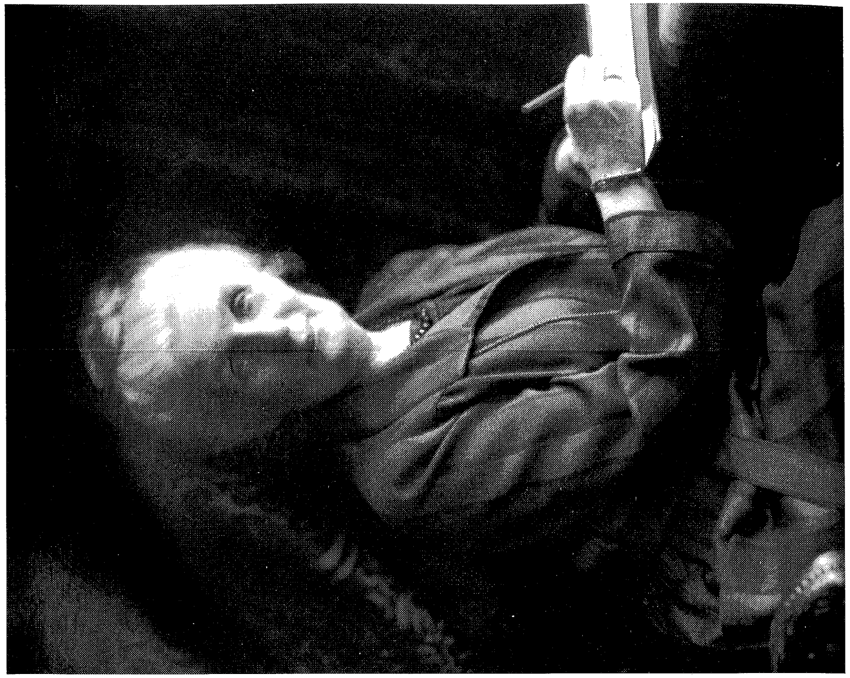
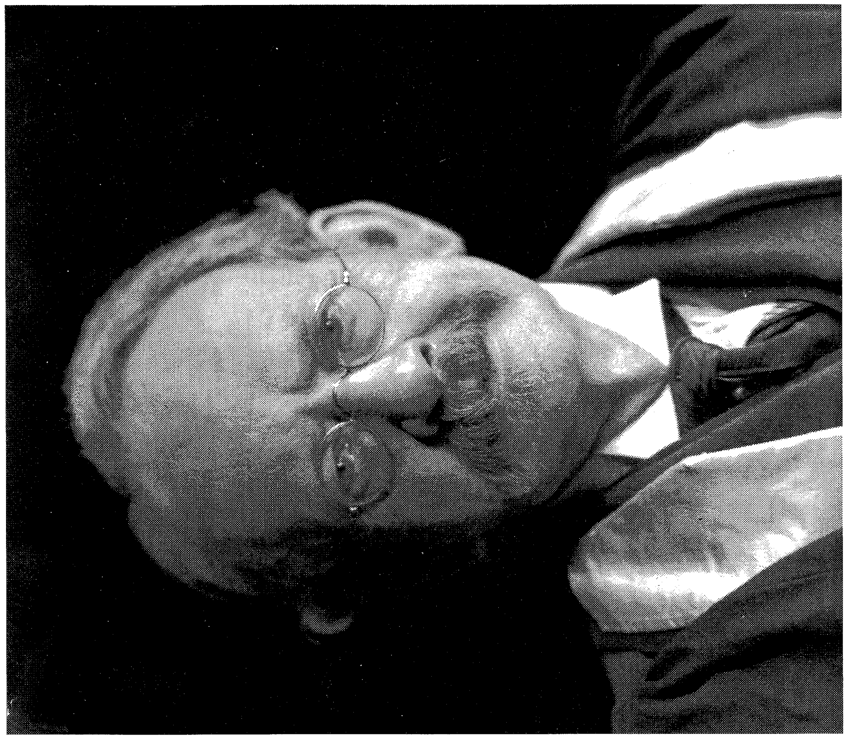
J.J. THOMSON

“The Structure of the Atom”

Royal Institution. Weekly Evening Meeting, Friday March 10, 1905.





J.J. Thomson and Rose Thomson in the 1930s

Royal Institution of Great Britain.

WEEKLY EVENING MEETING,

Friday, March 10, 1905.

HIS GRACE THE DUKE OF NORTHUMBERLAND, K.G. D.C.L. F.R.S., President, in the Chair.

PROFESSOR J. J. THOMSON, LL.D. D.Sc. F.R.S., Cavendish Professor of Experimental Physics, University of Cambridge.

The Structure of the Atom.

