CHAPTER 1.2

Plum puddings and Bohr's atom

*Jaume Navarro**

Abstract

Folk history of science speaks about a plum pudding atomic *model*, formulated by Joseph John Thomson with the use of his corpuscles (electrons), which was largely abandoned after Ernst Rutherford's experiments and Niels Bohr's quantum atom. In this paper I explore two related issues: to what extent should we understand Thomson's views as a *model* for the atom, and what happened with this *model* in the years after 1913. I argue that J.J. Thomson did not formulate a consistent atomic *model* with electrons as the main building block, since his views on electricity, matter and radiation always relied on what he called "Faraday tubes". These consisted of ether vortical tubes whose properties were meant to explain the mass and electrification of the corpuscles and of the atoms. They also became the physical structures underpinning any explanation of quantum phenomena like atomic spectra, the emission of light and, later on, in the late 1920s, electron diffraction. Thus, the only *model* he consistently defended were these Faraday tubes and not so much a plum pudding atom.

Key words: Joseph John Thomson; Faraday tubes; plum pudding model; ether; atomic model; corpuscles.

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* Ikerbasque Research Professor, University of the Basque Country, Spain.
E-mail: jaume.navarro@ehu.es

1. Introduction

The annual summer meeting of the British Association for the Advancement of Science in 1913 took place in Birmingham from 10 to 17 September. The first of three papers in *Philosophical Magazine* in which Niels Bohr presented his atomic model had appeared only in July, while the second instalment was fresh from the press in the September issue, and the third would appear two months later. Thus, Bohr's ideas were mentioned only in passing, and in the broader context of a discussion on the quantum theory of radiation. Indeed, the meeting was the first major event in which British physicists publicly engaged in an open debate on the validity of the quantum theory, a debate that was led by James Jeans.[1]

As is well known, most physicists, especially in the British tradition, had so far been working with the loose image of what was known as J.J. Thomson's plum-pudding model;[2] a model that stressed the role of the corpuscle-electrons and their configuration within the atom as a way to account for the physical and chemical properties of the elements, while leaving the nature of the positive electrification somewhat undefined. That had paved the way for Ernst Rutherford's suggestion that the positive charge might be occupying a minuscule position in the centre of the atom to make an impact among those interested in imagining and modelling a structure for the atom based on the intra-atomic configuration of electrons. Niels Bohr disappointing research stay in Thomson's Cambridge and later move to Rutherford's Manchester completes the picture of the genesis of Bohr's atom.[3]

The story-line one normally finds in popular books and historical introductions to science textbooks follows the pattern Thomson–Rutherford–Bohr, transmitting the idea of not only a continuity between these three "models", but also of the almost inevitable substitution of one model by the next. As a matter of fact, this pat-

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[1] Navarro (2013).

[2] For the origin of this expression see Hon and Goldstein (2013).

[3] See Aaserud and Heilbron (2013), chapters 1.2 and 1.3, for a first-person account of Bohr's experiences in both places.

tern is the one we find under the pen of historian John L. Heilbron, whose seminal work sets the formulation of the new quantum model by Bohr within the tradition of atomic model building that had originated with Thomson's own plum-pudding.[4]

In this paper, I want to explain a rather different story about Thomson's model. My purpose is to emphasise that his work between 1891 and 1930 can also be understood putting his Faraday tubes, rather than his corpuscles (later electrons), at the centre of his worldview. I shall stress the importance of this ether-based structure in what is usually known as the plum-pudding model, and the permanence of the tubes in his ulterior atomic models. As we shall see, Thomson used these tubes to account for the nature of the positive electrification in his early atomic model, later to become crucial in providing a more conventional–"classical"–explanation of the theory of the quanta. Furthermore, Faraday tubes became increasingly real in the mind of J.J. Thomson, a process that culminated with the direct observation of electron diffraction in 1927, which he took as the ultimate proof of his ether-based worldview.[5]

