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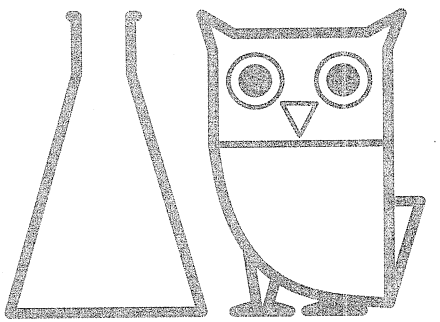

Königshausen & Neumann

How the Electrons Spend their Leisure Time: Philosophical Reflections on a Controversy between Chemists and Physicists[1]

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1. Introduction

This paper discusses an early 20th century controversy between chemists and physicists, concerning the behaviour of electrons within the atom, and its philosophical implications. First, I start with an explication of the notion of problem situation, a notion that, as I will argue, is necessary for making sense of the controversy in question. Second, I provide an outline of the controversy and account for it in terms of the different problem situations of chemists and physicists. Third, I address the question whether physicists and chemists were talking about the same thing, when they used the term "electron". To answer this question, I digress briefly and sketch the debate on the implications of meaning change for scientific realism. I show that, under certain conditions, meaning variance is compatible with a realist interpretation of theoretical entities and, thus, provide a way out for the aspiring realist, without however committing myself to a realist position. Finally, I explain in what sense the two communities were referring to the same entity by the term "electron".

2. Karl Popper and the Notion of Problem Situation

One of the most significant and neglected elements of Karl Popper's philosophy of science is his emphasis on scientific problems and problem situations. For Popper, scientific problems can be classified in two different kinds, empirical and theoretical. A scientist faces an empirical problem when

> «he wants to find a new theory capable of explaining certain experimental facts; facts which the earlier theories successfully explained; others which they could not explain; and some by which they were actually falsified.» (Popper 1968: 241.)

Theoretical problems, on the other hand, consist of «theoretical difficulties (such as how to dispense with certain *ad hoc* hypotheses, or how to unify two theories).» (*Ibid.*) Problems, according to Popper, always arise against a background which

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«consists of at least a *language*, which always incorporates many theories in the very structure of its usages ... and of many other theoretical assumptions, unchallenged at least for the time being» (Popper 1979: 165).

This background of theoretical beliefs and assumptions provides a framework that enables the emergence and formulation of a problem. «A problem together with its background ... constitutes what I call a *problem situation*.» (*Ibid.*) The background supplies the constraints that a solution to the problem should satisfy, as well as the conceptual resources that are employed to obtain that solution. Popper's notion of a problem situation has been developed by Larry Laudan, among others, who has extended Popper's insight to a comprehensive problem-oriented approach to scientific development. Laudan's major contribution is that he emphasised the importance of conceptual problems for scientific practice and provided a detailed analysis of their character. According to Laudan, there are two kinds of conceptual problems, "internal" and "external". Internal or intra-theoretic problems arise when a theory is «internally inconsistent or the theoretical mechanisms it postulates are ambiguous» or circular (Laudan 1981: 146). External problems are created when a theory

«makes assumptions about the world that run counter to other theories or to prevailing metaphysical assumptions, or when ... [it] makes claims about the world which cannot be warranted by prevailing epistemic and methodological doctrines... [or when it] fails to utilise concepts from other, more general theories to which it should be logically subordinate.» (*Ibid.*)

3. The Controversy

A kind of external conceptual problem is illustrated by a controversy between chemists and physicists which took place during the 1910s and 1920s. The controversy concerned the behaviour of electrons within the atom. The chemists advocated a static electron whereas the physicists favoured a dynamic electron that was in constant motion within the atom. The problem arose because the chemists chose to «adopt the concepts of atomic physics — electrons, nuclei, and orbits — and try to explain the chemical facts in terms of these», without «accept[ing] the physical conclusions in full, and ... assign[ed] to these entities properties which the physicists have found them not to possess».(Sidgwick 1929: Preface.) In Millikan's words, the controversy concerned «how the electrons spend their leisure time, the portions of their lives within the atom when they are not radiating.» (Millikan 1924: 1411)

The conflict goes back to 1902 when G.N. Lewis conceived a cubic model of the atom. The new ideas on the electronic constitution of matter along with the periodic properties of the chemical elements were the central elements of his problem situation. The two main desiderata were to portray the atom as composed primarily of electrons and to provide a physical interpretation, based on the new model of the atom, of the periodic table.

