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Before Bohr: Theories of atomic structure 1850-1913

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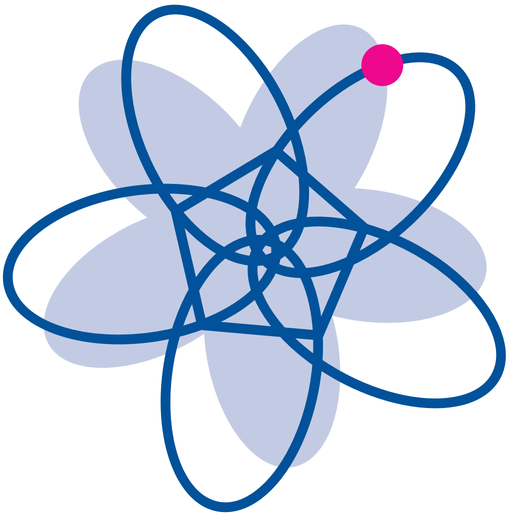

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Before Bohr: Theories of atomic structure 1850-1913

HELGE KRAGH[*]

Content

The first really successful theory of atomic structure was proposed by Niels Bohr in his epoch-making paper in *Philosophical Magazine* of July 1913. It was this theory that established atomic theory as a fundamental and progressive field of physics intimately connected with the new and still mysterious quantum theory. But although rational atomic theory, in the sense of a scientific theory dealing with the internal structure of the atom, dates from the beginning of the twentieth century, ideas of complex atoms and their structure can be found much earlier. This essay offers a review of pre-1913 atomic theories, starting in the mid-nineteenth century. Many of the theories of this early period were speculative

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suggestions with little or no foundation in experiment. Some of them were of a philosophical rather than scientific nature. They were all short-lived, but of course some lived longer and were more developed than others. The vortex theory and J. J. Thomson's electron theory were among the more successful of the pre-Bohr atomic theories. What matters is that the Bohr atom, revolutionary as indeed it was, was part of a long tradition in atom-building and to some extent influenced by earlier conceptions of atomic architecture.

It is important to realize that until about World War I atomic theory was not only a small field of physics, it was also not highly regarded. At the first (and only) International Congress of Physics held in Paris in 1900, only one of the 92 invited papers, namely the on of J. J. Thomson, dealt explicitly with atomic structure. The proposed models were rarely meant to be realistic pictures of the atom, but merely illustrations of mechanisms that might help understanding some aspect or other of atomic phenomena. Referring to the period about 1910, it has been said that "for the average physicist of the time, speculations about atomic structure were something like speculations about life on Mars – very interesting for those who liked this kind of thing, but without much hope of support from convincing scientific evidence and without much bearing on scientific thought and development."[1]

1. Pre-electron atomic speculations

The Daltonian atom of the early nineteenth century was a primitive body with no internal constitution, the atoms of the different elements having nothing substantial in common. Although this was the kind of atom that appealed to most chemists, from an early date there were suggestions that the atoms

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[1] Andrade 1958, p. 442.

themselves were somehow complex bodies. The English physician and chemist William Prout argued in 1815-1816 that the atomic weights indicated a common composition of the elements, namely that all the atoms were made up of hydrogen atoms. Prout's hypothesis was taken up and modified in various ways by several chemists, first and most effectively by the Scotsman Thomas Thomson who promoted it in a work of 1825 ambitiously entitled *An Attempt to Establish the First Principles of Chemistry by Experiments*. However, the hypothesis remained controversial throughout the century and was rejected by leading chemists from Berzelius to Mendeleev.[2] Not only was it speculative, increasingly accurate determinations of the atomic weights contradicted the original form of the hypothesis. Thus, the atomic weight of chlorine turned out to be close to 35.5, a value which evidently posed problems for Prout's hypothesis.

All the same, the general idea of a material unity in nature – that all matter ultimately consists of structures made up of a primitive particle or *protyle* – remained popular. The introduction of spectroscopy and the periodic system of the elements inspired further interest in neo-Proutean hypotheses, more often than not seen in connection with the evolutionary world view so popular during the Victorian era.

In some cases atomic speculations related to the Proutean tradition had a distinct air of Pythagoreanism, as in the works of the Danish-American chemist and polymath Gustavus Hinrichs, one of several precursors of the periodic system. Hinrichs, who combined his atomic theory with numerological considerations of spectroscopic and astronomical data, was convinced that all chemical elements were composed by a single substance.[3] For this basic element

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[2] On Prout's hypothesis and its role in nineteenth-century conceptions of atoms and elements, see Brock 1985, Kragh 1982 and Farrar 1965.

[3] Hinrich's ideas are described in Zapffe 1969 and van Spronsen 1969.

he proposed the name *pantogen*. While Hinrich's works were not well known, and "pantogen" never caught on, somewhat similar ideas were suggested by leading scientists in England in particular. The astronomer Joseph Norman Lockyer and the chemists William Crookes and Thomas Carnelley were among the most articulate and visionary advocates of evolutionary neo-Prouteanism. However, although this tradition in speculative atomic theory significantly influenced the first electron models of the atom, it did not include definite models of the composition of atoms. Moreover, neo-Prouteanism and related ideas were mainly of interest to chemists, astronomers and amateur scientists, whereas most physicists chose to ignore them. For this reason they need not be further examined.

Models of the internal architecture of atoms were proposed many years before the discovery of the electron. Some of them were based on hypothetical electrical particles, while other models assumed neutral but equally hypothetical subatomic constituents. These early atomic models had in common that they were speculative, and some of them very much so, and also that they made very little impact on mainstream science. In some cases they were merely casual speculations of a philosophical nature, such as was the case with the Danish physicist and engineer Ludvig August Colding, better known for his contributions to what became known as the law of energy conservation. In an unpublished note of 1854, he pictured atoms, or what he called ″molecules,″ as analogous to planetary systems. ″Many facts seem to me to indicate that every molecule constitutes an infinitely small planetary system, be it with or without a central body,″ he wrote. ″Each of these small planets has a characteristic rotation about its axis, and this rotation determines both the electric tension and magnetic polarity of the particle."[4]

By the mid-nineteenth century the ether was generally assumed to play an important role in microphysics, whether based on atoms or not. While the ether was usually considered a homogeneous imponderable medium, there was no scarcity of ideas assuming a corspuscular ether. To get an impression of mechanical ether atoms in the speculative tradition, consider the ideas of two scientists from German-speaking Europe. Ferdinand Redtenbacher, an Austrian-born director of the Polytechnic College in Karlsruhe, announced in 1857 an atomic theory based on what he called "dynamids."[5] According to his model, matter consisted of ponderable atomic particles surrounded by shells of imponderable ether. The material particles were kept together by a hypothetical mechanical force analogous to Newtonian gravitation, while the ether particles were assumed to be mutually repulsive and attracted by the massive atomic core. It was such a system of a massive core and minute ether particles, arranged in shells, that he called a dynamid. Redtenbacher related his dynamid theory to contemporary ideas of heat, gases, elasticity and optics, and discussed on its basis various expressions for the dispersion of light.

About thirty years later the respected Swiss botanist Carl Wilhelm von Nägeli proposed a detailed atomic theory that had some qualitative features in common with the older one of Redtenbacher, in particular that it was based on a corpuscular ether governed by mechanical forces of both a repulsive and

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[4] Note of 2 March 1854, reproduced in Dahl 1972, p. 177. The term "molecule" should not be understood in its modern, chemical sense. Throughout the nineteenth century the term, especially as used by physicists, often meant just a very small unit particle, what others would call an atom.

[5] Redtenbacher 1857. See also Rosenberger 1965, vol. 3, pp. 554-555, a reprint of a work that was first published 1886-1890.

attractive nature.[6] Nägeli pictured the atom as a tightly packed system of billions of tiny ether particles (”amers”), some of which were ponderable and would therefore tend to agglomerate into an atomic core. The ponderable ether core was surrounded with an ether atmosphere of density decreasing with the distance, a *Schwerätherhülle*. According to Nägeli, his etherial atomic model offered an explanation of several chemical problems, including the nature of affinity and the combination of atoms into molecules. He further thought that it was suggestive with regard to physiology and biology in general.

From about 1850 views of ether and matter became increasingly based on electrical rather than mechanical theory. One of the first suggestions of electrical atoms was made by Richard Laming, an English physician and amateur physicist, who in works between 1828 and 1851 postulated the existence of subatomic, unit-charged particles. According to Laming, the atom was composed of a material core surrounded by an “electrosphere” of concentric shells of electrical particles of both charges.[7] This kind of corpuscular electrical theory was unusual in England but popular among German physicists in favour of electrical actions propagating instantaneously over a distance. In 1846 a fundamental force law of this kind was proposed by Wilhelm Weber, who at the time served as professor of physics in Leipzig. Weber conceived his force law as the core of a unified theory of the future that might possibly lead to an explanation of all of nature. By the 1860s he had developed an electrical theory according to which the neutral ether consisted of positive and negative particles orbiting around

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[6] Nägeli 1884, pp. 681-820. See also Kragh 1989a. Rosenberger 1965 includes accounts of the atomic theories of Fechner, Weber, Grassmann, Nägeli and other scientists.

[7] Laming 1845. For background on Laming and his ideas, see Farrar 1969.

each other. Moreover, he extended his picture of the ether to an analogous picture of the chemical atoms.[8]

In his later works, some of them unpublished and of a fragmentary nature only, Weber considered the ponderable atom to be structured like a planetary system, with a large number of tiny electrically charged particles revolving around a heavy massive part. The system was kept together by electrical forces satisfying his force law. In a paper of 1871 he explained:

> Let *e* be the positively charged electrical particle, and let the negative particle, carrying an opposite charge of equal amount, be denoted –*e*. Let only the latter be associated with the massive atom, whose mass is so large that the mass of the positive particle may be considered negligible. The particle –*e* may then be considered as being at rest, while just the particle *e* moves around the particle –*e*.[9]

Weber came to the conclusion that the chemical elements were composed of an equal amount of positive and negative particles revolving around each other and possibly also performing vibrations. In this way he thought that the mass might be explained in terms of electricity and that an understanding of the periodic system was within reach. Moreover, he speculated that the chemical elements, if they were composites of electrical particles, might possibly be decomposed into lighter elements. The dream of the alchemists received justification from electrodynamics! According to Maxwell's electromagnetic field theory a circulating electrical particle would lose energy and hence cause the atom to

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[8] Descriptions of Weber's electro-atomic research programme and its connection to the works of other German physicists can be found in Wise 1981 and Schönbeck 1982.

[9] Weber 1871, p. 44, as quoted in Mehra and Rechenberg 1982, p. 169.

become unstable, but this problem (which later appeared prominently in atomic theory) did not appear in Weber's alternative theory.

Independent of Weber, Robert Grassmann, a brother and collaborator of the mathematician Hermann Grassmann, developed somewhat similar ideas of ether atoms consisting of electrical doublets. He considered chemical atoms to be composed of a positive particle surrounded by a spherical shell of polarized ether doublets. Although Robert Grassmann's ideas received little attention, they were critically reviewed by the physicist and pioneering psychologist Gustav Fechner, a close friend of Weber and himself an advocate of atomism.[10] Fechner had for long been interested in atomic theory, both in its scientific and philosophical aspects. As early as 1828 he suggested a dynamical model of the atom in close analogy to the solar system and governed by Newton's law of gravitation. The atoms, he said in this early work, "simulate in small dimensions the situations of the astronomical objects in large dimensions, being animated in any case by the same forces."[11]

The theories of Weber, Grassmann and other German scientists were based on hypothetical electrical particles. When the electron was turned into a real particle at the end of the century, physicists were generally puzzled that it existed in a negative form only. The neutrality of the ether seemed to require complete charge symmetry and yet the positive electron was conspiciously missing. Apparently without knowing of the earlier works of Weber and Grassmann, the British-Australian physicist William Sutherland suggested in 1899 that the ether consisted of doublets of negative and positive doublets, for which particles he coined the name "neutron." As he wrote in a paper two years

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[10] Fechner 1864. Grassmann 1862. On the electro-atomic ideas of the Grassmann brothers, see Kuntze 1909.

[11] Fechner 1828, p. 275, as quoted in Mehra and Rechenberg 1982, p. 169.

later, “In the free æther the positive and negative electron revolving … round their centre of inertia form what I have proposed to call the neutron, the electric doublet, which gives the æther its chief electric and magnetic properties.”[12] By that time atomic models were no longer based on purely hypothetical entities. It was now generally agreed that atoms contained a large number of electrons, all of them carrying the same negative charge, but there was no agreement as to the number or arrangement of them.

2. From vortex atom to electron atom

The atomic model developed by the famous Cavendish physicist Joseph John Thomson in the early years of the twentieth century can with some justification be called the first modern model of the atom. Contrary to earlier models it was based on an experimentally known entity, the electron, and for this and other reasons it could be subjected to experimental tests. While Thomson’s electron dates from his famous investigation of cathode rays in 1897, his electron atom did not simply grow out of these experiments. There were other and even more important roots, for Thomson had for several years been convinced that the atom is a complex body made up of a primordial particle or substance. He was in important respects a loyal follower of Prout. Moreover, as a theoretical entity the electron antedates the 1897 experiments, which explains why we can find ideas of electrons and electron atoms (as well as the name “electron”) in the literature even before that year.

