SCIENCE

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MSS. intended for publication and books, etc., intended for review should be sent to Professor J. McKeen Cattell, Garrison-on-Hudson, N. Y

THE STATIC ATOM[1]

I HAVE been asked to present in this symposium the relation between atomic structure and the "valence bonds" by which the atoms are regarded as tied together, to form the more complicated structure of the molecule. Now the whole theory of molecular constitution which I have developed rests upon the fundamental postulate that the atom is internally at rest or nearly so. On the other hand, Bohr, who has given special attention to the phenomena of spectral series, has been led to the view that the electrons in the atom are revolving rapidly about a central positive nucleus. Because of the wide acceptance by physicists of Bohr's theory of the atom and its orbital electrons, and especially in view of the very lucid arguments in favor of this theory which Professor Millikan has just presented to us, I am going to ask your permission to modify the subject of my paper, and to discuss not the specific methods of combination among the atoms, but rather the question as to whether the electrons in the atom and the molecule are in rapid motion or are essentially at rest; for upon our answer to this question any theory of molecular structure must depend.

Now assuming that the electron plays some kind of essential rôle in the linking together of the atoms within the molecule, and, as far as I am aware, no one conversant with the main facts of chemistry

[1] Presented at the symposium on "The Structure of Matter" at a joint meeting of the Sections of Physics and Chemistry of the American Association for the Advancement of Science, The American Physical Society and the American Chemical Society, New York, December 27, 1916.

would deny the validity of this assumption, let us consider the typical compounds of old-fashioned organic chemistry in regard to whose molecular structure we already know much—at the very least we may speak definitely of the relative positions of the atoms within their molecules. Among such compounds we find the striking phenomenon of isomerism. Numerous isomers, substances of precisely the same chemical constituents and differing only in the relative order in which the atoms are placed in the molecule, have been prepared. In the case of complex substances, if it were worth while, millions of such isomers could be prepared. Yet these isomers will keep for years, and probably would for centuries, without changing into one another. In these inert organic compounds the atoms are so persistently retained in definite positions in the molecule that in one part of the molecule atoms may be substituted for other atoms and groups for groups, sometimes through reactions of great violence, without disturbing the arrangement of the atoms in some other part of the molecule. It seems inconceivable that electrons which have any part in determining the structure of such a molecule could possess proper motion, whether orbital or chaotic, of any appreciable amplitude. We must assume rather that these electrons are held in the atom in fixed equilibrium positions, about which they may experience minute oscillations under the influence of high temperature or electric discharge, but from which they can not depart very far without altering the structure of any molecule in which the atom is held.

Let us therefore consider whether the physicists on their part offer any irrefutable arguments in favor of an atomic model of the type of Bohr's. In an atom of the simplest type, composed of a single positive particle and a single electron, if these fail to merge with one another until their centers are coincident—and it is universally assumed that they do not so merge—only two explanations are possible: either the ordinary law of attraction between unlike charges (Coulomb's law) ceases to be valid at very small distances, or the electron must be in sufficiently rapid motion about the atom to offset the force of electric attraction. The first of these explanations is the one which I have adopted. The second, which has been adopted largely because it appears to save Coulomb's law, is the one which has led to Bohr's atomic model, in which the electron revolves in definite orbits about the central positive particle. Now it has frequently been pointed out, and indeed it was well recognized by Bohr himself, that this model is not consistent with the established principles of the electromagnetic theory, since in the classical theory a charged particle subjected to any kind of acceleration must radiate energy, while, according to the Bohr hypothesis, radiation occurs only when an electron falls from one stable orbit into another. Since, however, the equation for electromagnetic radiation is one of the more abstruse and less immediate deductions of the classical theory, it might be possible by slight modifications of the fundamental electromagnetic equations to reconcile them with the non-radiation of the orbital electron. I wish therefore to point out a far more fundamental objection to the theory of the revolving electron, due to the fact that Bohr has been forced to assume that this revolution must continue even down to the absolute zero of temperature.[2]

If, in Fig. 1, the circle represents the orbit of an electron *B* revolving about the positive center *A*, and if *C* represents a charged particle in the neighborhood, then if the electron exerts any influence what-

