had some similarity to Debye's and Sommerfeld's and so was not untypical. He too, had no difficulty in accepting Bohr's quantum postulate for the stationary states, in fact he saw it as "closely connected with the quantum hypothesis of Planck", probably because like Planck's hypothesis it allowed one to think of the quantum exclusively as reflecting a property of the structure of atoms. Bohr's frequency postulate, on the other hand, he just repeated without comment, hence one can only guess as to how he conceived of it; my conjecture is that he regarded it as just a version of the triggering hypothesis. What is certain is that he gave no indication that he saw a fundamental conflict between this postulate and the many applications of Lorentz's electrodynamics in the electron theory of matter.

What was the status of the electron theory of matter twenty years after the discovery of the electron? In Richardson's opinion quite good. In fact, from a modern perspective, informed by the extensive historical literature on the quantum revolution with its emphasis on the failure of classical physics in accounting for the structure of matter and radiation, the tone of Richardson's book may seem surprisingly optimistic. He reported judiciously on difficulties as well as on successes, but usually as problems not yet solved rather than as insuperable obstacles. Typical of the general attitude of the book is a passage in the preface to the first edition in which he remarked that recent developments

> ... lead one to think that the difficulties which beset the electron theory of metallic conduction in its usual form may be overcome by the application of the ideas underlying Planck's theory of radiation. In any event the theories of Chapters XVII and XVIII should be valid at sufficiently high temperatures when the results of the quantum theory coalesce with those of the continuous theory. Many other branches of the subject are in a similar, though possibly less aggravated, situation; amongst these the questions of atomic structure, spectroscopic

> emission, X-rays and the magnetic properties of bodies are conspicuous examples. At the present time this field is unquestionably a very fruitful one both for the experimental and the theoretical physicist. (*ETM*[2], p. vi)

The message to Richardson's students would clearly have been that although many problems still remained to be solved, the numerous successes of the electron theory showed that electron physics was on the right track. In the same vein, after having laid out the theoretical difficulties involved in accounting for the details of the Hall effect and the change of resistance in a magnetic field, Richardson remarked:

> These effects are unquestionably very complicated, and so far the electron theory has not been able to furnish an adequate quantitative explanation of them. On the other hand it is the only theory which has been able to account for them qualitatively. (*ETM*[2], p. 409)

These passages give in a nutshell Richardson's general verdict on the achievements of the classical electron theory of matter up to 1916: it had been extremely successful and it still offered many possibilities for further exploration. The quantum theory did not pose a threat to the theory, on the contrary it formed one of the most promising of these possibilities.

NOTES

1. The best overall treatment is J. L. Heilbron: *A History of the Problem of Atomic Structure from the Discovery of the Electron to the Beginning of Quantum Mechanics*, Ph. D. dissertation, University of California, Berkeley, 1964, University Microfilms, Inc., Ann Arbor, Michigan.

2. For Thomson's views on physics education, and his role in the reform at Cambridge, see David B. Wilson: "Experimentalists among the mathematicians: Physics in the Cambridge Natural Sciences Tripos, 1851-1900", *Historical Studies in the Physical Sciences, 12* (1982) 325-371. Cf. also Andrew Warwick: "Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell and Einstein's Relativity 1905-1911, Part II: Comparing Traditions in Cambridge Physics" *Studies in the History and Philosophy of Science 24* (1993) 1-25, pp. 2-3.

3. E. W. Foster: "Richardson, Sir Owen Willans", *The Compact Edition of the Dictionary of National Biography*, vol. II, Oxford University Press 1975, p. 2856; W. Wilson: "Owen Willans Richardson 1879-1959", *Biographical Memoirs of Fellows of the Royal Society, 5* (1960) 206-215; Loyd S. Swenson, Jr.: "Richardson, Owen Willans", in: C. C. Gillispie, ed.: *Dictionary of Scientific Biography*, vol. XI, Charles Scribner's Sons 1975, pp. 419-423.

4. Isobel Falconer: "J. J. Thomson and 'Cavendish Physics', in Frank A. J. L. James, ed.: *The Development of the Laboratory: Esssays on the Place of Experiment in Industrial Civilisation,* Macmillan Press 1989, pp. 104-117.

5. This conception was put forward in J. J. Thomson: "Indications relatives à la constitution de la matière fournis par les recherches récentes sur le passage de l'électricité a travers les gaz", in: Ch.-Éd. Guillaume & L. Poincaré, eds.: *Rapports présentés au congrès international de physique réuni à Paris en 1900,* Paris (Gauthier-Villars) 1900, vol. III, pp. 138-151. This report was undoubtedly Richardson's first introduction to the electron gas concept or, in Thomson's phrase, "the corpuscular state of matter".

6. O. W. Richardson: "On an Attempt to Detect Radiation from the Surface of Wires Carrying Alternating Currents of High Frequency", *Proceedings of the Cambridge Philosophical Society 11* (1902) 168-178.