The leading electron theorist Joseph Larmor argued in 1894 that electrons – which he pictured as “singular points in the ether” – were the primordial units

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[12] Sutherland 1899. Sutherland 1901, p. 272. The physical chemist Walther Nernst reinvented the ether-neutron or possibly took it over from Sutherland (Nernst 1907, p. 392). On the problem of the positive electron until the discovery of the positron, see Kragh 1989b.

of all matter. The following year he went a step further, now suggesting "a molecule [atom] to be made up of, or to involve, a steady configuration of revolving electrons."[13] His picture was not unlike the one that Weber had earlier proposed on a more speculative basis. Larmor did not make it clear whether or not he conceived the electron as a subatomic particle, and it is quite possible that at the time he did not. However, two years later he did.

Thomson's unitary idea of matter consisting of subatomic electrical charges was indebted to his general predisposition toward neo-Prouteanism and, in particular, to his earlier work on the vortex theory of atoms. According to this theory, first proposed by William Thomson (Lord Kelvin) in 1867, atoms might be conceived as vortical modes of motion in a perfect, all-pervading fluid.[14] The fluid was generally taken to be identical to the ether. For about two decades the ambitious and mathematically complex vortex theory attracted much interest among mathematically inclined British physicists, including Peter G. Tait, Augustus Love, William Hicks, Micaih Hill and J. J. Thomson. It was applied to a variety of physical and chemical problems, such as line spectra, affinity, chemical combination, the behaviour of gases and even gravitation. Although not convinced of its truth, Maxwell was full of praise of the vortex theory because of its methodological virtues and ontological parsimony. In a deservedly famous article on "Atom" for the 1875 edition of *Encyclopaedia Britannica*, he singled ut Kelvin's vortex model as far the most attractive picture of atomic constitution.[15]

Among those who found the vortex atom attractive was also the mathematician and stastitician Karl Pearson, who however preferred an

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[13] Larmor 1895, p. 741. Parts of this section and of Section 3 rely on material in Kragh 1997 and Kragh 2003.

[14] A full historical account of the vortex atom theory can be found in Kragh 2002, which includes references to the literature.

[15] Maxwell 1965, Part II, pp. 444-484.

alternative version of the ultimate atom. In 1885 he proposed than an atom might be a differentiated spherical part of the ether, or perhaps a vacuum within the ether, pulsating with a natural frequency.[16] He found the conception of spherical atoms to be promising with respect to the understanding of a wide range of phenomena, including chemical affinity and spectral lines. Six years later he modified it into a theory of "ether squirts," point atoms from which ether continuously flowed into space.[17] In addition to the ether squirts, acting as points of positive matter, he postulated the existence of negative matter in the form of sinks that absorbed ether. Although Pearson developed his ambitious atomic ether theories in considerable mathematical detail, and attempted to link them to experimental knowledge, compared to the vortex atom they attracted very little interest.

In 1882 young J. J. Thomson examined theoretically the question of stability of vortices arranged at equal intervals round the circumference of a circle. Using standard perturbation theory he found after lengthy calculations that the configurations with n = 2, 3, 4, 5 and 6 vortices would be dynamically stable, but that seven vortices on the same ring could not form a stable system. For larger n he relied on an analogy with experiments with floating magnetized needles that the American physicist Alfred Mayer had made in 1878 and which could be taken to illustrate the periodic system of the elements (such that Kelvin had first pointed out). Although Thomson, like most other physicists, abandoned the vortex atom programme about 1890, the idea continued to guide him and appeal to him. Thus, in a work of 1890 he linked the periodic system with the vortex atomic model and pointed out the suggestive similarity between an arrangement of vortices and the regularity found among the chemical elements.

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[16] Pearson 1885. See also Porter 2004, pp. 179-192.

[17] Pearson 1891.

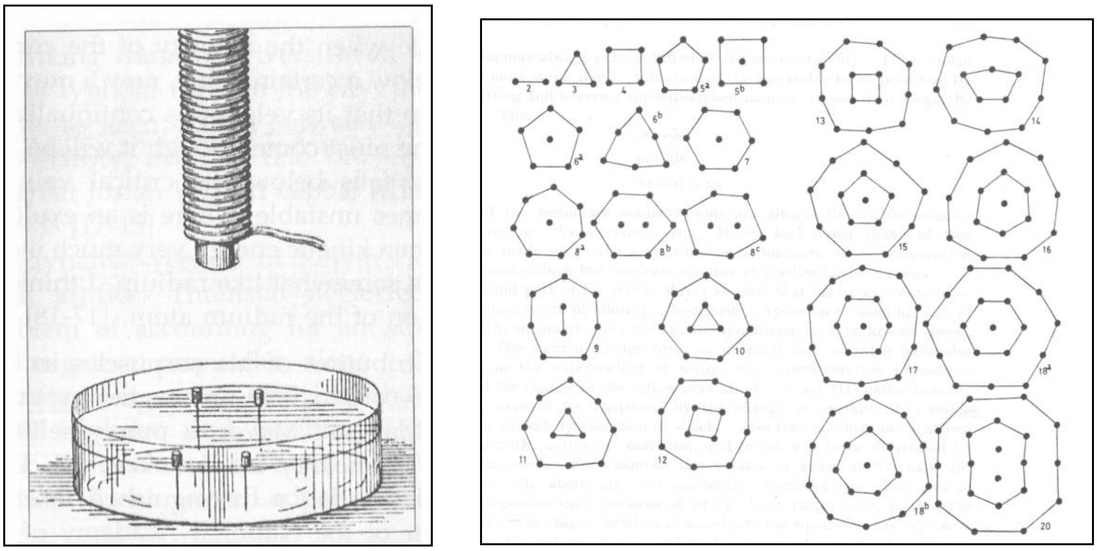

Fig. 1. Mayer's experiments with magnetized needles. To the right, some of his magnet configurations. Some of the configurations are unstable. For example, 5 needles may arrange themselves in a square with a central needle; but a slight mechanical disturbance will make the system turn into the stable pentagon configuration.

The vortex atom approach greatly influenced Thomson's thinking about the complexity of elements. In 1897 he no longer thought of the vortex atom as a realistic model, yet his new primordial particle, the electron, had more than a little similarity with the vortices of the old theory. In his seminal paper of October 1897, Thomson suggested that that the atom consists of a large number of electrons (which he insisted to call "corpuscles"), possibly held together by a central force. In this first version of the Thomson model, the atom was pictured as just an aggregation of electrons, and so, assuming Coulomb forces between the electrons, there was no attractive force to keep the atom from exploding. "If we regard the chemical atom as an aggregation of a number of primordial atoms [electrons]," he wrote, "the problem of finding the configurations of stable equilibrium for a number of equal particles acting on each other according to some law of force … is of great interest in connection with the relation between the properties of an element and its atomic weight."[18]

In 1897 Thomson only knew the *e*/*m* ratio of the cathode ray electrons and therefore had to assume that the particles were subatomic. Two years later the assumption was confirmed when he and his research students at the Cavendish Laboratory succeeded in determining the charge of the electron, which led to a mass of the electron of the order of one-thousandth of a hydrogen atom. The same year, in an address to the British Association for the Advancement of Science, Thomson expounded his atomic model in a fuller and more confident way. What became sometimes known as the "plum pudding" model, he explained as follows:

> I regard the atom as containing a large number of smaller bodies which I shall call corpuscles; these corpuscles are equal to each other; the mass of a corpuscle is the mass of the negative ion in a gas at low pressure, i.e. about 3×10^{-26} of a gramme. In the normal atom, this assemblage of corpuscles forms a system which is electrically neutral. … [T]he negative effect is balanced by something which causes the space through which the corpuscles are spread to act as if it had a charge of positive electricity equal in amount to the sum of the negative charges on the corpuscles.[19]

It was this picture that Thomson developed into a quantitative and sophisticated atomic model over the next few years (Section 4). In his book *Electricity and Matter*, based on the Silliman Lectures he gave at Yale University in May 1903, he provided a full if mostly qualitative account of the theory.

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[18] Thomson 1897, p. 313.

[19] Thomson 1899, p. 565.

Thomson's model was the most important of the electron atomic models of the early twentieth century, but it was not the only one. Shortly after Thomson's announcement of the cathode-ray electron in the spring of 1897, Kelvin suggested his "Aepinus atom," so named after Franz Aepinus, a German eighteenth-century natural philosopher who had pioneered a one-fluid electrical theory. Kelvin pictured the atom as a number of "electrions" embedded in a globe of positive electricity, a picture which had much in common with Thomson's but nonetheless differed from it. For example, Kelvin's hypothetical electrions did not have the same mass and charge as the electrons, and they were thought to be subject to an *ad hoc* force law more complicated than the ordinary Coulomb force. In works between 1902 and 1907 Kelvin applied the Aepinus model in an attempt to explain or illustrate the puzzling phenomenon of radioactivity, which according to Kelvin was probably triggered by etherial waves or some other external agency.[20] Very few physicists found the Aepinus model to be of any value. In spite of being the most elaborate attempt of the period to explain radioactivity in intra-atomic terms, the ideas of the aging Kelvin had almost no impact on the further development of atomic theory.

In his book *Electrons* of 1906, Oliver Lodge surveyed the various candidates of atomic structure at the time. Apart from ideas of the Thomson-Kelvin type he mentioned the possibility that the atom "consists of a kind of interlocked admixture of positive and negative electricity, indivisible and inseparable into units."[21] This may have been a reference to the picture of the atom favoured by Philipp Lenard, at the time professor of physics at the University of Kiel and the recipient of the 1905 Nobel Prize for his work on cathode rays. Based on his studies of the absorption of cathode rays in gases,

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[20] E.g., Thomson, William 1904.

[21] Lodge 1906, p. 149.

Lenard suggested in 1903 that the interior of the atom was mostly empty space.[22] To explain the experimental results he assumed the atom to be composed of impenetrable "dynamids," a kind of tightly bound neutral doublet consisting of a negative and positive electron. As mentioned, the idea of intra-atomic dynamids, or at least the name, had been introduced by Redtenbacher half a century earlier, but Lenard did not refer to his predecessor. The constituing dynamids were much smaller than the atom. He estimated the radius of a dynamid to be at most 3×10^{-12} cm, implying that the atom was nearly empty: "The space occupied by a cubic metre of solid platinum is empty, in the same sense that celestial space traversed by light is empty, except for the proper volume of the dynamids, which cannot in all exceed a cubic millimetre."[23] In this respect, if in no other, he anticipated the later Bohr-Rutherford atom.

Lenard found that the number of dynamids in an atom was proportional to the atomic weight, but did not offer a value for the factor of proportionality. Moreover, he assumed the dynamids to be in rapid rotation, which he thought might cast light on the nature of radioactivity. Although he was unconcerned with spectroscopic evidence, he outlined a mechanism according to which the atom would emit characteristic spectral lines when free electrons returned to equilibrium in the dynamic atomic structure. Lenard's atomic hypothesis of 1903 was qualitative and rather vague. Not only did it not address spectroscopic issues, it also did not connect with issues of chemistry. For example, he did not give the number of dynamid units in either hydrogen or other elements. For these and other reasons Lenard's work exerted little influence on the further development of atomic structure and almost none on the British atom builders.

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[22] Lenard 1903. For background on Lenard's atomic hypothesis, which was closely connected to his work on cathode rays and the photoelectric effect, see Wheaton 1978.

[23] Lenard 1903, p. 739.

His model of the atom was no more successful than Kelvin's Aepinus atom in attracting interest from other physicists.

Yet another conception of the atom, for a brief while popular among some physicists, was to assume the positive electricity to be located in the hypothetical positive electrons that could still be considered plausible if undetected particles in the early years of the new century. Primarily with the aim of explaining the mechanism of line spectra, in 1901 James Jeans proposed that the atom consisted of a large number of positive and negative electrons, supposed to differ only by the sign of their charge.[24] Jeans speculated that the electrons formed shells of alternating charges in the atoms, with the outermost layer consisting purely of negative electrons. To secure dynamical equilibrium he furthermore suggested that Coulomb's law would break down at very small distances.

An atomic model similar to the one of Jeans was argued by Lodge, who thought that "The whole of the atom may be built up of positive and negative electrons interleaved together, and nothing else."[25] Electrons in a state of violent motion would imply a loss of radiation energy, causing the atom to decay in a kind of atomic earthquake. To Lodge's mind this did not speak to the disadvantage of the model, for in that way he could offer a qualitative explanation of radioactivity. Of course, on this picture one would expect all elements to be radioactive, but this was just what many physicists believed at the time. In the first decade of the twentieth century it was often assumed that radioactivity was a common property of atoms, only exhibited more strongly in the heavy elements. Models of the type suggested by Jeans and Lodge were short-lived. Their explanatory force was limited, they made use of *ad hoc* assumptions, and they presupposed the existence of positive electrons for which

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[24] Jeans 1901.

[25] Lodge 1903 and Lodge 1906, p. 148.

there was no experimental evidence (although there were a few claims of evidence[26]). Compared to Thomson's model, they had little to offer.

Atomic models such as those mentioned, and most of those to be mentioned, were very much a British speciality. According to the Victorian tradition, models served heuristic purposes rather than represent some reality of nature. They were first of all mental illustrations formulated mathematically and based on the established laws of mechanics and electrodynamics. A model should not be taken literally, but seen as a method or picture that offers some insight in the inner workings of nature. Speaking of the vortex model of atoms, Larmor said in an address of 1900 to the British Association:

> The value of such a picture may be held to lie, not in any supposition that this is the mechanism of the actual world laid bare, but in the vivid illustration it affords of the fundamental postulate of physical science, that mechanical phenomena are not parts of a scheme too involved for us to explore, but rather present themselves in definite and consistent correlations, which we are able to disentangle and apprehend with continually increasing precision.[27]

This was a philosophy that not only governed British physics in the era of the vortex model but also in the first two decades of the twentieth century.

