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# A MAGNETON THEORY OF THE STRUCTURE OF THE ATOM

(WITH TWO PLATES)

BY
A. L. PARSON

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## PART I. INTRODUCTORY

### §1. General Remarks

The non-electrical bond between atoms, such as may be supposed to exist in the Hydrogen molecule, is an important factor in chemical union; but no plausible suggestion as to its nature has ever been made, and the failure to account for this bond is one of the greatest defects of the electronic theory of matter as it now stands.

Now the present theory is the outcome of an attempt made some years ago to remedy this defect even at the expense of a considerable departure from accepted fundamental ideas: it seemed then to the author that the idea of replacing the classical electron by the magneton here described, which makes the bond in question magnetic, was less revolutionary than any other that could definitely attain the end in view; and the contents of this paper bear witness to its subsequent fertility.

In postulating this magneton for chemical reasons, the phenomena of magnetism and radiation were of course not lost sight of. In the field of magnetism, the magneton has been at once and automatically as strikingly successful as in chemistry—as indeed we ought to require it to be. As regards its application to the phenomena of radiation, not much can be said at present; but the magneton seems *à priori* a promising conception here, and its possibilities have been looked into already by Dr. D. L. Webster in a paper on "Planck's Radiation Formula and the Classical Electrodynamics" (Amer. Acad., Jan., 1915).

As might be expected of a theory that had such an origin, the special considerations which led to the theory of Rutherford and Bohr, for example, were not taken into account; and thus any representation that it has been or will be able to give of the phenomena of $\alpha$-particle scattering, of spectrum series, of the Röntgen ray spectra, or of the mass of the atom, are necessarily of a supplementary nature: but the theory does not, I believe, exclude the possibility of such representation for any of these phenomena (see the note in §16).

The properties of atoms fall into two distinct classes, the nature of this distinction having been clearly defined by J. J. Thomson, who points out that the atom behaves as if it were made up of a few electrons in an "outer shell" which are responsible for the chemical and light-absorbing properties of the atoms, surrounding a dense central mass made up of other electrons and positive electricity which might be called the "core" of the atom and is the seat of the strictly additive properties such as the mass, the Röntgen ray emission, and the radioactivity: in the properties of the outer shell there is a periodicity, in those of the core not. To this brief sketch might be added the magnetic properties as obviously being due to the behavior of the outer part of the atom.

Now there is no theory that is able to explain, to any appreciable extent, both sets of phenomena. Nor even is there any that shows much promise in connection with the properties of the outer shell alone—especially the chemical and magnetic properties of the atom: most of the recent work (by Rutherford, Moseley, and others) has emphasized the other part of the problem—the properties of the core, or nucleus of the atom. Bohr's theory, based upon the conception of the nuclear positive charge, gives an interesting treatment of the problem of spectrum series, but its chemical application is very meager indeed (see §8). On the other hand, the present theory, since it originated in a study of the simpler aspects of chemical affinity, emphasizes the properties of the outer shell, though not necessarily at the expense of the other set of properties.

The essential assumption of this theory is that the electron is itself magnetic, having in addition to its negative charge the properties of a current circuit whose radius (finally estimated to be $1.5 \times 10^{-9}$ cm.: see §16) is less than that of the atom but of the same order of magnitude. Hence it will usually be spoken of as the *magneton*. It may be pictured by supposing that the unit negative charge is distributed continuously around a ring which rotates on its axis (with a peripheral velocity of the order of that of light: §§5, 6); and presumably the ring is exceedingly thin. It might at first sight be supposed that if the electron were really thus magnetic, this property would have been detected in the behavior of kathode rays, but it will be shown later (§18) why it could not.

This rotation of a ring-shaped negative charge is intended to replace the usual conception of rotating rings of electrons in providing that orbital motion of electricity which is required by all theories of the magnetic and optical properties of atoms. No attempt will be made, however, to discuss the internal structure of the magneton.

With regard to the positive part of the atom, it will be necessary to avoid Rutherford's conception of a nucleus of very small dimensions—while fully recognizing the value of the evidence upon which he bases it—because it could not allow magnetons to take up the configurations that are essential to this theory, while the uniformly charged sphere of the Kelvin or Thomson "atom" is particularly well adapted to the purpose. As for the possible intersection of positive spheres, since any great amount of intersection, or coalescence, of the model atoms of this or of any other theory must abolish their individuality, and since the positive sphere is little more than a simple mathematical expression of the coherence and individuality of the atom (see also §7), it is consistent, as well as very necessary, to assume that positive spheres cannot intersect. It will also be assumed that the volume of the positive sphere is normally proportional to its charge, that is, to the number of magnetons in the atom, but that it is compressible; and that the normal radius of the magneton is about half that of the positive sphere of the Hydrogen atom:[1] that the volume of the positive sphere of an atom is usually very different from the total space occupied by the atom, and a way to account for this, will be made clear later (§15).

Some reasons for believing that the electron is this magneton may be enumerated now, and discussed more fully afterwards. They are:

1. It seems to be the only satisfactory way of securing valence electrons which are at rest, or vibrating within narrow limits, near the surface of the atom—a great desideratum from a stereochemical standpoint—without abandoning the very essential idea of orbital motion in the atom.

2. Even if the orbital motion is abandoned, and we suppose that the atom does contain electrons of the usual type in positions of equilibrium near its surface, the purely electrostatic nature of their action would be altogether inadequate from a chemical point of view. The additional magnetic forces furnished by the magneton are exactly what the phenomena of chemical action require.

3. It alone can give the atom a structure that accords closely with what is known about the magnetic properties of matter.

A general discussion of these points is given in §§2, 3, 4, the last being considered first. In §5 there is a brief study of the forces between two magnetons. In §6 it is argued that a number of magnetons within a sphere of uniform positive electrification must *tend* to arrange themselves in groups of eight. This suggests structures for the atoms (§7) that are in good accord with the general relations in the Periodic Scheme. A model which partially illustrates the behavior of the group of eight magnetons is also described, and the accompanying plates (1 and 2) show photographs of it. In §8 these results are compared with what is known about the number of

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[1] The diagrams in this paper are drawn to scale on this basis.

electrons in the atom, especially in reference to the hypothesis of atomic numbers, with which they conflict to a certain extent. Then follows a detailed application of the theory to the problems of valence (§§9, 10, 12, 13), with a discussion of the residual magnetic and electric forces due to different groupings of magnetons (§11). §§14, 15 deal with the volumes of atoms, and after this (§16) it is convenient to recapitulate the assumptions of the theory, which is at that stage fully developed. §§17, 18 deal with the moment of the magneton and a few questions connected with it; and §§19-23 contain a full treatment of magnetic phenomena.

## §2. CONSIDERATIONS OF MAGNETISM

The arguments for the substitution of the conception of the magneton for that of the classical electron in orbital motion, in explaining magnetic phenomena especially, are principally concerned with the radiation difficulties involved in the latter conception, although conclusive arguments of another kind (pp. 9, 10) are also available. The radiation difficulties have of course been a matter of common knowledge, but since on account of the apparent impossibility of avoiding them they have largely been ignored, it is worth while to make a critical study of them as they occur in applications of the electron theory to magnetism.

Of all the theories so far suggested, the present magneton theory is the only one that allows the existence of orbital motion and so of steady magnetic forces in the atom without the accompaniment of radiation processes. Disturbances or irregularities of any kind in the rotation of the magneton's annular charge will give rise to radiations certainly, but these will be non-essential to the chemical and magnetic individuality of the atom, and will be set up always by chance external stimuli, just as all the radiation processes in atoms (not including the emission of $\alpha$ and $\beta$ " rays ") are known to be in actual fact.

The contrary is the case with the classical electron. Every system of such electrons that has as yet been devised to explain magnetic phenomena either permits of continuous radiation or precludes the possibility of the atom giving radiations of at all the same kind as are observed: this will be made clear in what follows.

To begin with, it has long ago been pointed out by Sir J. J. Thomson that it is out of the question to consider orbits containing only one classical electron, or a very few such, for these would radiate energy excessively fast.[1]

In a paper on "The Magnetic Properties of Systems of Corpuscles describing Circular Orbits" (Phil. Mag., 6, 673, 1903) he shows, however, that when the number in an orbit is as great as six and their linear velocity is small compared with that of light, the loss of energy becomes quite slow; and therefore he attempts to explain magnetic phenomena by means of rings of many corpuscles (electrons).

Now there are two great objections to such an explanation. In the first place, subsequent work by Barkla and others has shown that the lighter atoms, such as those of Hydrogen, Helium, Lithium, do not contain enough electrons to form even one such ring. It may be argued here that perhaps this evidence does not cover the total electron content of the atom. But at least it indicates that a certain number of electrons, distinct from the rest (if any), cannot be in orbital motion: and it is important to notice that these are the more loosely bound electrons, which play a part in chemical, magnetic, and optical phenomena.

The second objection originates in the fact that for diamagnetic atoms it is necessary to assume the existence of independent orbits in the atom that are so great in number or else undergo such rapid variations that they can be considered to have their axes uniformly distributed in three dimensions—this to account for a zero resultant magnetic moment. Now separate rings of this sort cannot maintain their individualities unless the difference in their radii is so great that their disturbance of one another is inappreciable. This condition, if granted, would limit the possible number of rings and the

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[1] Thomson has more recently proposed an electron with such properties that it could rotate in an orbit by itself. This is the electron with all its field concentrated along a narrow cone, or, to adopt Faraday's mechanism, with a single tube of force. Although he has not attempted to develop a theory of the structure of the atom from this, or to explain radiation or magnetism by it, he has used the conception in a theory of chemical affinity (Phil. Mag., May, 1914), though in a manner that is not at all definite, as may easily be imagined from the following considerations. Since the electron is attached to its equivalent positive charge by means of its single tube of force, it cannot exert any electric force upon any other body, and, even if it is in stable orbital motion, it cannot for the same reason give rise to magnetic forces or any sort of radiation. Hence, unless we accept some entirely new and at present inconceivable view of the properties of the electromagnetic field, such an electron is a wholly unprofitable conception. The assumptions made in Bohr's theory involve similar difficulties, which, however, are ignored in its development.

chance of their resultant moment being zero altogether too much, for most substances are diamagnetic; while if the radii are not different enough to prevent interference, an altogether chaotic motion will result in the atom. Hence rotating rings of electrons, where they can exist at all, must be coaxial, and all atoms containing them must have a magnetic axis. Now the diamagnetism of a substance does not of course extend to its constituent atoms in all cases, for stable molecules of no magnetic moment can be formed from magnetic atoms; but the diamagnetism of Helium and Argon gases (P. Tanzler, Ann. der Phys., 24, 931-938, 1907) must mean that the separate atoms of these elements are diamagnetic. Here it might perhaps be argued that rotating rings of electrons would have a gyroscopic action which, for perfectly independent atoms, would prevent a paramagnetic reaction. But this independence, which cannot be complete even in the gaseous state, must be lost in the liquid state, and yet there is no reason to believe that liquid Argon is paramagnetic (as far as can be ascertained, there have been no studied observations on the point); nor can the diamagnetism here be explained by the formation of polyatomic molecules. Also it should be observed that in oxygen and nitric oxide we have cases of paramagnetic gases.

Thus the idea of rings of electrons, which is used in the model atoms of Thomson, Rutherford, and Bohr, is experimentally shown to be untenable.

If the laws of electrodynamics are to be applied quite rigorously—and the present attempt to show that the magneton is fundamentally a better assumption than the classical electron in orbital motion of course requires this test—it may be said of a system of classical electrons that the separate electrons must either be at rest relatively to one another or else be in chaotic motion: in either case there may or may not be an additional rotation of the whole system about some axis passing through the center of the system. Now these conditions do not allow of a state such as was assumed in Thomson's theory of magnetism, as we have just seen, nor of a state such as was assumed in Langevin's theory, which we now come to consider.

Langevin (Ann. de Chim. et de Phys., 5, 70-127, 1905) assumes that the electrons rotate in individual orbits with radii not much smaller than that of the atom, thus producing average effects similar to those of ordinary current circuits; and that the axes of these orbits may be distributed in all directions.

But, as we have just seen, the mutual interference of these orbits, even if they each contained several electrons, would make their individual persistence impossible, and so the system would at once drift into chaotic motion. Let us therefore consider what modifications the supposition that there is this chaotic motion in the atom would make in Langevin's results.

It would not affect that part of the superstructure of his theory which deals with the orbits altogether statistically, for chaotic motion, from a statistical standpoint, is certainly equivalent to motion in a great many separate orbits whose axes are uniformly distributed in three dimensions. But for those parts of his work which deal with the Zeeman effect, or presuppose in any way the existence of separate definite periods of vibration in the atom, as, for example, where he says that the constancy of wave-lengths of spectrum lines shows that the interior of the atom is not much affected by temperature changes—for those parts, the assumption of motion in separate orbits is essential, and those parts would therefore have to be abandoned.

Again, in the case of either supposition, while the difficulty about accelerated motion of classical electrons being accompanied by continual radiation may be obviated by supposing that the atom contains so large a number of electrons that the compensation among their chance motions reduces the average radiation to an inappreciable amount, we still have the difficulty that for these compensations to be even approximately complete the number of electrons would have to be much greater than the number actually believed to be present in many atoms: this difficulty is thus similar to one that Thomson's theory encounters. Apart from this difficulty of the allowable number of electrons, the theory labors under the following dilemma: If the internal compensation is not complete, the radiation will be continual and promiscuous and will rapidly exhaust the atom's store of energy: if the compensation is complete, it does not seem possible to imagine any additional mechanism in such an atom that could explain the phenomena of radiation. We may notice also in passing that chaotic motion seems to be quite inadmissible from a chemical standpoint.

But in spite of the existence of such substantial objections to his fundamental assumption, even when it is replaced by the less objectionable one of chaotic motion, the superstructure of Langevin's theory is in excellent accord with the facts. The circumstance, then, that the substitution of the magneton here described for Langevin's electron in orbital motion not only removes all of the difficulties just mentioned, but leaves the superstructure of his theory almost intact, is a strong argument in favor of the magneton. That this substitution can be made will be made clear by a short quotation from the conclusion of his paper:

> . . . . and we can form a simple and exact picture of all the facts of magnetism and of diamagnetism by imagining the individual currents produced by the electrons to be indeformable but movable circuits of no resistance and very great self-induction, to which all the ordinary laws of induction are applicable.

The substitution I have suggested has further advantages: it makes a great advance upon Langevin's theory, owing to the fact that, whereas the reaction of one of Langevin's orbits to its environment must vary with the phase of the motion of its electron, each magneton has the properties of an ordinary current circuit at every instant, and it is no longer necessary to think of the orbits statistically either in respect to their number or in respect to time. The importance of this difference is easily shown. I will first give another quotation from Langevin.

After showing that a single one of his orbits can have a moment as great as that of the oxygen or iron atom, he says (*loc. cit.*, p. 122):

> Since the individual currents due to the other electrons present in the molecule neutralize one another just as in a purely diamagnetic body, it follows that, in magnetic molecules, one or more electrons are sharply separated from the rest and are alone responsible for the magnetic properties, while all the electrons co-operate to produce diamagnetism.
>
> These are perhaps the very same electrons, situated in the outer part of the system forming the molecule, that play a part in chemical actions, where we know that electrons equal in number to the valence come into action. That would account for the profound influence of the state of molecular association, physical or chemical, upon paramagnetism, and its virtual lack of effect upon diamagnetism.

It is remarkable how completely the present theory, by means of the magnetic forces between magnetons, realizes in a quite definite manner the state of affairs here hinted at by Langevin.[1] It should be observed, however, that he does not specify that the chemical forces due to his electrons are magnetic in nature. This is very probably

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[1] Langevin's deduction that the magnetism of the oxygen or iron atom must be due to a few sharply distinct orbits is perhaps not altogether valid on his theory: a rotation of the whole of an otherwise diamagnetic system of electrons, whether moving in individual orbits or in chaotic motion, could give the same result. It may also be pointed out that if the orbits containing the few valence electrons were distinct, as Langevin suggested, the radiation from them could not possibly be reduced to almost zero by compensations, on account of their small number.

because the magnetic forces set up by electrons moving in orbits with about one-hundredth the velocity of light, as his are, would be much too small to be of significance in interatomic actions. However, a still greater objection, to bring out which was the chief purpose of the above quotation, is that such systems, as it seems, would not attract but *repel* one another magnetically.

Suppose that two electrons are constrained to move in parallel orbits, and in the same sense. If they can move synchronously, keeping always on the same side of their orbits, they will attract one another magnetically; but it can be shown that this is not a stable configuration, at least for velocities small compared with that of light. For, since the electric repulsion between them is greater than the magnetic attraction, the resultant force between them is one of repulsion; and thus if by some chance one of them is slightly displaced relatively to the other, the action of the tangential component of the repulsion between them will increase the separation until they are on opposite sides of their orbits, in which positions they will repel one another magnetically, as well as electrically.

When, therefore, it is remembered that the whole of the explanation of chemical phenomena given by the present theory depends upon the possibility of magnetic attraction taking place between two magnetons, it is evident that the substitution of the magneton for Langevin's electronic orbit is imperative.

Thus the magneton not only provides in a simple way the orbital motion which must otherwise be secured by making inconsistent assumptions about the behavior of classical electrons, but, what is equally important, it supplies a foundation for a detailed explanation of specific interatomic attractions of all kinds by providing an orbit which is equivalent to a current circuit at every instant and not only as an average effect in time.

This theory was first worked out in connection with the phenomena of valence; and probably that was necessary, for chemical phenomena are, from their nature, very much more detailed and distinctive than magnetic phenomena; but the groupings of magnetons about to be discussed from a primarily chemical standpoint must also bear the test of criticism from a magnetic standpoint. This test I will apply in detail at the end of this paper, but enough will be said here to show why the atoms of the inert gases should be the most diamagnetic of all atoms—as they are. In the same place the empirical magneton of P. Weiss will be considered: that is not a mechanistic conception and so could not have been developed in connection with the topics dealt with here.

## §3. STEREOCHEMICAL EVIDENCE

The rapid orbital motion of the valence electrons, together with the other electrons in the atom, which is a feature common and essential to most theories of atomic structure, makes it hard to see how these latter can ever furnish an extended explanation of chemical phenomena.

The difficulty here is twofold. In the first place, it is known that the action of a single electron is the predominating feature of any chemical bond that undergoes electrolytic dissociation; and the general regularities of the Periodic Scheme make it highly probable that the same is true of bonds that do not, such as those in hydrocarbon molecules; besides, there is a fine gradation between these two extreme types. This, together with the stereochemical evidence for a definite spatial arrangement of the groups attached to a Carbon or other atom, makes it very unlikely that the valence electrons can be taking part in the rapid orbital motion of a system of electrons in rings. It is indeed conceivable that in a molecule of the type $XH_n$, where all the bonds are ionizable, the nuclear X atom may take into its own system of rings the electrons it has extracted from the H atoms, while the positively charged H residues arrange themselves symmetrically around it; but this could not apply to the bonds in which no actual transfer of an electron takes place, such as those probably are which do not ionize or leave charged groups when broken. In such cases, at least, it appears that the electron associated with a unit of combining action must remain near the point of contact with the atom that is held by that action.

The second objection, and for the Thomson model this merges with the first, is that rings of electrons must usually all rotate about the same axis, so that the symmetrical action in three dimensions which seems to be a normal property of the atom could be exerted by the Thomson atom only in the limited electrostatic sense already described, and not at all by Rutherford's atom. Fully to appreciate this difficulty one need only turn to that point in Dr. Bohr's papers (*loc. cit.*) at which he comes to consider the "tetrahedral" Carbon atom. We see there that the theory comes to a complete halt when confronted with the problems of "Chemistry in Space." Nor is the tetrahedral Carbon atom an isolated problem: the asymmetric compounds of other elements, such as Nitrogen and Cobalt, are still further beyond the reach of such theories, not only in their present form, but, it would appear, in any conceivable state of development along the same lines.

It should be noted in this connection that Werner, some years ago, put forward a theory of stereochemical phenomena (described in his "Stereochemie," pp. 48-50, 224) which discarded the notion of directed action, and represented the atom as exerting a uniform attractive force in all directions, without specifying the nature of that force. It did not profess to have a physical basis of any sort, but was meant to be nothing more than a symbolical representation of the facts, being directed chiefly against the narrow mechanical views of the time, according to which the Carbon atom was an actual tetrahedron and so forth. It is true that all the stereochemical phenomena for which ultra-mechanical explanations were at one time favored, such as optical activity, "ethylene" isomerism, and the facts that gave rise to Baeyer's "Strain Theory," or Bischoff's "Dynamic Hypothesis," can be better pictured by using the conception of equilibrium between more diffuse forces; but a compromise seems desirable on account of the difficulty in imagining the exact nature of such forces. Apart from other objections, a force like that of gravitation is too promiscuous in its action, while no concrete scheme of electrically charged or electrically polarized atoms is flexible enough to be consistently followed out through the molecule of the average Carbon compound. "Werner's Theory," then, is not a theory of chemical action so much as a clear statement of the conditions with which such a theory must comply. It will be seen that the structures derived for the atoms in this paper permit that mobility of linkages, the recognition of which led to the proposal of Werner's theory, without giving up the idea of definite units of combining action.

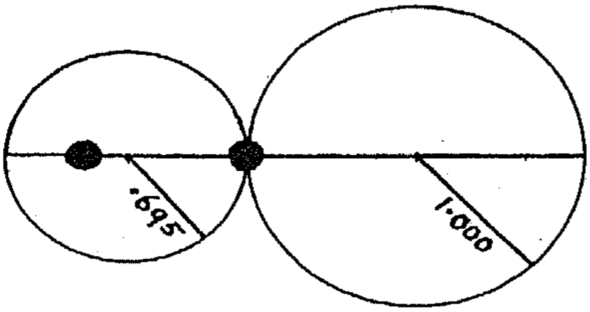
If, then, the valence electrons are in positions of equilibrium near the surface of the atom, the other electrons cannot have any translational motion, for these two states cannot coexist in the same system, except in the special case where the stationary electrons lie on the axis about which the others rotate. Now any attempt to reconcile this result with the certainty that there is some kind of orbital motion of electric charges within the atom leads inevitably to the idea of the magneton.

Again, theories involving rotating rings of electrons do not seem to provide a really satisfactory derivation of the valences of atoms. With them it is a question of how many electrons are stable in one ring; how many pass into another; and so on. Now, even if a limited agreement with the facts can sometimes be secured, the idea of rings of electrons cannot possibly harbor any essential peculiarity that could explain the definite system of "octaves" which is the predominating feature of the Periodic Scheme. On the other hand, the magneton gives more or less independent units of valence, while the explanation to which it leads for the "Law of Octaves" is dependent ultimately upon the three-dimensional nature of space, and the fact that of the simple figures which are symmetrical in three dimensions the *cube* is alone in furnishing an arrangement of magnetons with a very low magnetic energy.

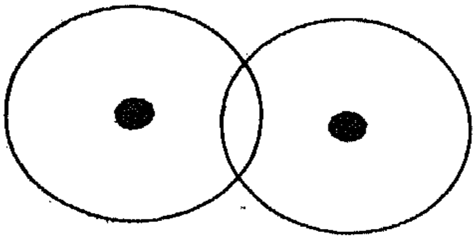
### §4. The Scope of Electrostatic Theories of Valence

Since we have concluded that the atom cannot contain spherical or "point" electrons in rotating rings, let us next consider what are the possibilities of such electrons if they are supposed to be in a state of rest in the atom. It must be borne in mind that anything which is true for such electrons must also be a factor in the electrostatic part of the behavior of the magneton.

The fundamental problem from a chemical point of view is to show how two electrically neutral systems, such as atoms must be, can attract one another at all; and an analogy originally due to Lord Kelvin is typical of the way in which this question can be approached on the basis of the electrostatic action of movable charges. If a single electron is situated within a sphere of uniform positive electrification of equivalent amount, the whole is electrically neutral, but the force required to drag the electron out of its positive sphere is the greater the more dense the latter is, being inversely proportional to the square of its radius. If two such systems are brought into contact, the smaller and denser sphere will just be able to extract the electron from the other if the ratio of their radii is .695 : 1.000, as in the figure: now, if the two spheres are pulled apart, there will be an electrostatic attraction between them, and they will resemble the ions of a diatomic molecule like HCl. This principle holds true for all kinds of electrons, and will have to be taken into account in subsequent developments of the present theory wherever necessary (see §16), but its inadequacy as the sole basis of an explanation of chemical action is shown by the mere fact that it requires a higher atomic volume for Hydrogen than for any halogen element.