IN 1897 I had the pleasure of bringing before the Royal Institution experiments showing the existence of *corpuscles*, i. e. negatively electrified bodies having a mass exceedingly small compared with that of an atom of hydrogen, until then the smallest mass recognised in physics. A suggestive and striking property of these corpuscles is that they are always the same from whatever source they may be derived. The corpuscles were first detected in the rays which are projected from the cathode when an electric discharge passes through a vacuum tube, and it was found that whatever the nature of the residual gas in the tube, or whatever the metal used for the electrodes, the corpuscles were always the same. Other sources of corpuscles soon came to light; they were found to be projected from incandescent metals, from metals illuminated by ultra-violet light, and from radio-active substances; but whatever their source the corpuscles were always the same. This fact, in conjunction with their small mass, suggests that these corpuscles form a part of the atom, and my object this evening is to discuss the properties of an atom built up of corpuscles. As these corpuscles are all negatively electrified, they will repel each other, and so if an atom is a collection of corpuscles, there must in addition to the corpuscles be something to hold them together; if the corpuscles form the bricks of the structure, we require mortar to keep them together. I shall suppose that positive electricity acts as the mortar, and that the corpuscles are kept together by the attraction of the positive electricity. We do not know nearly so much about positive as we do about negative electricity; we have never obtained positive electricity associated with masses less than the mass of an atom; in fact, appearances all point to the conclusion that positive electrification is produced by the withdrawal of corpuscles from a previously neutral body. These conditions are satisfied, if we suppose with Lord Kelvin that in the atom we have a sphere uniformly filled with positive electricity, and that the corpuscles are immersed in this sphere. The attraction of the positive electricity will tend to draw the corpuscles to the centre; the mutual repulsion between the corpuscles will tend to drive them away, and they will arrange themselves so that these tendencies neutralise each other.

Let us now consider the kind of atom we could build up out of corpuscles and positive electricity. The mathematical investigation of this problem leads to the following results. The simplest atom containing 1 corpuscle would have 1 corpuscle at the centre of the sphere of positive electrification; the 2 corpuscle atom would have the 2 corpuscles separated by a distance equal to the radius of this sphere; the 3 corpuscle atom would have the 3 corpuscles at the points of an equilateral triangle, whose side is equal to the radius of the sphere; 4 corpuscles would be at the corners of a regular tetra-

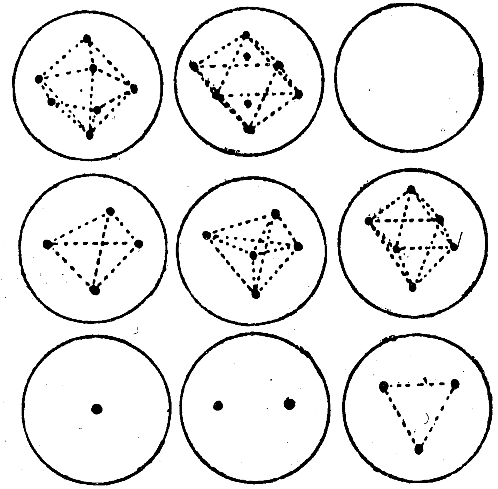
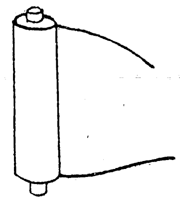


FIG. 1.

hedron, whose side is equal to the radius of the sphere; 5 corpuscles are situated, 4 at the corners and 1 at the centre of a tetrahedron; 6 at the corners of an octahedron; 7 and 8 are more complicated, as the simplest arrangements for 7 and 8, an octahedron with 1 at the centre and a cube, are both unstable; and for 7 we have a ring of 5 in one plane with 2 on a line through the centre at right angles to the plane; and 8 we have the octahedron with 2 inside. These arrangements are shown in Fig. 1.

When the number of corpuscles is large, the calculation of the positions of equilibrium becomes very laborious, especially the determination of the stability of the various arrangements. I will therefore treat the subject from an experimental point of view, and apply to this purpose some experiments made with a different object many

years ago by an American physicist, Professor Mayer. The problem of the structure of the atom is to find how a number of bodies, which repel each other with forces inversely proportional to the square of the distance between them, will arrange themselves when under the attraction of a force which tends to drag them to a fixed point. In these experiments the corpuscles are replaced by magnetized needles pushed through cork discs and floating on water. These needles having their poles all pointing in the same way repel each other like the corpuscles; the attractive force is due to another magnet placed above the surface of the water, the lower pole of this magnet being of the opposite sign to the upper pole of the floating magnets. This magnet attracts the needles with a force directed to the point on the water surface vertically below the pole of the magnet. The forces acting on the needles are thus analogous to those acting on the corpuscles in our model atom, with the limitation that the needles are constrained to move in one plane.



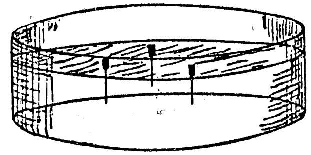


FIG. 2.