The *Philosophical Magazine* emerged as the premier journal for atom-builders in the British tradition. Models of a similar kind were rare among French and German physicists who generally favoured a more phenomenalist

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[26] The French physicist Jean Becquerel claimed to have obtained experimental evidence for positive electrons, but his claim was generally disbelived (Kragh 1989b).

[27] Larmor 1900, p. 625.

approach and looked upon dynamical models with some distrust. They might share the Britons' enthusiasm over the new physics based on electrons and ether, but typically without engaging in model making of the elaborate kind favoured by British physicists. For example, the atomic models of Lenard and Stark completely lacked the mathematical framework that was such a characteristic feature of British models of the Kelvin-Thomson tradition.

In 1901 Walter Kaufmann, a physicist at the University of Bonn, gave an address to the association of German scientists and physicians (Versammlung deutscher Naturforscher und Ärtzte) in which he surveyed the state and promises of electron physics. Much in the spirit of Thomson and Lodge he concluded that "the electrons would be the long-sought-for 'primordial atoms' whose different groupings would form the chemical elements, and the old alchemists' dream of the transformation of the elements would be brought a good deal nearer realisation."[28] He added that a mathematical treatment of the stability of the intra-atomic electrons might even lead to an explanation of the periodic system. Yet Kaufmann refrained from advocating a particular model of the atom corresponding to an arrangement of the electrons and he did not engage in the mathematical work to find the electron configurations.

3. The rise and fall of the Thomson model

In works of 1903-1904 Thomson transformed his crude picture of the atom into a quantitative and sophisticated atomic model.[29] From a physical point of view, the model consisted of a sphere of atomic dimension and uniformly filled with a positive fluid; within the sphere a large number of point-like negative electrons

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[28] Kaufmann 1901, p. 15, translated in *The Electrician* **48** (1901), 95-97.

[29] Thomson 1904a and Thomson 1904b. For historical studies of the Thomson atom, see Heilbron 1977a and Kragh 1997a.

moved in rings around the centre. Contrary to the electrons, the positive sphere was hypothetical, assumed to be frictionless and without mass. Its only function was to provide an elastic force upon the electrons and thus keep the atom together. According to Thomson and most contemporary physicists, even the ligthest atoms were highly complicated structures, the simplest one (hydrogen) being a congery of about n = 1000 electrons.

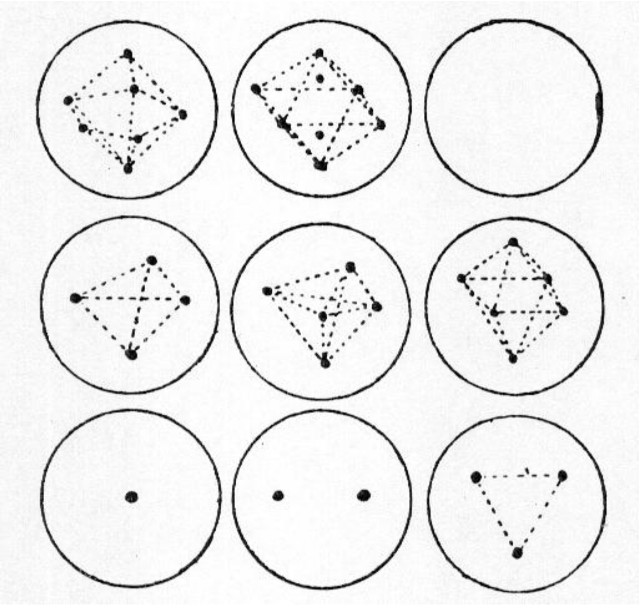

Fig. 2. Thomson atoms in 3 dimensions, as pictured by J. J. Thosmon in a lecture before the Royal Institution in 1905.

The models that Thomson examined mathematically were mostly planar, but this was merely a simplifying assumption. He was well aware that to obtain more realistic models he would have to consider three-dimensional structures, such as he did for a small number of electrons, n = 1 to n = 8. In any case, the function of his model was basically heuristic, to help physicists visualizing physical phenomena and thereby suggest new experimental and theoretical ideas. “My object,” he said, “has been to show that stable arrangements of corpuscles would have many properties in common with real atoms, and I have attempted to illustrate the properties by considering a special case chosen solely on the ground of simplicity.”[30]

It was an important feature of the 1904 model that the electrons were arranged on rings in circular motion. However, according to Maxwellian electrodynamics accelerating electrons will emit radiation energy and so, it would seem, the atom would eventually collapse. In the case of a single electron of charge e revolving with speed v on a circle of radius a, the average power radiated followed a formula derived by Larmor in his *Aether and Matter* of 1900. According to Larmor, the energy loss was given by

$$\frac{dE}{dt} = \frac{2}{3}\left(\frac{e^2 v^4}{ca^2}\right),$$

where c denotes the velocity of light. Fortunately, for more electrons the effect will not be additive. On the contrary, considering the case of n electrons on the same ring, Thomson proved that the radiation drain reduced drastically with n. For example, taking the radiation from a single electron as unity, he found that the radiation from a circle with six electrons moving with a speed of $v = 0.001c$ would be only 10^{-16}. For the general case of n equidistantly placed electrons on a single ring he derived the expression

$$\left(\frac{dE}{dt}\right)_n = \frac{2ce^2\beta^{2n+2}}{a^2}\frac{(n+1)n^{2n+3}}{(2n+1)!}$$

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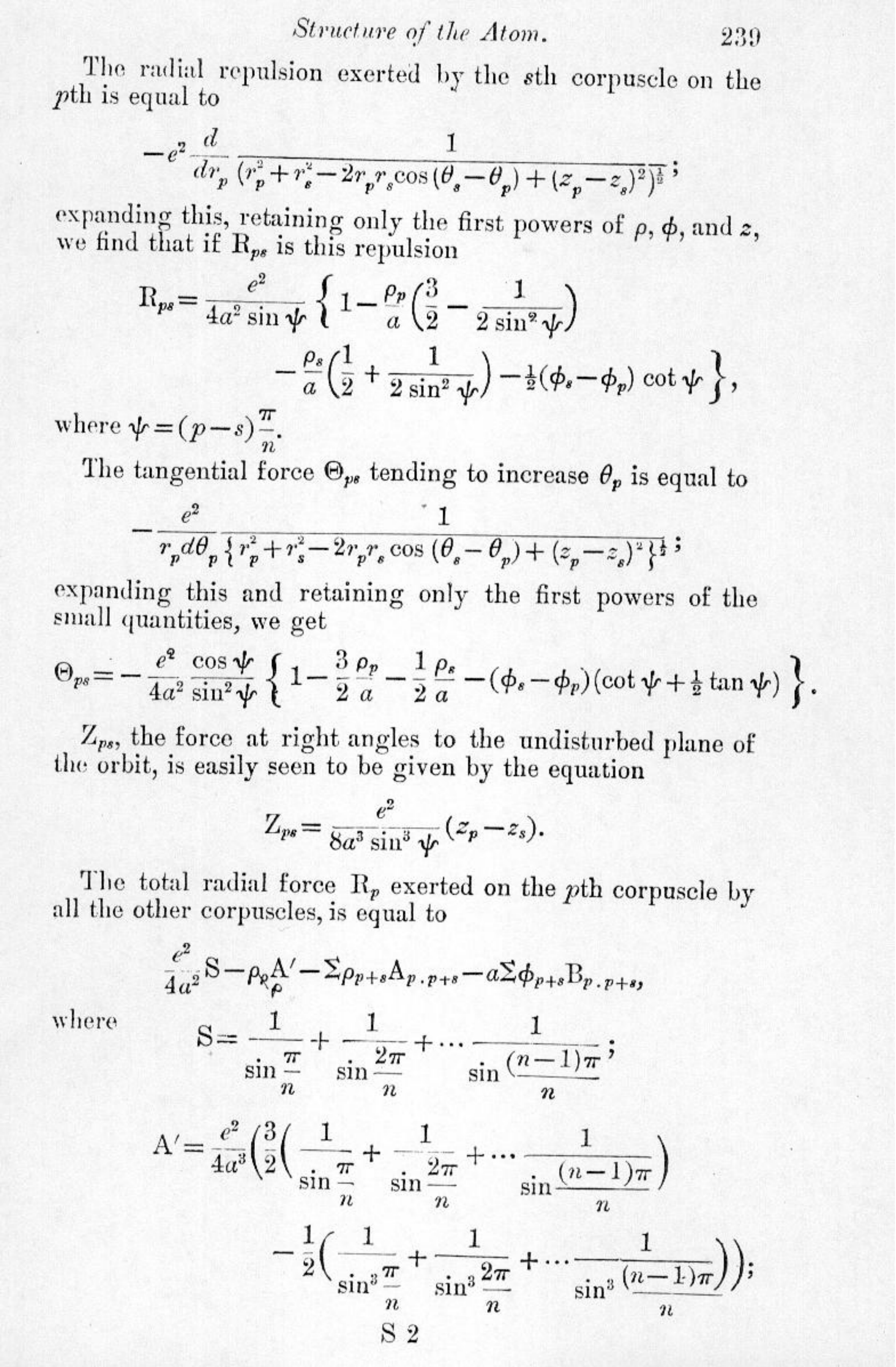
[30] Thomson 1904b, p. 119.

where the relative velocity $\beta = v/c$ was assumed to be small.

Of course, electrodynamic stability was not enough, the model atom also had to be mechanically stable. Let us follow a few of the steps in Thomson's paper of 1904. The model atom has n electrons arranged at equal angular intervals round a circle of radius a, the ring being placed concentrically in the sphere of positive electricity of radius b. The atom is assumed to be neutral, that is, the positive charge is ne. The ring may be at rest or rotate uniformly with angular velocity ω. For such a system it is readily shown that the equilibrium condition is

$$\left(\frac{a}{b}\right)^3 = \frac{S_n}{4n} + \frac{m\omega^2 a^3}{ne^2}, \quad \text{where} \quad S_n = \sum_{j=1}^{n-1} \frac{1}{\sin(j\pi/n)}$$

To determine the stability of the equilibrium configurations Thomson followed a method that closely resembled the one he had applied for vortex atoms more than twenty years earlier and which had its origin in celestial mechanics. The method was to calculate the frequencies q of the electrons when subjected to a small perturbation. If all the q values turn out to be real, the perturbed electrons will perform small oscillations about the equilibrium positions of the form $\exp(iqt)$, implying that the configuration is stable. On the other hand, if any of the q's contain an imaginary part the disturbance of the perturbed electron will increase exponentially and the equilibrium will be unstable. To carry out this programme Thomson derived general expressions for the frequencies of n electrons arranged equidistantly on a ring. There are $3n$ possible frequencies, $2n$ arising from vibrations in the plane and n from vibrations perpendicular to it. Thomson found that the rotation of the ring stabilized the equilibrium system against perturbations at right angles to the plane.



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The radial repulsion exerted by the *s*th corpuscle on the *p*th is equal to

$$-e^2\frac{d}{dr_p}\frac{1}{(r_p^2+r_s^2-2r_pr_s\cos(\theta_s-\theta_p)+(z_p-z_s)^2)^{\frac{1}{2}}};$$

expanding this, retaining only the first powers of ρ, ϕ, and z, we find that if R_{ps} is this repulsion

$$\mathrm{R}_{ps}=\frac{e^2}{4a^2\sin\psi}\left\{1-\frac{\rho_p}{a}\left(\frac{3}{2}-\frac{1}{2\sin^2\psi}\right)\right.$$
$$\left.-\frac{\rho_s}{a}\left(\frac{1}{2}+\frac{1}{2\sin^2\psi}\right)-\tfrac{1}{2}(\phi_s-\phi_p)\cot\psi\right\},$$

where $\psi=(p-s)\frac{\pi}{n}$.

The tangential force Θ_{ps} tending to increase θ_p is equal to

$$-\frac{e^2}{r_pd\theta_p}\frac{1}{\{r_p^2+r_s^2-2r_pr_s\cos(\theta_s-\theta_p)+(z_p-z_s)^2\}^{\frac{1}{2}}};$$

expanding this and retaining only the first powers of the small quantities, we get

$$\Theta_{ps}=-\frac{e^2}{4a^2}\frac{\cos\psi}{\sin^2\psi}\left\{1-\frac{3}{2}\frac{\rho_p}{a}-\frac{1}{2}\frac{\rho_s}{a}-(\phi_s-\phi_p)(\cot\psi+\tfrac{1}{2}\tan\psi)\right\}.$$

Z_{ps}, the force at right angles to the undisturbed plane of the orbit, is easily seen to be given by the equation

$$\mathrm{Z}_{ps}=\frac{e^2}{8a^3\sin^3\psi}(z_p-z_s).$$

The total radial force R_p exerted on the *p*th corpuscle by all the other corpuscles, is equal to

$$\frac{e^2}{4a^2}\mathrm{S}-\rho_p\mathrm{A}'-\Sigma\rho_{p+s}\mathrm{A}_{p\,.\,p+s}-a\Sigma\phi_{p+s}\mathrm{B}_{p\,.\,p+s},$$

where
$$\mathrm{S}=\frac{1}{\sin\frac{\pi}{n}}+\frac{1}{\sin\frac{2\pi}{n}}+\cdots\frac{1}{\sin\frac{(n-1)\pi}{n}};$$

$$\mathrm{A}'=\frac{e^2}{4a^3}\left(\frac{3}{2}\left(\frac{1}{\sin\frac{\pi}{n}}+\frac{1}{\sin\frac{2\pi}{n}}+\cdots\frac{1}{\sin\frac{(n-1)\pi}{n}}\right)\right.$$
$$\left.-\frac{1}{2}\left(\frac{1}{\sin^3\frac{\pi}{n}}+\frac{1}{\sin^3\frac{2\pi}{n}}+\cdots\frac{1}{\sin^3\frac{(n-1)\pi}{n}}\right)\right);$$

S 2

Fig. 3. A typical page from Thomson’s 1904 article on the structure of the atom, illustrating the highly mathemathical character of his theory.