2. The origin of Faraday tubes and their relation to the electron

"Faraday tubes", "Faraday tubes of force", or, simply, "tubes of force" were a working tool that J.J. Thomson started using in 1891, and which he managed to spread among many British physicists thanks to his influential position in early twentieth-century physics. This mental model was a *sui generis* extension of Faraday's lines of force designed to give an explicit dynamical account of the discreteness observed in electric phenomena. Electrostatically, they were unit tubes of electrostatic induction, all with the same strength corresponding to the electrolytic unit of charge; mechanically, they were structures in the ether in the form of vortical tubes that begin and terminate in matter or form closed circuits. These tubes had a

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[4] Heilbron (1964) and (1981).

[5] For a detailed account of this story, see Navarro (2012).

direction that determined the character of the charge (positive or negative) received by the atoms at the extremes of each tube.

In his presentations, Thomson attributed these tubes of force to Faraday and Maxwell, thus setting himself in the tradition of the two British authorities on electricity and magnetism. In his 1893 book *Recent Researches on Electricity and Magnetism*, for instance, which was intended as a sequel to Maxwell's *Treatise*, Thomson explicitly quoted the latter's description on how to generate a tube of induction force from a line of force: "If the line of force moves so that its beginning traces a closed curve on the positive surface, its end will trace a corresponding closed curve on the negative surface, and the line of force itself will generate a tubular surface called a tube of induction."[6] But, as Olivier Darrigol has pointed out, Thomson's Faraday tubes were a complex hybrid of concepts from Faraday and Maxwell, as well as from William Hicks, John H. Poynting, Hermann von Helmholtz and Arthur Schuster.[7]

Although triggered by his research project designed to understand the interaction between ether and matter in the phenomena of electric discharge in tubes filled with gases, Faraday tubes were, from the very beginning, much more than simply an *ad hoc* instrument to explain one specific set of phenomena: they constituted the basic structure of the ether itself, which Thomson understood in terms of a dynamic fluid. Furthermore, they were also an instrument to circumvent Maxwell's concept of electric displacement, which Thomson found impossible to visualize and, therefore, to fully rationalize.[8]

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6. Maxwell (1873), § 82.

7. Darrigol (2000), p. 269.

8. "Experience has, I think, shown that Maxwell's conception of electric displacement is of somewhat too general a character to lend itself easily to the formation of a conception of a mechanism which would illustrate by its working the processes going on in the electric field. For this purpose the conception of tubes of electrostatic induction introduced by Faraday seems to possess many advantages. If we regard these tubes as having a real physical existence, we may, as I shall endeavour to show, explain the various electrical processes, – such as the passage of electricity through metals, liquids, or gases, the production of a current, magnetic force, the induction of currents, and so on, – as arising from the contraction or elongation of such tubes and their motion through the electric field" (Thomson (1891), pp. 149-50).

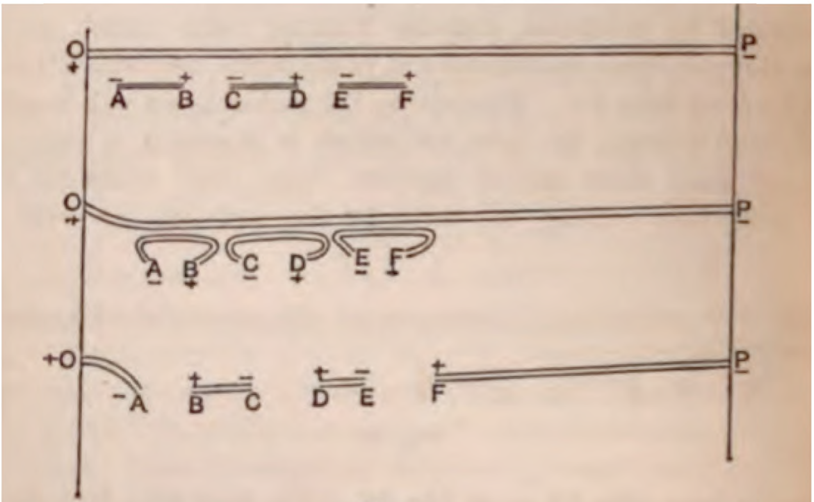

Fig. 17.