As I throw needle after needle into the water you see that they arrange themselves in definite patterns, 3 magnets at the corners of a triangle, 4 at the corners of a square, 5 at the corners of a pentagon; when, however, I throw in the sixth needle this sequence is broken. The 6 needles do not arrange themselves at the corners of a hexagon, but 5 go to the corners of a pentagon, and 1 goes to the middle; a ring of six with none in the inside is unstable. When, however, I throw in a seventh, you see I get the ring of 6 with 1 in the middle; thus a ring of 6, though unstable when hollow, becomes stable as soon as 1 is put in the inside. This is an illustration of the fundamental principle in the architecture of the atom: the structure must be substantial. If you have a certain display of corpuscles on the outside, you must have a corresponding supply in the interior; these atoms cannot have more than a certain proportion of their wares in their windows. If you have a good foundation, however, you can get a large number on the outside. Thus we saw that when the ring was hollow, 5 was the largest number of needles that could be stable. I place in the centre a large bunch of needles and you see that we get an outer ring containing 22 needles in stable equilibrium.

The proportion between the number which is in the outer ring and the number inside required to make the equilibrium stable is shown in the following table:

Number in outer ring	5	6	7	8	9	10	12	13	15	20	30	40
Number inside. . .	0	1	1	1	2	3	8	10	15	39	101	232

We see from these illustrations how the corpuscles would arrange themselves in the atom, confining ourselves for the present to the case where the corpuscles are constrained to move in one plane. The corpuscles will arrange themselves in a series of rings, the number of corpuscles in the rings getting greater and greater as the radius of the ring gets greater. By the aid of the above table we can readily calculate the way any number of corpuscles will arrange themselves. Let us suppose for example we have 20 corpuscles and try to arrange them so as to have as few rings as possible; we see from the table that we cannot have more than 12 in the outside ring, for 13 would require 10 inside, and would be impossible with less than 23 corpuscles: thus 12 will be the number in the outside ring and there are eight left to dispose of; these cannot form a single ring with no corpuscles inside, as 5 is the greatest number that can do this; the 8 corpuscles will therefore break up into two systems, a ring of 7 with 1 inside. You see that when I try the experiment with 20 magnets they arrange themselves in this way.

If we follow the kind of atoms produced as we gradually increase the number of corpuscles, we find that certain arrangements will recur again and again; thus take the case of 20 corpuscles; this consists of the arrangement 1–7–12, the arrangement for 8 is 1–7; the atom of 20 corpuscles may be regarded as formed by putting another storey to the atom of 8 corpuscles; if we go to 37 corpuscles, we find the arrangement is 1–7–12–17, i.e. another storey added to the atom of 20, while for 56 we have 1–7–12–17–19, the atom of 37 with another storey added. Thus the possible atoms formed by numbers of corpuscles from one to infinity could be arranged in classes, in which each member of the class is formed by adding another storey to the preceding member; the structures of all the atoms in this class have much in common, and we might therefore expect the physical as well as the chemical properties of the atoms to have a general resemblance to each other. This property is, I think, analogous to that indicated by the periodic law in chemistry. We know that if we arrange the elements in the order of their atomic weights, then, as we proceed in the direction of increasing atomic weight, we come across an element, say lithium, with a certain property; we go on and after passing many elements which do not resemble lithium, we come across another, sodium, having many qualities in common with lithium. Then as we go on, we lose these properties and come across them again when we arrive at potassium; exactly the kind of recurrence we should get with our model atoms, if we suppose the number of corpuscles in the atom to be determined by its atomic weight.

Let me give another instance of the way the properties of these

atoms resemble the properties of the chemical atom. I will take the electro-chemical property of the atom. Some atoms, such as those of lithium, sodium, potassium, have a strong tendency to be positively electrified, while others like chlorine, bromine, iodine, tend to be negatively electrified. Now the way our model atom gets positively electrified, is by losing a negatively electrified corpuscle; thus, those atoms in which the corpuscles are loosely held would tend to get positively electrified, while those whose corpuscles are very firmly held would not get positively electrified, and might be able to bear the disturbance due to another corpuscle placed outside without disintegration, and with this additional corpuscle they would be negatively charged. Now let us see how this property would vary from atom to atom. I will take a numerical case. Suppose we begin with 59 corpuscles; we should have by the table 20 on the outside, and 39 in the inside; but as 39 is the least number of corpuscles that can hold a ring of 20 in stable equilibrium, the equilibrium of this atom would have nothing to spare; it would be in rather a tottery condition, and a corpuscle would be easily detached, leaving the atom positively charged. Let us now go to the atom with 60 corpuscles; it would still have 20 on the outside, but it would have 40 on the inside, and be more stable than 59; it would not so easily lose a corpuscle; and would not thus be so electro-positive as 59; as we go on up to 67 we have still 20 on the outside but get more and more in the inside, the difficulty of getting a corpuscle out therefore increasing, and the atom getting more and more electro-negative. Let us see what happens when we get to 68; here we have 21 on the outside and 47 inside, but as 47 is the smallest number which can keep 21 in equilibrium, this equilibrium is shaky, and as in the case of 59 corpuscles the atom would be very electro-positive. Thus, as we increase the atomic weight, we get for a certain range, a continual diminution in the electro-positive character; this goes on until we get to 67, then there is a sudden jump from the electro-negative 67 to the electro-positive 68, followed again for a time by a continual decrease in electro-positive characteristics with increasing atomic weight. Compare this with the behaviour of the atoms of the chemical elements

Li	Bi	Bo	C	N	O	Fl
Na	Mg	Al	Si	P	S	Cl
K	—	—	—	—	—	—

The electro-positive character diminishes as we proceed from Li to Fl, then there is a sudden change from the electro-negative Fl to the electro-positive Na, then another diminution in the electro-positive character to Cl, and then another sudden change from Cl to K.