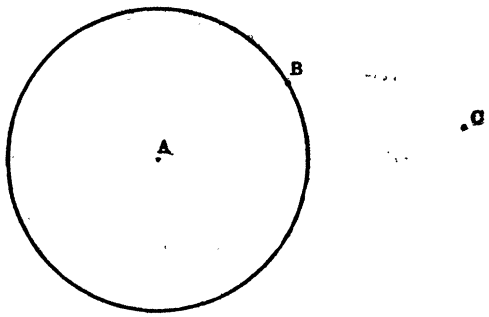

FIG. 1.

soever upon the particle *C*, the latter will be set into sympathetic motion, and a part of the energy of the *atom at the absolute zero* will be contributed to the particle *C*, contrary to the most fundamental principles of thermodynamics. Therefore, unless we are willing, under the onslaught of quantum theories, to throw overboard all of the basic principles of physical science, we must conclude that the electron in the Bohr atom not only ceases to obey Coulomb's law, but exerts no influence whatsoever upon another charged particle at any distance. Yet it is on the basis of Coulomb's law that the equations of Bohr were derived.

In spite of this and other similar serious objections to Bohr's atomic model, I should not wish to minimize the importance of his work. He has been the first to present any sort of acceptable picture of the mechanism by which spectral series are produced, and especially he has traced a relation between two important constants of nature, Rydberg's fundamental frequency, and the Planck constant *h* which plays so important a part in modern physical theory. I should therefore be loath to suggest an abandonment of the extremely interesting leads which Bohr's theory has suggested, nor do I think this necessary, for I believe that relationships similar to those obtained in Bohr's theory may be obtained, even if we substitute for the orbital atom of Bohr a static atom, and, moreover, I believe that by making this substitution we may not only obtain a model of the atom which is consistent with known chemical facts, but also one which does not require the abandonment of the principal laws of mechanics and electromagnetics. I should state at once, however, that I do not claim for the atomic model, which I am about to sketch in rough outline, the same finality that I would claim, for example, for the molecular model of methane which I have previously offered.[3] It is rather a suggestion of the direction in which we may work towards the solution of a problem of extraordinary difficulty with the most hope of ultimate success. It is evident to any one familiar with the extreme complexity of the spectra of some substances that many years must elapse before anything approaching to a final explanation of such baffling phenomena can be expected. All we can do at present is to suggest certain directions of investigation which may lead ultimately towards the desired end. With this understanding, you will not consider it too presumptuous if I start by discussing not the structure of the complicated system that we call the atom, but rather the structure of the electron itself, or, if you prefer, the structure of the field of force about the electron.

If we postulate, at small distances, the nonvalidity of Coulomb's law of force between the centers of two charged particles, we are doing nothing that is really new. In the older conception of the electron as a charged sphere of definite radius, the sphere being itself held together

2 It will be noted that this objection applies with equal force to the Planck oscillator which maintains energy even at the absolute zero.

3 I refer here and elsewhere to my paper "The Atom and the Molecule," *J. Am. Chem. Soc.*, 38: 762, 1916. See also *Proc. Nat. Acad.*, 2: 586, 1916.

by forces of an admittedly mysterious character, Coulomb's law, in the ordinary sense, would fail when two electron centers approach within one electron diameter of each other. If, on the other hand, we abandon the rather artificial spherical model of the electron, and if we assume that the electron has all its charge concentrated at its center, then also it has been well recognized that Coulomb's law must fail, for otherwise we could not account for the finite mass of the electron. In this case also we might, if we chose, speak of the size of the electron, meaning thereby the distance from the center at which the electric force differs by a certain amount from that calculated by Coulomb's law. Now in either sense of the word we must agree with Rutherford that the positive nucleus of an atom is far smaller than the electron. In other words, two such positive nuclei will repel each other according to Coulomb's law even at distances so small that the law would have quite lost its validity for two electrons or for a positive particle and an electron. In other words, an atom composed of a single positive particle and an electron is to be regarded as though the positive particle were imbedded in the electron and not the electron in the positive nucleus, as in the older theory of J. J. Thomson.