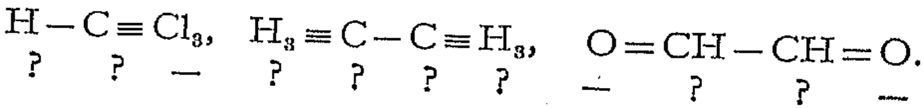
Attraction between neutral atoms might take place in another way. If their positive spheres intersect, thus:



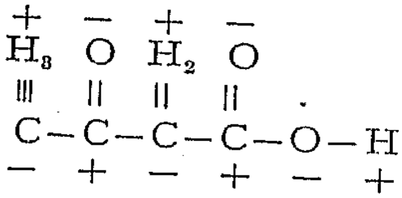
they will be attracted together. It can be shown, however, that in such a case there would be a tendency to complete coalescence (J. J. Thomson, "The Corpuscular Theory of Matter"); and the difficulties involved in such a possibility have already been emphasized in §1. Besides, an attraction of this sort could not explain valence.

Other suggestions of ways in which stationary valence electrons might account for attraction between neutral atoms have been made—mostly very tentative, and not physically definite enough to be criticised from the present point of view.

It is evident, then, that while the Kelvin model gives a rough representation of the HCl molecule, the cases of union between like atoms are a great difficulty from an electrostatic standpoint. The bond in the $H_2$ molecule is probably the simplest kind of combination between atoms, and yet it has proved to be the hardest of all to explain. Electrostatic explanations seem to be suited only to an alternate arrangement of the so-called "positive" and "negative" atoms. There is indeed a tendency to such an arrangement, even in organic molecules, aceto-acetic acid being a good example of this; and the tautomerism and acidic hydrogen atoms characteristic of such groupings are significant. But the assignment of positive and negative functions is not usually so easy: there is difficulty whenever groups of opposite nature are attached to the same Carbon atom, or groups of the same nature to contiguous Carbon atoms, as in the molecules



$$\underset{?}{H}-\underset{?}{C}\equiv\underset{-}{Cl_3},\quad \underset{?}{H_3}\equiv\underset{?}{C}-\underset{?}{C}\equiv\underset{?}{H_3},\quad \underset{-}{O}=\underset{?}{CH}-\underset{?}{CH}=\underset{-}{O}.$$



$$\begin{array}{cccccc} + & - & + & - & & \\ H_3 & O & H_2 & O & & \\ \vert\vert\vert & \vert\vert & \vert\vert & \vert\vert & & \\ C- & C- & C- & C- & O- & H \\ - & + & - & + & - & + \end{array}$$

We are forced to the conclusion that there is a factor in the union of atoms which is unconnected with electrical polarization, and is almost as independent, simple, and ready to hand, as the stroke that is used in a structural formula to represent its action. This is provided by the magneton, which is eminently adapted to function as a "link," for its two sets of forces enable it to hold to its parent atom by electrical attraction and to the magneton or magnetons of another atom by magnetic attraction at one and the same time.

## PART II. THE STRUCTURE OF THE ATOM

### §5. FORCES BETWEEN MAGNETONS

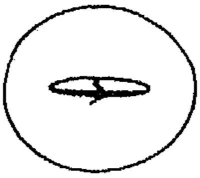
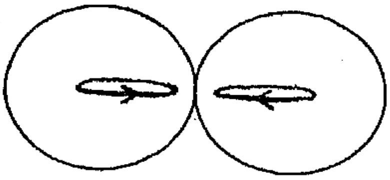
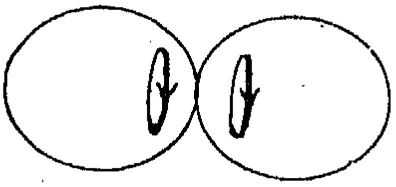
In assuming that the magneton has the properties of a current circuit (§1), we have pictured it as a rotating annular charge, and implied that the behavior of this charge is in accordance with the laws of ordinary electrodynamics. This picture I shall use in further delimiting the nature of the magneton as it is required by the present theory.

First must be considered the exact nature of the forces acting between two magnetons, and more especially the conditions under which they could be attracted together so closely as to coalesce; for coalescence, if spontaneous, would be an irreversible phenomenon, and therefore could not be possible for the magnetons that are concerned in the chemical actions of the atom. (We can, without inquiring into the nature of the magneton's structure, define coalescence as the coming of two magnetons into the most intimate contact.)

If two magnetons, of fixed dimensions and peripheral velocity, with their axes in the same straight line, are at a distance $d$ apart, the forces between them obey the following laws:

The magnetic attraction or repulsion ($M$) is as $\frac{1}{d}$ when $d$ is very small, and as $\frac{1}{d^4}$ when $d$ is very great, compared with the radius of the magneton. The corresponding functions for the electrical repulsion ($E$) are $\frac{1}{d}$ and $\frac{1}{d^2}$. Thus, when $d$ is small, as it would be just before coalescence, the forces are similar to those between two parallel linear charges of infinite length that are moving in the direcion of their length with a velocity equal to the peripheral velocity of the magneton ($v$). Then, if $c$ is the velocity of light, the ratio of the forces, $\frac{M}{E}$, is equal to $\frac{v^2}{c^2}$. Therefore, if $v<c$, $M<E$ and magnetons cannot coalesce; also the resultant force is one of repulsion for all values of $d$, because $M$ falls off more rapidly than $E$ as $d$ increases. Even with $v=c$, the ratio $\frac{M}{E}$ remains $<1$, except in its limiting value when $d$ becomes zero: this would just permit coalescence, but only if the magnetons were first brought together by extraneous forces. I have neglected the " thickness " of the magneton: on account of this it would require a value of $v$ somewhat greater than $c$ for coalescence. (It should be said that the cases $v=c$ and $v>c$ do not here violate the law of relativity, for the continuous distribution of the charge around the magneton ensures it a uniform field for all values of $v$.)

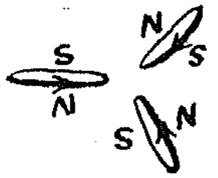
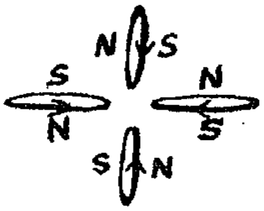
Now it will be shown in §6 that if the magnetic forces between magnetons are to be great enough to account for chemical actions satisfactorily, $v$ must not be much less than $c$. It is simplest, therefore, to assume $v$ to be equal to $c$. We can neglect the mutual induction between magnetons approaching one another, as, for magnetons that are far from coalescing, these will be small; even if two coalesced, the flux per magneton would only be halved.

Turning now to the phenomena of chemical combination, we find that the bond in the $H_2$ molecule, which presents such difficulties to electrostatic theories, is the simplest of all to explain. It may be attributed to the magnetic attraction between two electrically neutral atoms containing one magneton apiece. Diagrammatically, the H atom may be represented:  ; and the $H_2$ molecule:  or  . (These two configurations are equally satisfactory from a chemical point of view, but magnetically their properties would be very different.) The magnetons are pulled away from the centers of their positive spheres, and the fact that the $H_2$ molecule does not combine with more H atoms is accounted for by the obstructing action of the positive spheres, which prevent other magnetons from coming as close to these two magnetons as they are to one another. But residual magnetic forces remain, and would account, always for a part, and sometimes for almost the whole, of those actions between molecules and parts of molecules which are not indicated in structural formulæ and which find their most general expression in the phenomena of cohesion (§§11, 16). (For a calculation of the heat of dissociation of the $H_2$ molecule from this model, see §18.)

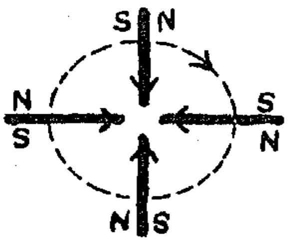
Before proceeding to the study of atoms containing more than one magneton, it may be well to point out that, although the fundamental concepts of this theory, the magneton and the positive sphere, are in themselves simple, yet the situations to which they can give rise are so exceedingly complex from a mathematical standpoint, that a rigid quantitative treatment is practically impossible. In what follows, therefore, I have not usually attempted to arrive at much more than the relative order of the various effects. But even so, it seems possible to extend the theory over quite a wide range of facts before the uncertainties in its development accumulate enough to make its application meaningless.

## §6. The Group of Eight

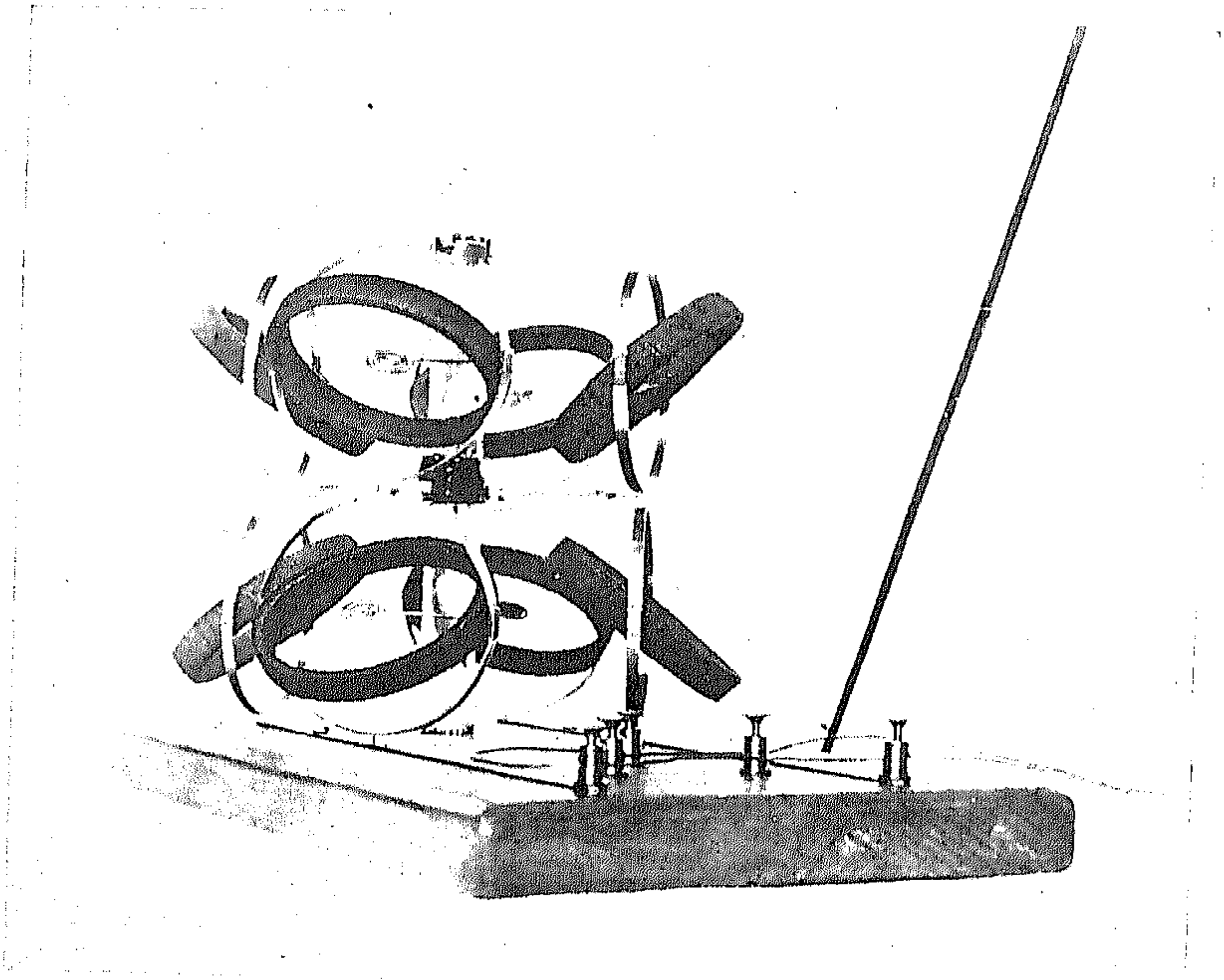
The configurations of small numbers of electrons at rest within a sphere of positive electrification have been described by Sir J. J. Thomson in his book, "The Corpuscular Theory of Matter," pp. 102-106, where he states that while three, four, and six electrons would take up triangular, tetrahedral, and octahedral arrangements respectively, the symmetrical cubical arrangement of eight can be shown to be unstable. The magneton, however, introduces two new factors into the problem: one, the extended ring shape of the electron, and another which is yet more significant, the "bi-polar" magnetic forces. To give a configuration with the minimum magnetic energy, it is evident that the currents in all adjoining parts of magnetons must be parallel and in the same direction, or, to take a cruder though possibly more vivid picture, the "N" and "S" poles of the magnetons must be placed alternately in every direction. From this point of view let us consider the groups of three, four, six, and eight magnetons (five and seven obviously have not the possibilities of the other numbers).

The stablest configuration for three magnetons is shown in the diagram . Four can have the configuration: , which under symmetrical electrostatic conditions would form an irregular tetrahedron (this, which has been produced in a model, may be pictured by imagining one pair of opposite magnetons to be raised above the plane of the paper). The octahedral group of six would probably be made up in a similar way of three pairs of magnetons; but six can have a configuration of lower magnetic energy than this, which, however, is not so symmetrical—this is a triangular-prism arrangement consisting of two parallel groups of three.

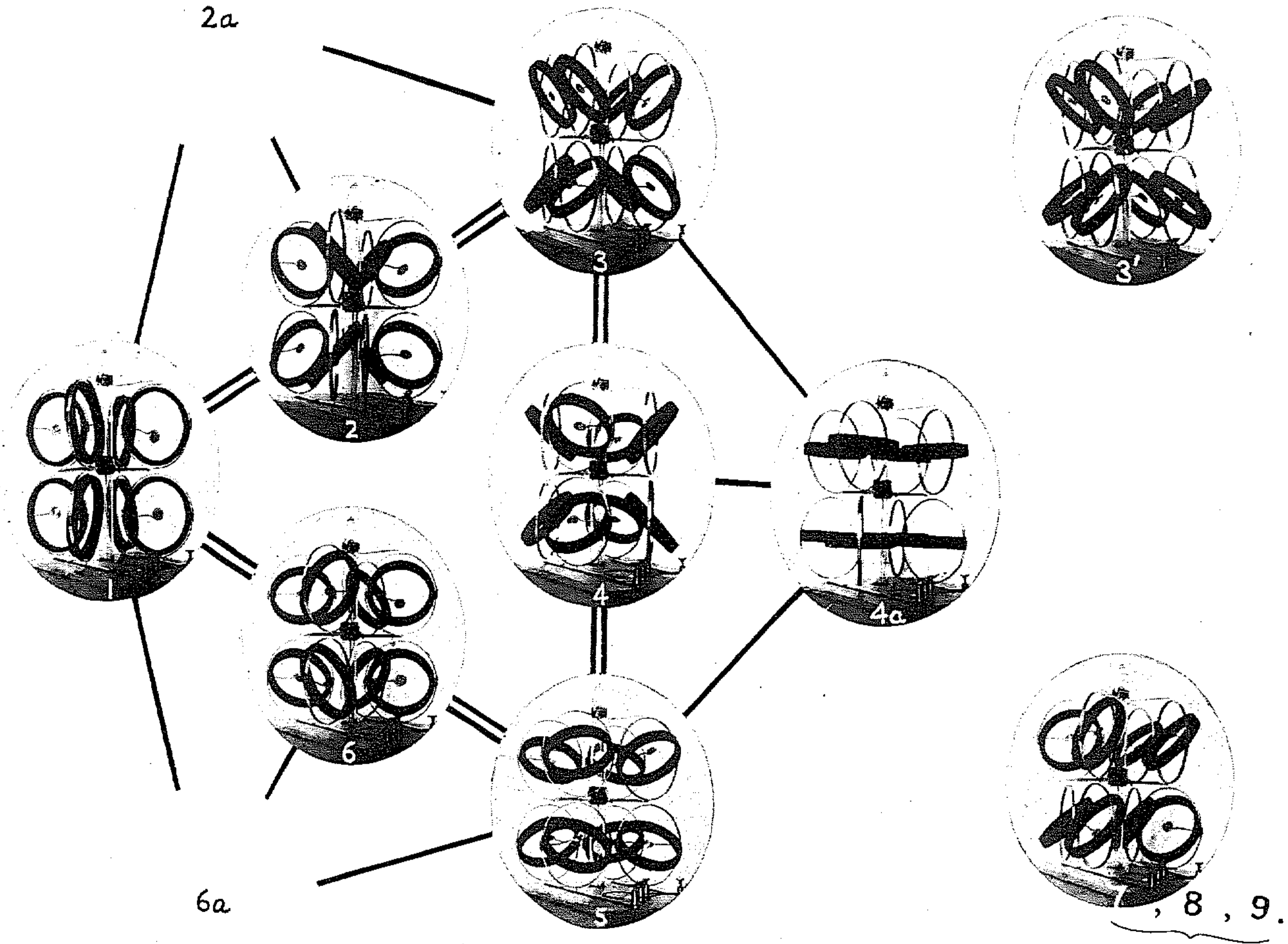
But quite apart from the lack of three-dimensional symmetry of some of these configurations (the effect of which will be seen shortly), they can none of them have so low a magnetic energy (in proportion to the number of magnetons) as the cubical arrangement of eight. This, with its three fourfold axes of symmetry, is magnetically ideal; and although it is not quite stable for spherical electrons, there is no doubt that it would be exceedingly stable for magnetons, because no other arrangement of eight can be nearly so symmetrical.

To illustrate the unique properties to be expected in this group of eight, I have made a model (plate 1) in which eight coils of insulated wire are set in gimbals at the corners of a cube, the side of which is two and a half times the radius of the coils. This cannot completely illustrate the behavior of the group, because the cubical arrangement is made compulsory, the distances are fixed, and the electric forces are absent; but, when excited by an electric current, it shows what configurations the eight can assume under such conditions. Most of these are shown on plate 2, where it may be seen that the most symmetrical and stable configurations resolve themselves into a cycle of six (figs. 1-6) which are very closely related to one another and easily interconvertible: 1, 3, and 5 are identical except for their relative attitudes in space, and the same is true of 2, 4, and 6. The group is thus very stable, and yet very mobile, for its magnetons can easily veer in all directions without destroying its identity. This mobility, which is not possible without three-dimensional symmetry, is a source of additional stability, for the group can adjust itself to casual external fields, such as it would continually meet with owing to the motion of the molecules, without needing to turn as a whole. The directions of the currents and of the flux in configuration 1 are shown in the following diagrammatic section of the upper four coils: 

. For the lower coils they are exactly reversed. The less symmetrical configuration numbered 7 is most easily described by saying that the four coils nearest to the camera have their "N" poles to the left, and the others have them to the



CONFIGURATIONS OF GROUP OF EIGHT
(See explanation Plate 2)



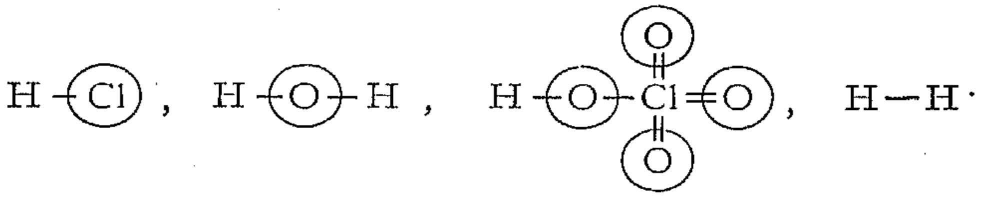
CONFIGURATIONS OF GROUP OF EIGHT

Note the effect of the earth's field, which lies in the direction shown by the line across Plate 1, in tilting the coils in config. 1; also in configs. 3 and 3′, which differ from one another only in the direction of the current in the coils.

right (or *vice versa*). All these configurations are free from magnetic moment; hence their presence in an atom would make for diamagnetism.

In its perfect symmetry, mobility, and very low magnetic energy, the group of eight evidently has a combination of properties which must make it more stable than groups of any number less than eight, or of any number not much greater than eight, as a consideration of the possibilities readily shows: it is reasonable, therefore, to suppose that this group will tend to be formed rather than other groups.

Further, the force retaining a magneton in a group of eight must be decidedly greater (*cet. par.*) than the force between two single magnetons—probably quite twice as great—and, if the magneton rotates with the velocity of light, would be great enough, in certain cases, to bring about the transfer of a magneton from one atom to another. We may then attribute to this effect that kind of combining action which is characteristic of electronegative atoms such as those of Oxygen or Chlorine. The former, as we shall see later, has six valence magnetons, and the latter seven, and each succeeds in making up a group of eight by extracting magnetons from other atoms. This state of affairs can conveniently be represented in structural formulæ by placing a circle around the symbol for every atom that is the seat of a group of eight thus formed, as follows:



$$\mathrm{H-Cl},\quad \mathrm{H-O-H},\quad \mathrm{H-O-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{Cl}}=O},\quad \mathrm{H-H}\cdot$$

The theory thus allows for the transfer of electrons in certain cases without requiring that it should be an inevitable accompaniment of chemical union (*cf.* the H—H molecule), and is in exact accord with the valence relations that are to be found in the short periods of the Periodic Scheme.

An atom containing exactly eight magnetons will neither extract magnetons from other atoms nor, under ordinary conditions, part with its own, and will have the properties of the Helium atom (*cf.* also its diamagnetism, §2). The photographs in plate 2 are thus a diagrammatic representation of the Helium atom, according to this theory.

## §7. The Constitutions of the Atoms

The singular properties of the group of eight may possibly explain the sequence of the elements throughout the Periodic Scheme also. It is at once evident that a separation of all the magnetons in the atom into groups of eight, with a remainder of valence magnetons, would give an ideal explanation of the " Law of Octaves." Indeed, no other arrangement of the magnetons—as, for example, in one large group—could give a picture of the facts, chemical and magnetic, that even approaches this in fidelity. What follows, therefore, is an attempt to analyze the behavior of large numbers of magnetons in a positive sphere with a view to finding conditions which could lead to such a grouping.

Any number of magnetons within a sphere of equivalent positive electrification must arrange themselves so as to secure an equilibrium between the two tendencies of the magnetic energy and the electric energy, respectively, to be at a minimum. The first would be satisfied by a gathering of all the magnetons into one very compact group, the second by an even distribution of single magnetons; and in view of the fact that magnetic forces increase more rapidly than electric forces as the distance diminishes, it might be thought that a likely compromise between the two tendencies would be the formation of groups containing the smallest number of magnetons that is compatible with a low magnetic energy, and at the same time with symmetry and mobility, in the group—that is, groups of eight. But more careful study of the matter shows that when a magneton is displaced from the position it would occupy in a plan of even distribution, the electrostatic forces of restitution are greater than the opposing magnetic forces; so that the stable condition is one of even distribution.

What has been said, however, implies the assumption that the positive sphere is rigid; if, on the contrary, it is compressible, we have a set of conditions that requires further consideration. This compressibility of the positive electricity will be found necessary to explain atomic volume relations and also the phenomena of gaseous collisions and $\alpha$-particle scattering (see the note at the end of §16): it will therefore be introduced here.

The hypothetical positive sphere we are using must be supposed to possess two distinct sets of properties. In the first place it is a uniform charge of positive electricity, and on that account tends to expand indefinitely into space. Secondly, it has a coherence due to forces, something like elastic forces, which are in equilibrium with the expansive electrostatic forces. Thus when isolated from magnetons it would be in a state of distension, and very compressible. Further, to preserve the individualities of the positive spheres of different atoms we need to assume an internal structure like that of an elastic solid rather than that of a fluid. What has been said does not, as might seem at first, burden the positive sphere with more complex assumptions than heretofore: it merely substitutes an elastic coherence for a rigid coherence, and it has the advantage of enriching the atom with additional degrees of freedom.

In such a sphere, each magneton will, by electrostatic attractions, condense positive electricity in and around itself, and thus its electrostatic action on other magnetons will be weakened: the first effect of endowing the positive sphere with elasticity will therefore be a general diminution in volume under the action of the electric and magnetic forces. In order that magnetons may not entirely neutralize themselves in this way, it must be further supposed that the elastic tension that obtains in the isolated positive sphere becomes zero when the charge density has increased to a certain value, and then changes sign, becoming a compression and combining with the electrostatic repulsion to oppose a further increase in charge density: such change of sign is of course connoted in the ordinary use of the term "elastic."