The model atoms we are considering are all built up of the same materials—positive electricity and corpuscles—hence the atoms of any one element would furnish the raw materials for the atoms of any other element, and a rearrangement of the positive electricity and corpuscles would produce transmutation of the elements. Whether the atoms of our elements will tend to break up into the atoms of other elements will depend upon the relative stability of the atoms, and the stability of an atom will depend mainly upon its potential energy; if this is large, the atom will be liable to break up or change. I have calculated for atoms containing from 1 to 8 corpuscles the potential energy of the atom per corpuscle: i.e. the potential energy of the atom divided by the number of corpuscles in the atom, making the assumption that positive electricity behaves like an incompressible fluid, i.e. that its density is invariable. The result is represented graphically in Fig. 3; the vertical ordinates represent the potential energy per corpuscle, the horizontal abscissæ the number of corpuscles in the atom. You will notice that the curve is a wavy line with peaks and valleys; the atoms corresponding to the peaks would have greater potential energy than their neighbours, and would therefore tend to be unstable, while those in the valleys, having relatively little potential energy, would be stable.

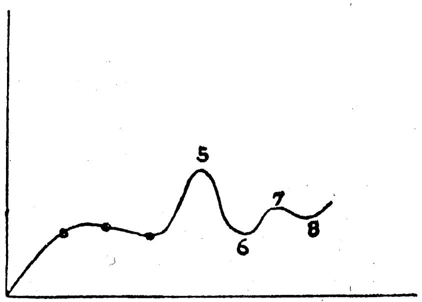


Fig. 3.

The case is in many respects very analogous to the case of a number of stones scattered over a hilly country whose section is represented by Fig. 3; the stones, if subject to disturbances, would run from the hills into the valleys, and though the stones might be uniformly distributed to begin with, yet in course of time they would accumulate in the valleys. So also in the chemical problem, though the number of atoms of the different elements might initially not be very unequal, yet, in course of time, those in the valleys would increase, and those on the peaks diminish, so that some elements would increase, while others would tend to become extinct. The smallest potential energy is that of an atom consisting of a single corpuscle; this is the goal which all the atoms would ultimately reach, if subject to disturbances sufficiently intense to lift them over the intervening peaks. Thus, on this view, the general trend of the universe would be towards simplification of the atom—though there might be local eddies. The final stage would be that in which all the atoms contained only one corpuscle. This result depends upon the assumption that the positive

electricity is incompressible, i.e. that its density is constant; if we had assumed that the volume of the positive electrification is the same whatever may be the quantity of electricity, we should have found that, although there would still have been changes from one element to another, the general trend would have been in the opposite direction, i.e. the simple atoms containing only one corpuscle would gradually condense into more and more complex atoms.

Chemical Combination. Action of the Atoms on each other.—We have hitherto confined our attention to the consideration of the stability of the arrangements of the corpuscles in the atom. We shall now proceed to discuss the question of the action of one atom on another, and the possibility of the existence of stable configurations of several atoms, in fact the problem of chemical combination.

As far as I know, the only cases in which the conditions for equilibrium or stable steady motion of several bodies acting upon each other have been investigated, is that suggested by the solar system; the case in which a number of bodies—suns, planets, satellites—attract each other with forces inversely proportional to the square of the distance between them. The complete solution of this problem, or anything approaching a complete solution, has proved to be beyond the powers of our mathematical analysis; but enough has been done to show that with this law of force, stable arrangements of the mutually attracting bodies only occur under stringent conditions. Thus, to take a very simple case, that of three bodies, it has been shown that, when the bodies are equal, there is no arrangement in which the steady motion is stable; if, however, the masses are very unequal, then it is possible for such an arrangement to exist. Another very interesting case is one investigated by Maxwell in connection with the theory of Saturn's rings. It is that of a large planet surrounded by a ring of satellites, each satellite following its neighbour at equal intervals round one circular orbit. Maxwell showed that this system was only stable under certain conditions, the most important being that the mass of the planet must be much greater than that of the satellite. The proportion between the mass of the smallest planet able to retain the ring in steady motion and the mass of one of the satellites increases very rapidly as the number of the satellites increases: if P is the mass of the planet, S that of a satellite, n the number of satellites, Maxwell showed P must be greater than $\cdot 43\, n^3$ S. The consequences of this are interesting from the analogy shown in the case of chemical combination. Thus, suppose the mass of a satellite were $\frac{1}{100}$ part of that of the planet, then the result shows that the planet could retain 1, 2, 3, 4, 5, 6 satellites, but not more than 6. With 6 satellites the planet is, to use a chemical term, saturated with satellites, and the behaviour of the system is equivalent to that of the atom of a sexavalent element, which can unite with 6 but with not more than 6 atoms of hydrogen.