Figure 1. Faraday tubes represent the electric field in a discharge tube (OP) and in the interior of every molecule (AB, CD, EF). A perturbation in OP would lead to its fracture and the split and rearrangement of molecules.

The immediate role of Faraday tubes was to obtain a tentative visual explanation of the process going on inside a discharge tube. Figure 1, extracted from *Recent Researches*, is rather self-explanatory:[9] the short Faraday tubes AB, CD and EF represent molecules of the gas which, in the presence of a field between the ends of the tube, represented by the long tube OP, line up in the direction of the field. The molecules of the gas thus polarized will attract the long tube OP, since this is of opposite sign to AB, CD and EF. When the field is strong enough, there will be a splitting of the tubes, which means a splitting of the molecules, creating what was known as a Grothus chain (last stage on Figure 1).

As Isobel Falconer has thoroughly documented, the introduction of Faraday tubes was a first step towards the treatment of charge in discrete units, a move that, in retrospect, was crucial for Thom-

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[9] Thomson (1893).

son's explanation of electricity in terms of corpuscle-electrons.[10] Prior to 1890, Thomson did not think in terms of discrete charges but rather in terms of exchanges of energy. The use of Faraday tubes (together with the analogy with electrolysis) changed things: charge was now a phenomenon at the interface between ether and matter, between Faraday tubes and matter, and, since the former had a fixed and specific strength, the magnitude of the electric charge was not continuous but discrete. If the tubes of force were real physical entities, and not merely ideal devices, there should be an actual physical limit to their divisibility. This idea opened the door to a quantification of energy and charge within the framework of a continuous ether: discreteness was not, for Thomson, an essential quality of the ether. In other words, Faraday tubes allowed for a theory in which electric charge was at the same time discrete and a boundary phenomenon, not a substance.

Thomson finally managed to formulate a theory of the conduction of electricity in gases making use of the corpuscles he found in 1897. As a matter of fact, Thomson's corpuscles were at first the tool for a final theory of conductivity, and only later a universal constituent of matter and a subatomic particle.[11] Moreover, as we shall see in the next section, the staging of the corpuscle did not, in the least, diminish the importance of Faraday tubes: both entities were compatible, but belonged to different explanatory layers.

3. The "corpuscular" theory of matter

Once the existence of corpuscles was settled, around 1900, J.J. Thomson began to explore all the possibilities of an entity that seemed to hold the key to the intimate connection between electricity and matter. It was the summit of his long-term project of understanding the relationship between matter and electricity – between matter and ether – that had been the driving force of his research programme on electric discharge in gases. It would also support a monistic understanding of nature if one could not only explain at-

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[10] Falconer (1987).

[11] Falconer (2001).

oms in terms of corpuscles but also understand corpuscles in terms of the ether. For a while, this monistic view of nature seemed to be only a step away.

The highlight of this period was Thomson's course in Yale, in May 1903, published immediately afterwards as *Electricity and Matter*. As was typical of him in those early years of the electron, the storyline he drew sought to demonstrate, first and foremost, the existence of corpuscles and their role in explaining electrification. For example, Chapter 4, "The Atomic Structure of Electricity", comes before the chapter on "The Atomic Structure of the Atom". Without the former, he could not argue for the latter. The contemporary reader may be further surprised by the content of the first three chapters, which are devoted to Thomson's discrete Faraday tubes. Corpuscles had not done away with them, on the contrary. Corpuscles were actually better explained in terms of Faraday tubes when supposing that the "mass of a charged particle arises from the mass of ether bound by the Faraday tube associated with the charge."[12] Thomson thus generalized his 1881 calculation of the apparent mass of a charged body due to the electromagnetic inertia, a calculation usually regarded as one of the foundations of the electromagnetic theory of matter.[13]