Some years ago I was led, through consideration of electron theory alone, and by the aid of plausible assumptions, to an equation for the field of force about an electron, which, at that time, seemed to me a reasonable first approximation to the equation which we must substitute for Coulomb's law. If f is the force acting on an equal positive charge at the distance r from the point charge electron, if ϵ is the charge of the electron, e the base of natural logarithms, and r_0 a characteristic distance which does not differ much numerically from the radius which is ascribed to the spherical electron, the equation reads

$$f = \frac{\epsilon^2}{r^2} e^{r/r_0}.$$

At large values of r this obviously reduces to Coulomb's law; at small values it would correspond to a curve such as that given in Fig. 2, where f is the ordinate and r the abcissa.

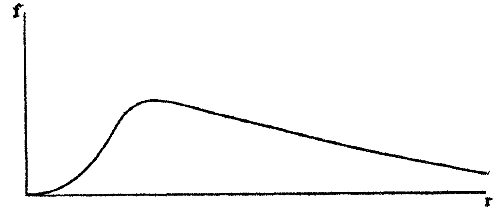

Fig. 2.

If now we assume that this is only a suggestion of the true equation and that the exponential term should be replaced by a similar function of periodic character, say a trigonometrical function of $1/r$, we might obtain an equation roughly represented by the curve given in Fig. 3. Any ordinary

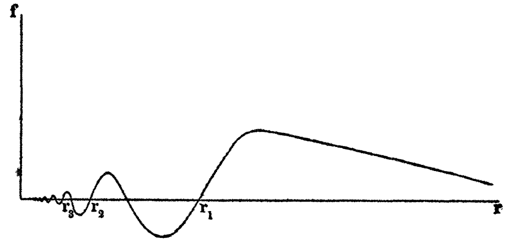

Fig. 3.

periodicity with respect to $1/r$ will make the curve which is plotted with respect to r intersect the axis of abscissæ an infinite number of times as r approaches zero. A positive particle (which we may regard as negligible in size but greatly preponderating in mass) situated at any of the intersections r_1, r_2, etc., where with diminishing r the force of attraction goes over into one of repulsion, is in a state of equilibrium with respect to the electron. Let us assume that the slope of the curve at each intersection increases towards a finite limit as r approaches zero. This slope df/dr is the restoring force per unit displacement, and its square root determines the natural frequency of oscillation of the electron.[3] We thus have a picture of a system which, consistently with recognized principles of mechanics and electromagnetics, would give a series of spectral lines analogous to the series which are known for various elements. The limiting value of df/dr as r approaches zero determines the limiting frequency of the series. In the case of Balmer's hydrogen series this limiting frequency is equal to one fourth of the fundamental frequency which Rydberg has found associated with the series of a large number of elements. It has been argued that the existence of this fundamental frequency speaks for similarity of constitution of different atoms. Is it not simpler to assume that it is characteristic of the one thing which is common to all atoms emitting light, namely, the electron?

The condition which we have imposed regarding the slope of our curve at its intersections does not determine the area which will lie under any section of it. As the curve is drawn, the area under the r axis between r_1 and r_2, r_2 and r_3, etc., is greater than the area above the axis. In other words, the potential energy of the system increases as the positive particle is brought from r_1 to r_2, from r_2 to r_3, and so on. If now we fix the form of the curve so that $\int_{r_m}^{r_n} fdr$ is proportional to the difference between the values for r_n and r_m of $(df/dr)^{1/2}$, the potential energy of our system at any point of equilibrium is a linear function of the frequency which is characteristic of that position of equilibrium. We then have what is, to my mind, a very suggestive explanation of the Einstein photo-electric equation. If an electron moving with a given velocity meet a positive particle, the latter would penetrate the electron field to one of the positions of equilibrium, and the electron would oscillate with a frequency depending solely upon the equilibrium position it reaches and therefore upon its original kinetic energy. The higher the original velocity, the higher the frequency it is capable of exciting. On the other hand, if we assume the presence of atoms in which the electrons are in various positions of equilibrium with respect to the positive particle, and these atoms are subjected to light of a given frequency, the electron which possesses this as its natural frequency will oscillate with greater and greater amplitude until it is able to leave its position of unstable equilibrium and will then be ejected from the atom, acquiring a kinetic energy equal to the potential energy of its original position. On our assumptions the relation between frequency and velocity will be quantitatively that given by the Einstein equation.