The existence of a limit to the number of systems in a ring, which a central system can hold in stable equilibrium, is not peculiar to any special law of force. We have already seen examples of it inside the atom, where the central force on the satellites is supposed to be proportional to the distance. We have just seen that it holds in the planetary system, where the central force varies inversely as the square of the distance. I have found that this limit exists for all the laws of force I have tried, although of course the number of satellites which can be held in equilibrium depends on, among other things, the law of force.

The law of the inverse square is not favourable to the formation of stable systems, even when, as in the astronomical problem, the forces between the various bodies are all attractive; it is quite inconsistent with stability when, as in the case of the chemical atoms, some of these bodies carry charges of the same sign, and so repel each other. Thus, suppose we have the central body charged with positive electricity, while the satellites are all negatively electrified, so that the central body attracts the satellites, while the satellites repel each other. With forces varying inversely as the square of the distances between them, it is easy to show that with more than one satellite stability is impossible.

The mathematical investigation of the case where the satellites repel each other shows that, in order to ensure stability, the central attraction must, in the neighbourhood of the satellite, increase when the distance of the satellite from the planet increases. Inside the atom we have supposed that the central attraction was proportional to the distance from the centre, so that in this region the central force increases rapidly with the distance at all points. It is not necessary for equilibrium that the increase should be as rapid as this, nor indeed that the force should everywhere increase with the distance; all that is necessary is that in the neighbourhood of the satellite the force should increase and not decrease as the distance increases.

It might appear at the outset as though atoms of the kind we have been considering, made up of positive electricity and corpuscles, could never form stable arrangements, for there is a theorem known as Earnshaw's theorem, to the effect that a system of bodies attracting or repelling each other with forces varying inversely as the square of the distance between them, cannot be in stable equilibrium. This result does not prevent the existence of stable arrangement of atoms in the molecule, for Earnshaw's theorem only applies to the case when the bodies are at rest; it does not preclude the existence of a state of steady motion, in which there is no relative motion of the atoms. Again, in the case of our atoms there are other forces besides the electrostatic attractions and repulsions, for if the corpuscles are in rotation inside the atom, they will produce magnetic forces, so that outside the atom there will be a magnetic, as well as an electric field. The magnetic field will greatly promote the stability of the atoms if these are charged, for it will, if strong, practically prevent motion at right angles to the direction of the magnetic force, so that the arrangement of atoms will be stable provided the electrostatic

forces give stability for displacements *along* the lines of magnetic force. For example, if at any point near an atom the magnetic force were radial, then a second charged atom at this point would be in stable equilibrium, provided the radial attraction between the atoms at that point increased as the distance between the atoms increased.

Let us now consider the forces produced by an atom of the kind we have described. Take the case of an uncharged atom, i.e. one where the sum of the charges on the negatively electrified corpuscles is just equal to the positive charge in the sphere in which the corpuscles are supposed to be placed. Let us consider the radial force to the centre due to such an atom. Since there is as much positive as negative electricity in the atom, the average radial force taken over the surface of a sphere with its centre at the atom is zero; this does not mean that the radial force is everywhere zero, but that at some places it is directed towards the centre, and at others away from it. There

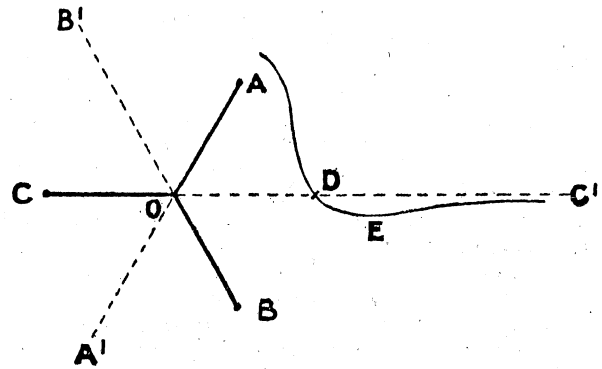


Fig. 4.

may be, as we shall see, certain directions in which the force changes from attraction to repulsion, or *vice-versâ*, as we travel outwards from the sphere.