7. For a brief survey of these early experiments on thermal emission of electricity, see O. W. Richardson: *The Emission of Electricity from Hot Bodies* (1916), 2. ed., London (Longmans, Green and Co.) 1921, pp. 2-4.

8. O. W. Richardson: "On the Negative Radiation from Hot Platinum", *Proceedings of the Cambridge Philosophical Society 11* (1902) 286-295.

9. I have changed Richardson's notation a little. Like Jeans, he had the confusing (to a modern reader) habit of denoting Boltzmann's constant by R and calling it 'the gas constant for a single corpuscle (or molecule)'. Cf. J. H. Jeans: *The Dynamical Theory of Gases*, Cambridge (At the University Press), 1904.

10. J. Patterson: "On the Change of the Electrical Resistance of Metals when Placed in a Magnetic Field", *Philosophical Magazine 3* (1902) 643-656; Thomson, *op. cit.* n. 5, § 4.

11. O. W. Richardson: "The Electrical Conducticity Imparted to a Vacuum by Hot Conductors", *Philosophical Transactions of the Royal Society 202A*, (1903) 497-549. On p. 498 he now referred to Drude's papers as well as Thomson's Paris report for "the hypothesis of the conduction in metals by corpuscles" and on p. 499 to Drude's application of the kinetic theory of gases to the free electrons in a metal.

12. For the importance of the electron vapour concept see W. Kaiser: "Early theories of the electron gas, *Historical Studies in the Physical and Biological Sciences 17* (1987) 271-297, on pp. 280-282.

13. O. W. Richardson: "Thermionics", *Philosophical Magazine 17* (1909) 813-833.

14. O. W. Richardson, *op. cit.* n. 7; for a list of 16 contributors to the field, see pp. 60-61.

15. Cf. Leonard S. Reich: "Irving Langmuir and the Pursuit of Science and Technology in the Corporate Environment", *Technology and Culture 24* (1983) 199-221, on p. 211; and Hugh G. J. Aitken: *The Continuous Wave: Technology and American Radio, 1900-1932*, Princeton University Press 1985, p. 231.

16. See *e. g.* Lorentz's 1924 Solvay Report, H. A. Lorentz: "Application de la théorie des électrons aux propriétés des métaux", in H. A. Lorentz: *Collected Papers*, vol. 8, The Hague (Martinus Nijhoff) 1935, pp. 263-306, on pp. 283-294; and R. Seeliger: "Elektronentheorie der Metalle" (1921), in: A. Sommerfeld, ed.: *Enzyklopädie der mathematischen Wissenschaften mit Einschluss ihrer Anwendungen* vol. 5 part 2, Leipzig (B. G. Teubner) 1904-1922, pp. 778-878, on pp. 835-851.

17. These points were all touched upon in Richardson's Nobel Lecture. See O. W. Richardson: "Thermionic phenomena and the laws which govern them" (1928), in: *Nobel Lectures. Physics 1922-1941*, Amsterdam (Elsevier) 1965, pp. 224-236

18. O. W. Richardson and F. C. Brown: "The Kinetic Energy of the Negative Electrons emitted by Hot Bodies", *Philosophical Magazine 16* (1908) 353-376; see particularly the discussion on pp. 374-376.

19. Cf. Kaiser, *op. cit.* n. 11, pp. 285-292.

20. O. W. Richardson: "The Electron Theory of Contact Electromotive Force and Thermo-electricity", *Philosophical Magazine 23* (1912) 263-278; and *id*.: "Some Applications of the Electron Theory of Matter", *ibid.*, 594-627.

21. H. A. Wilson: "On the Discharge of Electricity from Hot Platinum", *Philosophical Transactions of the Royal Society 202 A*, (1904) 243-275; see pp.273-275 for his criticism of Richardson's views.

22. O. W. Richardson: "The Emission of Electrons from Tungsten at High Temperatures: an Experimental Proof that the Electric Current in Metals is carried by Electrons", *Philosophical Magazine 26* (1913) 345-350.

23. O. W. Richardson, *op. cit.* n. 11, p. 535.

24. O. W. Richardson, *op. cit.* n. 20 ("Some Applications..."), pp. 615-627; *id.*: "The Theory of Photoelectric Action", *Philosophical Magazine 24* (1912) 570-574; *id.*: "The Laws of Photoelectric Action and the Unitary Theory of Light (Lichtquanten Theorie)", *Science 36* (1912) 57-58.

25. O. W. Richardson and Karl T. Compton: "The Photoelectric Effect", *Philosophical Magazine 24* (1912) 575-594; Karl T. Compton and O. W. Richardson: "The Photoelectric Effect.-II." *Philosophical Magazine 26* (1913) 549-565.

26. O. W. Richardson: "The Complete Photoelectric Emission", *Pilosophical Magazine 31* (1916) 149-155.

27. Compton and Richardson, *op. cit.* n. 25, pp. 557-558.

28. O. W. Richardson: "The Specific Charge of the Ions emitted by Hot Bodies", *Philosophical Magazine 16* (1908) 740-767. The apparatus is described on pp. 743-750.