As an illustration, consider the two cases $n = 2$ and $n = 6$. For $n = 2$ Thomson's formulae resulted in four planar frequencies,

$$q = \sqrt{\frac{6e^2}{mb^3} + \omega^2} \;, \quad q = \sqrt{\frac{2e^2}{mb^3}} \pm \omega \;, \quad q = 0$$

and two transversal frequencies,

$$q = \sqrt{\frac{2e^2}{mb^3}} \;, \quad q = \omega$$

Since all the frequencies are real, the two-electron system will be stable. In the case of $n = 6$ one of the frequencies turn out to be imaginary and for this reason six electrons distributed uniformly along a ring will not in general form a stable system. As general results of his lengthy calculations Thomson pointed out, firstly, that the ring structure can be stabilized by internal electrons and, secondly, that the stability may depend on a critical angular velocity. For example, for $n = 6$ the system will stabilize if ω becomes greater than about $3e^2/mb^3$. Thomson described the general picture of his planar model atom as follows:

> We have thus in the first place a sphere of uniform positive electrification, and inside this sphere a number of corpuscles arranged in a series of parallel rings, the number of corpuscles in a ring varying from ring to ring: each corpuscle is travelling at high speed round the circumference of the ring in which it is situated, and the rings are so arranged that those which contain a large number of corpuscles are near the surface of the

> sphere, while those in which there is a smaller number of corpuscles, are more in the inside.[31]

For a large number of electrons Thomson devised a graphical approximation method by means of which he could find the stable configurations. He assumed that the number of rings was a minimum, so that the outer rings were filled up with as many electrons as possible before new electrons were added to the internal structure. In this way he was led to ring structures such as those given in Table I. As Thomson pointed out, similarly to what he had done in his earlier work on the vortex atom, the electron configurations provided a striking analogy to the periodic system. If physical and chemical properties of the elements were associated with certain structures of electrons, one would expect that elements with, for example, 39, 58 and 80 electrons belonged to the same group. Contrary to later ideas of atomic chemistry, Thomson associated valency and other chemical properties with internal electron structures and not with the electrons in the outermost ring.

Thomson's model was considered attractive not only because it promised a reduction of all matter to electrons, but also because it was able to explain, if only in a vague and qualitative manner, a wide range of physical and chemical phenomena. The most important of these phenomena were radioactivity, photoelectricity, emission and dispersion of light, the normal Zeeman effect, and the periodic system of elements. In addition, Thomson could explain experiments on scattering of beta particles on matter by assuming that the basic mechanism in the scattering process was a collision between a beta electron and

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[31] Thomson 1904a, p. 254.

9 (1,8)	10 (2,8)	
21 (1,8,12)	22 (2,8,12)	23 (2,8,13)
37 (1,8,12,16)	38 (2,8,12,16)	39 (2,8,13,16)
56 (1,8,12,16,19)	57 (2,8,12,16,19)	58 (2,8,13,16,19)
78 (1,8,12,16,19,22)	79 (2,8,12,16,19,22)	80 (2,8,13,16,19,22)

Table I. Electron configurations in Thomson atoms. The symbol n (x_1, x_2, x_3, …) means a total of n electrons with x_1 electrons in the innermost ring, x_2 electrons in the second ring, x_3 electrons in the third ring, etc.

a bound atomic electron.[32] The observed deflection arose by multiple scattering, that is, the collective result of numerous individual electron-electron scatterings. Although Thomson's theory of beta scattering did not rely critically on his atomic model – the positive sphere of electricity played almost no role – it was consistent with it. Apart from indicating an explanation of the periodic system, Thomson's ideas of atomic structure also included a theory of valency in rough agreement with the one proposed by the German chemist Richard Abegg. In general his ideas attracted favourable attention among chemists.[33] In spite of the considerable explanatory force of Thomson's theory, its explanations had more the character of analogies than deductions. Its explanatory breadth was not followed by a proper predictive force.

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[32] Thomson 1906 and Thomson 1910, with historical analysis in Heilbron 1968.

[33] See Stranges 1982 and, for the role of chemical considerations in Thomsons research programme, Sinclair 1987.

Physicists in the early years of the nineteenth century did not recognize the spontaneous and inherently probabilistic nature of radioactivity. Like Kelvon's Aepinus atom, Thomson's model had the advantage that it provided a qualitative explanation of the phenomenon in terms of a rearrangement of the atomic electrons. In a stable atom the rings of electrons would rotate with a high velocity, but because of the small radiation drain the velocity would slowly diminish and eventually become subcritical. As Thomson explained:

> When, after a long interval, the velocity reaches the critical velocity, there will be what is equivalent to an explosion of the corpuscles, the corpuscles will move far away from their original positions, their potential energy will decrease, while their kinetic energy will increase. The kinetic energy gained in this way might be sufficient to carry the system out of the atom, and we should have, as in the case of radium, a part of the atom shot off. In consequence of the very slow dissipation of energy by radiation the life of the atom would be very long.[34]

This sketch remained the essential explanation of radioactivity within the framework of the Thomson atom and was for a while accepted by Rutherford, among others. However, the explanation was evidently a sketch only. For one thing, it failed to account for the exponential decay law; for another, it offered no explanation of why radioactivity was limited to elements heavier than lead. In addition, it referred loosely to parts of the atom being shot off, without making it explicit what these parts were. Latest by 1908 alpha particles were identified with helium ions, which according to Thomson were atomic systems including

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[34] Thomson 1904c, p. 265. On the problem of subatomic explanations of radioactivity, see Kragh 1997b.

spheres of positive electricity. How were these systems expelled from the mother atom? In spite of these and other problems the radiation-drain hypothesis remained popular for several years.

From the very beginning the Thomson model was plagued by conceptual as well as experimental problems. The imponderable sphere of positive electricity was a mathematical artifice, a ghost-like entity whose only function was to keep the electrons together. In a letter to Lodge of April 1904 Thomson admitted that "I have … always tried to keep the physical conception of the positive electrification in the background."[35] In the same letter he expressed the hope of explaining the positive electricity as an epiphenomenon due to the negative electrons:

> When one considers that all the positive electricity does, on the corpuscular theory, is to provide an attractive force to keep the corpuscles together, while all the observable properties of the atom are determined by the corpuscles, one feels, I think, that the positive electrification will ultimately prove superfluous and it will be possible to get the effects we now attribute to it, from some property of the corpuscles.

But Thomson did not succeed in either explaining or explaining away the positive electricity. On the contrary, his further research showed that the number of electrons was much smaller than originally assumed and that the positive electricity therefore could not be weightless or nearly so. It had to be substantial. But what was it?

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[35] Quoted in Davis and Falconer 1997, p. 195.

In an important paper of 1906 Thomson analyzed the experimental data on the scattering of various kinds of radiation (light, X-rays and beta rays) in relation to his theory of the atom with the aim of estimating the number of electrons in real atoms.[36] The chief result of his analysis was surprising, namely that the number of electrons must be of the order of the atomic weight. With this result he decimated the electronic population of atoms with a factor of about 1000. The consequences were uncomforting to the original Thomson model because they showed that the positive electricity made up far the most of the atom's mass. The small number of electrons reopened the radiation problem: physicists could no longer count on the reduction of the radiation drain caused by many electrons, at least not in the case of the lightest elements. If the radiation-drain mechanism of radioactivity were maintained, it would seem to imply that the light elements such as hydrogen and helium should be particularly radioactive, in stark contrast to experimental knowledge.

There was another reason why the conclusion of 1906 undermined (or ought to have undermined) the credibility of Thomson's plum pudding model. With the assumption of thousands of electrons in even the lighter atoms, there was no way in which a reasonably exact match could be established between the models atoms and those really existing. But if there were only, say, four electrons in a helium atom it meant that the model of a helium atom could be confronted with the chemical and physical properties of helium. In the case of the lightest elements it could no longer be argued that the number of electrons was too large or that three-dimensional calculations were not technically feasible. Thomson evaded the problem by ignoring it. This kind of exact comparison between a particular model and a particular atom was not part of his style of physics. As

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[36] Thomson 1906, which according to Heilbron (1968, p. 269) is "one of the most important papers on atomic structure ever written."

Bohr later said, "Things needed not to be very exact for Thomson, and if it resembled a little, it was so."[37]

By the early twentieth century a theory of atomic structure should preferably be able to account for the line spectra and their regularities, but in fact none of the models available at the time were able to do so. By and large, spectra were outside atomic theory and Thomson's model was no exception. Thomson did not even attempt to calculate the frequencies of spectral lines from the vibrations of the atomic electrons. The difficulty, which was not particular to the Thomson atom, was highlighted by several British physicists, including Jeans and Lord Rayleigh. In a paper of 1897 Rayleigh had analyzed the problem in general terms, concluding that vibrating systems of electrical charges would almost always result in formulae involving the square of the vibration frequencies. The empirical formulae of Rydberg, Balmer, Ritz and other spectroscopists were simple expressions in the first power of the frequency. Reconsidering the problem within the framework of an idealized Thomson model, in 1906 Rayleigh saw no way to escape the conclusion. As in a state of desperation he suggested that "the frequencies observed in the spectrum may not be frequencies of disturbance or of oscillations in the ordinary sense at all, but rather form an essential part of the original constitution of the atom as determined by conditions of stability."[38] With hindsight, Rayleigh happened to anticipate one on the key features of Bohr's later atomic theory.

At about 1910 Thomson had quietly abandoned his original atomic model and begun to focus his research on the positive electricity in the form of positive

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[37] Interview with Bohr of 1962, as quoted in Heilbron 1977b, p. 56.

[38] Rayleigh 1906, p. 123. The model Rayleigh used as an illustration was a kind of Thomson atom, but with an infinite number of "electrons" smeared out over the entire positive sphere. Other pre-1913 attempts of making sense of spectroscopic regularities in terms of atomic structure are discussed in Maier 1964.

rays or what continental physicists called canal rays. At the 1909 meeting of the British Association he no longer defended the plum pudding model but vaguely suggested that the atom contained negative as well as positive elementary charges, both kinds being ponderable. Shortly later Thomson's picture of the atom faced a new and grave difficulty, namely its inability to explain the scattering experiments with alpha rays made in Manchester by Hans Geiger and Ernest Marsden under Rutherford's supervision (Section 5). Although these experiments were highly important, the demise of the Thomson atom was not simply caused by them. The refutation of the classical Thomson process was a gradual process during which anomalies and conceptual problems accumulated until most physicists, including Thomson himself, realized that it could not be developed into a satisfactory state. Although Thomson never officially buried his model of 1904, he changed it so drastically that it became a new model.

A main feature of what may be called the second Thomson model was that the atom consisted of negative electrons bound together in stable equilibrium positions with positive particles in the form of hydrogen ions and alpha particles.[39] Contrary to what he had done in 1904, he made no attempt to calculate the configurations. The charged particles within the atom were assumed to be subject to two kinds of forces, a radial repulsive force varying inversely as the cube of the distance from the atomic centre and an inverse-square radial attractive force. Whereas the ordinary Coulomb force is isotropic, Thomson hypothesized that the attractive force was directive, namely, confined to a number of radial tubes in the atom. Making use of these and other assumptions Thomson succeeded to reproduce Einstein's equation for the

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[39] Thomson 1913. Thomson 1921.

photoelectric effect, including Planck's constant which he characteristically expressed by atomic constants. He found

$$h = \pi\sqrt{Cem}$$

where *C* was a force constant of such a value that it secured the right value for *h*. His model also provided an explanation of the production of X-rays and some of the data from the new field of X-ray spectroscopy. Moreover, Thomson and others applied models of this kind to throw light on the nature of valency and other chemical phenomena. In his presentation at the 1913 Solvay Congress he argued that his theory led to electron configurations for the simpler atoms that corresponded to the known periodicity of the elements. According to Thomson, many chemical properties could be understood on his model as due to a dipole-dipole interaction caused by the mobility of the atomic electrons. For the total number of electrons in the light elements he proposed the following figures: H = 1, He = 2, Li = 5, C = 6, O = 8, F = 11, Na = 13 and Cl = 19.

By the early 1910's the classical Thomson atom was no longer the subject of research or taken seriously as a realistic picture of the atom, and yet it continued to live on for several years. For example, it speaks to the appeal of the model that Owen Richardson, in the 1916 edition of his textbook *The Electron Theory of Matter*, covered it in great detail, in fact in greater detail than the Bohr model. Readers of Richardson's book would not suspect that Thomson's theory of the atom belonged to the past.

From about 1904 to 1910 the Thomson atom was generally accepted as the best offer of an atomic theory, especially in England but also on the continent where several physicists expressed interest in the theory. In a lecture in

Göttingen of 1909, Max Born dealt with Thomson's atomic model, which he found fascinating because of its "remarkable agreement" with the periodic system and other phenomena of nature. What appealed to him was the spirit of the model, not its details. According to Born: "Thomson's atomic model … is like a piano excerpt from the great symphonies of luminating atoms. Although it may seem in many ways to be crude and imprecise, yet it gives us a starting point for understanding this mighty music."[40] Given that Thomson's model was unable to account for the spectra it is ironic that Born spoke of it as a symphony of luminating atoms.