It is possible to make a somewhat elaborate study of the conditions in such an atom, but they are very complex and hard to discuss with any definiteness. Apart from the diminution of volume under the action of the electric and magnetic forces, the elastic sphere will apparently still behave, *under static conditions,* in much the same way as the rigid sphere; *i. e.,* there will probably be no spontaneous separation into groups. This statement is no more than a well-considered guess, because the complicated nature of the dependence of the repulsive forces in the elastic sphere upon the nature of the elasticity makes it very difficult to decide whether or not there can be conditions which would give us an unstable equilibrium in the case of even distribution. A spontaneous separation requires, of course, that at the point of even distribution the rate of change of the magnetic forces shall be greater than the rate of change of the combined electric and elastic forces as the magnetons move towards group formation.

There is, however, one important respect in which the two cases differ. Molecular collisions will cause much more irregular disturbances in an elastic than in a rigid sphere. Such disturbances will lead to the momentary formation of separate groups. Under these circumstances, the groups that form most often and have the longest average existence will be the smallest groups that can possess a minimum of magnetic energy and also great symmetry and mobility—the last being especially important under dynamic conditions. There is thus a strong probability of an average state of grouping into *eights* in the atom (see §6).

The effect just described is possibly sufficient in itself to determine the properties of an atom, although it would admittedly be more satisfactory to find a mechanism that could hold for a static condition of the atom also. If it should be found that the static separation is an essential idea, and that the elasticity of the positive sphere does not secure it, it would be better, I think, to make further and more arbitrary assumptions about the magneton or the positive part of the atom than to fall back upon the idea of a single large group of magnetons, because of the very much better picture of the facts that the grouping into eights affords us. One such set of assumptions has been suggested to me by Dr. D. L. Webster: the magneton might be supposed to exert magnetic forces that are greater than the electric forces at moderately short distances (as if $v$ were greater than $c$); this would secure separation into groups, and the coalescence of such magnetons could be prevented by the assumption of a new repulsive force which followed an "inverse cube" law up to very short distances.

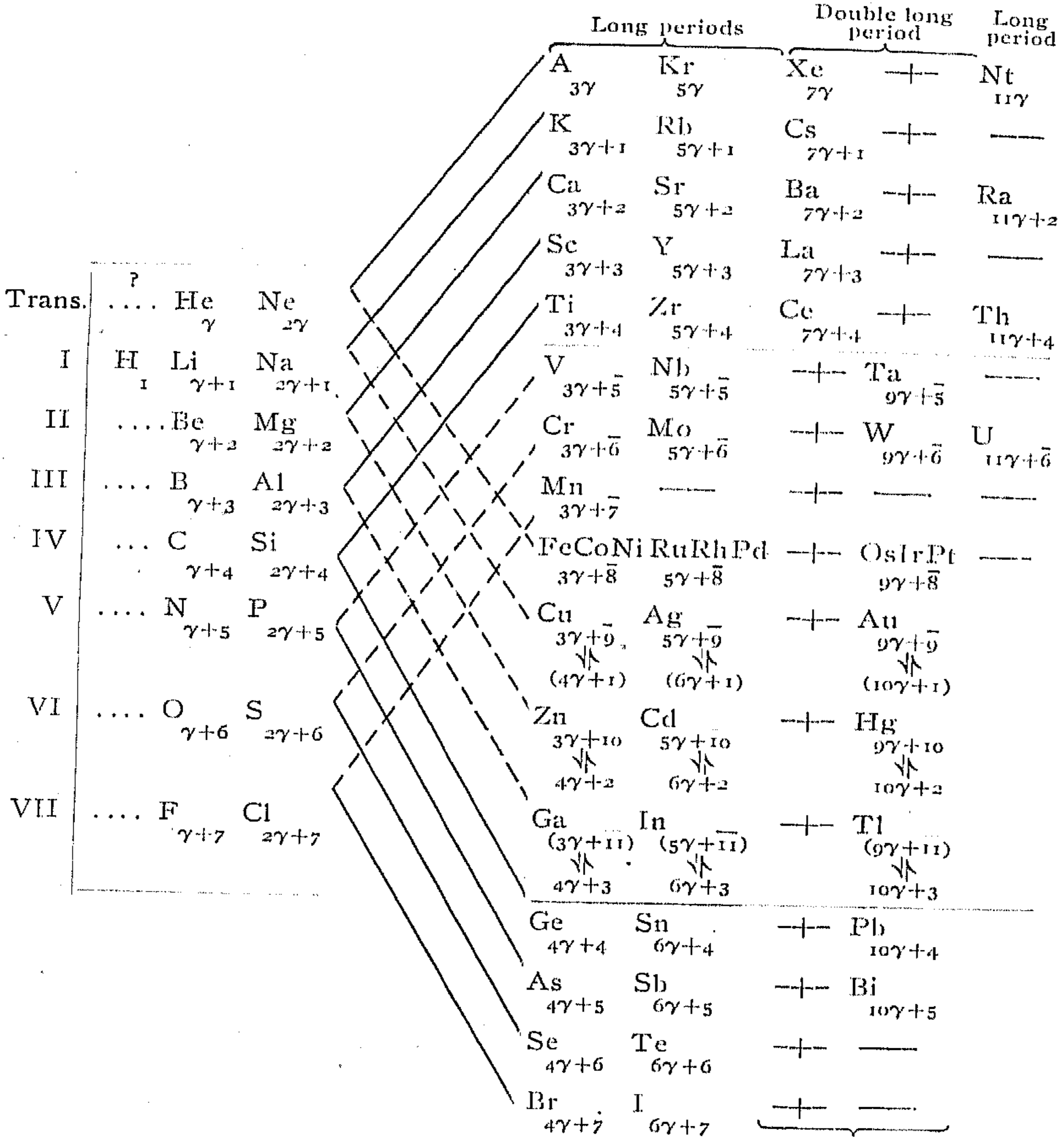
It must be remembered, of course, that a static condition of the atom cannot occur except at the absolute zero of temperature: furthermore, even if the distribution into groups of eight within an atom were statically stable, the reactivity of the valence magnetons could not be developed except under conditions of inter- and intra-atomic disturbance. On the other hand, if the grouping into eights owes its very existence to these disturbances, it is hard to see how the valence magnetons could retain, at any temperature, that marked individuality which is shown in the permanence of structure in organic molecules, and yet more in the stability of optical isomers—and which, indeed, was one of the original reasons for introducing the idea of this magneton (§§1, 3). However, we should expect, from the immediate point of view, to find just that relative stability of the "organic" compounds of Carbon, Silicon, and Titanium which is actually observed, because an increase in the number of groups of eight within the vibrating atom would more and more swamp the effect of the valence magnetons (in forming the "positive bond," at all events: see §9).

Without trying to settle this matter any more completely here, I will, for what follows, eke out the argument by the assumption that the separation into groups of eight actually can take place under static conditions—without, however, abandoning the dynamical conception of vibration and possibility of configurational changes within the atom, which is, as will be seen, the key-note of the treatment in this paper.

We can now derive constitutions for the atoms of all the elements in the manner shown in the accompanying table. Hydrogen, with one magneton only, is followed by a gap; then comes Helium with a group of eight (represented by "$\gamma$"), and the table goes on regularly with Lithium ($\gamma+1$), Beryllium ($\gamma+2$), Boron ($\gamma+3$), and so on. While this works out very well in the short periods, it is evident that for the long periods the plan must be modified; for Manganese ($3\gamma+7$) behaves very differently from Chlorine ($2\gamma+7$). Now a comparison of Vanadium with Phosphorus, Chromium with Sulphur, Manganese with Chlorine, and the Iron-Cobalt-Nickel trio with Argon, shows that these metals of the long period have just the properties that we should expect if there were no tendency in the systems represented by $3\gamma+5$, $3\gamma+6$, $3\gamma+7$ to form a fourth group of eight, and $4\gamma$ were really $3\gamma+8$. To represent this, I have placed a bar over the number referring to the valence magnetons, thus: $3\gamma+\overline{5}$, $3\gamma+\overline{6}$, $3\gamma+\overline{7}$, $3\gamma+\overline{8}$. This state of affairs, which accounts very well for the differences between what are usually called subgroups A and B, is carried on, in a diminishing degree, through Copper, Zinc, and Gallium, with the constitutions $\begin{array}{c}3\gamma+\overline{9}\\ \downharpoonleft\upharpoonright\\ (4\gamma+1)\end{array}$, $\begin{array}{c}3\gamma+\overline{10}\\ \downharpoonleft\upharpoonright\\ 4\gamma+2\end{array}$, $\begin{array}{c}(3\gamma+\overline{11})\\ \downharpoonleft\upharpoonright\\ 4\gamma+3\end{array}$, and the overdue group of eight is assumed not to be firmly established until Germanium ($4\gamma+4$) in group IV is reached. The constitutions assigned to these elements will be discussed in §13 of this paper.

I am unable to see any good reason for the non-formation of this group of eight, or to suggest any simple additional assumption that would secure it. It may be observed that each long period begins with an odd number of groups of eight already within the atom, but that is not likely to be of any particular significance. The non-formation, in certain cases, of the group of eight must then be classed as a subsidiary assumption (§§15, 16); but I have shown, in what follows, how well in accordance with the most various facts are the deductions that can be made from it. The tautomerism which has, as one result, been ascribed to the atoms of Copper, Zinc, and Gallium (and their analogues) seems to be a particularly fruitful conception (see §§13-15).

## THE PERIODIC CLASSIFICATION OF THE ELEMENTS, WITH THEIR ATOMIC CONSTITUTIONS IN TERMS OF MAGNETONS



...., Proto-elements (see § 8).

——, Unknown elements the possibility of whose existence is not contested theoretically.

—|—, Rare-earth elements, possibly with the constitutions $7\gamma+\bar{5}, \dots, 7\gamma+\overline{20}$ ($\rightleftharpoons 8\gamma+\overline{12} \rightleftharpoons 9\gamma+\bar{4}$). See § 13.

## §8. The Number of Magnetons in the Atom

The following table gives a comparison of the numbers of magnetons apportioned to the atoms in the last section with the "atomic numbers" of van den Broëk (which are the numbers of electrons in the atom, according to Bohr), and also the atomic weights of the elements:

| | H | He | Li | Be | B | C | N | O | F | Ne | Na... | S.. | Fe | Co | Ni.. | Os | Ir | Pt | Au.. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Magneton number ($N$) | 1....8 | | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17... | 22... | 32 | 32 | 32... | 80 | 80 | 80 | 81... |
| Atomic number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11... | 16... | 26 | 27 | 28... | 78 | 79 | 80 | 81... |
| Atomic weight | 1 | 4 | 7 | 9 | 11 | 12 | 14 | 16 | 19 | 20 | 23... | 32... | 56 | 59 | 59.. | 191 | 193 | 195 | 197... |

The two sets of numbers become identical for the heavy atoms for which Rutherford has calculated numbers of electrons from α-particle scattering, but for the lighter elements the atomic numbers seem at first to have much in their favor. First there is their close approximation to half the atomic weight, although this does not hold for Hydrogen or the heavy atoms. Secondly, the most definite calculations made from experimental results, viz., those from Barkla's work on the secondary Röntgen radiation (Phil. Mag., 5, 685-698, 1903; 21, 648-652, 1911), give numbers of electrons that are about half the atomic weight numbers for the lighter atoms.

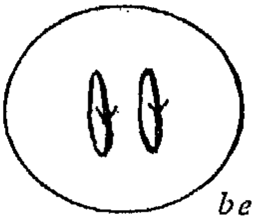
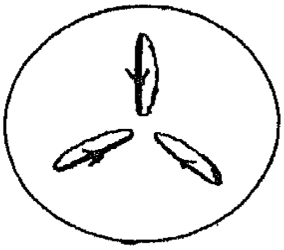
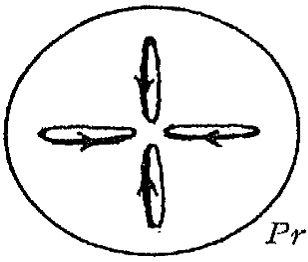
The point to be emphasized here, however, is that none of such calculations have any meaning for the present theory, for the following reasons:

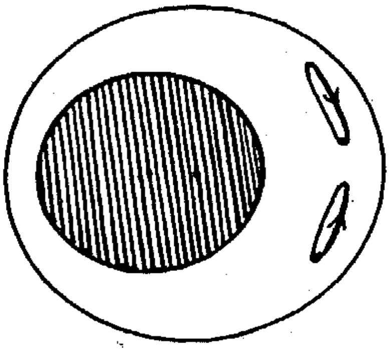
Rutherford's numbers, got from the phenomena of α-particle scattering, assume that the total charge on the electrons is equivalent to the charge on a small positive nucleus; but for the model atoms described in this paper, the nucleus, if there is any, must be neutral (see the note at the end of §16). Also the "characteristic numbers" got by Moseley, which, it should be remembered, are less than the atomic numbers by unity, have not been definitely correlated with the numbers of electrons in the atoms except through the idea of a positive nucleus. To turn to Barkla's work, the calculation of absolute values by means of Thomson's formula requires certain assumptions. One is that the dimensions of an electron are small compared with the length of a Röntgen ray pulse: this is not entirely the case with magnetons. Another, that the electrons in the atom are so far apart that any pulse can act on only one at a time: this can hardly be true of the electrons in the inner ring (radius $10^{-10}$ cm.) of the atoms of Bohr's theory, which is the prominent application of the hypothesis of atomic numbers. Again, the values of $e$ and $\frac{e}{m}$ used in the calculations are still subject to some uncertainty (an alteration in the accepted value of $e$ from $1.13$ to $1.55 \times 10^{-20}$ has changed the number of electrons calculated for the average molecule of air from 25 to 14). And lastly, it has been shown by Crowther that a large part of the radiation scattered at the smaller angles is not accounted for by Thomson's formula, and Webster has pointed out that this is due to Thomson's neglect of a mutual reinforcement of the scattered radiations from the separate electrons. With so many uncertainties, the extant calculations from Barkla's results cannot have much exact significance for any theory of atomic structure.

The hypothesis of atomic numbers fails to accord with the chemical properties of the elements. J. W. Nicholson, in a recent criticism (Phil. Mag., 27, 541-564, 1914), has shown that Bohr's arguments about the behavior of electrons in his model atom are open to objection, and that the system with three electrons, for example, which Bohr assigned to Lithium, would actually behave like an inert atom. If applied to the present theory, the hypothesis would cause the same confusion. Nitrogen, with seven magnetons then in the atom, would be the most electronegative element known; Oxygen, with a single group of eight, would be inert; and Fluorine (then $\gamma + 1$) would be expected to behave like Lithium.

A circumstance frequently made mention of on behalf of this hypothesis is that the $\alpha$-particle, which is a charged atom of Helium, always possesses exactly two units of charge. Now the sudden disappearance of the $\alpha$-particle (as such) when its velocity falls below $.82 \times 10^9$ cm. per second can hardly be due to anything but its neutralization at this point. If at that still enormous velocity it can become neutral, one would not expect it to lose all its electrons at velocities that are not very much higher, and a theory like Rutherford's, or Bohr's modification of it, shows no reason why the two electrons, if there are only two, should not be lost one by one; whereas, if the neutral Helium atom is stable up to a velocity of $.82 \times 10^9$ cm. per second, the present theory would actually predict that for a considerable range of velocity above that point the atom would be stable with a deficit of two magnetons, partly because each succeeding magneton is harder to extract than the previous one, but mostly because the group of six which would remain comes much nearer to the group of eight in its magnetic stability than does the group of seven or any other small group (§6).

Lastly, the lack of any very definite evidence of the existence of atoms intermediate in mass between those of Hydrogen and Helium is the main bulwark of the hypothesis of atomic numbers. According to the present theory, it must be remembered, there are missing from our observation on the earth's crust six theoretically possible elements, containing two to seven magnetons in the atom, which should occupy the gap between H (1) and He ($\gamma$). But it appears, on consideration, that even if such elements existed they would be inactive (with the exceptions mentioned below), because two to seven magnetons can form groups of much lower magnetic energy when alone in a positive sphere than in the presence of groups of eight, which must scatter them towards the surface of the atom.

The configuration inside the first two of these hypothetical atoms would be  *Proto-beryllium* and  *Proto-boron*, and in the third probably  *Proto-carbon*, perhaps with the four magnetons at the corners of an irregular tetrahedron (see §6). The last two of these have no magnetic moment and therefore no attraction for other magnetons at a distance; also they could not unite stably with H atoms even when brought into contact, for the intra-atomic forces beween the magnetons are too strong to allow them to separate for such a purpose. The first atom, Proto-beryllium, has a moment, and it might combine with *one* H atom (for the two magnetons are too strongly attracted together to be able to act separately); but it would not be expected to part with a magneton to make up a group of eight in another atom—as the H atom does in H–(Cl). The probable behavior of Proto-beryllium can be compared with that of Beryllium by considering the diagram for the atom of the latter. Thus the only kind of combination that seems possible for these proto-atoms is where a group of eight is made up within the atom itself. This would be impracticable except for atoms containing as many



as five magnetons already (§9), but Protofluorine (7), certainly, should be an even more strongly "negative" element than Fluorine $(\gamma+7)$.

As far as these atoms are inactive, or combine only with Hydrogen, their absence from the earth is to be expected, for they are light enough to escape from the atmosphere, as even Helium is believed to do slowly; but the absence (or excessive rarity) of Proto-oxygen and Proto-fluorine must be attributed to unknown causes of the same sort as condition the rarity of Neon, Krypton, and Xenon, and the apparent absence of the analogues of Manganese.

Strong evidence for the existence of the proto-atoms is the occurrence in the spectrum from the corona of the sun (where gravitation is much stronger than on the earth) of the bright unfamiliar line attributed to an unknown element, Coronium; on similar grounds an element Nebulium is believed to exist in the nebulæ. Such elements as these could apparently find no place in the Periodic Scheme except before Helium. (The proto-elements have been discussed, though from a different point of view, by J. W. Nicholson (Phil. Mag., 22, 864, 1911).)

A noteworthy feature of this magneton theory is that it leads to numerically identical constitutions for the atoms of the three elements in each of the triplets in the transition group (Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt). According to Moseley's calculations from the Röntgen ray spectra of the elements (Phil. Mag., 26, 1024-1034, 1913), the constant difference of one unit (presumably one electron) from atom to atom applies to these elements just as to the rest. There may indeed be some such regular difference in the nucleus, but we have seen above that Moseley's results cannot well mean anything for the "outer shells" of the model atoms of the present theory, and the way in which the physical and chemical properties of these elements throw them together in one group suggests strongly that there is in their case some less fundamental difference in the structure of that part of the atom.

## PART III. VALENCE

### §9. Two Kinds of Combining Action and Three Kinds of Bonds

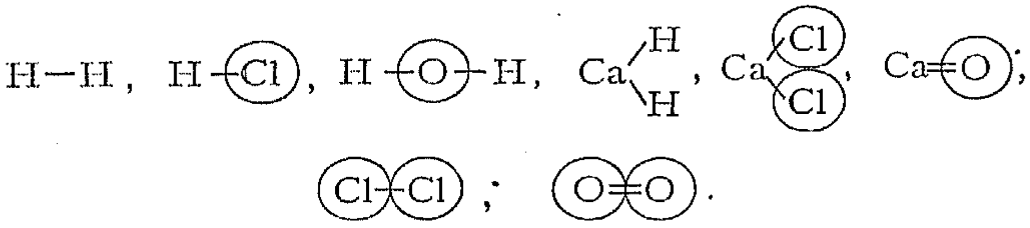
There is no simple term in general use for the "combining action" of an atom that is broad enough to include the ideas of a numerical factor (valence), an intensity factor (affinity?), and sign (in the conventional chemical sense), all within itself. I shall therefore frequently speak of the *action* of an atom, to include all this.

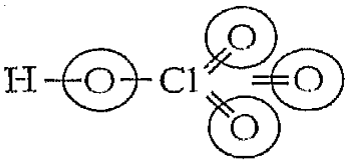
From the results in §§6, 7, we are able to distinguish between two distinct kinds of action for the atoms:

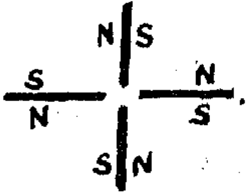
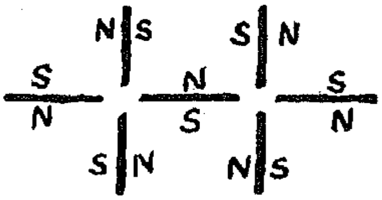
1. Where an atom combines with others through the magnetic forces due to its separate valence magnetons, no attempt being made to form a group of eight in the atom. This is characteristic of the atoms which have always been classed as "*positive*," so the term does very well to describe this kind of action; but it must be made clear that in this sense its connection with positive electricity is only incidental (*e. g.*, when the H atom combines with a Cl atom it gives up its single magneton to the latter and is then left with a positive charge, but this does not happen when it combines with another H atom in $H_2$, or with a C atom in $CH_4$: see below).

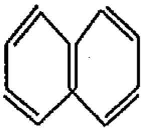
2. *Negative* action, where an atom which possesses nearly eight valence magnetons succeeds in making up a group of eight by extracting magnetons from other atoms.

In the following typical molecules, Ca and H atoms display *positive* action, and O and Cl atoms *negative:*

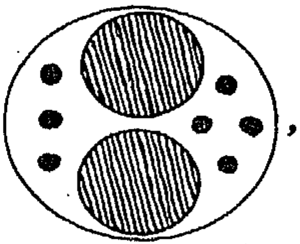


In , however, Cl is acting positively.

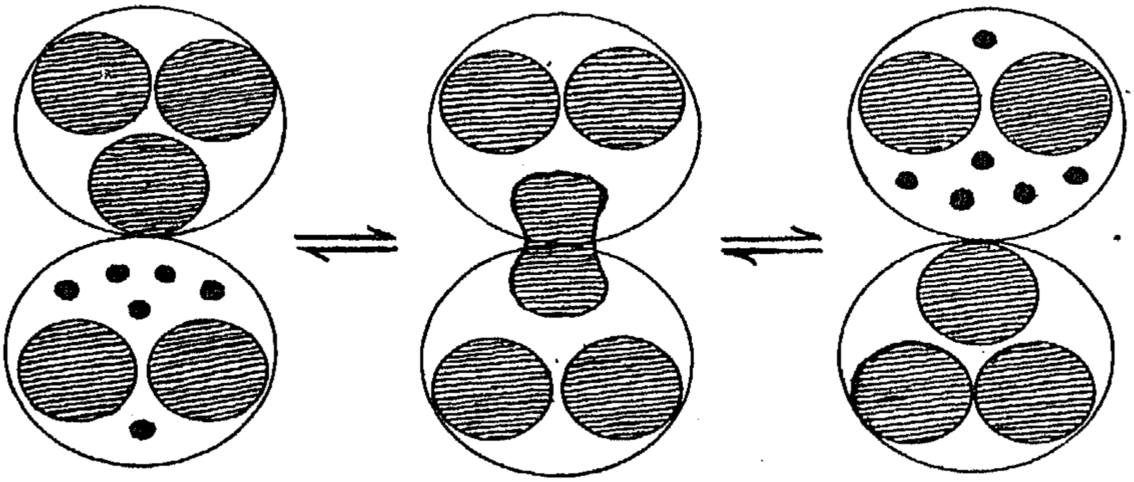
The way in which the $Cl_2$ and $O_2$ molecules have been represented requires explanation. In $Cl_2$ we have two atoms that contain seven valence magnetons each and are normally monovalent negatively. It is evidently impossible for them both to form groups of eight simultaneously, nor, on account of molecular collisions, would one be likely to form such a group permanently at the expense of the other: we are thus led to think that this group must oscillate between the two atoms. If this occurs, there must be formed, transitorily, a condensed group of fourteen magnetons, which is related to the group of eight very much as the naphthalene molecule is related to that of benzene. If we take a horizontal section through the upper four coils in config. 1 (see §6), we get the diagram . A similar section through the condensed group of fourteen would give us: 

(*cf.*  and  ). It may be seen from this that the group would have a certain degree of intrinsic stability, although not nearly so much as the more symmetrical and mobile group of eight. In the same way the $O_2$ molecule may contain a transitory group of twelve, which can be pictured by imagining config. 1 to have three coils in each vertical row instead of two: a condensed group of ten for the $N_2$ molecule is not so easy to imagine, but the same oscillation of the "negative" function can take place there: $\hat{\mathrm{N}} \equiv \textcircled{\mathrm{N}} \rightleftharpoons \textcircled{\mathrm{N}} \equiv \hat{\mathrm{N}}$ (where $\wedge$ represents a pair of free magnetons. A bond of this kind, which allows of the more or less rapid oscillation of the "negative" function (*i. e.*, of the group-of-eight formation) between two atoms, with the intermediate formation of a condensed group, will be called the *negative bond.*

Diagrammatically, then, the Cl atom may be represented:

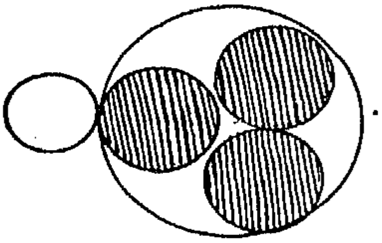
,

and the whole behavior of the $Cl_2$ molecule:



Since we have called the bond in $(\mathrm{Cl}{+}\mathrm{Cl})$ the *negative bond,* that in H—H may appropriately be called the *positive bond,* and that in H—(Cl) the *neutral bond*.[1] Diagrammatically the molecules H—H and H—(Cl) may be represented:

,

.