29. O. W. Richardson: "The Construction of Simple Electroscopes for Experiments on Radioactivity", *Nature 71* (1905) 274-276.

30. Anonymous: "Escape of Electrons from Hot Bodies", *Nature 98* (1916), 146.

31. O. W. Richardson: *The Electron Theory of Matter*, Cambridge (At the University Press) 1914; Second Edition 1916. In the following these two editions will be denoted ETM^1 and ETM^2.

32. N. B.: "Modern Electrical Theory", *Nature 95* (1915), 420-421. Although the initials do not identify the author with complete certainty there can be little doubt that the review was written by Niels Bohr. On the exchanges and correspondence between Bohr and Richardson on the electron theory, see Niels Bohr: *Collected Works*, vol. 1, Amsterdam (North-Holland Publishing Company) 1972, pp. 111-117 and 482-491.

33. "News and Views", *Nature 124* (1929), 814.

34. H. A. Lorentz: *The Theory of Electrons*, 1st ed. 1909; Reprint of 2d ed. (1915), New York (Dover Publications) 1952; Niels Bohr: *Studier over Metallernes Elektrontheori: Afhandling for den filosofiske Doktorgrad*, København (V. Thaning & Appel) 1911; English Translation in Bohr, *op. cit.* n. 32, pp. 291-395.

35. This section was modelled on the treatments by Larmor and Jeans, cf. Joseph Larmor: *Aether and Matter*, Cambridge (At the University Press) 1900, ch. VI; and J. H. Jeans: *The Mathematical Theory of Electricity and Magnetism*, Cambridge (At the University Press) 1908, ch XVI.

36. A. Einstein: "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen", *Jahrbuch der Radioaktivität und Elektronik 4* (1907) 411-462, reprinted in: *The Collected Papers of Albert Einstein*, vol. 2, ed. by John Stachel, Princeton University Press 1989, pp. 433-484; cf. p. 272 for Einstein's pedagogical efforts.

37. Jeans, *op. cit.* n. 9.

38. Richardson had developed this theory of conductivity in his 1912 paper, *op. cit.* n. 20 ("Some Applications..."), pp. 594- 601, and had noted that Niels Bohr had obtained identical formulae in his dissertation, cf. Bohr, *op. cit.* n. 32, pp. 46-63; English translation, pp. 335-345.

39. J. J. Thomson: "On the Theory of Radiation", *Philosophical Magazine 20* (1910) 238-247. For Thomson's discussion of the photoelectric effect and his attempt to avoid "the unitary theory of light", see pp. 243-246.

40. J. J. Thomson: "Conduction of Electricity through Metals", *Phil. Mag. 30* (1915) 192-202. In Thomson's model atomic dipoles will, below a certain critical temperature, show complete alignment in an external electric field combined with the internal field from the dipoles themselves; this alignment will be maintained by the internal field even after the external field has vanished, just like the alignment of magnetic dipoles in the case of permanent magnetization. In the internal field from the dipoles, loosely bound electrons will then be able to pass "along the chain of atoms like a company in single file passing over a series of stepping stones" (*op. cit.*, p. 195), thus producing an electric current even in the absence of an external electromotive force.

41. O. W. Richardson and Karl T. Compton: "The Photoelectric Effect", *Science 35* (1912) 783-784.

42. *Cf.* p. xxx above.

43. Bruce R. Wheaton: *The tiger and the shark: Empirical roots of wave-particle dualism*, Cambridge University Press 1983, pp. 178-180.

44. *Ibid*. ch. 8. Richardson's theory of the photoeffect and his attitude towards Einstein's lightquantum are discussed on pp. 236-238 and p. 260 where his attitude is characterised as typical for experimentalists at the time.

45. For a description of these experiments, see *ibid*., pp. 97-98 (Bragg) and p. 235 (Stuhlmann and Kleeman).

46. The preface is dated 11 January, 1916, so work on the book must presumably have been finished by the end of 1915.

47. Andrew Warwick: "Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell and Einstein's Relativity 1905-1911. Part I: The Uses of Theory", *Studies in the History and Philosophy of Science 23* (1992) 625-656, p. 633.

48. Heilbron, *op. cit.* n. 1, p. 296.

49. The Debye-Sommerfeld theory is discussed in detail in an unpublished M. Sc. dissertation, Kirsten Kragbak: *Udviklingen af teorien for optisk dispersion i den gamle kvantemekanik, med særligt henblik på perioden 1913-21*, University of Aarhus, History of Science Department, 1989, pp. 28-73. For the reactions of Bohr and Oseen, see Ulrich Hoyer's introduction in Niels Bohr: *Collected Works*, vol. 2, Amsterdam (North-Holland Publishing Company) 1981, pp. 336-341.