In his 1906 lectures at Columbia University, published three years later as *The Theory of Electrons*, Hendrik A. Lorentz considered a generalized version of the Thomson atom.[41] Rather than adopting Thomson's uniformly charged positive sphere, he assumed that the charge density varied in some unknown manner with the distance from the centre. As a special case Lorentz analyzed in detail the system of four electrons situated at the corners of a regular tetrahedron whose centre coincided with the centre of the positive sphere. Spatial models of the Thomson atom were later investigated by Arthur Erich Haas in Austria and Luwig Föppl in Germany.[42] Their laborious calculations did not result in new physical insight and were primarily mathematically motivated. Neither Haas nor Föppl was concerned with comparing their three-dimensional equilibrium structures with the physical and chemical properties of real elements. It is telling that Föppl's extensive work, which was part of his dissertation at the university of Göttingen, was done at the suggestion of the mathematician David Hilbert and published in a mathematics journal.

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[40] Born 1909, p. 1031.

[41] Lorentz 1952, pp. 120-123, 294-300.

[42] Haas 1911. Föppl 1912.

Whereas Haas's work on the equilibrium configurations according to "Thomson's spirited theory" was of no importance, a paper that he published two years earlier merits some attention because it was the first attempt to apply quantum theory to the structure of atoms.[43] Haas made use of Thomson's picture of the hydrogen atom, or what he took to be Thomson's picture, but assumed that the single electron would revolve along the surface of the positive sphere. It should be noted that in 1911 it was not generally accepted that the hydrogen atom contains only one electron. Thomson, for one, did not say so and neither did Rutherford in his paper on the nuclear atom of 1911. Because Haas' electron moved on the surface of the positive sphere, it was subjected to an electric force that might just as well come from the positive charge being concentrated in the centre. From this point of view his model can be seen as equivalent to the later nuclear atom. Haas assumed that the potential energy of the electron was given by $e^2/b = h\nu$, where ν denotes the frequency of revolution. From this follows an expression for Planck's constant, namely

$$h = 2\pi e\sqrt{mb}$$

Guided by Balmer's expression for the hydrogen spectrum, and making use of some rather arbitrary assumptions, Haas further obtained the formula

$$R = 16\pi^2 \frac{me^4}{ch^3} ,$$

where R is the Rydberg constant. The latter expression happens to be of the right order of magnitude and is, in fact, exactly eight times larger than the value Bohr

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[43] Haas 1910a and Haas 1910b, reprinted in Hermann 1965, pp. 27-60.

derived in 1913. Haas also considered the possibility that the mass of the electron was of electromagnetic origin, in which case he derived

$$h = \frac{2\pi e^2}{c}\sqrt{\frac{2b}{3r}}$$

where r is the radius of the electron.

Haas' theory attracted the critical attention of leading physicists, including H. A. Lorentz, Max Planck, Arnold Sommerfeld and Paul Langevin. It was discussed at the 1911 Solvay Congress, where Sommerfeld objected that Planck's constant of action should not be derived from atomic quantities. Rather than basing *h* on a special model of the atom, he preferred a general and model-independent theory of the constant. Sommerfeld's view corresponded to the one that Bohr adopted in his atomic theory of 1913, namely that *h* is an irreducible constant that can be used to explain atomic constants, while the opposite approach of Haas is illegitimate. Haas' model was also considered by his compatriot Arthur Schidlof, who modified it by assuming that, in the case of many-electron atoms, a part of the negative electricity was located at the centre of the positive sphere.[44] On this basis he found a more general expression of *h* in terms of atomic quantities and one which he thought conformed better to Thomson's atomic theory.

Johannes Stark, the professor of physics at the Technische Hochschule in Aachen, was one of the few physicists who supported an atomistic conception of light similar to the light quantum hypothesis proposed by Einstein.[45] Like other

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[44] Schidlof 1911.

[45] On Stark's support of Einstein's light quantum hypothesis and the views of the two physicists on this matter, see Mehra and Rechenberg 1982, pp. 99-105.

physicists at the time he was interested in the problem of the distribution of positive and negative electricity in atoms, but in this context he did not find the energy quanta of Planck and Einstein useful. From experiments on radioactivity and light emitted by positive rays he suggested in 1910 that atoms consisted of electrons and a massive "atomic ion" corresponding to the chemical atom. The positive charge of the atomic ion was not distributed uniformly over the atom's surface but concentrated in quanta at certain points of it. For the positive quanta Stark introduced the term "archion" and on this basis he developed a purely qualitative theory of the constitution of atoms and molecules.[46] The chemical atom, he said, consists solely of positive archions, which are characteristic of the element, and negative electrons that may be dissociated from the atom. Stark developed his theory of an "atomic dynamics" based on electrons and archions into an elaborate system, but it failed to convince other than himself. After about 1914 the archion fell into oblivion.

4. Planetary atoms

What John Theodore Merz in 1896 called the "astronomical view of molecular phenomena" has a long tradition in the history of science and ideas.[47] Postulating that the microcosm is structured in analogy with the macrocosm, and that the two realms of nature are governed by the same laws, the view reappeared in a new version when scientists in the nineteenth century began to speculate about the internal composition of atoms. As mentioned (Section 1), explicit analogies

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[46] Stark 1910, especially pp. 67-95. Whereas physicists ignored Stark's ideas of atomic and molecular constitution, for a while they attracted considerable interest among chemists. See Stranges 1982, pp. 192-200. For contemporary reviews, highlighting the chemical applications of Stark's theory, see Campbell 1913, pp. 341-348 and Hahn and Holmes 1915.

[47] Merz 1965, vol. 1, p. 354.

between atoms and the planetary system appeared decades before the discovery of the electron. Sometimes not more than metaphors, they continued to be popular in the first decade of the twentieth century. In his survey of 1906, Lodge included the picture of the atom as a kind of solar system, with the electrons revolving "like asteroids" around a solar concentration of positive electricity.[48] In a textbook published two years later, Sophus M. Jørgensen, a prominent Danish professor of chemistry, said about the atom that it "is, in fact, now considered to be a nucleus of positive electricity, around which negative electrons rotate with immense velocities in definite paths, like the planets in the solar system."[49]

The first scientist to propose a planetary atomic model based on electrons may have been the French physical chemist Jean Perrin, a physics Nobel laureate of 1926 for his work on Brownian motion and related phenomena. In a popular lecture of 1901 he suggested the following picture of the atom:

> Each atom will be constituted, on the one hand, by one or several masses very strongly charged with positive electricity, in the manner of positive suns whose charge will be very superior to that of a corpuscle, and, on the other hand, by a multitude of corpuscles, in the manner of small negative planets, … [with] the total negative charge exactly equivalent to the total positive charge, in such a way that the atom in electrically neutral.[50]

Perrin suggested an explanation of radioactivity on the basis of this picture and also indicated that it might have spectroscopic applications. However, his model

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[48] Lodge 1906, p. 150, who did not endorse the picture.

[49] Jørgensen 1908, p. 26. In what superficially looks like an anticipation of the Bohr-Rutherford model, Jørgensen probably had Nagaoka's model in mind. He seems to have thought, if so mistakenly, that this kind of atomic model was generally accepted.

[50] Perrin 1901, p. 460. See also Nye 1972, pp. 83-85.

was nothing but a rough sketch and probably not meant to be more than that. Thus, he did not attempt to calculate the configurations of the planetary electrons and showed no interest in the stability of their orbits.

Of much greater interest is the model proposed by the Japanese physicist Hantaro Nagaoka, although his was a "Saturnian" rather than a planetary model of the atom.[51] Nagaoka had done post-doctoral studies at the universities of Berlin and Munich and there become acquainted with Maxwell's 1856 essay on the mechanical stability of Saturn's system of rings. In this work, for which he was awarded the Adams Prize, Maxwell had concluded that Saturn's central body surrounded by a rotating ring with a large number of separate satellite particles would remain stable if the angular velocity of the ring was sufficiently high. In a paper of 1904 in the *Philosophical Magazine* Nagaoka, acknowledging his indebtedness to Maxwell's analysis, replaced Saturn's central body with a tiny positive charge and the multitude of satellites with electrons. The atomic system, he wrote,

> … consists of a large number of particles of equal mass arranged in a circle at equal angular interval and repelling each other with forces inversely proportional to the square of distance; at the centre of the circle, place a particle of large mass attracting the other particles according to the same law of force. If these repelling particles be revolving with nearly the same velocity about the attracting centre, the system will generally remain stable, for small disturbances, provided the attracting force be sufficiently great.[52]

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[51] On Nagaoka and his atomic model, see Yagi 1964 and Conn and Turner 1965, pp. 111-119.

[52] Nagaoka 1904, p. 445.

The Japanese physicist calculated that the central particle had to have a charge of at least 10,000 times the numerical charge of the electron. Nagaoka's elaborate calculations were primarily aimed at explaining the frequencies of band spectra (for which he found "a close resemblance"), but he also thought that his model was suggestive with regard to radioactivity, resonance, luminescence and "chemical affinity and valency, electrolysis and many other subjects connected with atoms and molecules." Like Thomson and other model builders of the period, he safeguarded his conclusions by adding that "the actual arrangement in a chemical atom may present complexities which are far beyond the reach of mathematical treatment."

Published in the leading journal of atomic theory, Nagaoka's atom was well known and attracted some interest. For example, it was positively evaluated by Henri Poincaré in his book *La valeur de la science* of 1908, where the French mathematician called the model "a very interesting attempt, but not wholly satisfactory." However, Nagaoka's calculations were severely criticized by George A. Schott, a physicist at the University College of Wales, who argued that the assumptions of Nagaoka were inconsistent and that the model could not possibly lead to the claimed agreement with experiments.[53] Schott proved in a general way that a system like Nagaoka's would be unable to generate the number of waves observed in either discrete spectra or band spectra. In reply to Schott's critique Nagaoka argued that it rested on a misunderstanding of his "ideal atom," but the rejoinder had no effect. The hypothesis of the atom consisting of a "central body charged with positive electricity, while the satellites are all negatively electrified" was also criticized by Thomson, although without

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[53] Schott 1904. Schott 1907.

mentioning Nagaoka by name.[54] By 1908 the Saturnian atom had disappeared from the scene of physics and it only reappeared, in an entirely different dressing, with the Rutherford-Bohr nuclear theory.

A new atomic theory which had some features in common with Nagaoka's was proposed in 1911 by John William Nicholson, at the time a lecturer at the Cavendish Laboratory.[55] (The following year he was appointed professor of mathematics in the University of London, King's College.) His paper on the constitution of the atom appeared some months after Rutherford had introduced the idea of an atomic nucleus, but although Nicholson was aware of Rutherford's work he was not inspired by it and did not conceive the two versions of the nuclear model to have much in common. Nicholson's atom was much closer to Thomson's model, both in spirit and calculational details, and has been aptly described as a Thomson atom "with the dimensions of the positive sphere shrunk from atomic size to one much smaller than the radius of the electron."[56] Incidentally, whereas Rutherford did not refer to the central charge as a "nucleus," Nicholson did, although he did not invent the name.[57]

Nicholson's model was different from earlier conceptions of the atom, not only because it offered definite constitutions of the chemical elements but also because it relied on astronomical evidence rather than laboratory evidence. The ambitious aim of Nicholson's theory was to derive all the atomic weights of the elements from combinations of certain proto-atoms, which he supposed existed in free form in the stellar realm only. He considered the massive positive nucleus

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[54] Thomson 1905, p. 142.

[55] Nicholson 1911a. On Nicholson's life and career, see Wilson 1956.

[56] McCormmach 1966, p. 165, which gives details of Nicholson's atomic model and its relation to Bohr's theory of the atom.

[57] Jørgensen 1908, quoted above, may have been the first to call the positive centre a nucleus.

to be purely of electromagnetic origin, hence much smaller than the electron, and located in the centre of the atom with rings of electrons revolving around it.

In agreement with the earlier evolutionary views of his compatriots Crookes and Lockyer, Nicholson was convinced that terrestrial matter had evolved from simpler forms that still existed in the stars and nebulae and could be studied by means of the spectroscope. To understand the architecture of atoms, the physicist would have to look to the heavenly regions. The atomic model proposed by Nicholson was mainly concerned with the four primary elements that were supposed to exist in the nebulae and the Sun's corona. Having oncluded that a ring atom with only one electron could not exist, his simplest atom ("coronium") consisted of a single ring of two electrons rotating about a nucleus of charge +2*e*. His four primary elements, their symbols, nuclear charges and atomic weights were the following:

coronium	--	2*e*	0.51282
"hydrogen"	H	3*e*	1.008
nebulium	Nu	4*e*	1.6281
protofluorine	Pf	5*e*	2.3615

Although Nicholson's three-electron "hydrogen" was closely related to the chemical elements hydrogen, he did not conceive the two atoms to be identical. Coronium was the simplest possible atomic system and ordinary hydrogen was seen as a kind of polymer of the primordial "hydrogen." Somewhat confusingly he chose the symbol H for this form of hydrogen. Whereas H, Nu and Pf were thought of as constituents of the chemical elements, this was not the case with coronium which resided in the solar corona only. For this reason he did not assign it a chemical symbol. In his paper of 1911 Nicholson derived the weights and compositions of all of the elements, simple examples being He = NuPf, Li = 3Nu2H and Be = 3Pf2H.

Nicholson's theory was not only about the constitution of elements, but also, and in his later publications increasingly so, about the spectral lines emitted by the primitive atoms and caused by vibrating ring electrons. His general method was to calculate the frequencies of the vibrations in coronium, nebulium and protofluorine and comparing the results to unassigned lines occurring in nebular and coronal spectra. In this way he was able to account for most of the lines and also to predict new lines in both types of spectra. For example, in the case of nebulium he predicted the existence of a line of wavelength 4353 Å, which shortly later was found in a nebular spectrum.[58] He similarly predicted a line of wavelength 6374.8 Å due to protofluorine, agreeing nicely with the later discovery of $\lambda = 6374.6$ in the spectrum of the solar corona. Naturally he took these confirmations as support for his theory.