Thus take the case of three corpuscles placed in a sphere. The corpuscles, when in equilibrium, are at the corners of an equilateral triangle A B C; let O be the centre of the atoms of which these corpuscles form a part. Consider the force on a positively charged particle. As we travel from A radially outwards, we find that the force is always towards O, and gets smaller and smaller as we get further and further away. As the attraction diminishes as the distance increases, there is no place at which the particle would be in equilibrium, stable or unstable. Suppose, however, we travel outwards along O C^1, the prolongation of C O, then when the particle is just outside A B, the force on the particle is repulsive. This repulsive force diminishes as we recede from the atom and vanishes at a certain distance D; at greater distances from the atom than D, the force is attractive and remains attractive at all greater distances; thus a positively charged particle would be in equilibrium at D, and it is easy to see that the equilibrium would be stable, for if the particle were made to approach O, the repulsive force would drive it back to D, while, if the particle were to recede from D, the attractive force would drag it back. If we represent the relation between the radial force and the distance by a graph, a point above the horizontal axis corresponding to repulsion, and one below it to attraction, we obtain a curve of the following character. The curve crosses the axis at the point D, the place where the force vanishes; after passing D, the force which is now attractive increases as the distance from the atom increases, until a point E is reached when the force is a maximum; beyond E the attraction diminishes as the distance increases. Thus, since in the region D E, the force is attractive and increases as the distance increases, a positive particle, placed in this region, might be in stable equilibrium, while outside this region the equilibrium would be unstable.

There would, of course, by symmetry be similar regions on O A[1], O B[1], the prolongations of O A and O B respectively. It will be seen

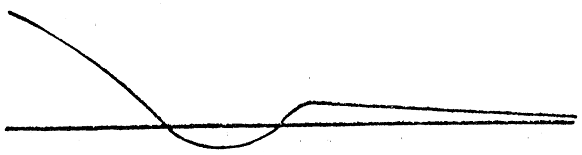


FIG. 5.

that the nature of the force between the atom and the charged particle, is of the type postulated by Boscovich, i.e. a repulsion at short distances succeeded by an attraction at greater ones. With the very simple type of atom we have been discussing, there is only one change from repulsion to attraction; with atoms containing more corpuscles, the graph representing the relation between force and distance becomes more complicated, and we may have several alternations between repulsion and attraction instead of only one as in Fig. 5.

However complicated the atom, a distribution of forces of this kind will only occur in a limited number of directions, or rather only along directions making small angles with a limited number of axes drawn in definite directions.

I have here an arrangement to show the change in direction of the force due to an atom. The atom is supposed to be one with three corpuscles; these are represented by the negative ends of three electromagnets arranged radially on a board, the positive ends of the magnets which represent the positive electrification in the sphere being at the centre. We see that along the lines O A[1], O B[1], O C[1], the magnetic force on a positive pole changes from repulsion to attraction at a

certain distance, and that the system can hold three floating magnets in stable equilibrium at a finite distance from its centre.

An atom analogous to the one we have just been considering would have the power of keeping three positively electrified particles

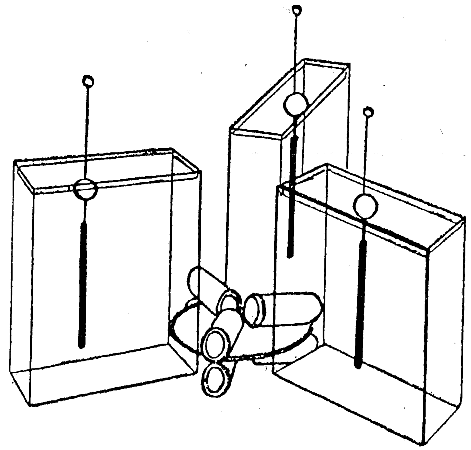


FIG. 6.

in stable equilibrium, provided these are placed at suitable distances along the lines O A[1], O B[1], O C[1]. With other arrangements of corpuscles, we should get atoms able to keep negatively electrified particles in equilibrium. Thus, for example, if we have 5 corpuscles placed at the corners of a double pyramid as in Fig. 7, then along the lines OA, O B, O C, at suitable distances from O negatively electrified particles could be in equilibrium, even if the atom were uncharged. If, however, the central atom were uncharged while the satellites were charged, the molecule, as a whole, would be charged, whereas we know the molecule is electrically neutral; we must consider, therefore, what would be the effect of giving a charge of electricity to the central atom.

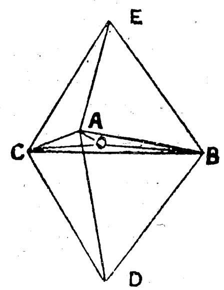


FIG. 7.

In the case of the three corpuscles, if we gave a negative charge to the central atom, the axes O A[1], O B[1], O C[1], might or might not cease to be axes of stable equilibrium for positively electrified particles. The effect of the charge would be to bring the point D of equilibrium closer to the atom—how much closer would depend upon the charge given to the atom; but as long as D kept outside the atom, stable equilibrium for positively electrified particles would be possible; if, however, D came inside the atom, the axes O A^1, O B^1, O C^1, would cease to be axes of possible equilibrium.