Thomson showed that this electromagnetic inertia was comparable to the inertia of a homogeneous fluid ether dragged by the tubes of force, this drag being maximal when the tube's axis was perpendicular to the motion of the tube, and zero in the parallel configuration (as would be the case for an open pipe moving through water). As he knew (from Heaviside) that the relative density of tubes in the equatorial plane increased with the velocity of the charged body, he concluded that the electromagnetic inertia should increase with the velocity of the particle, in qualitative agreement with the German theories of a purely electromagnetic electron: "When a Faraday tube is in the equatorial region it imprisons more of the ether than when it is near the poles, so that the displacement of the Faraday tubes from the pole to the equator will increase

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[12] Thomson (1904a), p. 41.

[13] Thomson (1881).

the amount of ether imprisoned by the tubes, and therefore the mass of the body."[14] Thomson went on to show that the "assumption that *the whole of the mass is due to the charge*",[15] to which he was highly inclined, agreed with Walther Kaufmann's measurement of the velocity-dependence of the mass of the corpuscle (electron).

If the mass of the moving charged sphere was associated with the mass of the ether carried along by the Faraday tubes, this would mean that, in principle, the mass of any charged particle extended indefinitely with the tubes. That was not a problem, he argued, taking into account that in small particles like the corpuscles, the mass of ether carried by the tubes decreased according to the fourth power of the distance from the particle, and thus, "all but the most insignificant fraction of mass is confined to a distance from the particle which is very small indeed compared with the dimensions ordinarily ascribed to atoms."[16] And from this he advanced his dreamt-of-ontology: "that the *whole* mass of any body is just the mass of ether surrounding the body which is carried along by the Faraday tubes associated with the atoms of the body. In fact, that all mass is mass of the ether, all momentum, momentum of the ether, and all kinetic energy, kinetic energy of the ether."[17]

And what was the relationship between these Faraday tubes and the charges of electricity? Only that the latter *were* "the beginnings and the ends" of these tubes. Here language failed him, since he was actually saying that there was no clear distinction between mass, charge and ether. If the mass of a particle expressed the mass of ether carried by Faraday tubes, electrification was the phenomenon at the ends of tubes. "If this view of the structure of electricity is correct, each extremity of a Faraday tube will be the place from which a constant fixed number of tubes start or at which they arrive."[18]

As for the structure of the atom, Thomson cited various empirical evidence that corpuscles could be ejected from the atom, and

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[14] Thomson (1904a), p. 43.

[15] Thomson (1904a), p. 48 (emphasis in the original).

[16] Thomson (1904a), p. 50.

[17] Thomson (1904a), p. 51.

[18] Thomson (1904a), p. 71.

concluded: "It may thus not be superfluous to consider the bearing of the existence of corpuscles on the problem of the constitution of the atom". At this stage, he did not have, strictly speaking, a model for the atom, but a research programme: "although the model of the atom to which we are led by these considerations is very crude and imperfect, it may perhaps be of service by suggesting lines of investigation likely to furnish us with further information about the constitution of the atom."[19]

And what was this atom like? J.J. Thomson thought of it as a collection of what he called doublets, "with a negative corpuscle at one end and an equal positive charge at the other, the two ends being connected by lines of electric force which we suppose to have a material existence."[20] Thus, the atom appeared as an assemblage of Faraday tubes with one very condensed end, forming the individual corpuscles, and another end spreading over a comparatively much-larger space. In this way, he could imagine that "the quantity of ether bound by the lines of force, the mass of which we regard as the mass of the system, will be very much greater near the corpuscle than elsewhere",[21] or, in other words, that the mass of the atom could be considered as the sum of the masses of what we see as corpuscles. This gives us an atom about which we can speak at different levels. Deep down, it is basically an assemblage of Faraday tubes; but, at the next level, we can visualize it as an assemblage of corpuscles in a sea of positive electrification. With the latter image, he discussed the problem of the stability of such a system, the light this threw on chemical bonding and also on radioactivity. And that is the part of the story that was really influential and which forms the backbone of the canonical histories on the modelling of the atom.