Both of these desiderata were fulfilled with his 1902 proposal of a cubic atom. According to that proposal, the atom had an elaborate cubic structure and was composed of electrons which occupied the vertices of a series of concentric cubes. The most important aspect of that theory, for my purposes, was that it portrayed the electron within the atom as a static particle to suit the chemical static atom. Despite the fact that «this theory of structure seemed to offer a remarkably simple and satisfactory explanation» of the formation of polar compounds it failed to explain «chemical combinations of a less polar type» such as take place in the formation of the majority of organic compounds. (Lewis 1923: 30.) Polar compounds were those that were composed of two oppositely charged ions, whereas compounds «of a less polar type» were those that were composed of neutral parts. The former were mainly inorganic substances, whereas the latter were predominantly organic substances. This is why Lewis' theory, while it was «discussed freely with my colleagues and in my classes, ... [was] given no further publicity.» (*Ibid.*)

The next stage in his development of the theory began in 1916. The most innovative aspect of that development was Lewis' idea that the chemical bond between two atoms in a molecule consisted of a *pair* of electrons that did not belong exclusively to either of the combining atoms but were, instead, shared by both of them. The origin of Lewis' conception of the shared pair bond is a question that has not been definitively answered. One thing that «seems fairly clear [is] that Lewis derived the shared pair bond in some way from the rich and suggestive speculations of [J.J.] Thomson ... and [Alfred] Parson on the nonpolar bond.» (Kohler 1971: 371). Lewis had already introduced the distinction between polar and nonpolar bonds in 1913 but he had not offered any physical mechanism that could account for the formation of nonpolar bonds. Such a mechanism was provided by Thomson in 1914 and by Parson in 1915. The problem then facing Lewis was to translate Thomson's and Parson's conceptions into the terms of his 1902 cubic model of the atom and to retain only those aspects of their theories that could fit into his own theory of atomic structure. I will briefly discuss Lewis' seminal paper "The Atom and the Molecule" and the problems that it tried to address, exhibiting the features of Lewis' conception of the electron that conflicted with those ascribed to it by the physicists.

In the beginning of that paper Lewis offered as a reason for «presenting this theory [of atomic structure] briefly in the present paper ... [that], while it bears much resemblance to some current theories of the atom, *it shows some radical points of departure from them*.» (Lewis 1916: 763; Emphasis added.) The cubic model of the atom seemed to Lewis «more probable intrinsically than some of the other theories of atomic structure which have been proposed». (Lewis 1916: 767)

Lewis' atom consisted of a core of negative and positive charges that did not partake in chemical phenomena and an outer shell of electrons that governed chemical changes. The net positive charge of the inner core was balanced by the negative charge of the outer shell so that the atom as a whole was electrically neutral. The most important aspect of that model, for my purposes, was that it portrayed the electrons as static particles which, moreover, did not strictly obey Coulomb's law. As Lewis remarked, «Electric forces between particles which are very close together do not obey the simple law of inverse squares which holds at greater distances.» (Lewis 1916: 768)

It is important to reconstruct the reasoning that led Lewis to abandon the unrestricted validity of Coulomb's law in order to see in what respects the physicists' electron, invariably subject to Coulomb's inverse square formula, was an obstacle for the understanding of chemical phenomena. There were two ways, according to Lewis,

> «in which one body can be held by another. It may, owing to a force of attraction, be drawn toward the second body until this force is gradually offset by a more rapidly increasing force of repulsion. In this case it comes to rest at a point where the net attraction or repulsion is zero...» (Lewis 1916: 772)

This was exactly the way in which electrons were held together in the atom, presumably under the attractive-repulsive action of the positive charges that were also in the atom and under their own mutual repulsion-attraction. It should be emphasised that Lewis kept silent about the nature and arrangement of the positive charges inside an atom and he did not offer any mathematically formulated alternative to Coulomb's law. As a result he was unable to show that the cubical structure and the stability of his atom followed from the collective interaction between electrons and positive charges. The qualitative nature of Lewis' model of the atom explains, to some degree, why it was not taken very seriously by the physicists.