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[1] In the case of the *neutral bond,* this formal terminology becomes somewhat artificial, and possibly misleading—for it is exactly there that an electric polarity is developed in the molecule by the transfer of a magneton. On the other hand, this bond has closely associated with it the idea of the union of oppositely charged ions to give an electrically neutral molecule.

But in any case the choice of terminology here is difficult. Perhaps the best, from a descriptive point of view, is that given by Bray and Branch in a paper on "Valence and Tautomerism" (Journ. Amer. Chem. Soc., 35, 1440-1447, 1913). Their "polar bond" is largely identical with the *neutral bond* here. But it would not be possible to use their term "non-polar" to describe what is here called the *positive bond,* because the latter can probably be "polar" in a few cases (*e. g.,* in metallic hydrides: these are not discussed in this paper, but see §16; and the present purpose is to classify bonds by the mechanism of their formation rather than by their ultimate effect upon the behavior of the molecule. However, the use of the terms "polar" and "non-polar" in a purely adjectival sense, such as their authors meant, is highly desirable: the *negative bond* might then be described as "ambi-polar," as I have indicated below.

The following table of some possible terminologies seems to show that the most formal, besides giving a good synthesis of ideas, is perhaps the safest:

| The action of an atom | | The bond between atoms | | | Criticism |
|---|---|---|---|---|---|
| positive | negative | positive | neutral | negative | Formal. |
| extensive | intensive | .... | .... | .... | Vaguely descriptive. |
| dispersed | collected | .... | .... | .... | |
| .... | .... | non-polar (not always) | polar | ambi-polar | Describes electric effect. |
| .... | .... | linear | cubical | oscillating cubical | Describes arrangement of magnetons. |
| simple | compound | simple | compound | oscillating compound | Vague. |
| .... | .... | two- | eight- | oscillating eight- | Gives number of magnetons used. |

With regard to these terminologies, objections besides those which I have mentioned will readily suggest themselves.

(The above diagrams are drawn on half the scale of those given in the previous sections. The black dots, representing valence magnetons, do not of course show their real distribution, whatever that may be.)

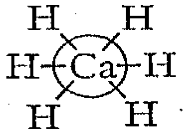
The exact use of the terms *positive, negative,* and *neutral,* in connection with this theory, in describing an atom's action on the one hand, and the bond between atoms on the other, is then as follows:
A *positive*[1] atom + a *positive* atom use the *positive bond:* H—H.

A *negative* atom + a *negative* atom use the *negative bond:* .

A *positive* atom + a *negative* atom use the *neutral bond:* .

There follows a table of the typical oxides and hydroxides that are so familiar in connection with the Periodic Scheme, together with the numerical values, and relative intensities (qualitatively: see below), of the combining actions derived for the atoms in this paper:

| Group: | 0 | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|---|
| Highest normal oxide | .... | $Li_2O$ | $BeO$ | $B_2O_3$ | $CO_2$ | $N_2O_5$ | .... | .... |
| | .... | $Na_2O$ | $MgO$ | $Al_2O_3$ | $SiO_2$ | $P_2O_5$ | $SO_3$ | $Cl_2O_7$ |
| Positive valence | 0 | 1 > | 2 > | 3 > | 4 > | 5 > | 6 > | 7 |
| Hydrides | .... | $LiH$ | $(CaH_2)$ | $BH_3$ | $CH_4$ | $NH_3$ | $OH_2$ | $FH$ |
| Negative valence | $\overbrace{0\text{[or }8}$ < | 7 < | 6 < | 5] < | 4 < | 3 < | 2 < | 1 |
| | | impracticable | | | ? | | | |

It will readily be seen that this scheme, which is a direct mechanical consequence of the assumptions of this theory, contains all the features of the well-accredited scheme of "valencies and contravalencies" which is associated with Abegg's name; and it also shows why the "contravalencies" in groups I-III should be merely hypothetical—for example, the Ca atom, with only two valence magnetons, can be seen, from electrostatic considerations, to have very little or no tendency to draw in six more from six H atoms to give the molecule  : instead, it simply combines with two, using the positive bond: H—Ca—H.

For those atoms that do show negative action, it is to be expected that its intensity will diminish as the number of outside magnetons

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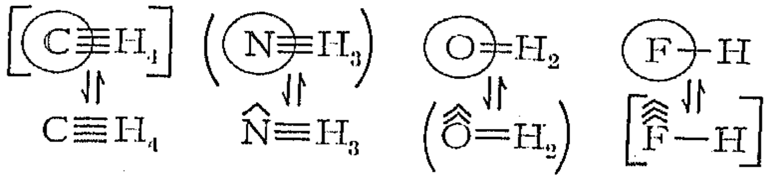
[1] Or better, "positively acting," and so for the rest.

required to make up the group of eight increases, because of the increasing electrostatic strain involved; and so the order of intensity is $\left.\begin{matrix}F\\Cl\end{matrix}\right\} > \left.\begin{matrix}O\\S\end{matrix}\right\} > \left.\begin{matrix}N\\P\end{matrix}\right\} > \left.\begin{matrix}C\\Si\end{matrix}\right\}$. If the intensity of the negative action of the atom of an element is to be judged by the readiness with which it unites with Hydrogen or with the metals, as is reasonable, Nitrogen and Phosphorus must be fairly weak in this respect, and Carbon and Silicon can have very little tendency to combine negatively; this is just as theory here would lead us to expect.

Further, this gradation in the tendency to form the group of eight leads us to the conclusion that there must be, in the molecules of the hydrides of these elements a kind of tautomerism or dynamical equilibrium between the two possible modes of union, as follows:



neutral bond (polar),

positive bond (non-polar),

the proportion of polarized molecules increasing regularly from $CH_4$, where it is very small, to HF, in which it greatly predominates. In view of the incessant vibrations of all molecules, this is mechanically a more likely condition than the statical one in which the Carbon atom just does not, and the Nitrogen atom just does, succeed in forming the group of eight. The constitutions of these molecules are of fundamental importance in chemistry, for they are the four typical molecules of the old type theory, and three of them, viz., $NH_3$, $OH_2$, and FH, typically represent almost all ionizing solvents; these three also differ from $CH_4$, as we have seen, in that the unpolarized tautomer contains a certain number (always even) of valence magnetons that are free—that is, it is unsaturated.

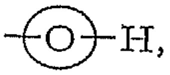
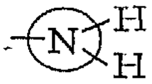
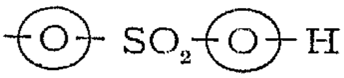
With regard to the intensity of the positive action of an atom (as shown in its typical oxide), the increasing number of magnetons that must be extracted from an atom in forming its typical oxide, as we pass from group I to group VII, results in a decreasing stability of that oxide, for electrostatic reasons. Hence we have the following stability relations:

$$\begin{array}{lllll} B_2O_3 > & CO_2 > & N_2O_5 > & [OO_3] & [F_2O_7], \\ Al_2O_3 & SiO_2 > & P_2O_5 > & SO_3 > & Cl_2O_7, \\ & TiO_2 & V_2O_5 > & CrO_3 > & Mn_2O_7, \text{ etc.} \end{array}$$

The progress from basicity to acidity in the hydroxides as we pass from group I to group VII is a matter of the greatest interest, and much light can be thrown upon it by considering the electrostatic forces set up by the extraction of different numbers of magnetons from the parent atom: I hope to discuss this in a somewhat quantitative way, when dealing with the " retaining powers " of atoms for magnetons (see §16).

In this section the relations between analogous atoms in any group of the Periodic Scheme have not been discussed: this also must be postponed.

## §10. MOLECULES CONTAINING THE NEGATIVE BOND

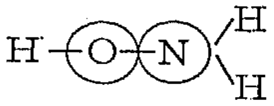
The more typical compounds of the elements have been briefly classified in the last section: many compounds of less ordinary types may be brought into the general scheme by means of the negative bond. As in the case of , this is formed between those atoms and groups only that are capable of negative action. Some such are: , ,  (which is for the most of the time in the other phase: see §9), ; and among their binary compounds we have:

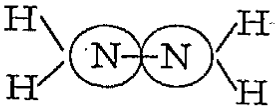

, chlorine molecule;

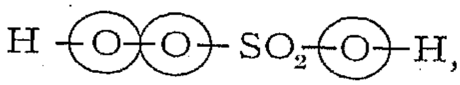

, hypochlorous acid;


, chloramide;

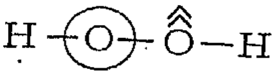
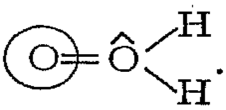
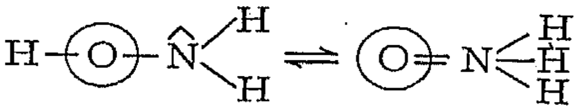
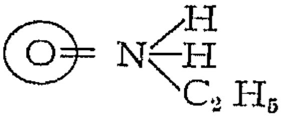
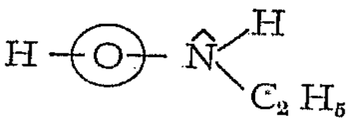

, hydrogen peroxide;

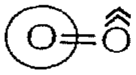

, hydroxylamine;

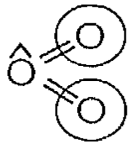
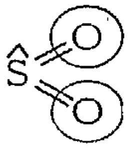
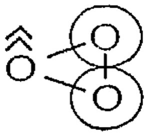

, hydrazine;


, monopersulphuric acid;


, persulphuric acid.

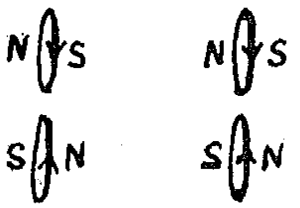
Molecules like these are liable to the same kind of tautomerism as HCl, $H_2O$, $H_3N$ molecules (§9), but it will be more complicated, for either half can tautomerize. The constitution given to $H_2O_2$, for example, is only one phase in the oscillations of a very mobile molecule. The half-polar tautomer  might easily pass over into . This would be exactly analogous to the change  for hydroxylamine; and while there is no definite evidence that this takes place in the simple substance, it is known that the attempt to get an amine oxide like  always yields the β-hydroxylamine  (unless the amine is tertiary).

With regard to the "double" negative bond in the $O_2$ molecule, the unsaturated tautomer, which most likely predominates,  (§9), would account for that adding on of whole molecules which seems to be the first stage of oxidation by gaseous oxygen (*cf.* "autoxidation" phenomena).

Ozone, which is formed by the union of an $O_2$ molecule with a nascent O atom, may then, in different phases, be  (like  : see §11), or  with the negative bond oscillating around the ring.

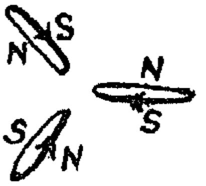
### §11. Residual Forces, Magnetic and Electric

In discussing the actions between atoms in the foregoing pages, we have considered only the primary, or valence, effects of the magnetons, and have left out of account the residual magnetic forces that must be exerted to a greater or less extent by all combinations of magnetons. Now, as a rule, these forces would be negligible in determining the *number* of atoms in molecules such as are stable in the gaseous state, because they are so much weaker than the primary forces; although this may not be so invariably, just as it is not true that the primary forces are always effective in holding together the parts of the molecule of a gas (*cf.* $N_2O_4$, or $I_2$). But the residual forces *within* a molecule might affect its properties considerably. These forces, as they are magnetic, will be forces of attraction wherever possible, and we can in many cases form a rough idea of their distribution, magnitude, and influence on the molecule.



Let us first consider the factors that would determine the amount of attraction between two magnetons. In the case of simple groups, such as groups of two each, it is evident that they must take up certain "complementary" attitudes towards one another, as shown in the figure, if there is to be any great amount of attraction between them, and such complementary attitudes are not possible unless the two groups are very similar in structure. For instance, the two groups

AND



can attract each other when in the relative attitudes I have depicted, but not so much as the more symmetrical pair first mentioned.

This principle seems to be perfectly general; and, in applying it to the present theory, we can distinguish between two very distinct types of groups: (1) groups of eight, with their stable symmetrical distribution of magnetons; and (2) less symmetrical groupings, where the magnetons are "free" or in positive bonds (no doubt further distinctions could be made here).

The group of eight has a symmetrical but very checquered field, and is not fitted to attract a single magneton very strongly, or any group that is not very similar to itself. In the same way, less regular groups may under favorable circumstances have more attraction for one another than they could have for groups of eight.

Not the least important feature of these attractions is that the external field of a group of any kind of structure will tend to impose a similar structure upon any neighboring group, so as to increase the attraction between them and lower their mutual energy. This tendency will affect irregular groups more than groups of eight, for their magnetons are less firmly held, so that irregular groups will more frequently be able to take up configurations such that they can attract one another. It must be remembered, of course, that, from the very nature of magnetic forces, no groups of magnetons could affect one another appreciably at distances that are much greater than the distances between the magnetons within the groups, for changes such as could decrease the mutual energy of the groups must, except for slight changes, increase their internal energy still more, because the distances there are smaller. However, intra-molecular distances would not usually be too great, for we have assumed the radius of the magneton to be of the same order of magnitude as that of the atom.

We have now reached the following generalizations about the mutual action of groups of magnetons:

1. Groups of eight can attract one another and irregular groups can attract one another much more than irregular groups can attract groups of eight.

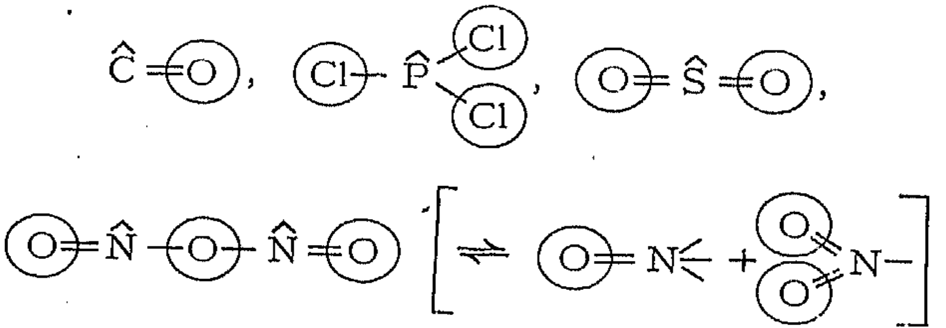
2. A group of eight will tend to induce the formation of other such groups in its vicinity; and conversely, an irregular part of the molecule will tend to weaken any groups of eight that are near to it. Groups of eight will also mutually reinforce one another.

These principles are of great promise in connection with the influence of "negative" groups in the molecules of Carbon compounds, for the negative action of an atom has been identified, in the preceding pages, with its tendency to form a group of eight. Another application is to the properties of unsaturated molecules (§§12, 13), for these will naturally show the disturbing influence of free magnetons on groups of eight, if the present conclusions are correct.

There are also residual electrostatic forces to be considered. It has long been recognized that the bond in a molecule like HCl is electrostatic, and owes its existence to the extraction of an electron from the H atom by the Cl atom, whatever may be the cause of that extraction. The electrical polarity which presumably is thus set up in the molecule has been used to explain many phenomena by Sir J. J. Thomson in a recent paper on "The Forces between Atoms and Chemical Affinity" (Phil. Mag., May, 1914); also a discussion of this effect from a more chemical standpoint is given by G. N. Lewis in a paper on "Valence and Tautomerism" (Journ. Amer. Chem. Soc., 1448-1455, 1913), and by others. Now the explanations of the magnitude of the dielectric constant, extent of molecular association, and other things, by means of this conception are not affected by the assumptions of the present theory (except in so far as they may in some cases be made more definite); but a part of the phenomena which it has been attempted to explain as due to electrostatic induction between molecules will be found to be more plausibly ascribed to a magnetic induction. It should be noted that the electrostatic induction, which must of course occur, would often have much the same effect as the magnetic induction described above, especially in actions between separate molecules; but there is much in the *intra*-molecular influences in carbon compounds that can be explained by the latter conception only. This I hope to discuss in a future paper, but it may be pointed out now that the two effects (electrostatic and magnetic) are closely interdependent, according to the present theory, for electric polarization of a molecule has its origin in a rearrangement of magnetons to form the group of eight.

## §12. UNSATURATION IN INORGANIC COMPOUNDS

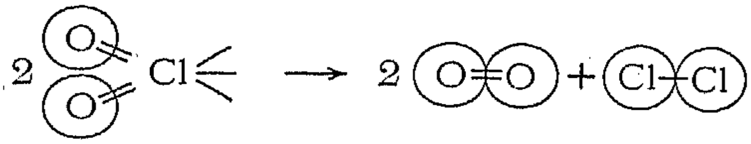
This only occurs when an atom, acting positively, has a valence less than its maximum; for negative valence is fixed—for example, an atom with six valence magnetons can part with any number up to six, but to make up a group of eight within itself it must take in exactly two. The formulæ



explain themselves. In most of such molecules the unsaturated atom has a pair of free magnetons, which is represented by the symbol ∧. This tendency of free magnetons to go in pairs is referred to again below.

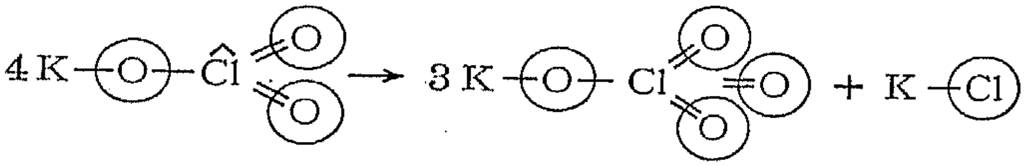
Now these free magnetons may be expected to produce two effects in the molecule. One is obvious: it is a tendency to form the corresponding saturated molecule, $CO_2$, $PCl_5$, $SO_3$, $N_2O_5$, $N_2O_4$, and so lower the magnetic energy. But this must always raise the electric energy—*e. g.*, in $SO_2$ the S atom has lost four magnetons, in $SO_3$ six—and that tends to oppose saturation. The point of equilibrium between these two tendencies, apart from metastable conditions of the molecule, will naturally be further and further from the point of saturation as we pass from group IV to group VIII of the Periodic Scheme: an inspection of the oxides in these groups shows that this prediction agrees with the facts.

The other effect is due to their influence upon what linkages are already formed. We have seen (§11) that free magnetons weaken neighboring groups of eight. This results in a tendency for unsaturated molecules to break down in such a way as to form molecules of other types that are more saturated, if that is possible. This may occasionally take place by the formation of the molecules of the elements, as in the reaction



..........A,

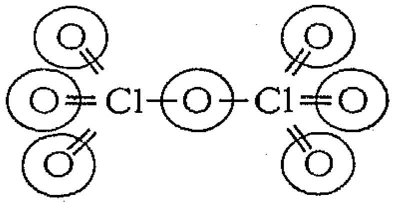
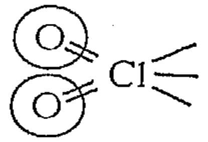
but more often by a change of the following type:

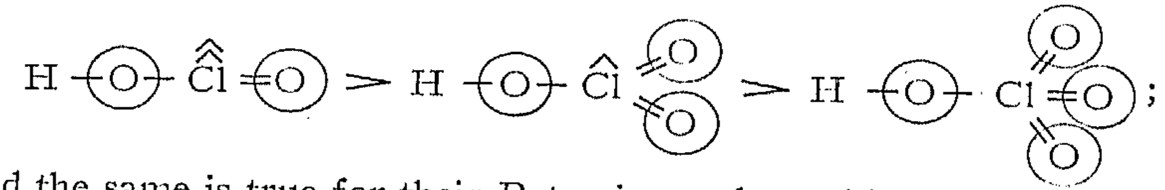


...B,

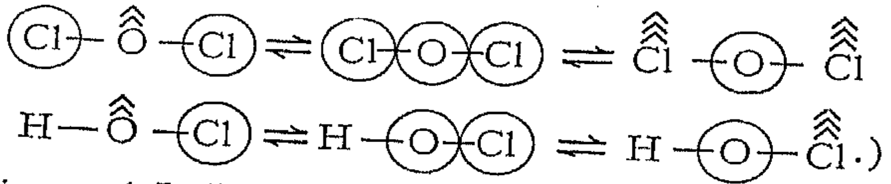
which combines the two effects of the free magnetons.

Changes of type A do not take place readily unless the resulting elementary molecules are well saturated in character, for if they are not, the reverse action readily occurs. The nature of elementary molecules cannot be discussed at this stage; but it is noteworthy that the high molecular weights of gaseous Sulphur and Phosphorus and the high melting points of Carbon and Silicon are in accordance with the fact that their oxides, even when unsaturated, do not break down into the constituent elements; while the metastable nature of the oxides of Nitrogen is in accordance with the saturated character of the $N_2$ molecule. The facts in these cases could have been predicted, quite independently of any theory, from the mere conception of unsaturation; but the same cannot be said of the comparisons which now follow.

To see clearly the effect of free magnetons in loosening linkages, it is necessary to compare the Oxygen compounds of some element whose oxides are all metastable, that is, an element which will not combine directly with Oxygen at all. Thus we eliminate the reverse action which confuses the issue in the case of Sulphur, Carbon, etc. Fluorine and Oxygen are too extremely negative to possess oxides (except for $O_3$), but we have an ideal case in Chlorine. Of the oxides of Chlorine,  is found to decompose less readily than  ; and this remarkable result is only to be explained by the absence of free magnetons from the molecule of the former, for that oxide must have much the higher electric energy of the two. In the case of the oxyacids of Chlorine, the velocities of decomposition, under equal conditions, are in the following order:



and the same is true for their Potassium salts. Also the heat evolution for complete conversion into KCl + Oxygen is much greater for $KClO_3$ than for $KClO_4$, and very probably is greater still for $KClO_2$. (I have left $Cl_2O$ and HOCl out of account, because they contain the negative bond, thus:

and 

For Bromine and Iodine the relations are less regular: $HBrO_4$ is not known, and $HIO_4(2H_2O)$ is less stable than $HIO_3$. In the case of Nitrogen the oxyacids obey the rule, but most of the oxides do not. No other negative elements satisfy the condition of not combining directly with Oxygen.

As examples of changes of the type B, we have the following that take place on heating:

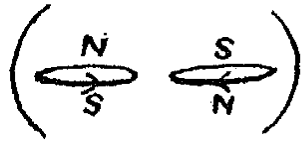
$$4\mathit{KClO_3} \rightarrow 3KClO_4 + KCl \quad \Big\} \text{ group VII,}$$
$$3\mathit{HClO_3} \rightarrow HClO_4 + H_2O + 2\mathit{ClO_2}$$
$$4\mathit{Na_2SO_3} \rightarrow 3Na_2SO_4 + Na_2S \quad \Big\} \text{ group VI,}$$
$$4\mathit{H_3PO_3}\text{ aq.} \rightarrow 3H_3PO_4 + PH_3 \quad \Big\} \text{ group V;}$$
$$5\mathit{Na_3AsO_3} \rightarrow 3Na_3AsO_4 + 3Na_2O + \mathit{As}$$

and others that are spontaneous at ordinary temperatures:

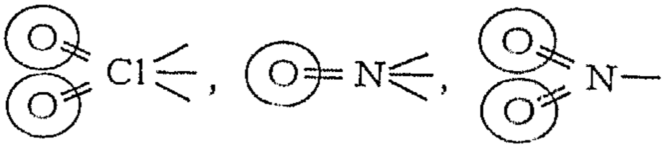
$$3\mathit{H_2MnO_4}\text{ aq.} \rightarrow 2H_2MnO_4 + 2H_2O + \mathit{MnO_2} \quad \Big\} \text{ group VII,}$$
$$3\mathit{HNO_2}\text{ aq.} \rightarrow HNO_3 + H_2O + 2\mathit{NO} \quad \Big\} \text{ group V,}$$
$$2\mathit{Na_2SnO_2}\text{ aq.} \rightarrow Na_2SnO_3 + 2NaOH + \mathit{Sn} \;. \quad \Big\} \text{ group IV.}$$

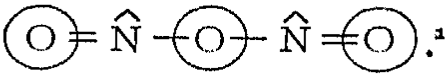
(Unsaturated molecules are italicized throughout.) The effect thus seems very general, although it will be recognized that two or three of these examples may not have much significance. In many cases (as with nitrites, bromates, iodates) such changes have not been observed, but when it is remembered that the electric strain is invariably greater in the saturated than in the unsaturated molecule, it seems that the evidence here collected is enough to establish the principle of the interfering action of free magnetons.