The highly speculative tone of the Yale lectures partly disappeared in a 1904 paper in the *Philosophical Magazine*.[22] Certainly, in that paper, as well as in a public lecture on 10 March 1905, Thom-

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[19] Thomson (1904a), p. 92.

[20] Thomson (1904a), p. 93.

[21] Thomson (1904a), p. 94.

[22] Thomson (1904b).

son described his atoms as an assemblage of corpuscles, without reference to their intrinsic nature as endpoints of Faraday tubes. His starting point was then the existence of corpuscles, the only building block from which he constructed his atomic model, without reference to their intimate nature: "if the corpuscles form the bricks of the structure, we require mortar to keep them together. I shall suppose that positive electricity acts as the mortar, and that the corpuscles are kept together by the attraction of positive electricity."[23] Faraday tubes and corpuscles were entities at different ontological levels and Thomson thought it would be more helpful to present his model of the atom on the basis of corpuscles, leaving their nature for other, more speculative, audiences like the one in the Silliman lectures in Yale.[24] In this way, he managed to present his atom in a fashion that was very appealing to chemists as well as physicists. J.J. Thomson wanted to be very clear in 1905 that his corpuscular atom was both the atom of the physicists and of the chemists and, thus, he could claim to have found the final link between the two scientific traditions.

4. Faraday tubes and radiation

From 1907 to 1910, J.J. Thomson did not explicitly speculate any further on his atomic model. He did not change or abandon it, but he certainly had no further arguments to give it more consistency, due to the problem with positive electrification and the challenge it posed to his monistic view. That explains why his research shifted toward the analysis of "positive rays", an experimental program that would occupy him thereafter and on which he would have great expectations.[25]

Like many other physicists, Thomson was also busy trying to understand the nature of radiation, especially the new x rays. Faraday tubes were again the explanatory tool he used since, being dis-

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[23] Thomson (1905), p. 1.

[24] The Silliman lectures were designed to show the presence and providence of God as manifested in the natural world and were, thus, a forum for speculative thinking.

[25] Falconer (1988).

crete ether structures, they could account for both the corpuscular and undulatory aspects this radiation seemed to possess. Only indirectly, his explanations of radiation phenomena based on Faraday tubes implied a continuation of his atomic model.

As early as 1898, Thomson published a paper in which he put forward "a theory of the connexion between cathode and Röntgen rays."[26] When a moving corpuscle suddenly came to a halt, some time was required for the change to propagate through the surrounding electric and magnetic fields, the further away from the corpuscle the more time it took. Such a change would be communicated in the form of a pulse generated by the stopping of the charged corpuscle in the electromagnetic field. In 1903, he developed this idea more fully and in the more visual terms of his Faraday tubes:[27]

> Let us consider the case of a charged point moving so slowly that the Faraday tubes are uniformly distributed, and suppose the point to be suddenly stopped, the effect of stopping the point will be that a pulse travels outwards from it ... , but as the Faraday tubes have inertia they will until the pulse reaches them go on moving uniformly ... , i.e. they will continue in the same state of motion as before the stoppage of the point. ... Thus the stoppage of the charged particle is accompanied by the propagation outwards of a thin pulse of very intense electric and magnetic force; pulses produced in this way constitute, I believe, the Rontgen rays.[28]

Now that he had a theory to account for x rays, light surely *had* to be explained in similar terms. Thus, if one pulse of vibration on a Faraday tube came from the sudden stopping of a corpuscle, one could equally imagine that "if a charged body were made to vibrate in such a way that its acceleration went through periodic changes, periodic waves of electric and magnetic force would travel out from the charged body."[29] These would, by Maxwell's theory, be light

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[26] Thomson (1898).

[27] For a full account of Thomson's work to explain radiation see Wheaton (1983).

[28] Thomson (1903), pp. 537-539.