The second way in which the electrons could be held together in the atom was the physicists' way, most notably Rutherford's. According to that model electrons were revolving around a massive, positively charged nucleus under the action of an inverse square, attractive force. Rutherford did not make any attempt to employ his model in order to explain the chemical properties of the elements and, not surprisingly, his theory did not appeal to chemists. As Lewis remarked, the so-called "planetary" model of the atom

> «seems inadequate to explain even the simplest chemical properties of the atom, and I imagine it has been introduced only for the sake of maintaining the laws of electromagnetics which are known to be valid at large distances.» (Lewis 1916: 772)

Furthermore, the advantage of «maintaining the laws of electromagnetics» was not preserved in the most sophisticated among the planetary models, namely Bohr's semi-classical model. Bohr's dynamic electron violated classical electromagnetic theory in two respects: First, it was influenced by Coulomb forces only when «the angular momentum of the electron round the nucleus in a stationary state of the system is equal to an entire multiple of a universal value [$h/2\pi$; where h is Planck's constant], independent of the charge on the nucleus.» (Bohr 1963: 15) Second, in these "stationary" states the electron violated classical electrodynamics, since it did not emit radiation.

In Lewis' view, the predictive success of Bohr's theory vis-à-vis the lines of the hydrogen spectrum could be duplicated by his own model if one assumed «that an electron may be held in the atom in stable equilibrium in a series of different positions, each of which having definite constraints, corresponds to a definite frequency of the electron». (Lewis 1916: 773) It is evident that Lewis proposed a totally classical picture of the electron which dispensed with quantum conditions. This was one of the sources of resistance to Lewis' proposal by those physicists that were engaged with the development of quantum theory.

So far we have identified three characteristics of Lewis' model that might have led to its negative reception by the physics community. First, its qualitative, non-mathematical formulation; second, its disregard for quantum conditions; and third, its violation of the strict validity of Coulomb's law. That final feature of Lewis' theory was closely related with the magnetic properties of the electron. If the electron was a tiny magnet, as Parson had suggested in 1915, the configuration of electrons inside the atom would be the product of the operation of magnetic forces, in addition to the operation of Coulomb-like electric forces. The repulsive, inverse square force between two electrons would be counteracted by an attractive, magnetic force. Thus, Parson's attribution of magnetic properties to the electron explained why electrons did not strictly obey Coulomb's law and thus justified on physical grounds a crucial aspect of Lewis' theory.

The idea of a magnetic electron also enabled another crucial innovation that Lewis introduced in 1916, namely the conception of the chemical bond as consisting of a pair of electrons shared between the combined atoms. The two electrons occupied the vertices of an edge that was common to both cubic atoms. A chemical bond of this kind would not have been possible if the only force acting between two electrons was electrostatic repulsion. A magnetic force was necessary to overcome that repulsion and draw the two particles together. Lewis theory of the shared pair bond could explain the formation of both polar and nonpolar molecules through the same single mechanism and solved problems such as the structure of ammonia and ammonium ion, «which has proved extremely embarrassing to a number of theories of valence.» (Lewis 1916: 777).

We have seen how Lewis' conception of the electron emerged out of his problem situation that consisted of a series of chemical problems along with a set of methodological constraints that determined what counted as an acceptable solution. The difference between these constraints and those that were part of the physicists' problem situation helps to explain the divergence between the physicists' and the chemists' conceptions of the electron. Before discussing the philosophical implications of that conflict it would be helpful to recapitulate the contrasting characteristics of those two conceptions.

4. A Recapitulation of the Conflict

Chemists, on the one hand, conceived the electron as a classical, static particle endowed with magnetic properties and not always subject to Coulomb forces. Physicists, on the other hand, regarded the electron as a dynamic non-magnetic particle, endowed with quantum properties, and being constantly in very high-speed elliptic motion around a positively charged nucleus under the influence of Coulomb-like attractive forces. We have already discussed the problem situation out of which the chemists' picture of the electron emerged. Central to that problem situation was the requirement for a chemical bond consisting of a pair of electrons that was shared by the atoms that constituted a molecule. From a geometrical point of view, a static electron could easily fulfil that requirement. A dynamic electron, on the other hand, that revolved around the atomic nucleus could not perform the role that was required for the interpretation of chemical phenomena, i.e., it could not belong simultaneously to more than one atoms.

There were many arguments, however, that supported the notion of a dynamic electron. First, Bohr had derived from the postulates of his atomic theory in 1913 a formula for the Rydberg constant that predicted very accurately the corresponding experimental value. Second, Bohr's theory had predicted that the spectral lines due to ionised helium (He^+) should be at a slightly different position from the corresponding hydrogen lines. Again, the predicted difference agreed exactly with the one obtained experimentally.