A difficulty in interpreting the chemical data arises from the fact that, although a reaction will not take place at all unless it causes a diminution in free energy, the velocity of the reaction is very little dependent upon the amount of that diminution. It seems, on consideration, that the loosening effect of the presence of free magnetons ought to have a more definite effect in accelerating a change (as in the decomposition of the oxyacids of Chlorine) than in conditioning it, thus resembling a catalyst: for it is impossible to predict whether the magnetic energy due to the presence of free magnetons in the molecule would or would not be greater than the increase in electric energy which accompanies saturation. In the case of a reaction like $4K\hat{Cl}O_3 \rightarrow 3KClO_4 + KCl$, however, it should be noticed that while the magnetic energy of all four molecules is diminished, the electric energy increases in only three of them, being greatly diminished in the fourth.

The rule (with numerous exceptions) that the positive valence of an atom, when it has not its maximum value, has a value that is less than that by two units, is in accordance with the present conceptions; because a group of two magnetons  not only has considerably less than twice the magnetic energy of a single magneton, but on account of its nature will interfere less with the stability of a group of eight, for the latter is made up of four such pairs. A group of three, whatever its configuration, must have as great a disturbing effect as a single magneton. Again, four free magnetons probably could not maintain a compact symmetrical configuration, because they lie in an outer layer of the atom (§§7, 14), and would probably be distributed so as to act like two groups of two, thus causing about twice the amount of disturbance that one of these can cause: in accordance with this, we find that molecules like $\textcircled{\text{Cl}}-\hat{\hat{S}}-\textcircled{\text{Cl}}$ and $H-\textcircled{\text{O}}-\hat{\hat{Cl}}=\textcircled{\text{O}}$ are quite rare, and very unstable.

The exceptional cases



can reasonably be attributed to the fact that in the case of penta- and hepta-valent elements those oxides which have an *even* number of free magnetons in the atom are bound to have cumbrous molecules like .[1]

The frequent occurrence of a pair of magnetons as a subsidiary group in the outer part of the atom, and its comparative stability, are the reasons for the use here of the symbol $\wedge$ to represent it.

Unsaturation in Carbon compounds is quite a different kind of phenomenon and will not be discussed in the present paper.

## §13. The Transition Series of Elements

In §6 constitutions were assigned to the elements of the series as follows:

| | Ti | V | Cr | Mn | (Fe Co Ni) | Cu | Zn | Ga | Ge |
|---|---|---|---|---|---|---|---|---|---|
| $(3\gamma+)$ | 4 | $\overline{5}$ | $\overline{6}$ | $\overline{7}$ | $\overline{8}$ | $\overline{9}$<br>$\wedge$ | $\overline{10}$<br>$\wedge$ | $[\overline{11}]$<br>$\wedge$ | |
| $(4\gamma+)$ | | | | | | [1] | 2 | 3 | 4 |

They were based on an arbitrary assumption—that in certain specified cases (*i. e.*, in the middle of the long periods) the group of eight was not formed by eight or more free magnetons. The justification for this is that it enables us, without any further assumptions whatever, to systematize and explain the outstanding properties—at first sight so irregular—of these elements.

In the first place, some of the properties of the first four are quite normal. For example, Mn, which is $3\gamma+7$, although without negative action, has a positive valence of seven, as is shown in $Mn_2O_7$ (*cf.* $Cl_2O_7$) and $KMnO_4$ (which is isomorphous with $KClO_4$). Similarly, in the nature of their higher oxygen derivatives, V and Cr

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[1] The kinetic effect here implied should of course be taken into account continually in any complete analysis of the behavior of atoms, but it is difficult to see how this can be done even in a qualitative way except in the very simplest cases.

resemble P and S. The elements Fe, Co, Ni have been given the constitution $3\gamma+\overline{8}$, and, although they themselves are not known to be octovalent, the analogous elements Ru $(5\gamma+\overline{8})$ and Os $(9\gamma+\overline{8})$ give the oxides $RuO_4$ and $OsO_4$.

Again, Cu, Zn, and Ga, the last three of the series, give compounds in which they are mono-, di-, and tri-valent respectively, thus resembling the typical elements of the groups I, II, and III, in which they lie. Now we have seen (§7) that the atoms of these elements may be supposed to undergo an intra-atomic tautomerism similar to the intra-molecular tautomerism described for $CH_4$, $NH_3$, $OH_2$, HF, in §9; and, as in that case, brackets have been used to represent roughly the proportions we may expect of the two phases. What we should predict from this is true in fact, for the first long period at all events: compounds of monovalent Cu (from the $4\gamma+1$ phase) are less stable than those of divalent Cu (from the $3\gamma+\overline{9}$ phase, as explained below), while compounds of trivalent Ga (from the $4\gamma+3$ phase) are stabler than the other compounds of Ga. In the case of Zn, it will be shown that both phases make for divalency. For the other two long periods the agreement is not so good.

In addition to the individual properties already referred to, all the elements of this series give basic oxides in which the atom of the metal tends to be trivalent towards the left of the series, and divalent towards the right. The very regularity of this series of oxides indicates that they are in some way due to the $3\gamma$ phases of these atoms: $(3\gamma+)$ $\overline{5}, \overline{6}, \overline{7}, \overline{8}, \overline{9}, \overline{10}, \overline{11}$; but the connection seems at first sight to be remote. It appears as if the successive additions of magnetons have a very slight effect in these transitional series, as far as the basic oxides are concerned (compare with this the even greater monotony in the series of rare-earth elements: see the table of the Periodic Scheme at the end of §7).

Of course Cu, for example, could not be expected to give stable salts in which it is 9-valent, such as $CuCl_9$, not only because of the mechanical hindrance to this, but also because the extraction of so many magnetons from the Cu atom would have to be effected against comparatively great electrostatic forces: towards *negative* groups the atom must remain unsaturated, and some of its nine magnetons will be free. This brings us to yet another application of the principle of the disturbing action of free magnetons, which was discussed in §12. We get the result, paradoxical at first sight, that the more free magnetons an atom possesses, the fewer it can use to combine with negative radicles—unless it succeeds in using them all, which is not possible beyond a certain number (*cf.* the instability of $Cl_2O_7$ and $Mn_2O_7$). This would account for the steady progress from trivalence to divalence that has just been noted. Subjoined is a list of the valences of the transition metals in their chlorides:

| | $X_2O_5$ | $XO_3$ | $X_2O_7$ | $XO_4$ | | | ← Saturated oxides | | |
|---|---|---|---|---|---|---|---|---|---|
| | V | Cr | Mn | (Fe | Co | Ni) | Cu | Zn | Ga |
| 3γ | 4 | .. | 4 | .. | .. | .. | .. | .. | .. |
| | **3** | **3** | 3 | **3** | 3 | 3 | .. | .. | **(3)** |
| | 2 | 2 | **2** | 2 | **2** | **2** | **2** | **(2)** | 2 |
| | .. | .. | .. | .. | .. | .. | (1) | .. | 1 |
| | Nb | Mo | — | (Ru | Rh | Pd) | Ag | Cd | In |
| 5γ | **5** | 5 | .. | .. | .. | .. | .. | .. | .. |
| | .. | 4 | .. | **4** | 4 | 4 | .. | .. | .. |
| | **3** | **3** | .. | **3** | **3** | .. | .. | .. | **(3)** |
| | 2? | 2 | .. | 2 | 2 | **2** | .. | **(2)** | 2 |
| | .. | .. | .. | .. | .. | .. | **(1)** | .. | 1 |
| | Ta | W | — | (Os | Ir | Pt) | Au | Hg | Tl |
| 9γ | **5** | 5 | .. | .. | .. | .. | .. | .. | .. |
| | 4 | **4** | .. | **4** | **4** | **4** | .. | .. | .. |
| | 3 | .. | .. | 3 | **3** | .. | **3** | .. | (3) |
| | .. | 2 | .. | 2 | 2 | 2 | 2? | **(2)** | .. |
| | .. | .. | .. | .. | .. | .. | (1) | 1? | **1** |
| + | $\overline{5}$ | $\overline{6}$ | $\overline{7}$ | $\overline{8}$ | | | $\overline{9}$<br>⇅<br>$[\gamma+1]$ | $\overline{10}$<br>⇅<br>$\gamma+2$ | $[\overline{11}]$<br>⇅<br>$\gamma+3$ |

The numbers in heavy type represent the chlorides that are stablest to oxidation or reduction (as far as the relations could be ascertained), and the decrease in effective valence from left to right is brought out clearly. The values in parentheses do not of necessity belong to this scheme, but can be due to the other phase of the atom's structure: however, the tendencies of the two phases may coincide, as in the case of Zn, Cd, and Hg. (Monovalent Hg, in the sense in which Ag is monovalent, is of doubtful existence, for the mercurous ion has been shown to be double: $Hg_2^{++}$.)

The case of Ag is remarkable. We would certainly expect $AgCl_2$ or $AgCl_3$ to exist, even if they were not as stable as AgCl, but Ag is monovalent in its salts almost without exception. However, this atom's power to form complex ions, which, as I hope to show later, is a characteristic property of these unsaturated atoms and conditioned by their unsaturation, is good evidence for the existence of the $3\gamma+\bar{9}$ phase.

The whole of this explanation, apart from its simplicity and consistency, is strongly supported by the nature of the physical properties of these elements; for there is marked parallelism between their high melting points, electrical conductivities, and magnetic susceptibilities, and the large numbers of free magnetons in their atoms. Their small atomic volumes are also in accordance with the results of this paper, as may be seen in the next section (§14).

## PART IV. VOLUME

### §14. The Volume of the Positive Sphere

The atomic volume of an element in the liquid or solid state is, as is well known, far from being, even approximately, a simple function of its atomic weight, or of the number of magnetons that are in the atom according to the present theory. The elements at the maxima of the well-known atomic volumes curve have atomic volumes that are about seven times as great as those of the elements at the minima. The periodic nature of these fluctuations, however, and their obvious relation to fluctuations in other properties of the elements, such as their valences or melting points (the relation being of an inverse character in these two cases), have made it fairly clear that they are to be ascribed to differences in the forces acting between atoms rather than to corresponding fluctuations in the volumes that the atoms might have if they could be isolated.

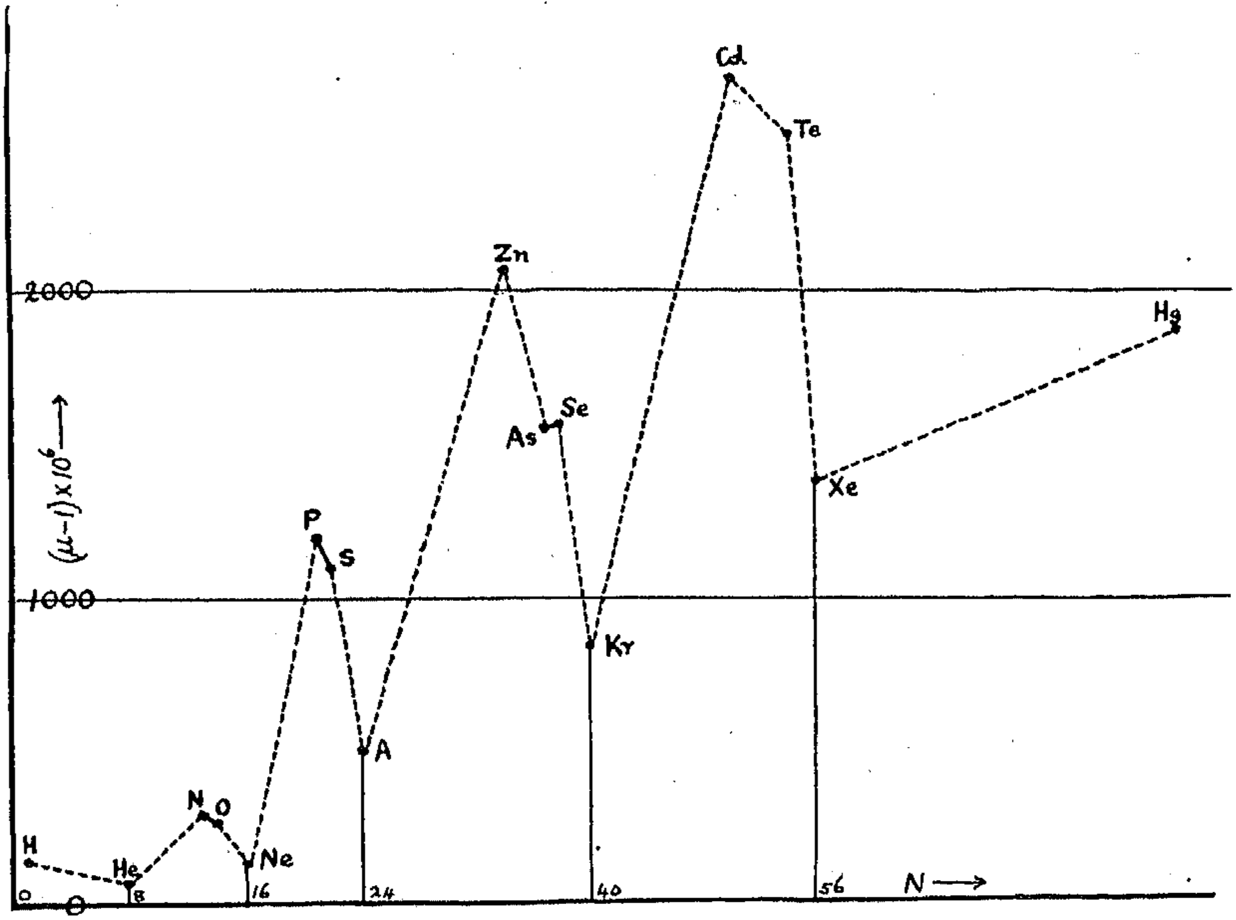
This is the "Hypothesis of Compressible Atoms" for which T. W. Richards has brought forward many kinds of evidence (Faraday Lecture, 1911; Journ. Amer. Chem. Soc., 36, 617-634, 1914; etc.); and the final justification for bringing this idea very concretely into the present theory (which has already been done in §7) is that the elements which lie along the minima of the atomic volumes curve are just those to which we have ascribed the maximum numbers of magnetons not bound in groups of eight or tending to form them (the constitutions assigned to (Fe Co Ni), Cu, Zn, Ga, and their analogues being, in that respect, the new features of the present treatment, §§7, 13). Also the fact that the maxima of magnetic susceptibility are almost coincident with the minima of atomic volumes (even in the case of Cu salts) takes on a new significance when the forces between atoms are attributed to specific attractions between magnetons, as they are here.

Evidence about the volumes of isolated atoms is not entirely lacking; and, as might be expected, it has been got from the behavior of gases, especially those with monatomic molecules. If $\mu$ is the refractive index of a monatomic gas for very long waves, and the atom is assumed to be made up of electrons within a uniform positive sphere, it can be shown that $\mu - 1$ is proportional to the volume of this sphere. Values for $\mu$ have been got for various gaseous elements by Cuthbertson and Metcalfe (Phil. Trans. A., 207, 138, 1907), and the corresponding values for $\mu$-1 are tabulated in Thomson's "Corpuscular Theory of Matter," chap. VII, p. 165. I have tabulated them below together with the atomic volumes of the elements in the solid or liquid state, their atomic weights, and their magneton numbers ($N$).

| | Atomic weight | Atomic volume | | $(\mu-1)\times 10^6$ ∝ gaseous atomic volume | $N$ ∝ Normal volume of the positive sphere |
|---|---|---|---|---|---|
| | | Solid | Liquid | | |
| *Hydrogen .. | 1 | 13.1 | 14.3 | 139 | 1 |
| Helium ...... | 4 | .... | 27.4 | 72 | 8 |
| Neon ....... | 20 | .... | — | 137 | 16 |
| Argon ....... | 40 | .... | 28.1 | 507 | 24 |
| Krypton...... | 82 | .... | 37.9 | 850 | 40 |
| Xenon....... | 128 | .... | 36.4 | 1378 | 56 |
| Zinc ......... | 65 | 9.2 | .... | 2060 | 34 |
| Cadmium..... | 112 | 13.0 | .... | 2675 | 50 |
| Mercury..... | 200 | .... | 14.7 | 1866 | 82 |
| *Oxygen..... | 16 | 11.2 | 12.6 | 270 | 14 |
| *Sulphur .... | 32 | 15.5 | .... | 1101 | 22 |
| *Selenium.... | 79 | 16.5 | .... | 1565 | 38 |
| *Tellurium .. | 128 | 20.4 | .... | 2495 | 54 |
| *Nitrogen ... | 14 | 13.6 | 16.9 | 297 | 13 |
| *Phosphorus. | 31 | 14.1 | .... | 1197 | 21 |
| *Arsenic..... | 75 | 16.0 | .... | 1550 | 37 |

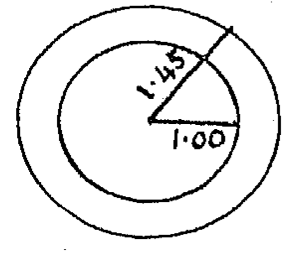
* Not monatomic.

It may be seen from this table that the values of $\mu - 1$ for the elements of any group show a much greater parallelism to the magneton numbers than do the ordinary atomic volumes (except in the single case of Hg); but if these values are plotted against the magneton numbers to give a curve of gaseous atomic volumes as shown below, a much more striking relation is brought out. Incomplete as this curve is, it may be seen that its maxima correspond closely to the minima of the ordinary atomic volumes curve. It is true that the $\mu - 1$ relation holds in strictness for monatomic gases only, but if O, N, P, S, etc., could be obtained in the monatomic state, their values for $\mu - 1$ would almost certainly be even higher than they are here, for the atoms in a polyatomic molecule must be somewhat compressed.



It seems then that the presence of a large number of valence magnetons, which we have held responsible for the abnormally low atomic volumes of some solid elements, is accompanied by an abnormally high atomic volume in the case of gaseous elements. This result, remarkable as it may seem at first, is not at all out of harmony with the present assumptions: indeed, the curve of gaseous atomic volumes is easier to explain than the other.

We saw in §7 that the extent of the compression of the positive sphere depended in part upon the magnetic attractions between the magnetons. Now when an atom contains valence magnetons (*i. e.*, magnetons not in groups of eight), the average magnetic energy per magneton is higher and the average attractions between the magnetons are less. Since the valence magnetons are distinct from the others (as an average effect at all events), this will show itself chiefly in the existence of a rather less compressed outer layer in which the valence magnetons lie, but partly also in an expansion of the groups of eight in the atom owing to the disturbing effect described in §11. The total result is thus an expansion of the atom, the amount of which must be roughly proportional to the number of valence magnetons in it. Hence we would expect a periodic fluctuation of the atom's normal volume just like that in the curve given above. There, the maximum volumes are about three times as great as the minimum, but it should be borne in mind that this only means a 45 per cent increase in the radius of the atom for the transfer of about one-third of its magnetons from a closely to a loosely bound condition.



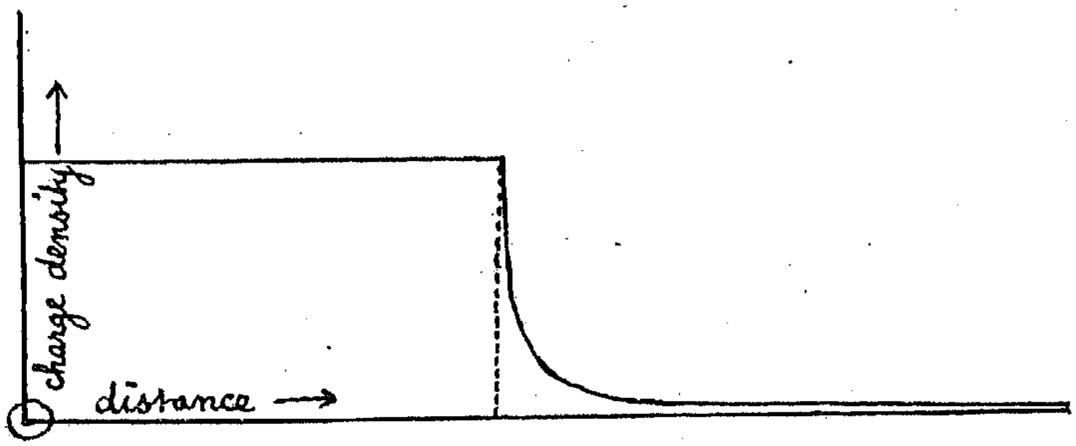
The abnormally high value of $\mu - 1$ for Hydrogen is not entirely unexpected, because, although the positive spheres of all atoms are internally compressed to the same extent by electrostatic forces (§7), the Hydrogen atom is the only one that is not further compressed by internal magnetic forces, for it contains only one magneton. Even in the $H_2$ molecule the compression cannot be nearly so great as in the Helium atom; so that the volume of the positive sphere of the atom of gaseous Hydrogen may be expected to be abnormally great—if not quite so great as the $\mu - 1$ relation indicates.

## §15. Atomic Volumes in the Liquid and Solid States

In considering now the volumes of atoms in liquids and solids, it might loosely be taken for granted that the action of valence magnetons on atoms such as I have hitherto described could produce the differences in volume that are observed. This involves a fallacy, the avoidance of which leads to an important conclusion about the distribution of the atom's positive sphere, which up to the present has been assumed to be uniform in the absence of magnetons.

If a naturally uniform positive sphere contains magnetons proportional in number to its charge (and normal volume), which are not attached to it except by electrostatic forces, the average compression in a cluster of such spheres must be about the same whether the magnetic forces are acting almost entirely within the separate spheres, or are acting largely between them, and so the average volume per magneton should be about the same in the two cases. If there is any difference at all between the two cases, it is that the cluster in which the forces between atoms are considerable will be compressed even less than the other; because it is rarely possible for valence magnetons to reach a state of such low magnetic energy as exists in an atom where the magnetic forces are acting almost entirely within the atom owing to all its magnetons being in groups of eight. Even in the case of a molecule like H-(Cl), where it is true that all the magnetons are in groups of eight, the electrostatic strain must increase their magnetic energy and expand the groups somewhat.

This theoretical result is of course directly at variance with the facts. A cluster of atoms of Argon ($3\gamma$) or of Krypton ($5\gamma$) has about four times the volume per magneton of a cluster of Iron, Cobalt, or Nickel atoms ($3\gamma+8$); and a similar relation holds between Helium atoms ($\gamma$) and Carbon atoms ($\gamma+4$). The great decrease in volume that is undoubtedly caused by an increase of the magnetic forces between the atoms at the expense of the magnetic forces within the atoms is much more than a filling in of "spaces" could account for, and can have only one explanation: the positive sphere must have a much lower charge density and a much greater compressibility at its boundary than in its interior; and thus the compression of this boundary layer, since it is due to the action of the valence magnetons chiefly, is found to be a "periodic" effect as the atomic weight increases.



This boundary layer, which I shall call the *envelope* of the atom, will be assumed to exist quite independently of the action of magnetons upon the positive sphere, and may reasonably be supposed to be of the same thickness for all atoms, since it abuts upon a positive sphere which has the same normal charge density for them all. It may be of uniform density, but it seems more natural to suppose that its density falls off rapidly as the distance from its inner boundary increases,[1] as shown in the diagram, where O represents the center of the atom. With regard to its extent in the case of an isolated atom there is no need to speculate. If it is to fulfill the purpose for which its existence was assumed, it must be supposed to have so low a charge density that magnetons do not lie in it, and therefore its presence does not appreciably affect the values of $\mu - 1$ (§14). As being by far the most compressible part of the atom, the envelope is the seat of the greater part of the volume change that accompanies a chemical or physical change, and it may be supposed to be compressed into a very small space when the forces between atoms are strong.