In his attempts to explain the line spectra and determine the dimensions of the primary atoms, Nicholson was led to introduce Planck's constant in his theory. Up to this time the quantum of action had always been associated with energy, in the form $E = h\nu$, but now Nicholson extended its physical meaning. In 1912 he argued that in the case of a 5-electron ring (protofluorine) the angular momentum could be written as $L = 25\ h/2\pi$; for the rings of 3 and 4 electrons (hydrogen and nebulium) he similarly found $L = 18\ h/2\pi$ and $L = 22\ h/2\pi$. He generalized that the angular momentum of simple atoms could only change by integral multiples of the quantity $h/2\pi$, that is,

$$L = n\frac{h}{2\pi}, \qquad n = 1, 2, 3, \ldots$$

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[58] Nicholson 1911b and Nicholson 1912a.

Nicholson offered the following picture of the radiating atom:

> The quantum theory has apparently not been put forward as an explanation of "series" spectra, consisting of a large number of related lines given by comparatively simple atoms. Yet … we are led to suppose that lines of a series may not emanate from the same atom, but from atoms whose internal angular momenta have, by radiation or otherwise, run down by various discrete amounts from some standard value. For example, on this view there are various kinds of hydrogen atoms, identical in chemical properties and even in weight, but different in their internal motions.[59]

No wonder that Bohr, when he came across Nicholson's atomic theory, found it to be interesting as well as disturbingly similar to his own ideas. Although today forgotten or only recalled by historians of physics, in the period 1913-1915 Nicholson's atom was a rival to Bohr's and Nicholson the chief critic of Bohr's ideas of the quantum atom.[60]

5. Rutherford's nuclear atom

Ernest Rutherford's scientific reputation rested on his pioneering contributions to the study of radioactivity, a field of research he immersed himself fully in. When he was awarded the Nobel Prize in 1908, it was in chemistry and for his work on radioactive decay. He was not particularly interested in atomic models except that until about 1908 he was generally in favour of a model of the kind

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[59] Nicholson 1912b, p. 730.

[60] On Nicholson's sustained critique of Bohr's theory, see Kragh 2011.

proposed by Thomson, which he found useful in explaining certain qualitative features of radioactive phenomena. In broad conformity with Thomson's model, he conceived the atoms of even the lightest elements as conglomerates of thousands of electrons. In *Radioactive Transformations*, a book based on the Silliman Lectures of 1905, he included a section on atomic constitution in which he, in a general and guarded way, endorsed a Thomson-like picture of the atom. As Rutherford phrased it, "The mobile electrons constitute, so to speak, the bricks of the atomic structure, while the positive electricity acts as the necessary mortar to bind them together."[61] Although he found this "a somewhat arbitrary arrangement," at the time he could see no better alternative.

Only in 1910 did Rutherford turn seriously to atomic theory, primarily as a result of his deep interest in the behaviour and nature of alpha particles.[62] In 1908 he had definitely shown the alpha particle to be identical with a doubly charged helium ion, although the nature of the ion was unknown. In the same year Hans Geiger, a German physicist working with him in Manchester, reported preliminary results of the scattering of alpha particles on metal foils. Geiger noticed an appreciable scattering and the following year he investigated the matter more fully in collaboration with Ernest Marsden. They found that heavier metals were far more effective as reflectors than light ones and that a thin platinum foil reflected (that is, scattered an angle $\phi > 90°$) one of every 8,000 of the alpha particles striking it.

The experiments induced Rutherford to investigate the scattering of alpha particles and compare the results with Thomson's 1910 theory of the scattering of beta particles. This theory, according to which the beta electrons were multiply

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[61] Rutherford 1906, p. 266.

[62] For details on Rutherford's road to the nuclear atom, see Heilbron 1968. See also Andrade 1958.

scattered through small angles, seemed to agree nicely with experiments made by James Arnold Crowther, a young Cambridge physicist. According to Crowther, Thomson's theory was brilliantly confirmed and implied that the number of electrons in an atom was about three times the atomic weight. For example, Crowther found that aluminium, with atomic weight 27, must have 85 electrons. Suspecting that Crowther's interpretation was biased in favour of the Thomson theory, Rutherford set about to find a unified theory that could account for the scattering of both beta and alpha particles.

According to Thomson, the alpha particle was of atomic dimensions and contained 10-12 electrons. Rutherford, on the other hand, came to the conclusion that the alpha particle must be considered a point particle, like the electron. Because the alpha particle was a helium atom deprived of its two electrons, this view implied, in effect, a nuclear model of the helium atom. Rutherford reached this important conclusion before he developed his scattering theory based on the idea of pointlike alpha particles. By late 1910 he was focusing on a new picture of atomic structure consistent with scattering experiments. In a letter to the American radiochemist Bertram Boltwood of 14 December 1910 he wrote: "I think I can devise an atom much superior to J.J.'s, for the explanation of and stoppage of α and β particles, and at the same time I think it will fit in extraordinarily well with the experimental numbers."[63] Rutherford presented his new and superior atom, primarily based on the scattering experiments by Geiger and Marsden, in a landmark paper in *Philosophical Magazine* of May 1911.

In this paper Rutherford concluded that in order to produce the observed deflections of $\phi > 90°$ scattering had to take place in a single encounter between

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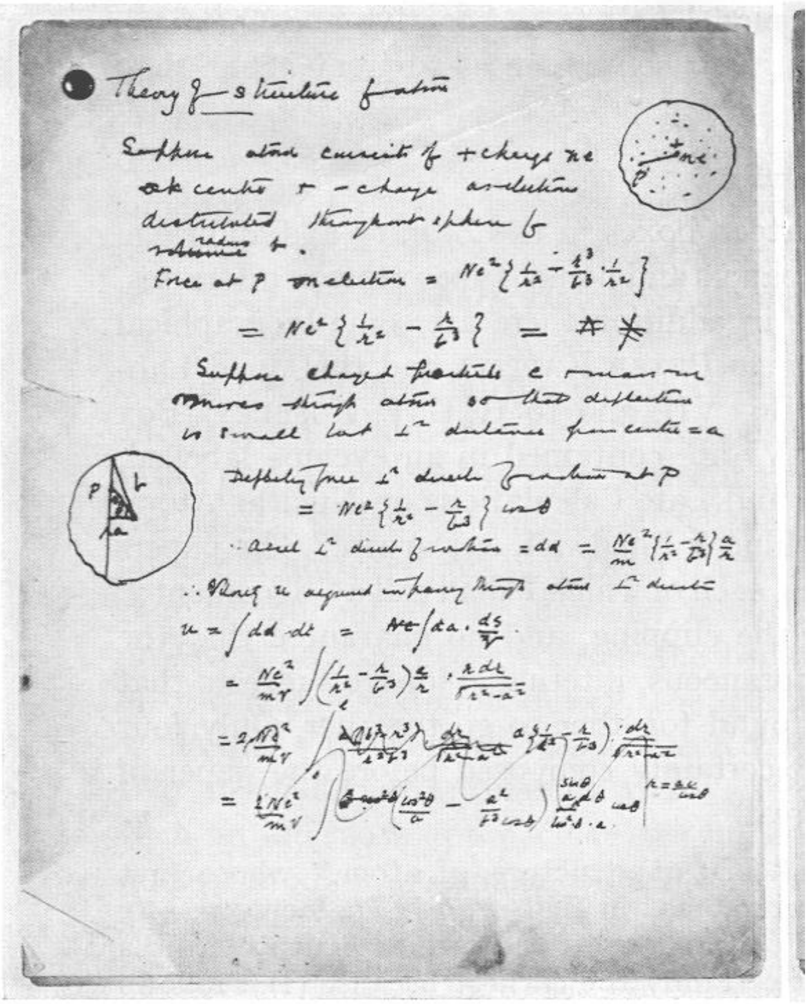
[63] Badash 1969, p. 235.



Theory of structure of atoms

Suppose atom consists of + charge ne at centre & − charge as electrons distributed throughout sphere of ~~volume~~ radius b.

Force at P on electron $= Ne^2\left\{\frac{1}{r^2} - \frac{r^3}{b^3}\cdot\frac{1}{r^2}\right\}$

$= Ne^2\left\{\frac{1}{r^2} - \frac{r}{b^3}\right\}$

Suppose charged particle e of mass m moves through atom so that deflection is small & let ⊥ distance from centre = a

Deflecting force ⊥ direction of motion at P

$= Ne^2\left\{\frac{1}{r^2} - \frac{r}{b^3}\right\}\cos\theta$

∴ accel ⊥ direction of motion $= d\alpha = \frac{Ne^2}{m}\left\{\frac{1}{r^2} - \frac{r}{b^3}\right\}\frac{a}{r}$

∴ Velocity u acquired in passing through atom ⊥ direction

$u = \int d\alpha\, dt = \int d\alpha \cdot \frac{ds}{V}$

$= \frac{Ne^2}{mV}\int\left(\frac{1}{r^2} - \frac{r}{b^3}\right)\frac{a}{r}\cdot\frac{r\,dr}{\sqrt{r^2-a^2}}$

$= 2\frac{Ne^2}{mV}\int \ldots a\left\{\frac{1}{r^2} - \frac{r}{b^3}\right\}\cdot\frac{dr}{\sqrt{r^2-a^2}}$

$= \frac{2Ne^2}{mV}\int\left(\frac{\cos^2\theta}{a} - \frac{a^2}{b^3\cos\theta}\right)\frac{\sin\theta\, a\, d\theta}{\cos^2\theta \cdot a}$ $\quad r = \frac{a}{\cos\theta}$

Fig. 4. Rutherford’s early calculations of the scattering of alpha particles, and a sketch of the nuclear atom as he saw it in early 1911 (Heilbron 1968). He pictured a heavy atom as consisting of a central positive charge surrounded by an atmosphere of negative electrons, but without caring about the configurations of the electrons.

the alpha particle and a highly charged and concentrated mass. He therefore suggested that the atom contained at its centre a massive charge *Ne* surrounded by a cloud of opposite electricity. Since the results of his calculations were independent of the sign of the charge, the nucleus could just as well be a concentration of electrons embedded in a positive fluid, not unlike an extreme case of the Thomson atom: "Consider an atom which contains a charge $\pm Ne$ at its centre surrounded by a sphere of electrification containing a charge $\mp Ne$ supposed uniformly distributed throughout a sphere of Radius R. … For convenience, the sign [of the central charge] will be assumed to be positive." Rutherford admitted that the experimental evidence did not rule out the possibility that "a small fraction of the positive charge may be carried by satellites extending some distance from the centre."[64]

Based on this picture of the atom, Rutherford derived a formula that expressed the number of charged (alpha or beta) particles y scattered a certain angle ϕ at a distance from the scattering material. The formula related $y = y(\phi)$ to the mass and velocity of the incident particles, the number of atoms in a unit volume of the scatterer, and the nuclear charge N of the scatterer. As Rutherford demonstrated, in the case of alpha particles in particular his formula agreed very well with the experimental data obtained in Manchester. Although the scattering of alpha particles was the most important evidence for the nuclear atom, he also found good agreement in the case of beta scattering. Taken together the data indicated "that the value of this central charge for different atoms is approximately proportional to their atomic weights, at any rate for atoms heavier than aluminium." According to Rutherford's analysis, the gold atom had a charge of $N \cong 100$, which agreed with what he suspected was a general approximation, namely $A/2 < N < A$.

The nuclear atom introduced by Rutherford in the late spring of 1911 did not make a splash in the world of physics. Surprisingly from a later perspective, the model was met with indifference and scarcely considered to be a new theory

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[64] Rutherford 1911, p. 670 and p. 687.

of the constitution of the atom. It was not mentioned in the proceedings of the first Solvay Congress, taking place in the fall of 1911 with Rutherford as a participant, nor did it receive much attention in the physics journals. The second edition of the Cavendish physicist Norman Campbell's *Modern Electrical Theory*, preface dated March 1913, included a chapter on the structure of the atom in which the theories of Thomson and Stark were singled out, but where no mention was made of Rutherford's nuclear atom. Campbell was not impressed by the state of research in atomic structure: "It cannot be pretended that we have at present any but a most rudimentary theory of the atom; none of the suggestions which have been made as to its structure lead in any case to the possibility of calculating in detail one property of an atom from a knowledge of the others; no quantitative relations can be deduced."[65]

Rutherford himself does not seem to have considered his discovery as the epoch-making event that it turned out to be. For example, in his massive 1913 textbook on radioactivity, titled *Radioactive Substances and their Radiations*, with the preface being dated October 1912, there was only two references to the nuclear atom and its implications. He now declared the nucleus to be positively charged, surrounded by electrons "which may be supposed to be distributed throughout a spherical volume or in concentric rings in one plane." The nucleus was extremely small, but not pointlike. On the contrary, Rutherford pictured it as a complex body held together by what would become known as nuclear forces, the first example of strong interactions. He wrote as follows:

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[65] Campbell 1913, p. 349. The first edition of the book, issued in 1907, contained a detailed review of Thomson's atomic theory, without mentioning alternatives. According to Campbell this was justified, "for there is no rival theory of importance in the field" (p. 232).