Third, Sommerfeld had shown in 1916 that «the consideration of the relativistic change of mass of the electron leads to slightly different energies for orbits of equal major axis but different eccentricity, so that each energy level will show an n-fold fine structure.» (Pauling and Goudsmit: 1930: 17). An observable consequence of this relativistic phenomenon was that the hydrogen spectral line corresponding to a transition from the second energy level to the first would exhibit a doublet structure. This prediction, obtained by Sommerfeld's relativistic correction of Bohr's model of the atom, was experimentally confirmed. Fourth, Bohr's model of the atom was successfully employed by Epstein to account for the Stark effect - the splitting of spectral lines when their source is placed under the influence of an electric field.

As a result of these and other successes predicated on the notion of a dynamic electron Millikan declared in 1924 that

> «the theory of non-radiating electronic orbits is one of the established truths of modern physics. ... [A truth that is] as much hypothetical to-day as is the theory of the rotation of the earth upon its axis or of the planets around the sun.» (Millikan 1924: 1414)

Those successes were too dramatic to be ignored by the chemists. Lewis himself, several years after his proposal of a static model of the atom, commented on the «remarkable quantitative success» of «the brilliant theory proposed by Bohr (1913).» (Lewis 1923: 52 and 43 respectively.) There were two available options: either to give a mathematical formulation of Lewis' theory of the static atom and try to emulate the quantitative achievements of Bohr's theory, or to attempt to reconcile the two theories through an appropriate reinterpretation of both. The former option was followed by Irving Langmuir; the latter by Lewis himself.

The controversy, however, would not be fully resolved before the advent of the exclusion principle, spin, and eventually quantum mechanics. The exclusion principle gave a satisfactory explanation of the facts of the periodic table that superseded all previous accounts. Spin, in its original classical interpretation, substantiated the chemists' relatively vague conception of the electron as the ultimate magnetic particle. And quantum mechanics, at least in its dominant interpretation, dispensed with the notion of electronic orbits. Thus, aspects of both conceptions were incorporated into the quantum-mechanical representation of the electron.

We can now address the question that was raised in the beginning of this paper. In view of the divergent representations of the electron in early twentieth century physics and chemistry, could one still maintain that both physicists and chemists referred to the same thing when they used the term "electron"? It is important to point out that this question was raised by the scientists themselves. As Sidgwick pointed out, chemists were «open to the reproach of an eminent physicist, that 'when chemists talk about electrons they use a different language from the physicists'.» (Sidgwick 1929: Preface.) And the British physicist Edward Andrade argued that «The electrons in the Langmuir atom [a development of the Lewis atom] have, in fact, so few of the known properties of electrons that it is not immediately clear why they are called electrons at all.» (Andrade 1927: 642.) An adequate discussion of this issue requires an examination of the meaning and reference of scientific terms. This will be the subject of the following section.

5. Meaning Change and Scientific Realism

When Kuhn and Feyerabend pointed out in the early 1960s that the meaning of scientific terms changes over time, it seemed that the instability of scientific concepts had as an immediate corollary the collapse of scientific realism (Kuhn

1970; Feyerabend 1962). Given the then prevalent belief (inspired by Frege) that the meaning of a term is specified by a set of conditions which are individually necessary and collectively sufficient for the correct application of that term, the slightest change in those conditions (meaning change) would imply that the term as previously used was vacuous, i.e. it referred to nothing at all. This alleged failure of scientific terms to refer would imply that there is no legitimate sense in which all those physicists and chemists who used the term "electron" were "talking about the same thing".

Hilary Putnam was alarmed by the antirealist implications of this view of meaning and developed an alternative theory whose purpose was to sustain a central realist intuition, namely that the development of scientific knowledge amounts to learning more and more about the *same* things. According to Putnam's theory the reference of a term is an independent component of the term's meaning and is not affected by any changes the other components might undergo (Putnam 1975: 215-271). In order for his theory to get off the ground there must be a way to fix a term's referent without relying on the descriptive part of the term's meaning. This limitation makes his conception of meaning applicable only to proper names that denote individual observable objects (e.g., Statue of Liberty) and, perhaps, to natural kind terms whose referents are classes of observable objects (e.g., cats). On the other hand, it is not clear how this view of meaning would handle terms that denote unobservable entities (e.g., quarks), since we have no access to those entities independently of the descriptions provided by our theories.