This envelope, the assumption of which will enable us to give a qualitative explanation of practically all the observed volume relations, must be distinguished from the comparatively very dense layer in which the valence magnetons lie as they surround the groups of eight, and which owes its existence entirely to the presence of the valence magnetons, being simply a less compressed part of the positive sphere proper (see §14). In the diagrams hitherto used in this paper, both this layer and the envelope have been disregarded, but they are represented in the more complete diagrams which are given below for the atoms of Argon ($3\gamma$) and Iron ($3\gamma + \overline{8}$) when these elements are in the liquid and solid states respectively. Their magneton numbers are 24 and 32, but because of the expanding effect of the valence magnetons (which approximately trebles the volume: see §14), the volumes of their positive spheres, neglecting the envelopes, are 24 and 96 respectively (in arbitrary units). These are represented by the circles in the diagrams. The dotted hexagon represents the total space, frequently duodecahedral in shape, that is occupied by the atom when it is one of a cluster. In the case of Iron, this space is shown as being only a little greater than the volume of the positive sphere proper; *i. e.*, about 110 units. The total space for the Argon atom is therefore represented as having a volume of about 430 units, to accord with the relative atomic volumes observed for these elements. It may be seen that the distances across which the interatomic forces must act are thus made to be about as we

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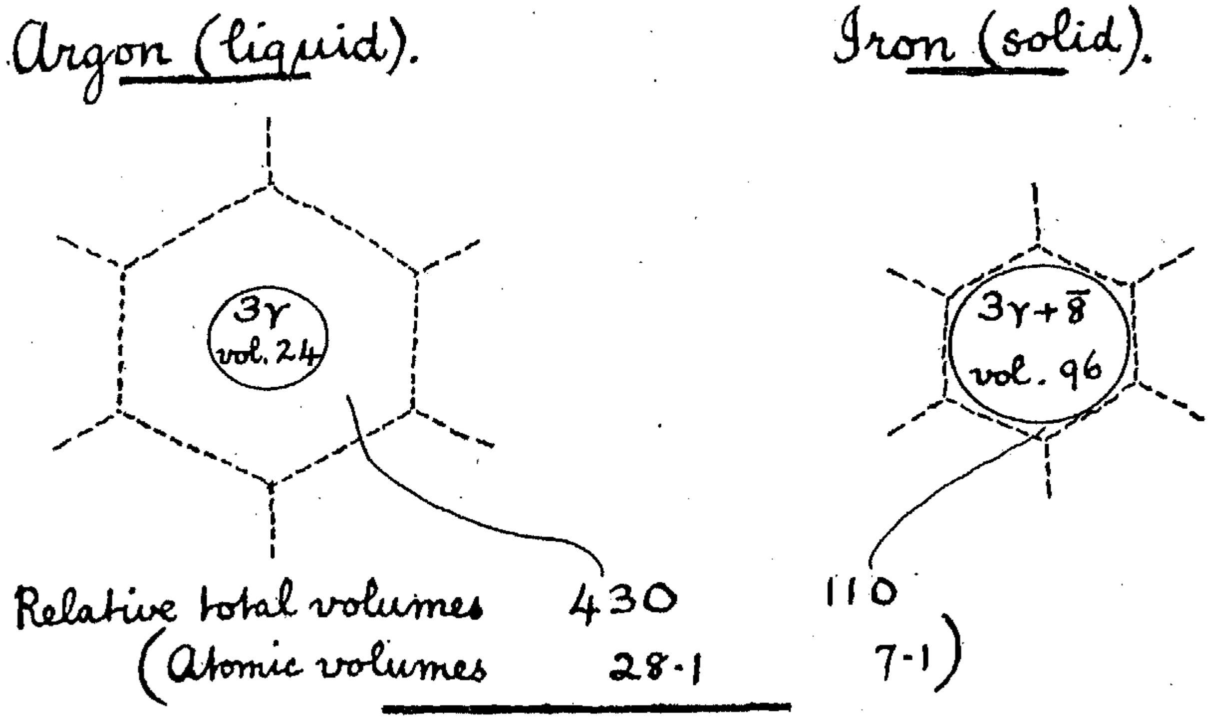
[1] This gives the "thickness" a meaning even if the envelope is infinite in extent.

would expect from what is known of the cohesion of these two substances, especially in view of the fact that the Iron atom has eight valence magnetons and the Argon atom none. The assumption that the envelope of the Iron atom is already compressed to a very small volume (as shown in the figure) is justified by the exceedingly low compressibility of this element—as found by T. W. Richards.

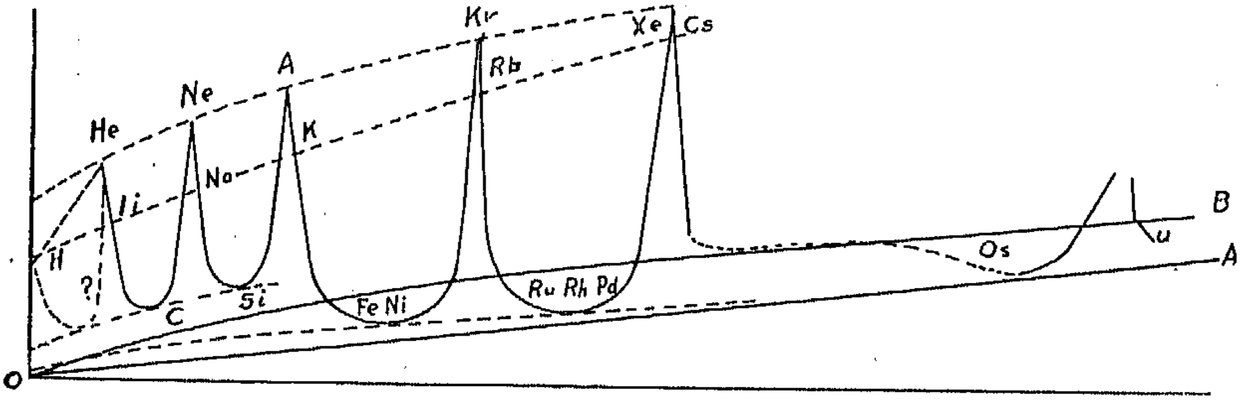
*The curve of atomic volumes.*—Owing to the complexity of the factors involved, it is useless to try to make up an expression that would yield a complete atomic volumes curve; but it is nevertheless possible to predict a number of the features of such a curve.



In the first place, the force that compresses the atoms is likely to come chiefly from the valence magnetons, and to a less extent from the groups of eight in the atom. Now the slight cohesion of the inert elements shows that the latter factor is small enough to be neglected when there are valence magnetons present—in the present rough treatment at any rate. It is important, however, to find out the effective numbers of the valence magnetons in the various atoms. That these are not necessarily the same as the actual numbers may readily be seen by comparing the probable behavior of Cl $(2\gamma+7)$ with that of Mn $(3\gamma+\overline{7})$. The former has a strong tendency to form the group of eight, and so in its cohesive action it will behave as if it contained fewer than seven magnetons. This argument applies to all the halogens, and to a less extent to the nega-

tive elements of groups VI and V of the Periodic Scheme. Thus in the short periods the effective numbers of magnetons will be nearer to *1 2 3 4 3 2 1*
than to 1 2 3 4 5 6 7, although this almost certainly underestimates the numbers in groups V-VII. Similarly, in the long periods we can substitute for the actual numbers, which are
1 2 3 4 5 6 7 8 9 10 (11)
⇅ ⇅ ⇅
(1) 2 3 4 5 6 7, the effective
numbers: *1 2 3 4 5 6 7 8 7 6 5 4 3 2 1.* The use of these numbers (in italics) would place C and Si at the minima of the curve in the short periods, and Fe Co Ni and the Platinum metals at the minima in the long periods—as they are in the curve of actual atomic volumes.

With regard to the shape of the curve, since the envelope, as we have pictured it, is bound to be more compressible at small than at great compressions, we could predict the flat minima and peaked maxima that are observed, and would expect, from what has been said, a curve of the general shape shown in the figure (the significance of the "dotted" loci is explained below). The chief defect in this curve is that it places all the inert elements at the maxima. In actual fact He is at the first maximum, and Ne probably at the second (its density in the liquid state has apparently not been determined), but the other maxima are occupied by the alkali metals K, Rb, Cs. Now although it is difficult to explain why the atomic volumes of these elements should be greater than those of A, Kr, Xe, it is easy to see why they should not be very much less. When each atom in a cluster has only one valence magneton, the chance that the valence magnetons will cooperate effectively to compress the cluster is very small, and much less, for example, than one-fourth of the chance when each atom contains four—not only because of their small



number, but also because the greater depth of the atom's envelope (due to the smaller compression) makes it less likely that the magnetons will be able to maintain the most favorable attitudes. Most of their action will be upon groups of eight, for which their attraction is slight. Also this difficulty will increase as *N* (and the size of the atom) increases: this is represented by the locus for the alkali metals in the above diagram. For similar reasons the elements Be, Mg, Ca, Sr, Ba would lie rather higher on the curve than might at first have been expected.

Now if the atoms had no envelopes, and all their magnetons were in groups of eight, their volumes would be nearly (but not quite: see *a*, below) proportional to their magneton numbers, and they would lie on a straight line such as *OA* in the diagram. But for any series of analogous elements the volume will not increase as fast as *N*, for three reasons:

*a*. Even the volume of the positive sphere proper does not increase quite as fast as *N*, because the amount of compression due to internal magnetic forces increases somewhat as *N* increases: this makes most difference in the case of H (see §14).

*b*. The expanding effect of a given number of valence magnetons (§14) becomes proportionately less as *N* increases. The locus of the atomic volumes of the elements with 8 valence magnetons will then be about as I have drawn it through the minima of the curve, it being assumed for simplicity (and the flatness of the minima fairly justifies the assumption) that the envelope has practically disappeared in these cases. There will probably be some envelope left in C and Si: hence their positions.

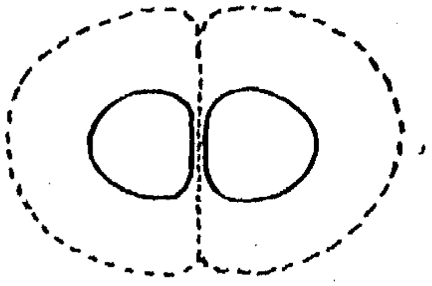
*c*. The addition of the envelope will increase the volume of a small positive sphere proportionately more than that of a large one, for the envelope has been assumed to be of the same "thickness" for all atoms; thus, if two spheres with radii in the ratio 1 : 2 (volumes 1 : 8) have added to each of them an envelope with a thickness equal to the radius of the larger, their new radii are in the ratio 3 : 4, and their volumes now 27 : 64—a very different ratio. This effect, while it is more important for H than for any other single atom, will affect the series of inert elements more than any other series, for their envelopes should be less compressed than those of other elements: this is shown by the locus in the diagram. The actual relation in the case of these elements is in excess of the prediction, for the atomic volumes scarcely increase at all as *N* increases, that of Argon being even less than that of Helium: but valence magnetons are absent, and the compression is due entirely to the action of the increasing number of groups of eight—which might account for the increasing compression, though, on consideration, it cannot be definitely said that it would.

There is another reason why atomic volumes should not increase as fast as *N*, which is not general but applies only to the halogens and the other "negative" elements for which we chose corrected "effective numbers" on account of their tendency to form the group of eight. This tendency to form the group of eight will be diminished as *N* increases;[1] hence the effective number of valence magnetons will be increased.

In this unavoidably involved set of predictions there is still another factor to be taken into account. As the surface of the atom increases with *N*, the average force on unit area that is caused by the action of a given number of valence magnetons must diminish—more rapidly at first than for large values of *N*. This will be true for all except the inert elements (see *c*, above). Hence, as *N* increases, atomic volumes (except for He, Ne, etc.) will increase faster than we have supposed, and the final predicted curve could be got from the curve in the diagram by multiplying the separate values which it represents by a set of factors whose relative magnitudes are roughly indicated by the curved line *OB*.

The extremely qualitative and even uncertain nature of this reasoning is very apparent, but it is the best that can be done under the circumstances.

If atoms have envelopes, as has been assumed in this section, we would expect the envelopes in a diatomic gas molecule to be distributed somewhat as follows:



the compressions due to collisions (see T. W. Richards, Journ. Amer. Chem. Soc., 36, 617-634, 1914) affecting the envelopes chiefly. The advantage of this idea is obvious, for if polyatomic molecules were

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[1] This effect has not been alluded to as yet, but it is doubtless connected with the fact that as the number of groups of eight in the atom increases, the valence magnetons must be more and more scattered.

not "padded" into a more or less approximately spherical shape in some such way as this, they would be expected to dissociate more readily than they do in actual fact. This padding need not be so complete as to abolish the so-called energy of rotation.

With regard to the assumptions that have been made in this paper about the existence, distribution, and compressibility of the positive sphere, it might be argued that a reference of the ordinary superficial conceptions of volume and compressibility to a more fundamental conception that is equally gross is no explanation at all. But a simplification has undoubtedly been made by the present method.

Again, it is obviously desirable to avoid a multiplicity of fundamental concepts; but it has not hitherto been found possible to base any theory of the constitution of matter upon a single concept. For example, the nearest approach that has as yet been made to such a fundamental concept is the electric charge. Now, in the first place, this cannot explain observed mass relations except through the idea of the volume of a charge. In the second place, an electric charge, if it is nothing more than that, must be dissipated throughout all space on account of the repulsions between the separate portions of it. Thus the various ideas of the electron, the magneton here described, the uniform sphere of positive electrification of Kelvin and Thomson, and the minute positive nucleus of Rutherford, all imply the existence of some *non-electric constraint* which has essentially the same kind of action upon the electric charge as the forces of cohesion have upon gross matter. If then the introduction of this idea is necessary, as it seems to be, it is both legitimate and useful to develop it to its fullest possible extent.

## §16. SUMMARY OF ASSUMPTIONS, ETC.

I have attempted in the foregoing pages to show that this magneton theory can go a long way towards explaining the most diverse kinds of chemical combination; and further applications, to phenomena such as those of ionization (§9), the formation of complex salts and molecular compounds (§13), and the structural influences in the molecules of Carbon compounds (§11), have been suggested. Before these latter can be adequately dealt with, however, one other factor in the behavior of magnetons must be studied: this is the electrostatic retaining force which opposes the extraction of a magneton from its parent atom (see Kelvin's analogy, §4), and is important because it determines the strength of a linkage and sometimes its mode of dissociation also.

Quite another field opens up before this theory in the physical properties of matter, for it has professed to take into account, in a qualitative way, most or all of the factors in the action of atoms upon one another. The interaction of magnetons and "positive spheres" should account not only for the chemical properties of the elements and their compounds, but also for their melting and boiling points, tenacities, atomic volumes under various conditions (already touched upon in §§14, 15), electrical conductivities, and, above all, for their magnetic properties (see §§2, 13 and Part V). It is evident, however, that the application of the theory to the details of these phenomena must be a very complex and difficult matter.

I will conclude this part of the work by summarizing the assumptions made in the course of it, and the working material derived from them.

### ASSUMPTIONS

1. The atom is made up of a positive part and *magnetons,* which are ring-shaped negative charges (hitherto called electrons and supposed to be spherical or concentrated at a point) rotating with a peripheral velocity of the order of that of light, their radii being comparable with but less than that of the atom (§1). Their rotation is independent of any attracting positive charge.

2. The positive part of the atom is a sphere of uniform positive electrification, with the properties of an elastic solid (§§7, 14), and with a volume *normally* proportional to the number of magnetons it contains (§1). It is surrounded by an atmosphere or envelope of very low charge density, which is also elastic (§15).

3. The formation of the group of eight (of low magnetic energy), which is practically proved for a system of eight magnetons, is assumed to take place also in atoms containing more than eight. [This is not altogether an assumption, as the reasoning in §7 shows.]

4. To explain the occurrence of long periods in the Periodic Scheme, and at the same time the properties of the elements in these periods (§§13, 15), it is necessary to assume that there is in certain cases a hindrance to the formation of a group of eight when it is normally due. [An arbitrary assumption: see §7.]

The last two, although they come early in the development of the theory, are assumptions which it would be very desirable to avoid: further study of the behavior of magnetons or some alteration in the more fundamental assumptions may make this possible.

These assumptions have furnished the following factors in the behavior of magnetons, atoms, and molecules:

1. The simple magnetic attraction between two magnetons (§5).
2. The tendency to form the group of eight (§6).
3. The residual magnetic forces exerted by all combinations of magnetons: their attracting and inducing actions (§11).
4. The electric polarization set up by the extraction of a magneton from one atom by another atom: its attracting and inducing actions (§11).
5. The effect upon the nature of a linkage of the electrostatic retaining power of an atom for magnetons (not yet discussed).
6. The pressure and volume changes that are possible in the positive sphere, and more particularly in the envelope, of the atom (§§14, 15).

In quantity and variety this working material far surpasses that which is afforded by any purely electrostatic theory of the atom (and strictly speaking, no theory is purely electrostatic: see §15).

This work was done largely in England, but has been amplified and completed at Harvard University and at the University of California.

Note.—Besides his work on radiation, which is not confined to the paper mentioned in §1, Dr. Webster has made an important addition to this theory in suggesting that a minute nucleus could be added to the model atom here described, without much affecting the behavior of its other parts if the nucleus were neutral or nearly so. This, which I have only mentioned casually in §8, will be discussed in connection with $\alpha$-particle scattering and other matters in a forthcoming paper by him.

## PART V. MAGNETISM

### §17. The Radius and Moment of the Magneton

From the results of the last section it is possible to calculate approximately the radius of the magneton, starting from the assumption originally made that it is about half that of the positive sphere of the Hydrogen atom. Since that assumption was made, however, we have seen that the radius of the Hydrogen atom's positive sphere is a less significant quantity than that of the positive sphere of a large atom, because Hydrogen is exceptional in having no internal magnetic compression and therefore has an abnormally large positive sphere.

Since the volume ($V$) of the positive sphere of a large atom is nearly proportional to its magneton number ($N$), the radius of the magneton which has been used to construct atoms in the preceding section will be about $\frac{1}{2} \times \sqrt[3]{\frac{V}{\frac{4}{3}\pi N}}$. Now values for $V$, though not experimentally accessible for most atoms, are given by the ordinary atomic volumes in the case of those elements in which the compression is reasonably supposed to be so great that the envelope has practically vanished (see §15). Such are Iron and Platinum. Dividing the atomic volumes of these by Avogadro's constant ($6.0\times10^{23}$), we get $11.4\times10^{-24}$ and $14.6\times10^{-24}$ as values for $V$ in the two cases. Since their respective magneton numbers are 32 and 80, the two values $2.2\times10^{-9}$ and $1.8\times10^{-9}$ are got for the magneton's radius. That Iron should give the larger value was to be expected, for the assumption that the envelope has vanished is less nearly true for it than for Platinum, as their relative compressibilities show. Allowing, then, for the presence of some envelope even in metallic Platinum, we may take the radius of the magneton to be about $1.5\times10^{-9}$ cm. This is only about one-tenth of the radius of the total atomic space usually found in a solid or liquid, where the envelope may occupy a large part of it.[1]

Now since the velocity at the circumference of the magneton has been assumed equal to $c$ (the velocity of light), we have for the moment of the magneton:

$$
\begin{aligned}
\text{Moment} &= \text{area}\times\text{current}\\
&= \pi r^2 \times \frac{ec}{2\pi r}\\
&= \frac{rec}{2}\\
&= (1.5\times10^{-9})\times(1.55\times10^{-20})\times(3\times10^{10})\div 2\\
&= 3.5\times10^{-10}\ \text{E. M. U.}
\end{aligned}
$$

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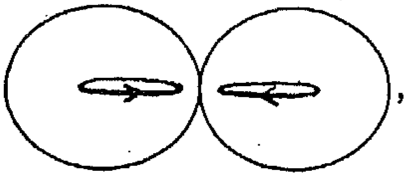
[1] The radii of some atomic spaces may be given for comparison with those of the corresponding positive spheres, and that of the magneton. It should be noticed that the values of ($R'$—$R$) got from the table below give the volume of the envelope.

| | $R'$ (of atomic space) | $R$ (of positive sphere) | $r$ (of magneton) |
|---|---|---|---|
| H (solid) .......... | $1.7\times10^{-8}$ | $.36\times10^{-8}$ | $.15\times10^{-8}$ |
| He (liquid) .......... | 2.2 " | .72 " | |
| C (solid) .......... | 1.1 " | .83 " | |
| O " .......... | 1.7 " | .85 " | |
| Na " .......... | 2.1 " | .91 " | |
| K " .......... | 2.6 " | .98 " | |
| Fe " .......... | 1.4 " | 1.1 " | |
| Pt " .......... | 1.5 " | 1.5 " | |

The values given for $R$ must all be too great because they are derived from the assumption that the envelope has quite disappeared in solid Platinum. In the case of H there is also a factor that would tend to make it too small—the lack of internal magnetic compression has been left out of account. In a subsequent paper, evidence will be adduced from the phenomena of electrolytic dissociation to show that the positive sphere of this atom has a radius of about $.50\times10^{-8}$.

In comparison with this we have for the moment of the Iron atom in the metal at saturation the value $2\times 10^{-20}$ only, and for the Iron atom in salts or for the Oxygen atom considerably smaller values. Also the moment of Weiss' magneton is $1.85\times 10^{-21}$.

If, therefore, the magneton under discussion were required to correspond to an empirical unit of magnetic moment, as does Weiss' magneton, this result would be fatal to it: but with magnetons which are movable current circuits, the result is exactly what we would look for. On the present theory, it can be definitely affirmed that no atom, however many magnetons it contains, can have a moment greater than that of one magneton, and that the moment of most atoms will be very much less than this, because the force between the magnetons in an atom will always tend to orient them so as to make their resultant moment zero. The group of eight, with a very low magnetic energy, has no moment: the free, or valence, magnetons will always tend to lie in configurations of no moment; and indeed the only atoms that could be imagined to have a moment as great as that of the magneton are the atoms H, Li, Na, K, Rb, Cs, of the constitution $n\gamma+1$, which contain only one valence magneton each. Further, what has just been said applies only to isolated atoms: in polyatomic molecules, or in the liquid or solid state, the moment of the atom will be still further reduced by the mutual actions of the magnetons of different atoms. To take an illustration, the isolated H atom should have the moment of one magneton, but the $H_2$ molecule can have the configuration , with no moment, while in HCl or HI all the magnetons are in groups of eight (for most of the time). Nothing, I believe, is known about the magnetic properties of any substances as monatomic gases except Helium and Argon (see §2), and perhaps Mercury. The investigation of them would present exceptional difficulties, but it would be a valuable test of much of this magneton theory, and will be undertaken at the earliest opportunity.

Meanwhile, the view here taken that the moment of the Iron atom, even, is a comparatively small difference effect has everything to recommend it. The great dependence of the moment upon temperature and upon the mode of chemical combination makes it clear that it is a very delicately balanced effect which is due beyond all doubt to certain favorable configurations of those portions of the atom which are responsible for the forces exerted on other atoms. It is most unlikely that it could be due to any simple rectilinear arrangement of unit magnets or current circuits, such as N|S – N|S – N|S – N|S, etc., which is the only conception of the atom's structure that could give Weiss' magneton any structural significance.

## §18. The Possibility of Detecting the Magneton Directly: The Heat of Dissociation of Hydrogen

That the magneton has never yet been detected directly by its magnetic moment is not at all surprising, for a consideration of the possibilities shows that this is either beyond or just at the limit of the present experimental resources.

First, in kathode rays: We have for the force which produces the familiar deflection across the lines of magnetic force:

$$\begin{aligned} Hev &= H \times 1.57 \times 10^{-20} \times 3 \times 10^{9} \\ &= H \times 5 \times 10^{-11} \text{ dynes.} \end{aligned}$$

Now the force on the magneton due to any non-uniformity in a magnetic field through which it passes is

$$\frac{dH}{ds} \cdot M = \frac{dH}{ds} \times 3.5 \times 10^{-10} \text{ dynes.}$$

Seeing that in experiments on kathode rays, $H$ has been perhaps 500 gauss, and that a gradient $\frac{dH}{ds}$ can scarcely be made to exceed 50,000 gauss per cm. by any means whatever, it is obvious that the second force is too small ever to be detected by any deflection of kathode rays.

Another line of attack is more promising. If the electron has a magnetic moment, we may expect to be able to increase the concentration of electrons in an earthed conductor by setting up a magnetic field over it. In this case we can calculate the potential reached ($V$) by equating the electric work gained with the magnetic work lost for the movement of each magneton.

$$\frac{Ve}{2} = HM.$$

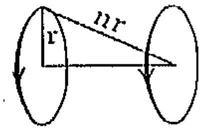
$$\begin{aligned} \therefore\ V &= H \times \frac{2 \times 3.5 \times 10^{-10}}{1.57 \times 10^{-20}} \\ &= H \times 45 \text{ E. M. U.} \\ &= H \times 4.5 \times 10^{-7} \text{ volts.} \end{aligned}$$

Now over a conductor of such a size and situation as to have a reasonably great capacity (such as 10 E. S. U.), it is difficult to set up a magnetic field of more than 1,000 gauss. Assuming this field, we have $V = 4.5 \times 10^{-4}$ volts. Complications apart, this is within the range of the most sensitive electrometers, but a practical study of the problem shows many difficulties. However, experiments on this matter are in progress.