> Practically the whole charge and mass of the atom are concentrated at the centre, and are probably confined within a sphere of radius not greater than 10^{-12} cm. No doubt the positively charged centre of the atom is a complicated system in movement, consisting in part of charged helium and hydrogen atoms [alpha particles and protons]. It would appear as if the positively charged atoms of matter attract one another at very small distances for otherwise it is difficult to see how the component parts at the centre are held together.[66]

It is customary to speak of Rutherford's atomic model, but in 1911 there was not really such a model, at least not in the sense of "atomic model" ordinarily adopted at the time. This observation goes a long way in explaining the initial lack of interest in the nuclear atom.

Rutherford presented his theory primarily as a scattering theory and realized that, considered as a theory of atomic structure, it was most incomplete. First and foremost, it could offer no suggestion of how the electrons were arranged, the very issue that was central to atomic models. "The question of the stability of the atom proposed need not be considered," he wrote, "for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts."[67] His nuclear atom was impotent when it came to chemical questions such as valency and the periodic system, and it fared no better when it came to physical questions such as spectral regularities and dispersion. An atomic theory anno 1911 would be considered really convincing only if it included the system of electrons. After all, it was agreed that this part of

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[66] Rutherford 1913, p. 620.

[67] Rutherford 1911, p. 671.

the atom was responsible for the majority of the atomic phenomena that could be tested experimentally.

The status of Rutherford's theory increased in the spring of 1913, when Geiger and Marsden published new data on the scattering of alpha particles which were in excellent agreement with the scattering formula. "We have completely verified the theory given by Prof. Rutherford," they said. The experimental results afforded "strong evidence of the correctness of the underlying assumptions that an atom contains a strong charge of the centre of dimensions, small compared with the diameter of the atom."[68] The new experiments sharpened the relationship between the nuclear charge and atomic weight, which Rutherford now took to be $N \cong A/2$. The work of Geiger and Marsden confirmed Rutherford's atomic model considered as a scattering theory, but not as a theory of atomic constitution. The results of the two Manchester physicists were as irrelevant for the electronic configurations as Rutherford's atom was silent about them.

6. Isotopy and atomic number

The existence of isotopes – species of the same chemical element with different atomic weights – was not foreseen by any of the theories of atomic structure, whether Thomson's, Rutherford's or Nicholson's. The idea was however anticipated by Crookes as early as 1886, when he suggested to the British Association that "when we say that the atomic weight of, for instance, calcium is 40, we really express the fact that, while the majority of the calcium atoms have an actual weight of 40, there are not a few which are represented by 39 or 41, a

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[68] Geiger and Marsden 1913, p. 606, and Conn and Turner 1965, pp. 150-163.

less number by 38 and 42, and so on."[69] Crookes' idea, which was one more attempt to save Prout's hypothesis, led him to interesting speculations about "meta-elements," but the idea turned out to be unviable.

It was primarily the perplexing study of radioactive decay series some two decades later that first indicated the possibility of atoms with different properties belonging to the same element.[70] Some of the substances found in the radioactive series and identified by their radioactive properties turned out to have a strong chemical resemblance to other elements; in fact, they were inseparable from them and yet they were not identical to them. In desperation, some scientists grouped several radio-elements (say, radium emanation, actinium emanation and thorium emanation) into the same place in the periodic system; others chose to extend the periodic system to accommodate the new radio-elements. By 1910 Frederick Soddy, Rutherford's former collaborator, concluded that radium, mesothorium 1 and thorium X, although of different atomic weights and radioactive properties, were not merely chemically similar, but chemically identical. Soddy did not believe that the hypothesis of different species of the same element was restricted to the radioactive elements in the upper part of the periodic system. When he coined the word "isotope" in late 1913, he related it to Rutherford's nuclear atom:

> The same algebraic sum of the positive and negative charges in the nucleus, when the arithmetical sum is different, gives what I call 'isotopes' or 'isotopic elements,' because they occupy the same place in the periodic table. They are chemically identical, and save only as regards the

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[69] Crookes 1886, p. 569.

[70] The history of isotopy in the period 1910-1915 is covered in Brock 1985, pp. 196-216 and Bruzzaniti and Robotti 1989. On the casual connection to occultism, see Hughes 2003.

> relatively few physical properties which depend upon atomic mass directly, physically identical also.[71]

The Polish physical chemist Kasimir Fajans had in an earlier paper suggested essentially the same hypothesis, calling a group of chemically identical elements a "pleiade."[72] While "isotope" caught on, "pleiade" did not. In fact, Fajans may have been alone in using the term. Contrary to Soddy, he did not accept Rutherford's nuclear atom, but argued that alpha particles were expelled from the outer layer of the atom. He found Nicholson's atomic theory to be "extremely tempting" and superior to Rutherford's.

Radioactive decay was not the only phenomenon that pointed towards isotopy, so did the positive rays investigated by J. J. Thomson. Francis Aston, who served as Thomson's assistant in parts of his research programme, analyzed positive rays of neon, known to have the atomic weight 20.2. Surprisingly, Aston's experiments revealed not only rays corresponding to atomic weight 20 but also weaker rays corresponding to atomic weight 22. In lack of a proper explanation, he suggested to have found what he called "meta-neon," possibly a new inert gas. After a brief period of confusion, Aston and Soddy realized that what Aston had discovered was a heavy isotope of neon. Thomson at first thought that the recorded species of atomic weight 22 might be the compound NeH_2 and only reluctantly agreed that neon was probably a mixture of chemically inseparable species with different atomic weights. Understandably, he did not agree with Soddy's interpretation of isotopy in terms of the nuclear model of the atom.

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[71] Soddy 1913, p. 400. Reprinted together with other historical papers on radiochemistry and isotopes in Romer 1970 (pp. 251-252).

[72] Fajans 1913.

Before 1913 the order of the elements in the periodic system was taken to be given by the atomic weight. Although this caused some anomalies, such as related to the "reversed" atomic weights of tellurium and iodine, the dogma of atomic weight being the defining property of a chemical element was rarely questioned. Rutherford's argument that the number of positive charges in the nucleus varied with the atomic weight as $N \cong A/2$ did not question the standard view, it merely sharpened it and connected it to the atomic nucleus.

According to Charles Galton Darwin, who at the time was a lecturer at Manchester University, the 1913 scattering experiments of Geiger and Marsden convinced Rutherford and his group that the nuclear charge was the defining quantity of a chemical element.[73] The idea certainly was in the air, but it took until November 1913 before it was explicitly formulated, and then from the unlikely source of a Dutch amateur physicist. Trained as a lawyer, Antonius van den Broek had since 1907 published articles on radioactivity and the periodic system. Guided by neo-Proutean speculations he thought that consecutive elements in the periodic system differed by two units in weight, an idea which he combined with the relation $N \cong A/2$ made plausible by the Manchester experiments. In a short communication to *Nature* dated November 10 he disconnected the ordinal number from the atomic weight and instead identified it with the nuclear charge N (or Z, as it subsequently became known). This hypothesis, he said, "holds good for Mendeleev's table but the nuclear charge is not equal to half the atomic weight."[74]

Van den Broek's suggestion was quickly adopted by Soddy, Bohr and Rutherford and his group. As Rutherford pointed out, the idea of an "atomic

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[73] Darwin 1955.

[74] Van den Broek 1913, p. 373. For details on van den Broek and his work, see Snelders 1974 and Scerri 2007, pp. 165-169.

number" – a word that he possibly coined – had already been used by Bohr in his atomic theory and it received convincing confirmation in the new X-ray spectroscopic experiments made by Henry Moseley.[75]

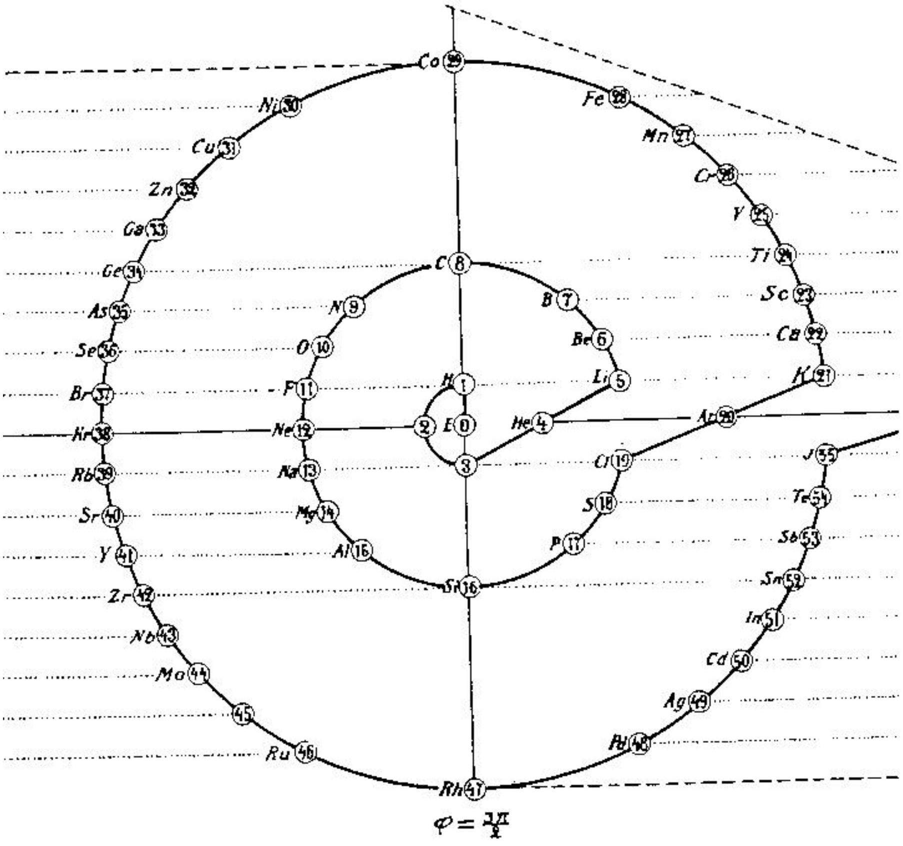

Fig. 5. Part of Rydberg's periodic system og 1913, based upon an ordinal number different from the one adopted by van den Broek, Rutherford and Bohr. Notice the two elements between hydrogen and helium, and also that Rydberg considered the electron (with ordinal number 0) a kind of chemical element.

What was often referred to as "van den Broek's hypothesis" remained controversial for several years, one of the reasons being that it restricted the number of chemical elements. Some chemists and physicists, Nicholson among them, denied that the atomic number defined the place of an element in the

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[75] Rutherford 1913b.

periodic system and thus limited the number of elements in a period. The recognized Swedish spectroscopist Johannes Robert ("Janne") Rydberg admitted the notion of an ordinal number different from the atomic weight but argued that it was two units greater than the one of van den Broek. According to Rydberg, in the first period there were four elements rather than just hydrogen and helium, lithium should be element number 5, beryllium element number 6, and so forth. In his periodic system of 1913, he included the hypothetical coronium and nebulium among the light elements.[76]

As pointed out by Soddy and others, the new notion of atomic number fitted very well with the notion of isotopy and both fitted with Rutherford's nuclear model of the atom. The atomic number also implied a new meaning of the term "element" that in some respects differed rather drastically from the one traditionally accepted by the chemists. For this reason isotopy and the atomic number became controversial in some chemical circles. Only after World War II was the atomic number officially adopted as the defining quantity of a chemical element. In 1921 the *Deutsche Atomgewichtkommission* decided to base their new table on the atomic number, and two years later the International Committee on Chemical Elements followed the same policy.[77]

When Bohr developed the final version of his atomic theory in the spring og 1913, he was aware of most of the work done by Thomson, Nagaoka, Nicholson, Rutherford, Soddy and van den Broek. Although his theory was highly original, some of this work influenced his thinking and the way he formulated his theory.

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[76] Rydberg 1913. Pauli 1994 (originally published 1955).

[77] On the controversial reconceptualisation of chemical elements in the period, see Kragh 2000.

Bibliography

Andrade, E. N. da C. (1958). ”The birth of the nuclear atom,” *Proceedings of the Royal Society A* **244**, 437-455.

Badash, Lawrence (1969). *Rutherford and Boltwood: Letters on Radioactivity*. New Haven: Yale University Press.

Born, Max (1909). “Über das Thomsonsche Atommodell,” *Physikalische Zeitschrift* **10**, 1031-1034.

Brock, William H. (1985). *From Protyle to Proton: William Prout and the Nature of Matter 1785-1985*. Bristol: Adam Hilger.

Bruzzaniti, G. and Nadia Robotti (1989). “The affirmation of the concept of isotopy and the birth of mass spectrography,” *Archives Internationales d'Histoire des Sciences* **39**, 309-334.

Conn, G. K. T. and H. D. Turner (1965). *The Evolution of the Nuclear Atom*. London: Iliffe Books.

Crookes, William (1886). “Presidential address to Section B,” *Report, British Association for the Advancement of Science*, 558-576.

Dahl, Per F. (1972). *Ludvig Colding and the Conservation of Energy Principle*. New York: Johnson Reprint Corporation.

Darwin, Charles G. (1955). “The discovery of atomic number,” pp. 1-11 in Wolfgang Pauli, ed., *Niels Bohr and the Development of Physics*. London: Pergamon Press.

Davis, E. A. and Isobel J. Falconer (1997). *J. J. Thomson and the Discovery of the Electron.* London: Taylor & Francis.

Fajans, Kasimir (1913). “Die radioaktiven Umwandlungen und die Valenzfrage vom Standpunkte der Struktur der Atome,” *Verhandlungen der Deutschen Physikalischen Gesellschaft* **15**, 240-259.

Farrar, W. V. (1965). ”Nineteenth-century speculations on the complexity of the chemical elements,” *British Journal for the History of Science* **2**, 297-323.