Despite this defect of Putnam's theory, I think that it is promising and deserves to be further developed. As I have argued elsewhere, there is a way to separate the referential component of meaning from the rest even for (some of the) terms which denote unobservable entities (Arabatzis 1995). When presented with such a term, one has to identify the various experimental situations which are taken to manifest the presence of (are causally attributed to) the unobservable entity in question. Those situations which are deemed to involve the given entity collectively provide the referent of that term.[2]

If one wants to rescue scientific realism from meaning change, one has several options. To begin with, one could suggest that a realist attitude with respect to a particular entity is justified to the extent that a core of meaning has remained stable throughout the evolution of the meaning of the corresponding term. (Cf. Putnam 1975: 275). This option is open to the aspiring realist vis-à-vis the electron, who is faced with the controversy outlined above. Both physicists and chemists shared the belief that the electron was a universal constituent of matter, with a certain mass and charge, and that it was the agent of radiation. However, one might want to challenge the view that this common core of meaning enables a realist perspective to get off the ground. In particular, one might ask for the specific criteria that privilege this set of beliefs (the "core") over the rest of beliefs about electrons that were not shared between the two communities. I will not attempt to respond to this line of criticism, because I think that there is another way out for the aspiring realist.

[2] This proposal is not applicable to entities that have not been (and perhaps cannot be) subject to experimental investigation (e.g., black holes). Furthermore, it remains to be seen whether it can be extended to entities whose experimental counterparts are not manifest (e.g., molecular orbitals).

This alternative amounts to maintaining that in science descriptions are used referentially and not attributively. In the former case, a description is used to pick out a specific entity. If by the help of the description one successfully picks out the entity in question then the description has served its purpose, even if it later turns out that it was altogether wrong. In the latter case, on the other hand, it is demanded that the entity picked out by a description satisfies completely every feature of that description. (Cf. Donnellan 1966.)

However, as I indicated above, when it comes to unobservable entities the claim that descriptions are used referentially cannot be easily maintained, because it is not clear in what sense a description of an unobservable entity "picks out" that entity. There are two options at this point. First, one could suggest that the description enables us to differentiate the entity in question from other unobservable entities. Thus, the description plays an essentially taxonomic function. It might adequately play that function even if it is (in some respects) wrong. For example, any description of the electron which includes the values of its charge and rest mass will differentiate it from other elementary particles even if it is in other respects misleading. As long as the classification of unobservable entities remains invariant, scientific realism remains immune to changes in the descriptions of those entities. The second option is to suggest, as I argued above, that the reference of a term denoting an unobservable entity coincides with the "family" of experimental situations which are the observable manifestations of the entity in question.(Cf. Kitcher 1982: 695; and Putnam 1975: ix.) Only certain aspects of the description associated with an unobservable entity enable one to pick out the corresponding experimental situations, namely those aspects which are involved in the prediction of those situations. For example, the charge to mass ratio of the electron is involved in the prediction of the behaviour of cathode rays under the influence of electric and magnetic fields. Again, as long as that "family" remains invariant (or expands in a cumulative fashion) scientific realism (vis-à-vis the entity in question) is not threatened by variations in that entity's description.

Both of these options are open to the aspiring realist vis-à-vis the electron, who is faced with the controversy outlined above. The criteria that were used in the classification of electrons were shared by the two scientific communities. The chem-

ists' and the physicists' beliefs about the electron's charge, mass, and dimensions coincided. It was those beliefs that differentiated electrons from other unobservable entities (e.g., ions).

After 1896, one can also establish the referential continuity of the term "electron". The reference of this term underwent a cumulative expansion and gradually came to cover an increasing variety of different experimental situations (e.g., cathode rays, the Zeeman effect, β-rays, the photoelectric effect, thermionic emission, cloud chamber tracks, Millikan's oil-drop experiments). Once an experimental situation was interpreted as the observable manifestation of electrons, its attribution to the agency of the electron was never challenged. Both chemists and physicists shared the view that the electron manifested itself in the same experimental situations. As far as I know, there were no phenomena which physicists attributed to the electron and chemists to some other entity, or vice versa.

In conclusion, physicists and chemists were talking about the same thing when they used the term "electron", both because they employed the same taxonomic criteria and because they referred to the same phenomena as the observable manifestation of electrons.

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