In some cases, the communication of a charge to the atom might, in addition to affecting the position of equilibrium along the axes for the uncharged atom, introduce axes of stability which did not exist when the atom was uncharged; thus, in the case of a double pyramid Fig. 7, if we gave a positive charge to the atom, the axes O E, O D, which were not axes of equilibrium for the uncharged atom, would become so for the charged one; for if the atom had a positive charge, the force on the negatively electrified particle would at a point a great distance from the centre along O E be an attraction, while close to E it would be a repulsion; there must be some point then when the force changes from repulsion to attraction, so that this axis will be one of equilibrium.

In the case of a more complicated atom giving a distribution of force changing from repulsion to attraction more than once, as in the case represented in Fig. 5, there would be places along this axis where a negatively electrified particle would be in stable equilibrium and other places where a positively electrified particle would be in stable equilibrium. The effect of giving a positive charge to this alone would be to make the positions of equilibrium for the negative particles approach the atom, those for positive particles recede from it; the effect of a negative charge would displace those positions in the opposite directions.

The forces we have been considering are those exerted by an atom on a charged particle; they would be a part (and in many cases, I think, the most important part) of the forces acting on a second atom, if that atom had an excess of one kind of electricity over the other. Remembering, however, that there is an electric field round an atom, even when it is uncharged, and that an uncharged atom is not an atom in which there is no electricity, but one where the negative charge is equal to the positive, we easily see that two uncharged atoms may exert forces on each other; the calculation of these forces is, on account of the complex nature of the atom, very intricate, and I shall not go into it this evening. I shall treat the subject from the experimental side. I have here two systems, each built up of magnets, each containing as many positive as negative poles, and thus analogous to an uncharged atom; one of them is suspended from the arm of a balance, Fig. 8. You see that I can place these systems so that they repel each other when close together and attract each other when further apart, so that these atoms would be in stable equilibrium under each other's influence when separated by the distance at which repulsion changes to attraction.

The force which an atom A exerts on another atom B may be conveniently divided into two parts: the first part, which we shall call the force of the E type, depends upon the charge on B; it is proportional to this charge and independent of the structure of B, and we might, without altering this force, replace B by any atom we pleased,

provided it carried the same charge. The other part of the force, which we shall call the M part, is independent of the charge on B, but depends essentially on its structure; this part of the force would be entirely altered, if we replaced B by an atom of a different kind.

The question now arises, What part do these two types of force play in determining the nature of the molecule? Is the stability determined by forces of the E or of the M type?

The E forces depend on the charges carried by the atom, so that in those compounds in which stability is due to the E forces, the

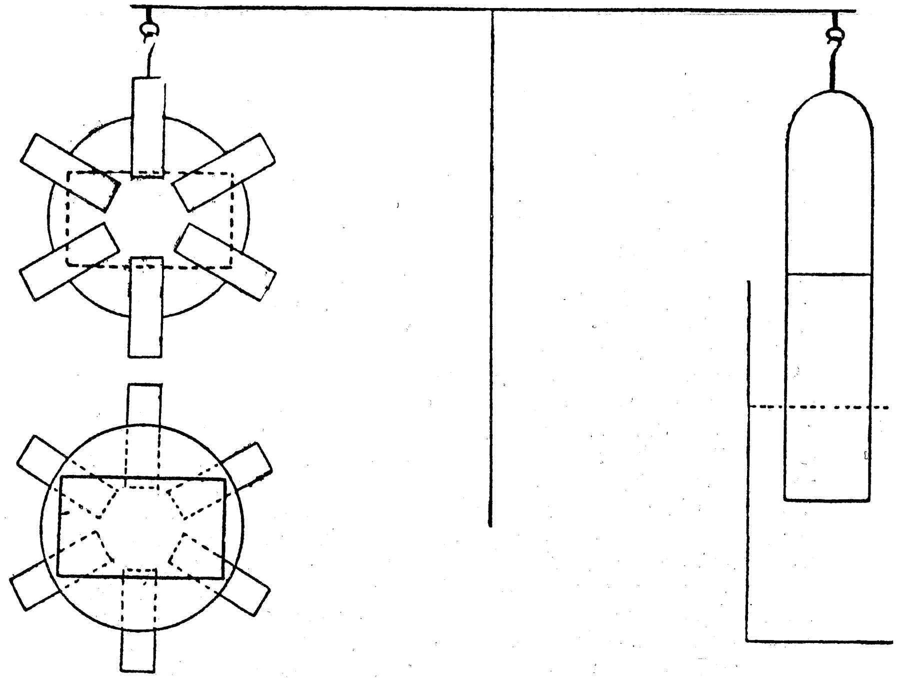


Fig. 8.

atoms must be charged. We are thus confronted with the question, Are the atoms in a molecule charged with electricity, or are they electrically neutral? Thus, to take a definite case, in the molecule of marsh gas, which we picture as a carbon atom at the centre of a tetrahedron with the four hydrogen atoms at the corners, are the hydrogen atoms charged with equal quantities of negative electricity, the carbon atom having a four-fold charge of positive, or are both carbon and hydrogen atoms uncharged? It is difficult to get direct evidence on this point, since the molecule as a whole is neutral on either supposition. There is, however, considerable indirect evidence to support the view that the atoms in many compounds are electrified. I may mention, as examples of such evidence, the power possessed by certain molecules, such as those of sugar, of rotating the plane of polarisation of light passing through them,. This power, which is associated with the presence of the asymmetric carbon atom with four dissimilar atoms attached to it, is readily explained by the electromagnetic theory of light; if the atoms in the molecule are charged, it is difficult to see how uncharged atoms could produce sufficient rotation.