--- (1969). “Richard Laming and the coal-gas industry, with his views on the structure of matter,” *Annals of Science* **25**, 243-253.

Fechner, Gustav T. (1828). "Über die Anwendung der Gravitationsgesetzes auf die Atomlehre," *Kastners Archiv für die gesamte Naturlehre* **15**, 257-291.

--- (1864). *Über die physikalische und philosophische Atomenlehre*. Leipzig: Hermann Mendelssohn.

Föppl, Ludwig (1911). "Stabile Anordnungen von Elektronen im Atom," *Journal für Reine und Angewandte Mathematik* 141, 251-302.

Geiger, Hans and Ernest Marsden (1913). "The laws of deflexion of α particles through large angles," *Philosophical Magazine* **25**, 604-623.

Grassmann, Robert (1862). *Körperlehre oder Atomistik*. Stettin: Stettin Buchhandlung.

Haas, Arthur E. (1910a). "Über eine neue theoretische Bestimmung des elektrischen Elementarquantums und des Halbmessers des Wasserstoffsatom," *Physikalisches Zeitschrift* **11**, 537-538.

--- (1910b). "Der Zusammenhang der Planckschen elementaren Wirkungsquantums mit den Grundgrössen der Elektronentheorie," *Jahrbuch der Radioaktivität und Elektronik* **7**, 261-268.

--- (1912). "Über Gleichgewichtlagen von Elektronengruppen in einer äquivalenten Kugel von homogener positiver Elektrizität," *Sitzungsberichte d. kaiserliche Akademie d. Wissenschaften (Wien)* IIa, **120**, 1111-1171.

Hahn, Dorothy A. and Mary E. Holmes (1915). "The valency theory of J. Stark from a chemical standpoint," *Journal of the American Chemical Society* **37**, 2611-2626.

Heilbron, John L. (1968). "The scattering of α and β particles and Rutherford's atom," *Archive for History of Exact Sciences* **4**, 247-307.

--- (1977a). "J. J. Thomson and the Bohr atom," *Physics Today* **30** (April), 23-30.

--- (1977b). "Lectures on the history of atomic physics 1900-1922," pp. 40-108 in Charles Weiner, ed., *History of Twentieth Century Physics*. New York: Academic Press.

Hermann, Armin, ed. (1965). *Arthur Erich Haas. Der erste Quantenansatz für das Atom*. Stuttgart: Battenberg.

Hughes, Jeff (2003). "Occultism and the atom: The curious story of isotopes," *Physics World* **16** (September), 31-36.

Jeans, James (1901). "The mechanism of radiation," *Philosophical Magazine* **2**, 421-455.

Jørgensen, Sophus M. (1908). *The Fundamental Conceptions of Chemistry*. London: Society for the Promotion of Christian Knowledge.

Kaufmann, Walter (1901). "Die Entwicklung des Elektronenbegriffs," *Physikalische Zeitschrift* **3**, 9-15.

Kragh, Helge (1982). "Julius Thomsen and 19th-century speculations on the complexity of atoms," *Annals of Science* **39**, 37-60.

--- (1989a). "The aether in late nineteenth century chemistry," *Ambix* **36**, 49-65.

--- (1989b). "Concept and controversy: Jean Becquerel and the positive electron," *Centaurus* **32**, 204-240.

--- (1997a). "J. J. Thomson, the electron, and atomic architecture," *The Physics Teacher* **35**, 328-332.

--- (1997b). "The origin of radioactivity: from solvable problem to unsolved non-problem," *Archive for History of Exact Sciences* **50**, 331-358.

--- (2000). "Conceptual changes in chemistry: The notion of a chemical element, ca. 1900-1925," *Studies in History and Philosophy of Modern Physics* **31**, 435-450.

--- (2002). "The vortex atom: A Victorian theory of everything," *Centaurus* **44**, 32-114.

--- (2003). "The electron, the protyle, and the unity of matter," pp. 195-226 in Jed Z. Buchwald and Andrew Warwick, eds., *Histories of the Electron: The Birth of Microphysics*. Cambridge, Mass.: MIT Press.

--- (2011). "Resisting the Bohr atom: The early British opposition," *Physics in Perspectives* (forthcoming).

Kuntze, Friedrich (1909). "Die Elektronentheorie der Brüder Hermann und Robert Grassmann," *Vierteljahrschrift für wissenschaftliche Philosophie und Soziologie* **13**, 273-298.

Laming, Richard (1845). "Observations on a paper by Prof. Faraday concerning electric conduction and the nature of matter," *Philosophical Magazine* **27**, 420-423.

Larmor, Joseph (1895). "A dynamical theory of the electric and luminiferous medium. Part II. Theory of electrons," *Philosophical Transactions of the Royal Society* **186**, 695-743.

--- (1900). "Presidential address to Section A," *Report, British Association for the Advancement of Science 1900*, 613-628.

Lenard, Philipp (1903). "Über die Absorption von Kathodenstrahlen verschiedener Geschwindigkeit," *Annalen der Physik* **12**, 714-744.

Lodge, Oliver (1903). "Modern views of matter," *Annual Report of the Smithsonian Institution, 1903*, 215-228.

--- (1906). *Electrons, or the Nature and Properties of Negative Electricity* (London: Bell and Sons).

Lorentz, Hendrik A. (1952). *The Theory of Electrons and its Applications to the Phenomena of Light and Radiant Heat.* New York: Dover Publications.

Maier, Clifford L. (1964). *The Role of Spectroscopy in the Acceptance of an Internally Structured Atom 1860-1920*. Ph.D. dissertation. University Microfilms no. 64-10,272.

Maxwell, James Clerk (1965). *The Scientific Papers of James Clerk Maxwell*, ed. W. D. Niven. New York: Dover Publications.

McCormmach, Russell (1966). "The atomic theory of John William Nicholson," *Archive for History of Exact Sciences* **3**, 160-184.

Mehra, Jagdish and Helmut Rechenberg (1982). *The Historical Development of Quantum Theory*, vol. 1. New York: Springer.

Merz, John T. (1965). *A History of European Thought in the Nineteenth Century*, 4 vols. New York: Dover Publications.

Nägeli, Carl W. (1884). *Mechanisch-Physiologischen Theorie der Abstammungslehre*. Munich: R. Oldenbourg.

Nagaoka, Hantaro (1904). "Kinetics of a system of particles illustrating the line and the band spectrum and the phenomena of radioactivity," *Philosophical Magazine* **8**, 445-455.

Nernst, Walther (1907). *Theoretische Chemie*. Stuttgart: Ferdinand Enke.

Nicholson, John W. (1911a). "A structural theory of chemical elements," *Philosophical Magazine* **22**, 864-889.

--- (1911b). "The spectrum of nebulium," *Monthly Notices of the Royal Astronomical Society* **72**, 49-64.

--- (1912a). "On the new nebular line at λ4353," *Monthly Notices of the Royal Astronomical Society* **72**, 693.

--- (1912b). "The constitution of the solar corona. III," *Monthly Notices of the Royal Astronomical Society* **72**, 729-739.

Nye, Mary J. (1972). *Molecular Reality: A Perspective on the Scientific Work of Jean Perrin*. London: MacDonald.

Pauli, Wolfgang (1994). "Rydberg and the periodic system of the elements," pp. 73-77 in Charles P. Enz and Karl von Meyenn, eds., *Wolfgang Pauli: Writings on Physics and Philosophy*. Berlin: Springer-Verlag.

Pearson, Karl (1885). "On a certain atomic hypothesis," *Transactions of the Cambridge Philosophical Society* **14**, 71-120.

--- (1891). "Ether squirts," *American Journal of Mathematics* **13**, 309-372.

Perrin, Jean (1901). "Les hypothèses moléculaires," *Revue Scientifique* **15**, 449-461.

Porter, Theodore M. (2004). *Karl Pearson: The Scientific Life in a Statistical Age*. Princeton: Princeton University Press.

Rayleigh, Lord (1906). "On electrical vibrations and the constitution of the atom," *Philosophical Magazine* **11**, 117-123.

Redtenbacher, Ferdinand (1857). *Das Dynamidensystem: Grundzüge einer mechanischen Physik*. Mannheim: Friedrich Bassermann.

Romer, Alfred (1970). *Radiochemistry and the Discovery of Isotopes*. New York: Dover Publications.

Rosenberger, Ferdinand (1965). *Die Geschichte der Physik*, vols. 1-3. Hildesheim: Georg Olms Verlagsbuchhandlung.

Rutherford, Ernest (1906). *Radioactive Transformations*. London: Constable & Co.

--- (1911). "The scattering of α– and β–particles and the structure of the atom," *Philosophical Magazine* **21**, 669-688.

--- (1913a). *Radioactive Substances and their Radiations*. Cambridge: Cambridge University Press.

--- (1913b). "The structure of the atom," *Nature* **92**, 423.

Rydberg, Johannes R. (1913). "Untersuchungen über das System der Grundstoffe," *Lunds Universitets Årsskrift* **9**, No. 18.

Scerri, Eric R. (2007). *The Periodic Table: Its Story and its Significance*. Oxford: Oxford University Press.

Schidlof, Arthur (1911). "Zur Aufklärung der universellen elektrodynamischen Bedeutung der Planckschen Strahlungskonstanten *h*," *Annalen der Physik* **35**, 90-100.

Schönbeck, Charlotte (1982). "Atommodelle um 1900," pp. 67-96 in Charlotte Schönbeck, ed., *Atomvorstellungen im 19. Jahrhundert*. Paderborn: Ferdinand Schöningh.

Schott, George A. (1904). "On the kinetics of a system of particles illustrating the line and band spectrum," *Philosophical Magazine* **8**, 384-387.

--- (1907). "On the electron theory of matter and on radiation," *Philosophical Magazine* **13**, 189-213.

Sinclair, Steve B. (1987). "J. J. Thomson and the chemical atom: From ether vortex to atomic decay," *Ambix* **34**, 89-116.

Snelders, Harry A. M. (1974). "A bio-bibliography of the Dutch amateur physicist A. J. van den Broek (1870-1926)," *Janus* **61**, 59-72.

Soddy, Frederick (1913). "Intra-atomic charge," *Nature* **92**, 399-400.

Stark, Johannes (1910). *Prinzipien der Atomdynamik, Teil I: Die Elektrischen Quanten*. Leipzig: Hirzel.

Stranges, Anthony N. (1982). *Electrons and Valence: Development of the Theory, 1900-1925.* College Station: Texas A&M University Press.

Sutherland, William (1899). "Cathode, Lenard and Röntgen rays," *Philosophical Magazine* **47**, 269-284.

--- (1901). "The cause of the structure of spectra," *Philosophical Magazine* **2**, 245-274.

Thomson, Joseph J. (1897). "Cathode rays," *Philosophical Magazine* **44**, 293-316.

--- (1899). "On the masses of the ions at low pressures," *Philosophical Magazine* **48**, 547-567.

--- (1904a). "On the structure of the atom," *Philosophical Magazine* **7**, 237-265.

--- (1904b). *Electricity and Matter*. London: Constable & Co.

--- (1904c). "On the structure of the atom: An investigation of the stability and periods of oscillation of a number of corpuscles arranged at equal intervals around the circumference of a circle," *Philosophical Magazine* **7**, 237-265.

--- (1905). "The structure of the atom," *Proceedings of the Royal Institution* **18**, 1-15.

--- (1906). "On the number of corpuscles in an atom," *Philosophical Magazine* **11**, 769-781.

--- (1910). "The scattering of rapidly moving electrified particles," *Proceedings of the Cambridge Philosophical Society* **15**, 465-471.

--- (1913). "On the structure of the atom," *Philosophical Magazine* **26**, 792-799.

--- (1921). "La structure de l'atome," pp. 1-74 in Robert B. Goldschmidt, Maurice de Broglie and Frederick A. Lindemann, eds., *La structure de la matière. Rapports et discussions du Conseil de Physique tenu à Bruxelles du 27 au 31 octobre 1913 sous les auspices de l'Institut International de Physique Solvay*. Paris: Solvay Institute.

Thomson, William (1904). "Plan of a combination of atoms having the properties of polonium or radium," *Philosophical Magazine* **8**, 528-534.

Van den Broek, Antonius J. (1913). "Intra-atomic charge," *Nature* **92**, 372-373.

Van Spronsen, J. W. (1969). ”Gustavus Detlef Hinrichs discovered, one century ago, the periodic system of chemical elements,” *Janus* **56**, 47-62.

Weber, Wilhelm (1871). “Über elektrodynamische Massenbestimmungen, insbesondere über das Princip der Erhaltung der Energie,” *Abhandlungen der Sächsischen Gesellschaft der Wissenschaften (Leipzig)* 10, 1-62.

Wheaton, Bruce R. (1978). ”Philipp Lenard and the photoelectric effect, 1899-1911,” *Historical Studies on the Physical Sciences* **9**, 299-322.

Wilson, William (1956). “John William Nicholson, 1881-1955,” *Biographical Memoirs of Fellows of the Royal Society* **2**, 209-214.

Wise, M. Norton (1981). “German concepts of force, energy, and the electromagnetic ether: 1845-1880,” pp. 269-307 in Geoffrey N. Cantor and Michael J. S. Hodge, eds., *Conceptions of Ether: Studies in the History of Ether Theories 1740-1900.* Cambridge: Cambridge University Press.

Yagi, Eri (1964). “On Nagaoka’s Saturnian atomic model,” *Japanese Studies in the History of Science* **3**, 29-47.

Zapffe, Carl A. (1969). ”Gustavus Hinrichs, precursor of Mendeleev,” *Isis* **60**, 461-476.

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