[29] Thomson (1904a), p. 62.

waves. With this link between Faraday tubes and the propagation of light, Thomson introduced some sort of discreteness in the structure of light:

> The Faraday tubes stretching through the ether cannot be regarded as entirely filling it. They are rather to be looked upon as discrete threads embedded in a continuous ether, giving to the latter a fibrous structure; but if this is the case, then on the view we have taken of a wave of light the wave itself must have a structure, and the front of the wave, instead of being, as it were, uniformly illuminated, will be represented by a series of bright specks where the Faraday tubes cut the wave front.[30]

A few years later, he followed this thread in trying to visualize the discrete structure of light. In 1907, he supposed that "the ether has disseminated through it discrete lines of electric force and that these are in a state of tension and that light consists of transverse vibrations, Röntgen rays of pulses, travelling along these lines."[31] The energy of the wave would be concentrated in these pulses, thus giving a discrete appearance to the wave-front when traversing a black screen: "the energy of the wave is thus collected into isolated regions, these regions being the portions of the lines of force occupied by the pulses or wave motion." The effect would be, of course, very similar to that given by what he calls "the old emission theory" that spoke of corpuscles of light. The independence of intensity was explained in the following terms: "if we consider light falling on a metal plate, if we increase the distance of the source of light," and considering spherical symmetry from the source, "we shall diminish the number of these different bundles or units falling on a given area of the metal, but we shall not diminish the energy in the individual units."

Although, ten years later, Robert Millikan saw this theory as almost equivalent to Einstein's 1905 corpuscular theory of light,[32] it is

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[30] Thomson (1904a), p. 63.

[31] Thomson (1907), p. 421.

[32] Millikan (1917), pp. 221-223.

clear from Thomson's words that his structured light is perfectly within the bounds of ether physics. It is the physicality of Faraday tubes which allows for this structure of light:

> Thus the structure of the light would be of an exceedingly coarse character, and could perhaps best be pictured by supposing the particles on the old emission theory replaced by isolated transverse disturbances along the lines of force. The greater the frequency of the light the greater is the energy in each unit, so that if it requires a definite amount of energy to liberate a corpuscle from a molecule of a gas, light whose wave length exceeds a particular value, which may depend on the nature of the gas, will be unable to ionize the gas, for then the energy per unit will fall below the value required to ionize the gas.[33]

As is well known, the dichotomy between corpuscular and undulatory theories of light would persist until the general acceptance of the Einstein's quantum of light and the formulation of a generalized principle of wave-particle duality, both in the mid-1920s.[34] In the meantime, physicists had to come to terms in the best way they could with what Thomson famously called a "battle between a tiger and a shark."[35]

A related conundrum was the increasing impact of the quantum theory. J.J. Thomson could certainly not agree to a theory in which the transfer of energy was in discrete units not as a result of the nature of mechanism (like in his Faraday tubes model) but as an *a priori* imposition on the model. The quantum had to be a consequence, not a pre-condition. That is why Thomson moved a step forward in his search to accommodate the discrete phenomena of light in a continuous ether-filled world.

Around 1909, he thought of reducing the number of Faraday tubes originating from a corpuscle to one. Following the tradition that the electric field spreads out from a charged body in all direc-

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[33] Thomson (1907), p. 423.

[34] Stuewer (1975).

[35] Thomson (1925), p. 15. Wheaton (1983) takes its title from this quote.

tions, J.J. had so far imagined a large number of Faraday tubes starting from one corpuscle and dispersing with spherical symmetry into space. But now he decided to regard this uniformity of the field in all directions as a statistical measure stemming from the fact that most work on electricity was done with bodies containing a large number of corpuscles, "the result [being] the same whether each individual field is uniformly distributed in all directions or is confined within a small solid angle."[36] What he got from this was that "the electric field due to a number of corpuscles is a mosaic, as it were, made up of a number of detached fields. The electric field itself, as well as the electric charges in it, being molecular in constitution." As in his previous model, radiation would originate in the sudden stopping of a corpuscle and the transmission of the corresponding kick along the Faraday tube. By contrast, however, energy would not spread in all directions but only in one: the direction corresponding to the one and only Faraday tube.