Langmuir's recent work on atomic Hydrogen opens up another line of attack, for the H atom should have the same moment as one magneton. Langmuir found that these atoms could be made to travel some distance from the point of their dissociation without recombining, and could then increase the resistance of a coil of fine platinum wire in which they dissolved. The present author proposes to study the effect of a non-uniform magnetic field on their movements.

Although there has not as yet been any direct detection of the moment of the magneton, it is possible to make a rough calculation of the heat of dissociation of the $H_2$ molecule from the assumptions of this theory.

In §5 was given a diagrammatic representation of the $H_2$ molecule. Using the original assumption that the radius of the magneton is about half that of the H atom, we see that the two magnetons in this molecule are about twice the length of their radius ($r$) apart.



Let the distance from the circumference of one magneton to the center of the other be $nr$.

Now the field due to one magneton, at a point lying on its axis and distant by $nr$ from its circumference, is

$$2\pi \cdot \frac{M}{\pi r^2} \cdot \frac{r^2}{(nr)^3} = \frac{2M}{n^3 r^3}.$$

Hence the magnetic work done in bringing the other magneton from infinity up to this point is roughly

$$\frac{2M^2}{n^3 r^3} = \frac{2 \times (3.5)^2 \times 10^{-38}}{n^3 \times (1.5)^3 \times 10^{-27}}$$
$$= \frac{7.5 \times 10^{-11}}{n^3} \text{ ergs,}$$

and for a gram-atom of Hydrogen this amounts to

$$\frac{4.5 \times 10^{13}}{n^3} \text{ ergs.}$$

Substituting the values 1, 2 (most probable), and 3 for $n$, we have

$$4.5 \times 10^{13}, \qquad 5.6 \times 10^{12}, \qquad 1.7 \times 10^{12} \text{ ergs}$$

for the heat of dissociation. Now Langmuir's calculations from experiment give as the probable value about 77,000 cal.[1] or

$$3.2 \times 10^{12} \text{ ergs.}$$

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[1] Phil. Mag., 27, 188, 1914.

If it had been assumed that $v$ for the magneton was about $.01 \times c$ (which is the sort of velocity usually attributed to the electron in orbital motion), the calculated heat of dissociation would have been 10,000 times less, and even if the radius of the magneton were supposed to be as great as that of the whole atom, the value would only be increased 10 times. This is strong support for the assumption $v=c$, which was made originally on more general grounds.

In the foregoing calculation the electric work required to draw the magnetons from the centers of their atoms, and the elastic work required to compress the envelopes of the atoms, have been neglected. These would obviously be smaller quantities, as they are associated with secondary effects, and could not affect the order of magnitude of the result. Their effect would, in fact, be to diminish the work required to separate the two atoms, and so, probably, to bring the calculated value into even better agreement with the actual value. It should also be borne in mind that the calculation has been made for the more improbable of the two conceivable configurations of the molecule (see §§ 5, 20); but it is certain that the resultant forces would be very much the same in the two cases, although the mathematics involved would be more intricate for the other configuration.

## §19. The Magnetic Properties of Matter

A brief survey of the present state of our understanding of magnetism may be included at this point.

A theory giving a complete account of magnetic phenomena must, in its final deductive aspect, proceed in certain logical steps. First it must provide a sub-atomic mechanism that would actually be expected to produce, in a general way, the external magnetic phenomena that are observed for gross matter. Secondly, it must include a fairly detailed view of the structures of the different atoms, so as to explain their different magnetic properties. And lastly, the combining properties which it gives to the atoms must be such that the explanation can be extended to the magnetic properties of all kinds of molecules and solid aggregates of atoms and molecules.

Hitherto no theory of magnetism has attempted to go further than the first step, and I have shown in §2 how incomplete even that has been. The present theory, on the one hand, is of so definite and far-reaching a character that it is able, in a certain sense, to cover the whole ground. It is true that very little is known as yet about the magnetic properties of the atoms themselves, but what is known is explained by it (see §2, and below, for Helium and Argon).

Again, while the theory gives a good account of the magnetic changes that may be expected to accompany chemical changes, it has up to the present yielded very little in explanation of ferromagnetism. This phenomenon, after all, is generally recognized to be due to a fortuitous alignment, which can occur only in favorable circumstances, of the magnetic effects of separate atoms or molecules; and the problems connected with it, when regarded from the present fundamental point of view, are of a higher order of difficulty altogether than the problems of paramagnetism: the two stand in much the same mutual relation as the problem of the structure of a solid bears to that of a simple molecule. This has been emphasized by Curie and Weiss.

In the study of the magnetic properties of gross matter, the most important step in recent years is recognized to have been the formulation of Curie's laws: 1. *Ferromagnetic* substances have a transition point, at different temperatures for different substances, at which they lose most of their moment and become merely paramagnetic (the "Curie point"). This transition is compared to that between a liquid and its vapor. The moment of a ferromagnetic substance is not proportional to the field intensity, but reaches a maximum value, called the saturation value. (These things had long been appreciated in the case of Iron.) 2. The susceptibility ($\kappa$) of a *paramagnetic* substance is inversely proportional to the absolute temperature ($T$)—so that $\kappa T$ is a constant (the "Curie constant"): $\kappa$ is independent of the field intensity. 3. The susceptibility of a diamagnetic substance is independent of both the temperature and the field intensity.

These results led to a consistent theory of "external" magnetic phenomena based on Langevin's electronic orbit as the unit upon which the field acts. Diamagnetism, due to currents induced in these orbits, would be expected to be independent of the temperature, because for other reasons, such as the constancy of wave-lengths of spectrum lines, the interior of an atom is supposed to be not much affected by atomic collisions. Paramagnetism is obtained when the atoms of a substance have a magnetic moment great enough to outweigh the ever present diamagnetic effect: molecular vibrations are bound to interfere with the orientation of these atoms by the external field, and in this way the temperature relation found by Curie has been explained by Langevin (*loc. cit.*, §2). Ferromagnetism, only possible below a critical temperature, is the state in which the disturbing effect of the vibrations is overcome and the atoms align themselves definitely, in greater or less numbers according to the strength of the external field, until at saturation they are all aligned.

The relation $\kappa T = \text{const.}$ for paramagnetic substances was found by Curie to hold for Oxygen, Palladium, and certain salts, and over a certain range of temperature for Magnetite; but it has been amply demonstrated that the law is not of universal application. Weiss and Kamerlingh Onnes have shown (Journal de Physique, 1910) that Iron, Nickel, and Cobalt are exceptions; and that the susceptibilities of Vanadium, Chromium, and Manganese are not increased by cooling to the boiling point of Hydrogen (14° abs.), whereas according to Curie's law they should increase about twentyfold. It is remarkable also that, even down to such low temperatures, no transition into a ferromagnetic state is observed in these elements. Again, the work of Honda (*loc. infra*) has shown that there is a class of substances whose susceptibilities even increase with rise of temperature.

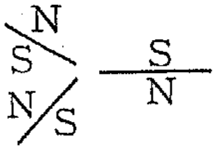
This last effect is to be expected from the magneton theory, because sometimes magnetons which at lower temperatures are held quasi-rigid by interatomic forces might at higher temperatures be more free to add to the paramagnetic effect. We may say, then, that the occurrence of molecular collisions will tend to make paramagnetism obey Curie's law, but that the action of intermolecular and interatomic forces would be expected to enhance paramagnetism as the temperature rises, although the latter effect would not be marked except during a change of molecular complexity, such as occurs during gaseous dissociation and to a less extent during fusion and volatilization (see §22).

The law for diamagnetism—that it is independent of temperature—is not universally true either. As a striking example of this, Bismuth becomes less diamagnetic as the temperature rises, and at the melting point the change is so great that liquid Bismuth is the least diamagnetic substance known.

These departures from Curie's laws will seem less anomalous after considering the vivid picture of the distribution of magnetic forces within atoms, molecules, and lumps of solid matter, which this theory affords.

In beginning to apply the theory, we can see at once that the stable group of eight magnetons (§6) is an almost ideally diamagnetic system. It has no intrinsic magnetic moment, and on account of its low magnetic energy is not easily given one. The way in which an external field would tend to distort the group is well shown in configs. 1, 3, 3*a* on plate 2 (§6): this illustrates the paramagnetic part of the behavior of the group. But when we remember that the earth's field is for that model relatively very much stronger than any possible field can be for actual atoms, it is easy to see that the paramagnetic effect would be slight.

The presence of free magnetons, on the other hand, would make for paramagnetism; but would not necessarily succeed in producing it in all cases, for even "free" magnetons may form fairly stable groupings of no intrinsic moment, such as $\frac{\mathrm{N}}{\mathrm{S}}$ $\frac{\mathrm{S}}{\mathrm{N}}$ for two,



for three, and so on. It must always be borne in mind that the observed magnetic effect is the difference between the separate paramagnetic and diamagnetic effects, as Langevin points out; and unless it is large in proportion to the number of magnetons in the atom, it gives very little clue to the absolute value of either of them. (This explains those cases where diamagnetism seems to be dependent upon temperature.) These considerations will make it clear that, while any obvious contradictions will be evidence against the theory, not too much in the way of positive correlation of magneton constitutions with magnetic phenomena must be expected from it at this first attempt.

There follows now a set of references to the investigations from which I have collected data, with the letters (in parentheses) by which they will be referred to in what follows:

(Q) *Quincke:* Gases at pressures up to 40 atm.: method of the effect of a magnetic field on gas-liquid surfaces (Wied. Ann., 34, 401, 1888).

(C) *P. Curie:* Effect of temperature on the magnetic properties of typical substances (Ann. de Chim. et de Phys., 1895).

(M) *Stephan Meyer:* Magnetic properties of the elements, and periodicity in them (Wied. Ann., 68, 325, 1899). A survey of all classes of inorganic compounds in search of additive relations (Wied. Ann., 69, 236, 1899; Ann. der Phys., [3] 1, 189, 1900).

(L) *Liebknecht and Wills:* Cr, Mn, Fe, Co, Ni, Cu, in their salts (Ann. der Phys., [3] 1, 177, 1900); *du Bois and Liebknecht:* Rare-earth elements in their chlorides (Ann. der Phys., [3] 1, 189, 1900).

(T) *P. Tanzler:* Susceptibilities of He, A, air, compressed in glass bulbs: method of moment in a non-uniform field (Ann. der Phys., [5] 24, 931, 1907).

(U) *Urbain and Jantzsch:* Rare-earth oxides (C. R., 147, 1286, 1908).

(P) *P. Pascal:* The susceptibilities of many non-metallic elements and easily liquefiable gases—all diamagnetic: also carbon compounds studied, and additive relations found, but constitutive influences are very marked—all diamagnetic (Ann. de Chim. et de Phys., 19, 5, 1908). The magnetism of V, Cr, Mn, Fe, in relation to their state of combination (C. R., 147, 742, 1908).

(B) *Bernstein:* $H_2$ and $Cl_2$ gases at 1 atm. (diss: Halle, 1909). I am unable to find out his method, or whether his results are reliable.

(H) *K. Honda:* The specific susceptibilities of the elements, and their temperature coefficients, with special allowance made for ferrous impurities in the specimens used (Ann. der Phys., 32, 1027, 1910).

(W) *P. Weiss and co-workers:* (Papers in C. R., 150; 152; Jour. de Phys., [4] 9, 1910). A summary of his whole work (Jour. de Phys., [5] 1, 900, 965, 1911).

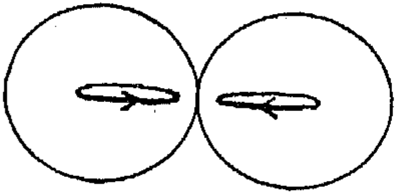
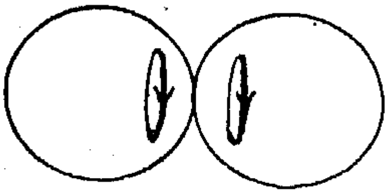
(F) *E. Faytis:* Complex salts, especially cobaltammines, are almost always diamagnetic: molecular paramagnetism is greater in hydrated than in anhydrous salts (C. R., 152, 708, 1911).

(O) *A. E. Oxley:* Iron and Nickel carbonyls and $K_4Fe(CN)_6$ are diamagnetic; $K_3Fe(CN)_6$ is slightly paramagnetic (Proc. Camb. Phil. Soc., 17, 450, 1914).

In all cases where the authors give specific susceptibilities, the atomic or molecular values have been calculated for use here, except where the contrary is stated: for uniformity all values are expressed as $x \times 10^{-6}$ and the $10^{-6}$ factor is dropped.

## §20. THE MAGNETIC PROPERTIES OF THE ELEMENTS

Turning to the structures derived for the atoms in Part II, we see that the atoms of the inactive rare gases should be the most strongly diamagnetic of all atoms. That this is so, with the barely possible exception of H in the $H_2$ molecule (see below), may be seen from the accompanying table. Comparing atomic susceptibilities, we find that Helium ($\gamma$) is more diamagnetic than any element (of another group) lighter than *solid* Zirconium ($5\gamma+4$), while Argon ($3\gamma$) is second only to *solid* Bismuth ($10\gamma+5$). This is especially significant because the gaseous state, particularly the monatomic gaseous state, must be less favorable to diamagnetism than the liquid or solid state, for it allows any "free" magnetons to have their fullest freedom (see §22).

The case of the $H_2$ molecule is difficult to deal with. The two possible configurations described in §5 would correspond to very different magnetic properties.  would be expected to be diamagnetic, as it has no natural moment, but  strongly paramagnetic. On account of the

|  |  | $\gamma$ | $2\gamma$ | $3\gamma \ldots 4\gamma$ | $5\gamma \ldots 6\gamma$ | $7\gamma \ldots 8\gamma$ |  | $11\gamma$ |
|---|---|---|---|---|---|---|---|---|
|  |  | He —38.8(T) | Ne | A — 212(T) | Kr | Xe | + | Nt |
| +1 | H —? | Li + 2.7 | Na +11.7 | K + 15.6 | Rb + 47.6 | Cs | + | — |
| +2 |  | Be + 7.1(M) | Mg +13.3 | Ca | Sr | Ba | + | Ra |
| +3 |  | B — 7.8 | Al +17.6 | Sc — $x$(M) | Y | La —$x$(U) | + | — |
| +4 |  | C — 5.9(diamond)<br>—24 | Si — 3.7 | Ti + 90(M) | Zr — 40.8 | Ce | + | Th +42 |
| $+\bar{5}$ |  |  |  | V + 77 | Nb +132 | + | Ta +168 | — |
| $+\bar{6}$ |  |  |  | Cr + 193 | Mo + 3.8 | + | W + 16 | U +215 |
| $+\bar{7}$ |  |  |  | Mn +1000(?) | — | + | — | — |
| $+\bar{8}$ |  |  |  | Fe<br>Co<br>Ni Ferro-magnetic | Ru + 57<br>Rh +113<br>Pd +619 | +<br>+<br>+ | Os +7.8<br>Ir + 29<br>Pt +209 |  |
| $+\bar{9}$ ⇅ $\gamma+1$ |  |  |  | Cu — 5.5 | Ag — 22 | + | Au — 30 |  |
| $+\overline{10}$ ⇅ $\gamma+2$ |  |  |  | Zn — 10.1 | Cd — 19 | + Almost all strongly paramagnetic (L, U). | Hg — 38 |  |
| $+\overline{11}$ ⇅ $\gamma+3$ |  |  |  | Ga — $x$(M) | In — 11 | + | Tl — 61 |  |
| +4 |  |  |  | Ge — $x$(M) | Sn + 3(cryst.)<br>— 42(grey) | + | Pb — 25 |  |
| +5 |  | N + 10.5(Q) | P —19.2 | As — 23.2 | Sb —114 | + | Bi —291 |  |
| +6 |  | O +1840(C)<br>+1367(T) | S —15.4 | Se — 25.3 | Te — 41 | + | — |  |
| +7 |  | F | Cl —20.9(P) | Br — 32 | I — 46 | + | — |  |

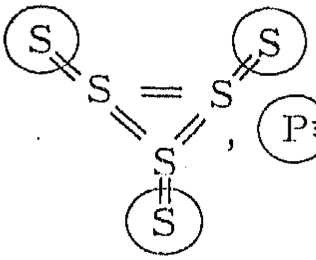
(Except where otherwise stated, the values are got from the work of Honda (*loc. cit.*). Many of Meyer's results must have been vitiated by ferrous impurities; *e. g.*, he gives +47 for B, +13,000 for La, +1,600 for Th: all such values have been omitted.)

number of factors in the problem it is hard to say which configuration to predict from the original assumptions. The two factors of magnetic attraction between the magnetons and electric attraction between each magneton and its positive sphere would make for the first configuration, but the electric repulsion between the magnetons for the second.

Nor do there seem to be any reliable data for the susceptibility of this gas, the low density of which makes a determination very difficult. Quincke (*loc. cit.*) obtained for the susceptibility per cc. the value +.008 at 1 atm., but ±.000 at 40 atm. The only other determination available seems to be that by Bernstein (*loc. cit.*), who gets the value −.005 for the specific susceptibility at 1 atm., which corresponds to an atomic susceptibility of $-50$ ($\times 10^{-6}$). But his only other result (according to Landolt's tables)—the value $-78$ for the atomic susceptibility of gaseous Chlorine at 1 atm.—is nearly four times as great as Pascal's more reliable value ($-20.9$) for Chlorine in the liquid state, where the element certainly could not be *less* diamagnetic (see §22). It seems, therefore, that the $H_2$ molecule, if diamagnetic, is less so, and probably much less so, than two He atoms.

But the solid alkali metals, whose atoms, like H atoms, contain only one valence magneton, are slightly paramagnetic. In their case, however, one of the factors that made for the diamagnetic configuration in the $H_2$ molecule—the attraction of the positive spheres for the magnetons—is obviously modified by the presence of the groups of eight in such a way as to make the diamagnetic configuration of the valence magnetons less stable than in the case of $H_2$: also, the vibration of the neighboring atoms would tend to prevent the formation of a stable positive bond such as the $H_2$ molecule possesses, thus leaving the magnetons freer than they could be in the latter, which, though isolated, has its two atoms firmly united together.

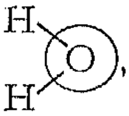
With regard to periodicity in magnetic properties, the first short period of the Periodic Scheme is exceptional in some respects, but as we pass along the second short period we find that the presence of 1, 2, and 3 valence magnetons makes the atom more and more paramagnetic, though not in proportion to their number. The absence of proportionality may be attributed partly to the superimposed diamagnetic effect of the two groups of eight, which is probably similar to that of the Neon atom ($2\gamma$) in all three; and partly to the interference of the valence magnetons, in the same and in contiguous atoms, with one another's freedom. The intra-atomic part of this interference culminates towards the end of the period in the tendency to form a new group of eight that is characteristic of the "negative" atoms: this destroys the paramagnetism. If Phosphorus, Sulphur, or Chlorine atoms were isolated, they might be found to be paramagnetic (it may be possible to test this with monatomic Iodine gas); but the ordinary state of Chlorine is $\textcircled{Cl}\!+\!\textcircled{Cl}$, in which all the magnetons are bound for most of the time (see §9), while the complexity of the gaseous molecules of Sulphur and Phosphorus leaves little doubt that most of the valence magnetons are in groups of eight or double positive bonds[1] as in



, $\textcircled{P}\!\equiv P = P \equiv\!\textcircled{P}$, etc.

In the first short period, the diamagnetism of Boron $(\gamma+3)$ is explainable on the principles already set forth; and the striking feature is the strong paramagnetism of the Oxygen $(\gamma+6)$ molecule as compared with the comparative magnetic inertness of the Nitrogen $(\gamma+5)$ molecule. The only available determinations for Nitrogen appear to be Quincke's, who gives for the susceptibility per cc. $+.001$ at 1 atm., and $+.04$ at 40 atm.: these are evidently more reliable than his values for Hydrogen, but there is the possibility here of contamination with Oxygen.

As for Oxygen, since in oxides, such as



$H_2\textcircled{O}$, $Ca\!=\!\textcircled{O}$, it is invariably diamagnetic, its paramagnetism in the molecular state has led J. J. Thomson and others to suppose that one of the two atoms is acting "positively." This, according to the present theory, would be represented by $\textcircled{O}\!=\!\hat{\hat{O}}$, which formula has already been given in §9: there it was supposed that the molecule had another phase containing the double negative bond: $\textcircled{O}\!\neq\!\textcircled{O}$. If the existence of the first phase is the true explanation of the paramagnetism of the $O_2$ molecule, we should expect the $N_2$ molecule, $\textcircled{N}\!\equiv\!\hat{N}$, to be para-

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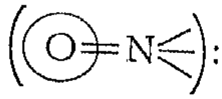
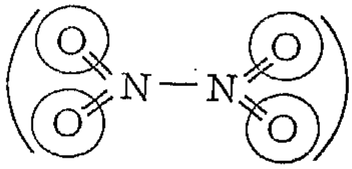
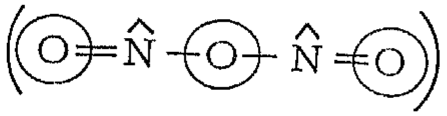
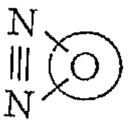
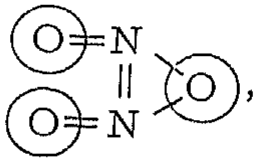
[1] A double positive bond is expected to have no magnetic moment, as will be shown in a future paper: as we have seen for the $H_2$ molecule, a single positive bond need have none.

magnetic also, unless, as is possible, it is easier, in the presence of a group of eight, for two magnetons to form a group of no moment than for a larger number (see arguments at the end of §12). A diatomic molecule very similar in constitution to $N_2$ and $O_2$ is NO : this is strongly paramagnetic (Q); and, contrary to the usual impression, the paramagnetism must lie in the unsaturated N atom rather than in the O atom, according to the present view. Liquid $N_2O_4$  and $N_2O_3$  are diamagnetic (P), but liquid Oxygen retains its paramagnetism almost unaltered (K. Onnes). $N_2O$, whose constitution is possibly , or , is according to Quincke slightly paramagnetic. Possibly $N_2O_3$ has a more condensed structure than has just been written, *e. g.*, , which would accord better with its diamagnetism. From all this, we may see the possibility of diatomic sulphur vapor being paramagnetic, and we would expect $NO_2$ to be less diamagnetic than $N_2O_4$ or even paramagnetic: these points have not as yet been investigated experimentally.

Turning to the long periods, we find that the assumption made on chemical grounds about the absence of a tendency to form the group of eight is justified in the magnetic properties of the transition metals. Unlike P $(2\gamma+5)$, S $(2\gamma+6)$, Cl $(2\gamma+7)$, A $(3\gamma)$, which are all diamagnetic, V $(3\gamma+5)$, Cr $(3\gamma+6)$, Mn $(3\gamma+7)$, (Fe Co Ni) $(3\gamma+8)$ are all paramagnetic, quite apart from ferromagnetism. The same is true of the corresponding series in the second and third long periods: Nb, Mo, ——, (Ru Rh Pd); and Ta, W, ——, (Os Ir Pt). The rare-earth elements, which precede Tantalum, and whose structures have been compared with those of the elements just mentioned (§13), are also strongly paramagnetic, some of their salts being even more so than Iron salts.

In the second half of the long periods we find that the elements are all diamagnetic. For the first three of them,

$$\begin{array}{ccc} \mathrm{Cu} & \mathrm{Zn} & \mathrm{Ga} \\ 3\gamma+\overline{9} & 3\gamma+\overline{10} & [3\gamma+\overline{11}], \\ \downharpoonleft\!\upharpoonright & \downharpoonleft\!\upharpoonright & \downharpoonleft\!\upharpoonright \\ [4\gamma+1] & 4\gamma+2 & 4\gamma+3 \end{array}$$

this is somewhat surprising, although their $4\gamma$ phases, certainly, would not be expected to be particularly magnetic. We may note, however, that Cu and Zn are much less diamagnetic than elements which are expected to be so; *e. g.*, A, Bi, Cl, Br, etc. As, Se, Br and Sb, Te, I are diamagnetic for the same reasons as P, S, and Cl are.