In the time which has been allotted to me I can not further elaborate these points, but I hope that I have succeeded in making it seem plausible that some model of a static atom, perhaps only roughly resembling the one that I have outlined to you, may be expected to give at least as satisfactory an explanation of the phenomena of spectroscopy, and of the rela-

[3] It will of course be understood that, owing to its much smaller mass, it is the electron that oscillates and not the positive particle. I am referring above to oscillations in the line of centers. In general the oscillations of an object which is held in space in a fixed position by constraints which differ in different directions will be resolved by either mathematical or physical analysis to give three frequencies corresponding to the three axes of constraint. If the constraint along two of these axes is the same the corresponding two frequencies will be identical. I venture to offer this as an explanation of the well-known fact that the lines of a series spectrum occur often as pairs or triplets.

tionships between the natural constants which have been found in the study of radiation, as can be afforded by the orbital atom. If this is granted we may proceed with greater confidence to the further study of the group of atoms which we call the molecule, and to the nature of valence. I can not repeat here the reasons which I have given in another place for believing that it is these very electrons held in rigid positions in the outer shell of the atom which may, in case of chemical combination, become the joint property of two atoms, thus linking together the mutually repellant positive atomic kernels and themselves constituting the *bond* which has proved so serviceable in the interpretation of chemical phenomena. In some molecules, such as those of nitrogen, the linking electrons are held by powerful constraints. The molecule is inert and incapable of taking part readily in chemical reaction. In others, like those of iodine, in which the bond is said to be weak, the connecting electrons are held by loose constraints and the molecules are extremely reactive. But whether the bond be weak or strong, we may feel pretty sure that it solely consists of those electrons which are held as the joint property of two atomic shells and constrained to definite positions by forces which we do not at present understand, but which do not obey the simple law of inverse squares which characterizes the attraction or repulsion of charged bodies at relatively large distances from one another.

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ZOOLOGICAL RESEARCH[1]

I speak with mixed emotions. I long ago planned to attend this spring meeting of the Indiana Academy of Science, the first I have been able to attend in several years. I was asked to assist at the dedication of a new biological building, and find I am one of the orators on the rare occasion of the unveiling of a monument to a man still alive and present. It is not possible to speak in the presence of so lively a corpse of the appropriateness of having your newest and best building named in honor of Stanley Coulter. If he were not present and listening with such apparent anxiety, I should like to recall his many good qualities and my good fortune in being associated with him for a third of a century. In these years we have traveled together, played together, worked together, fought together and against each other, and I think I am beginning to know him in part. It would make him too vain were I to say all of the nice things I should feel more than justified in saying, if his family were in mourning. As it is, I can only commend the authorities in honoring the teacher, the director of the Indiana Biological Survey, the charter member of the Indiana Academy of Science, the leader in nature study, the investigator, the dean of the school of science of Purdue University, and over and above all, the real human being.

It will not detract from his merits if I tell you in confidence that he deserves but part of the credit for what he has done. The poet truly said: "There is a Divinity that shapes our ends." At least half the credit should go to his wife, who has made him possible, and whom those of us who know her love even more than we do Stanley. I hope, I am sure the Academy as well as Purdue University hope, that they will long be able to work in the building so well named. The best of it is that the building was not needed to perpetuate the memory and influence of our friends.

The dedication of this, your best building, in part to zoology is a just recognition of the importance of the subject. It is quite proper, therefore, that we should consider what we mean by zoology, for our interpretation determines the nature of the work to be done within the walls of Stanley Coulter Hall.

Zoology is a study of animals. The study of

[1] Remarks at the dedication of Stanley Coulter Hall, the new biological building at Purdue University, during a meeting of the Indiana Academy of Science.