As for phenomena like interference, he thought that, unlike a purely corpuscular theory of light, his theory could also account for those. In his view, one could get interference if a large number of Faraday tubes with related frequencies in their fluctuations went through a slit. And this might be possible, taking into account that, although each Faraday tube was originating in one corpuscle only, one could easily imagine that corpuscles close to each other would have movements of related frequencies: "For consider a corpuscle vibrating in a definite period; in its neighbourhood there will be many other systems having the same time of vibration, and the vibrations of these will be excited by resonance and will be in phase relation with the primary vibration."[37] Even though, as usual, Thomson basically stayed at a qualitative level, his model seemed to be superior to the quantum hypothesis, since the latter could not at all explain interference phenomena.

The interaction between radiation and matter, which had been the origin of Planck's hypothesis, was a different matter. The early quantum theory was gaining in popularity since it was successfully

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[36] Thomson (1910), p. 302.

[37] Thomson (1910), p. 311-312.

explaining an increasing array of phenomena. In 1913, he challenged the quantum theory by suggesting that "we cannot assume that the forces due to the charges of electricity inside the atom are of exactly the same character as those given by the ordinary laws of Electrostatics."[38] And he imagined that corpuscles inside the atom were subject to two kinds of forces: an attractive one, proportional to the square of the distance, and a repulsive one, proportional to the cube of the distance. Capitalising on his earlier suggestion that every corpuscle was the origin of only one Faraday tube, he now assumed rather that each corpuscle was trapped in one tube of force, not entering "at this stage into any consideration as to the origin of this force; we shall simply postulate its existence."[39] The atomic corpuscle could oscillate in the direction of the tube, but needed a minimum amount of energy to move transversely and quit the tube. This minimal energy would coincide with multiples of Planck's constant. Once again, his main point was to emphasize that one need not assume that "radiant energy is molecular in structure," but that the same results could be obtained "if the mechanism in the atom by which the radiant energy is transformed to kinetic energy is such as to require the transference to the mechanism of a definite amount of energy."[40] However, the mechanisms Thomson was putting forward to explain radiation were more and more *ad hoc* and were not fully capable of giving a consistent picture of the structure of the atom.[41]

5. Faraday tubes after the Great War

Bohr's atomic model, especially after the work done by Sommerfeld during and immediately after the war, did not bring Thomson's speculations to an end. Faraday tubes had increasingly become more and more real in Thomson's mind, and he sought to legitimise them by using them in areas other than radiation. Particularly interesting

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38. Thomson (1913), p. 793.
39. Thomson (1913), p. 794.
40. Thomson (1913), p. 792.
41. See also Thomson (1912).

is their migration to explain chemical bonding. Already in 1914 he had suggested that the key to understand the bond between atoms in a molecule was twofold: the tendency of all atoms towards "saturation" and the existence of Faraday tubes. The former was achieved when the atom had eight corpuscles in the outmost layer. In that case, corpuscles were fixed in their relative positions. When their number was less than the maximum eight, corpuscles were mobile inside the atom, a mobility that was only limited by the fact that every corpuscle was linked to the positive part of the atom – which he by now accepted occupied a central position in the atom – by a Faraday tube. This allowed for the possibility of a particular corpuscle gaining stability, not by abandoning the atom, but by having its Faraday tube ending in the positive part of another nearby atom.[42]

As was often the case, Thomson did not explain the mechanism by which this dislocation of the Faraday tubes might take place, but he merely emphasized the explanatory power of this model for a large number of molecules, especially organic compounds. During the War, the school of organic chemistry headed by Gilbert N. Lewis in America was highly influenced by Thomson's ideas on molecular bonding, and they regarded him as one of the founding fathers of the new field of physical chemistry. In turn, Thomson would see the dashes used in organic formulation as a representation of his Faraday tubes.