Let us consider the difference in the chemical properties of a substance according as the atoms in the molecules are held together by forces of the E or M type and one held together by the M type. Let us take the molecule of marsh gas as an example, and suppose that the molecule is in equilibrium under the E forces exerted by the carbon atom on the negatively electrified hydrogen atoms and the mutual repulsions between these atoms. The forces exerted by these hydrogen atoms depend entirely on the charge carried by the hydrogen atom; none of these forces would be affected if we replaced any or all of the hydrogen atoms by any atom which carried the same charge. Hence, without altering the architecture of the molecule, we might replace any or all of the hydrogen atoms by atoms of any univalent substance. In this case, the replacement of an atom by another of the same valency would be a very simple thing.

Suppose, however, that the atoms in the molecule were held together by forces of the M type, then the forces between two atoms would depend on the structure of both the atoms. If now we were to replace one of the H atoms by an atom of another kind, not only would the force exerted by the carbon atom on this atom be altered, but the forces exerted by the atoms on the remaining three hydrogen atoms would be radically changed; this change in the forces would involve a complete change in the structure of the molecule. Thus the effects of replacement are much more serious when the forces are of the M type than when they are of the E type. The forces of the E type are, I think, those which are most effective in binding atoms of different kinds together, while the M type of forces finds its chief scope in binding similar atoms together as in the molecule of an element, or as in the connecting the carbon atoms in the carbon compounds.

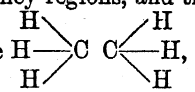
Let us sum up the results we have arrived at. We have seen that an atom built up of corpuscles in the way we have described possesses, whether charged or uncharged, the following properties. There are certain directions fixed in the atoms, along which or in directions not too remote from which, electrified particles, positively electrified for some kinds of atoms, negatively electrified for others, and either positively or negatively electrified for still other kinds of atoms, will be in stable equilibrium, if placed at suitable distances from the centre of the atom. We may call those directions the valency directions, and the regions within which the equilibrium is stable the valency regions. Those who are familiar with the beautiful theory of Van't Hoff and

Le Bel on the asymmetric carbon atom, which supposes that the attractions exerted by a carbon atom are exerted in certain definite directions, these directions being such that, if the carbon atom is at the centre of a regular tetrahedron, the attractions are along the lines drawn from the centre to the corners, will perceive the resemblance between that theory and the results we have been discussing. There is, however, an important difference between the two, for on our theory the forces exerted by the atom are not confined to any special direction; the atom exerts forces all round. It is only, however, in certain directions that these forces can keep a second atom in stable equilibrium. We picture, then, the atom A as being connected with a limited number of closed regions of finite size, and any body attached to the atom must be situated in one of these regions; when each of these regions is occupied by another atom, the atom A can hold no more bound to it, and is said to be saturated.

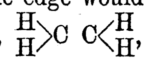
I have not time this evening to discuss in any detail further developments of these ideas. I may however, in conclusion, call attention to a point which is illustrated by the behaviour of the carbon compounds. Suppose that C_1 C_2 are two carbon atoms near together. Then when

$$C_1 \quad \alpha \quad \beta \quad C_2$$

both atoms are present, regions α, β near the line joining C_1 C_2, which were valency regions for C_1 and C_2 when these atoms were alone, may cease to be valency regions when both are present. For take the case when the stability is due to the magnetic force produced by the rotation of the corpuscles within the atoms. Along the line C_1 C_2, the magnetic force due to C_1 and C_2 will be in opposite directions, and in the region near the middle of C_1 C_2 the resultant magnetic force would be very small, so that in this the equilibrium of a charged body would be unstable; thus α β would cease to be valency regions. This reasoning would not apply to the valency regions of C_1 on the side opposite to C_2, nor of those of C_2 on the side away from C_1, so that six valency regions would remain. Thus if we consider the tetrahedra formed by the valency regions round our carbon atoms, then if two carbon atoms are placed so that two vertices of these tetrahedra come together, the regions near these vertices will cease to be valency regions, and the compound formed would have to be of the type



the two carbon atoms being held together by forces of the M type. If the tetrahedra were placed so that two edges of the tetrahedra came together, we could show similarly that the four valency regions at the ends of the edge would be suppressed and the compound would be of the type,



while if two faces of the tetrahedra came together the valency regions in these faces would be suppressed, and the compound would be of the type H—C C—H.