As regards the cases just noted where diamagnetism is found instead of the paramagnetism at first expected, we may say that, as already indicated, the interference of free magnetons with one another's orientation, both in the same atom and in neighboring atoms, holds out a possibility of a sufficient explanation, although the rules governing this interference must be very complex and are at present obscure. More definite corroboration of the principles of the magneton theory is got from a consideration of certain compounds, which follows now.

## §21. The Magnetic Properties of Compounds

The typical saturated compound has no free magnetons; and of most saturated inorganic molecules we can say more: all the valence magnetons of the constituent atoms have gone to make up groups of eight. Thus it is that, while $O_2$ is paramagnetic and the metals Li, Na, K, Be, Mg, Ca, Sr (?), Ba are all paramagnetic, the oxides and chlorides of these metals, such as $\mathrm{Mg}{=}\enclose{circle}{\mathrm{O}}$, $\mathrm{K}{-}\enclose{circle}{\mathrm{Cl}}$, are without exception diamagnetic.

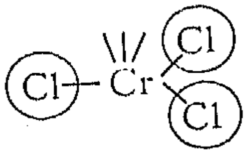
The ordinary salts of Fe, Ni, Co, which according to the present views must contain free magnetons, are strongly paramagnetic, while the complex Fe salts and the "cobaltammines," in which, presumably, these free magnetons are bound, are very slightly paramagnetic, or, more often, diamagnetic.

A table of data illustrating these points and the arguments which follow is given herewith. It was found necessary to supplement the available data by a few determinations for the complex compounds of Cu, Ag, Au, Zn, Hg: the rough method used gave results which agreed with known values (in the case of other substances) to ·10 per cent or so.

| Group | Element and valence | Form | Atomic suscept. | No. of free magnetons |
|---|---|---|---|---|
| V | $V^0$ | metal | +77.8(H) | $\bar{5}$ |
| | $V^{II}$ | $VCl_2$ | +1390(P) | $\bar{3}$ |
| | $V^{III}$ | $(V_2O_2)SO_4$ | +1150(P) | $\bar{2}$ |
| | $V^{IV}$ | $V_2O_4$ | +660(P) | $\bar{1}$ |
| | $V^{V}$ | $NaVO_3$ | −300(P) | 0 |
| VI | $Cr^0$ | metal | +193(H) | $\bar{6}$ |
| | $Cr^{III}$ | alum | +6290(P) | $\bar{3}$ |
| | | $CrCl_3$ | +6250(Weber) | |
| | $Cr^{VI}$ | $CrO_3$ | − 5.0(P) | 0 |
| | | $K_2Cr_2O_7$ | +18.5 | |
| | $U^0$ | metal | +215(H) | $\bar{6}$ |
| | $U^{IV}$ | $U(SO_4)_2$ | +3200(P) | $\bar{2}$ |
| | $U^{VI}$ | $(UO_2)SO_4$ | −56(P) | 0 |
| VII | $Mn^0$ | metal | +600 to 2000(H) | $\bar{7}$ |
| | $Mn^{II}$ | $MnSO_4$ | +15000(P) | $\bar{5}$ |
| | $Mn^{III}$ | $MnPO_4$ | +10840(Weber) | 4 |
| | $Mn^{VII}$ | $KMnO_4$ | +255(P) | 0 |
| | | $KMnO_4$ (solid) | +33 | |
| VIII | $Fe^0$ | metal | ferromagnetic | $\bar{8}$ |
| | $Fe^{II}$ | salts | very strongly paramagnetic | $\bar{6}$ |
| | $Fe^{III}$ | salts | | $\bar{5}$ |
| | $Fe^{VI}$ | ferrates | diamagnetic | 2 |
| | $Fe^{VI+?}$ | complex salts | diamagnetic | 0(?) |
| | Similar relations for Co and Ni. | | | |
| I B | $Cu^0$ | metal | −5.5(H) | $\bar{9}\rightleftharpoons\gamma+1$ |
| | $Cu^I$ | CuCl | −26 | $\bar{8}\rightleftharpoons\gamma$ |
| | | CuCN | −43 | |
| | $Cu^{I+?}$ | $KCu(CN)_2$ | −80 | $<\bar{8}$(?) |
| | $Cu^{II}$ | $CuCl_2$ | +1000 | $\bar{7}$ |
| | | $CuCrO_4$ | +1070 | |
| | | $CuSO_4$ | +1730 | |
| | | $Cu(NH_3)_4SO_4 \cdot H_2O$ | +1750 | |
| | | $CuAc_2$ | + 550 | |
| | $Ag^0$ | metal | −22(H) | $\bar{9}\rightleftharpoons\gamma+1$ |
| | $Ag^I$ | AgCN | −51 | $\bar{8}\rightleftharpoons\gamma$ |
| | | $AgNO_3$ | −38 | |
| | $Ag^{I+?}$ | $KAg(CN)_2$ | −64 | $<\bar{8}$(?) |
| | $Au^0$ | metal | −30(H) | $\bar{9}\rightleftharpoons\gamma+1$ |
| | $Au^I$ | AuBr | −27 | $\bar{8}\rightleftharpoons\gamma$ |
| | $Au^{III(?)}$ | $AuBr_3$ | −70 | $\bar{6}$(?) |
| II B | $Zn^0$ | metal | −10(H) | $\bar{10}\rightleftharpoons\gamma+2$ |
| | $Zn^{II}$ | $Zn(NO_3)_2 \cdot 6H_2O$ | −128 | $\bar{8}\rightleftharpoons\gamma$ |
| | | $Zn(CN)_2$ | − 67 | |
| | $Zn^{II+?}$ | $K_2Zn(CN)_4$ | −102 | $<\bar{8}$(?) |
| | $Hg^0$ | metal | − 38(H) | $\bar{10}\rightleftharpoons\gamma+2$ |
| | $Hg^{I(?)}$ | $Hg_2Cl_2$ | − 76 | $\bar{9}\rightleftharpoons\gamma+1$ or $\bar{8}\rightleftharpoons\gamma$ |
| | | $Hg_2(NO_3)_2$ | − 73 | |
| | $Hg^{II}$ | $HgCl_2$ | − 87 | $\bar{8}\rightleftharpoons\gamma$ |
| | | $Hg(NO_3)_2$ | − 93 | |
| | | $Hg(CN)_2$ | −113 | |
| | $Hg^{II+?}$ | $K_2HgI_4$ | paramagnetic | $<\bar{8}$(?) |

(Pascal's values (P) are for solutions. All values have been multiplied by $10^6$.)

In comparing these values two things should be borne in mind: first, that susceptibilities of paramagnetic substances in solution are in general greater than for the undissolved substances (Pascal's values under (P) are for solutions); and second, the values obtained for diamagnetic salts have little significance for the metal atoms that are in them except to show that they are not decidedly paramagnetic, for the acid radicles themselves are diamagnetic.

In the table I have given space to the compounds of the transition metals of groups V, VI, VII, VIII, I B, II B only, because there the relations are much more complex. We may notice first that the free elements V, Cr, Mn, are much less paramagnetic than their salts. This, I think, is due to the same cause as the general rule that these salts are more paramagnetic when hydrated than when anhydrous (F), and still more so in solution. If, as this theory would indicate, paramagnetism is an effect of free magnetons in the metal atom, then the farther removed from one another these atoms are, the more free from constraint must be their magnetons (as many as remain free). In metallic Chromium, for example, the six valence magnetons are used to a considerable extent, as the high melting point indicates, in binding the atoms together by positive bonds (not so diamagnetic an arrangement, however, as if it involved groups of eight). In  it is true that only three free magnetons are left, but these are likely to be more free from the influence of other Cr atoms than can be the case in metallic Chromium. In hydrated $CrCl_3$ they are still more free, not being used up in combining with $H_2O$ molecules as might at first be suspected, for since $H_2O$ is most of the time in the "saturated" phase (see §9) it would not have much attraction for free magnetons. For other facts illustrating this general principle see §23.

Turning to the relations between the compounds of these metals of groups V-VIII, we see that, if the uncombined metals are excepted, the paramagnetism runs parallel with the number of free valences or magnetons, until in the saturated compounds it vanishes ($NaVO_3$, $CrO_3$), or becomes very small ($KMnO_4$). This relation has been roughly indicated by Pascal (*loc. cit.*).

In the transition metals of groups I B and II B, however, we find a different set of relations. We have seen that a great deal is explained by the tautomerism which naturally falls to the lot of these elements (see table of Periodic Scheme, §7). The very striking fact that

Copper, while diamagnetic as metal or in cuprous compounds, is paramagnetic in cupric compounds, is attributable to this tautomerism also.

In monovalent Cu, Ag, Au, and in the salts of Zn, Cd, Hg, there are 8 free magnetons left, and the tautomerism $8 \rightleftharpoons \gamma$ is still possible: therefore we expect, and find, diamagnetism. But in bivalent Cu, where only 7 are left, this tautomerism is no longer possible, and the salts are strongly paramagnetic, as this theory would predict. Another prediction—that AuBr ($8 \rightleftharpoons \gamma$) should be diamagnetic, and $AuBr_3$ (6) paramagnetic—is not so successful, for both are diamagnetic: but the obvious refuge from the difficulty will suggest itself. Compounds of bivalent or trivalent Silver are of course not available for comparison.

The complex salts of these metals were also studied, in the hope of getting results analogous to the well-known relations for Fe and Co (F). Bivalent Cu was obviously the best point of attack, but the most stable complex cupric salt obtainable seems to be $Cu(NH_3)_4SO_4 \cdot H_2O$, and this is still very paramagnetic: a cupricyanide ($K_2Cu(CN)_4$), if it were stable, might be expected to show a much diminished paramagnetism, just as ferri-cyanides do. The complex cyanides derived from salts which are diamagnetic already, *e. g.*, those of $Cu^{I}$ ($8 \rightleftharpoons \gamma$), $Ag^{I}$ ($8 \rightleftharpoons \gamma$), $Zn^{II}$ ($8 \rightleftharpoons \gamma$), are all diamagnetic, although it is hard to see how, in a small complex molecule like $KAg(CN)_2$, all the 8 free magnetons of the monovalent Ag atom can be involved. However, the effect we should be inclined to look for in such cases—a paramagnetism—has been observed in one compound at least. Pascal found that the salt $K_2HgI_4$ in solution is paramagnetic; so it seems that not all of the free magnetons of bivalent mercury, $Hg^{II}$ ($8 \rightleftharpoons \gamma$), are involved in this case.

## §22. THE DEPENDENCE OF MAGNETISM UPON TEMPERATURE AND PHYSICAL STATE

In the preceding sections (esp. §19), the influence of neighboring atoms and molecules on one another's magnetism has been continually spoken of, and it has been brought out in a general way that this may be expected to diminish a resultant paramagnetism or increase a resultant diamagnetism. A summary of the experimental evidence on this point will now be given; and in considering this, it should be remembered that the influence of one atom or molecule upon another becomes diminished as the temperature rises.

1. For the paramagnetism of a metallic atom we have the following relations:

Salts in solution > Hydrated salts > Anhydrous salts > Free metal.

This is true for V, Cr, or Mn. In the case of ferromagnetic metals, the last step in the series does not hold, of course, except above the Curie point. These relations have not been established with any great completeness, and possibly some exceptions exist.

2. In mixtures of liquid Oxygen and Nitrogen, the molecular susceptibility of the Oxygen becomes greater as its concentration becomes less (K. Onnes).

3. Contrary to Curie's law, almost half of the paramagnetic elements become increasingly paramagnetic as the temperature rises (H). This can only be due to increased freedom acquired by the magnetons that are responsible for the forces between atoms, as explained in §19.

4. Most of the diamagnetic solid elements (*e. g.*, Bi, Sb, Pb, Tl, Te, In, Cu) become less diamagnetic as the temperature is raised (H), the change being in some cases especially marked at the melting point, after which a further rise in temperature does not usually alter the magnetic properties. Evidently we have here cases of complex molecules which become less stable as the melting point is approached, and which at that point are suddenly broken down into the atoms or molecules that are stable in the liquid phase. From the magneton theory we should expect this process to be accompanied by the magnetic changes that are observed. Those elements which do not show this effect are for the most part elements of lower atomic weight which are known to give stable complex molecules persisting in the liquid and even in the gaseous state (*e. g.*, P, As, S, Se): these, therefore, act more like the substances described under the next heading (5). A very striking example of the effect of fusion is given by the alloy $FeZn_{10}$; when solid this is non-magnetic, when liquid it is very strongly magnetic: a comparison of the susceptibility of this alloy with that of the Iron atom in salts would be of great interest, but appears not to have been made. An example of the effect of dissociation by dilution is given by solutions of Bismuth in mercury, which when very dilute are less diamagnetic than pure mercury: this must be due to the dissociation of the complex Bi molecules. There are, however, a few exceptions to this general rule. Ag and I become more diamagnetic as the temperature rises (H). Crystalline Tin is slightly paramagnetic, liquid Tin is diamagnetic; but here we have grey Tin, which is still more diamagnetic.

5. Diamagnetic compounds, such as NaCl, HCl, $H_2O$, etc., do not show noticeable magnetic changes as the temperature or physical state is changed. This also would be expected from the magneton theory, because the simplest possible molecules of these substances contain no free magnetons, and are essentially diamagnetic: hence polymerization or solidification, which it should be observed is brought about in these cases by the electrostatic forces mentioned in §12 rather than by magnetic forces, cannot appreciably affect the magnetic susceptibility.

To summarize: As the changes,

Complex molecule → Simple molecule → Atom,

take place, from whatever cause, we may expect, with the qualifications already noted, that diamagnetism will give way to paramagnetism. Gaseous dissociations are the cases where new evidence is most urgently needed—and where it is most difficult to get.

This collected evidence seems conclusive for para- and diamagnetic substances, but it is important to observe that we are driven to exactly the opposite conclusion in the case of ferromagnetism. Here it seems that it is easier to obtain a system with a large magnetic moment that is made up of constituents drawn from two or more atoms than to obtain such a system within a single atom. The conclusive evidence on this point is the behavior of the Heusler and similar alloys: in these, as has frequently been pointed out, the ferromagnetic units must be groups of several atoms; it is very likely, then, that the same is true for ferromagnetic elements like Iron. The way in which these complexes are built up is not at all indicated by the magneton theory up to the present; but see §19.

## §23. WEISS' MAGNETON, AND QUANTITATIVE RELATIONS

With regard to a comparison of the results of the theory here described with Weiss' work on "the magneton," I will first quote a few sentences (translated) from the conclusion of a summary of his work that appeared in the Journal de Physique, [5] 1, 900, 965, 1911. These should be compared with the passages already quoted from Langevin (§2).

"What is the rôle of magnetic phenomena in chemical combination? Are chemical forces magnetic in nature? Are the valences, indeed, referable in some way to magnetons?" In the same paper he mentions the possibility that his magneton is the same as the unit magnet postulated by Ritz in the latter's theory of spectrum series.

Notwithstanding these suggestive passages, Weiss' magneton is not in any way identified with the electron, but is an empirical quantity directly derived from the magnitudes of the susceptibilities of paramagnetic elements and compounds, and for such substances only: it has no meaning for diamagnetic substances. He maintains that the moments of paramagnetic atoms and molecules, when extrapolated to the absolute zero where the disturbing effect of molecular motions vanishes, are in simple integer ratio to one another. The highest common factor is 1122.7 for the paramagnetic salts, and 1123.5 for the ferromagnetic elements; and the agreement between these two values is certainly close. On this basis, the numbers of magnetons in some atoms and molecules are: Fe—11.0, Co—8.6, Ni—3.0 (8 and 9 at higher temperatures); $\frac{1}{3}(Fe_3O_4)$—4, 5, 6, 8, 10, in five successive states corresponding to five linear portions of the curve plotting the inverse of the saturation magnetism against the temperature. There follow his numbers (to the nearest integer) for some compounds:

*In solution*

| | |
|---|---|
| $K_3Fe(CN)_6$ | 10 |
| Ferric ammonium citrate | 22 |
| $FeCl_3$ | 28 |
| $\frac{1}{2}Fe_2(SO_4)_3$ | 30 |
| $NaFe^{II}$ oxalate | 27 |
| $FeSO_4$ | 30 |
| $KMnO_4$ | 4 |
| $CuSO_4$ | 10 |
| $Cu(NH_3)_4SO_4$ | 6 |
| $U(SO_4)_2$ | 15 |
| $CoCl_2$ | 25 |
| $MnSO_4$ | 30 |

*In the solid state*

| | |
|---|---|
| $FeCl_3$ | 29 |
| $FeCl_3 \cdot 2NH_4Cl \cdot H_2O$ | 27 |
| $FeF_3 \cdot 3H_2O$ | 21 |
| $FeF_3 \cdot 3NH_4F$ | 29 |
| $Fe^{III}$ acetylacetonate | 25 |
| $\frac{1}{3}(Mn_3O_4)$ | 18 |
| $CrCl_3$ | 20 |
| $Co^{II}$ acetylacetonate | 21 |

| | |
|---|---|
| $\frac{1}{2}Neodym_2O_3$ | 18 |
| $\frac{1}{2}Sa_2O_3$ | 8 |
| $\frac{1}{2}Eu_2O_3$ | 18 |
| $\frac{1}{2}Gad_2O_3$ | 41 |
| $\frac{1}{2}Ter_2O_3$ | 50 |
| $\frac{1}{2}Dyspr_2O_3$ | 56 |

With regard to the integral nature of the exact numbers, divergences of .1 or .2 are quite frequent, while there are values such as:

| | |
|---|---|
| Co | 8.6 |
| Chrome alum (violet) | 19.45 |
| " " (green) | 19.25 |
| $VCl_2$ | 9.21 |
| $VCl_4$ | 6.65 |
| $\frac{1}{2}V_2O_3(SO_4)_2$ | 8.41 |

Thus the degree of approximation to integers seems to be about the same as in the case of the atomic weights of the elements. Further, in arriving at the number 9 (8.78) for the curious paramagnetic salt $K_2HgI_4$, Weiss makes corrections for the diamagnetism of the three constituent elements, a thing which is apparently not done in other cases.

It seems, therefore, that whatever may be the significance of the integral values for the metals Fe, Co, Ni (even here the value for Co is poor), the larger numbers obtained for the various hydrated and complex salts shown above cannot have any simple theoretical meaning—certainly none in so far as they may profess to represent definite numbers of natural unit magnets. Almost any mechanistic interpretation of Weiss' magneton involves the fallacy that elementary magnetic units can be additive in their effect on the magnetism of atoms and molecules in the same way as elementary electric units can be. This is no more true than that the moments of bar magnets, in an assemblage of such, are in general additive. Recently H. S. Allen (Phil. Mag., May, 1915) has discussed, in connection with Weiss' magneton, a magnetic atom model in which he surmounts this difficulty by ascribing the different magneton numbers to the presence of different numbers of electrons in a rotating ring, and to different angular velocities of this ring and of the central positive charge, which is also supposed to rotate. But the insuperable objections to hypotheses of rotating rings of electrons have already been explained (§2); and besides, the arbitrary nature of the assumptions which this model requires compares very unfavorably with the simplicity of Langevin's scheme or with the "automatic" way in which the model atoms of the present theory show a qualitative agreement with the most diverse facts of magnetism.

The futility of trying to express the magnetic properties of most atoms as simple functions of their magneton constitutions has been amply demonstrated in §§19-22. Apart from the paramagnetism expected in the isolated H atom, the only case in which, in the present state of the theory, we can make an absolute prediction of even the sign of the magnetism, is when the atom or molecule contains no free magnetons and only groups of eight. The atoms of He, Ne, A, Kr, Xe fulfill this condition, and for two of them we know the values (T):

$$\text{He }(\gamma)\ -38.8,$$
$$\text{A }(3\gamma) -212.8\ (=3\times70.9)=(3\times38.8)+96.4).$$

Unlike paramagnetic moments, diamagnetic moments must always be additive; but the value for Argon would be expected to be more than three times that for Helium, because groups of eight mutually strengthen one another (§11). Thus we may with some confidence take the susceptibility of the isolated group of eight to be about −38.8.

Now, while the groups of eight in the Argon atom are strengthened, those in "salt" molecules like K–(Cl), $H_2$=(O), H–(Cl), etc. (which contain nothing but groups of eight), are weakened by the electrostatic strain set up by the transfer of magnetons from one atom to another: the groups of eight in such molecules retain their structure in spite of electrostatic forces.[1] We expect, then, what the following table shows to be the case—a decreased diamagnetism.

| | –(F) | –(Cl) | –(Br) | –(I) | =(O) | ≡(N) | –(OH) | –(NO$_3$) | =(SO$_4$) |
|---|---|---|---|---|---|---|---|---|---|
| H$^{\mathrm{I}}$ | | —.80<br>—9.7 | | | —.79<br>—7.1 | —1.1<br>—9.3 | | | |
| Li$^{\mathrm{I}}$ | | —.47<br>—5.0 | | | | | | | |
| Na$^{\mathrm{I}}$ | —.40<br>—4.1 | —.41<br>—4.8 | —.37<br>—5.4 | —.31<br>—5.2 | | | | —.31<br>—2.9 | —.64<br>—6.2 |
| K$^{\mathrm{I}}$ | —.36<br>—4.2 | —.47<br>—5.8 | —.35<br>—5.2 | —.31<br>—5.2 | | | | —.32<br>—3.2 | —.42<br>—4.5 |
| Ca$^{\mathrm{II}}$ | —.30<br>—3.3 | —.39<br>—4.8 | | | —.27<br>—3.0 | | —.39<br>—4.1 | | —.38<br>—4.0 |
| Sr$^{\mathrm{II}}$ | —.26<br>—3.6 | —.44<br>—6.3 | —.31<br>—5.1 | —.35<br>—6.3 | | | | | |
| Ba$^{\mathrm{II}}$ | —.13<br>—2.1 | —.32<br>—5.1 | —.31<br>—5.4 | | —.10<br>—1.7 | | —.25<br>—3.9 | | |
| Zn$^{\mathrm{II}}$ | | —.50<br>—6.8 | | | —.26<br>—3.5 | | —.42<br>—5.2 | | —.53<br>—6.1 |
| Cd$^{\mathrm{II}}$ | | —.25<br>—3.8 | —.30<br>—5.1 | —.25<br>—4.6 | | | | | |
| Hg$^{\mathrm{II}}$ | | —.15<br>—2.5 | —.24<br>—4.3 | —.26<br>—5.1 | | | | | |

The numbers here are calculated from the data in the comprehensive work of Stephen Meyer on diamagnetism (*loc. cit.*). The upper

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[1] Not merely one group of eight in the chloride ion, –(Cl)$^-$ (3γ) (which is got from the chlorine atom, Cl (2γ + 7)), suffers in this way, for the strain must be evenly distributed among all three.

value in each case gives the susceptibility per gram (small type) and the lower value the susceptibility per group of eight (large type). It may be seen that while the former varies between $-1.1$ and $-.10$ (ratio 11), the latter varies only between $-9.7$ and $-1.7$ (ratio 5.7): this makes the present view of the atom's structure seem all the more plausible.

We have seen on a broad scale the gradation between the reinforced, isolated, and strained groups of eight (susceptibilities $-70.9$, $-38.8$, and about $-5$, respectively); but it must be admitted that no gradations of a definite kind can be seen in the table just given for salt molecules. This may possibly be due to impurities in the materials used by Meyer. In any case a more careful scrutiny of these relations, with more accurate data perhaps, may yield some useful information about the structure of molecules.

## NOTE ON EXPERIMENTS SUGGESTED BY THIS THEORY

1. The effect of a magnetic field on the electron concentration in an earthed conductor, or on the potential of an insulated conductor: A P. D. of $4 \times 10^{-4}$ volt is expected for a field of 1,000 gauss, but there are many complications (§18).

2. The effect of a non-uniform magnetic field on the movements of the H atoms worked with by I. Langmuir: The expectations from this experiment are vague (§18).

3. The magnetic properties of monatomic Iodine gas, diatomic Sulphur gas, Sodium gas, $N_2O_4$ and $NO_2$, etc.: These determinations present forbidding difficulties.

Some of this work is under way, but it may readily be seen that the problems are of such a nature that the attainment of significant results may be a very slow and difficult process. This very circumstance, however, is a promising sign, for it is not likely that so important a property of the electron as is here dealt with would have remained undiscovered if the discovery of it were to be at all easy.

The absence of chemical problems from this list may be noted. Here, the theory has up to the present been occupied in correlating a vast body of facts and lesser generalizations in a field where the accumulation of experimental data has always far outstripped the assimilation of it into theory; and the result mentioned is therefore to be expected at this stage.