A last use of his Faraday tubes as an explanatory tool both for the structure of the atom and the discreteness of radiation came in 1925. Thomson gave a lecture on the structure of light in which he challenged what he saw as the uncritical acceptance of Bohr's theory, a lecture that was much reported in the popular science media. In it, Thomson stressed that quantification was only the result of a process in the continuous medium. Figures 2 and 3 show very graphically his idea for the process of photon emission and absorption, respectively, in the simple case of a hydrogen atom. Assuming, as he did, that the proton (P) and electron (E) in the atom interacted by means of a Faraday tube connecting them, one could imagine what happened to the tube when an electron "jumped" from one orbit of high ener-

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[42] Thomson (1914), p. 782.

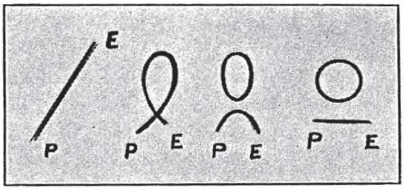

Figure 2

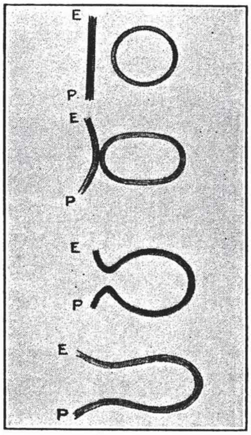

Figure 3

gy to an orbit of lesser energy. The Faraday tube would first bend, and then form a loop that would detach from the original tube: this would constitute the emission of a photon. Similarly, a quantum of radiation, in the form of a closed-loop Faraday tube, could be absorbed by the tube uniting a proton and an electron, providing the energy for the electron to jump to a higher energy state.[43]

Faraday tubes received a last boost when J.J. Thomson's son, George Paget Thomson, obtained the first photographs of electron diffraction, thus proving the principle of Louis de Broglie.[44] The father felt his ontology had proved true and that electron diffraction was a sign that discrete models of matter and energy were only rough approximations of reality. In his mind, the "very interesting theory of wave dynamics put forward by L. de Broglie," was not in contradiction to classical mechanics. In the first of a series of papers he tried to show that "the waves are also a consequence of classical dynamics if that be combined with the view that an electric charge is not to be regarded as a point without structure, but as an assemblage of lines of force starting from the charge and stretching out into space."[45]

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[43] Thomson (1924) and (1925).

[44] Navarro (2010).

[45] Thomson (1928a), p. 191.

The diffraction experiments showed that "we have energy located at the electron itself, but moving along with it and guiding it, we have also a system of waves."[46] Following the similarities with his structure of light of 1924, he supposed that the electron "had a dual structure, one part of this structure, that where the energy is located, being built up with a number of lines of electric force, while the other part is a train of waves in resonance with the electron and which determine the path along which it travels."[47] For him, the association of a wave with an electron was not a new phenomenon. It had already been made when, in the late eighteenth century, the corpuscles of light that Newton had postulated needed to be complemented by wave explanations. It was not so strange to see that the new corpuscles, the electrons, had to receive similar treatment. And Faraday tubes were the key to this dual conception.

6. Conclusion

Having discussed the background to J.J. Thomson's highly popular (then and now) plum pudding model and the fundamental importance of his Faraday tubes, we can now have a more informed comparison between Bohr's and Thomson's atomic models. One could argue that Bohr's 1913 atom was a physical model *tout court*, in the sense that it included a clear set of pieces (electrons and nuclei) arranged in a very particular way (quantised orbits), while Thomson's was not so much a model but a consequence of a larger research program (with his Faraday tubes as the key feature). Thus, Thomson's underdetermined model was more flexible than Bohr's early atom. The importance of Faraday tubes in the mind of J.J. Thomson also explains why he did not see Bohr's as a competing atomic model but only as a (for him invalid) theory of radiation. Faraday tubes had been and still were his true model and Bohr's atom came only as a challenge and an opportunity to expand their explanatory power and, thus, to reinforce their reality as ethereal structures.

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[46] Thomson (1928b), p. 22.

[47] Thomson (1928b), p. 23.

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