

THE ELECTRON AS AN ELEMENT
COMPOUNDS OF ELECTRONS
THE DISRUPTION OF THE SO-CALLED
ELEMENTS¹

LECTURE I

THE ELECTRON AS AN ELEMENT

THE independent existence of the electron is now conclusively demonstrated; in my opinion, it is, next to the first and second laws of energy, the most far-reaching discovery which has yet been made, both in its application to the elucidating of our former views concerning matter and its nature, and to our control over what are popularly termed "the forces of nature."

Although progress in human thought has usually been achieved from the practical standpoint, still, after a sufficient number of observations have been made, a consistent theory, which permits of the knitting together of such isolated parts into a complete whole, suggests the trend of further research, and renders easy what previously was justly regarded as difficult. It is thus with the idea of the electron as an entity. Once it has been realized that the part played by the electron is all-pervading; that it enters as an element into the constitution of chemical compounds; that when they undergo

¹ Three lectures delivered at the inauguration of the Rice Institute, by Sir William Ramsay, K.C.B., F.R.S., Professor of Chemistry in the University of London.

change, that change is brought about by a shifting of electrons from one form of combination to another; when we realize that a current of electricity flowing along a wire is merely the passage of almost infinitely numerous electrons from place to place, and the formation and decomposition of temporary compounds; when we can clearly conceive that the starting and stopping of such a current of electrons cause ethereal waves, themselves capable of starting or stopping similar currents of electrons in wires parallel to the first; when we realize that by the expenditure of energy such streams of electrons can be set in motion and can be stopped,—then we have acquired knowledge which will enable us to contrive machines better than those which we already possess, whereby the direction of motion of electrons can be controlled.

The fact that electrons cannot be seen need now prove no stumbling-block. For men were for long unable to realize that invisible gases could be put to use. The wind was by our forerunners regarded as semi-spiritual; a ghost and a gust were akin; and I find it difficult to convince my non-scientific, and even some of my scientific, friends that it is much easier to work with and to manipulate gases than liquids or solids. And now gases, in the form of compressed air, compressed steam, or compressed products of explosion, are our chief agents for conveying energy from place to place; they are, electrons excepted, the means by which almost all our energy is transmitted. They have the advantage of being easily moved; of being elastic; and of being conveyed rapidly from place to place without loss. Indeed, if it were necessary to characterize the past century by a single expression, the “age of compressed gases” might be aptly chosen.

The story of the measurement of the mass of an electron has often been told. The “kathode rays” were discovered by Lenard to be able to pass through a thin sheet of alu-

minium; and after their passage they were found to be able to penetrate the atmosphere for some distance, although they were somewhat rapidly dispersed; in fact, the dispersion, with the loss of their activity, has been likened to the passage of light through water to which a few drops of milk have been added. Crookes's previous researches had proved that kathode rays can be concentrated to a point from an aluminium kathode, shaped like a parabolic mirror; that they produce great rise of temperature at their focus; that their impact can impart rotatory motion to a paddle-wheel on the blades of which they impinge; and that they have the property of causing phosphorescence in various objects—many minerals, for example, glowing with marvelously brilliant colors. They are unable to penetrate thick objects; hence a metal cross or other object can be made to cast a kathode shadow when placed in their path, and the shadow can be well seen on the side of the glass vessel in which the rays are generated; the glass phosphoresces with a beautiful green or blue color, except where it receives the shadow of the metal cross.

Crookes also showed that two such streams of electrodes, each arising from its own kathode, repel each other; for if the kathodes were parallel, the streams were not parallel, but divergent. On the other hand, streams of kathode particles, passing in opposite directions, attract each other.

Goldschmidt, many years ago, had noticed that the streams of kathode rays can be deflected by a magnet; and it was this property of the rays, taken with that of their being attracted by a positive and repelled by a negative electric field, which led to the possibility of measuring the ratio of the charge which they carry to the mass of the electron.

Knowing this ratio, it follows that if the magnitude of the charge be known, the mass of the electron will then be deter-

mined. Now, accurate measurements show that this ratio involves one of two alternative suppositions: either that the negative charge is 1830 times the positive charge carried by one atom of hydrogen in the ionic state, or that the mass of the particle is only $\frac{1}{1830}$ of that of an atom of hydrogen. It appeared improbable that the first supposition should be correct; and the matter has been decided without a shadow of doubt from experiments made by Mr. C. T. R. Wilson. A property of ions in a gas is to cause the condensation of supersaturated water-vapor to droplets. The number of such droplets can be counted; the velocity of their fall can be measured. This affords a means of determining the diameter of each droplet, and from that the volume of a droplet can be deduced; and as the total quantity of electricity carried down by the precipitated liquid can be easily measured, the charge on each particle can be estimated. It is that which may be attached to one, two or more electrons; for the ion of a gas may be attached to electrons, and each ion corresponds to one water droplet. Wilson's experiments, as well as the beautiful experiments of Milliken, agree in the conclusion that the electric value of a unit charge, or electron, is 4.78×10^{-10} electrostatic units; and it follows from this that the mass of an electron is $\frac{1}{1830}$ of that of an atom of hydrogen.

It is possible now to go further and to determine the actual mass of an electron. Experiments by M. Perrin on what may be termed visible molecules—namely, particles of gamboge in an aqueous emulsion—have enabled him to deduce with great accuracy the mass of an atom of hydrogen; it is 1.63×10^{-24} gram. Dividing by 1830, the mass of an electron is found; it is 0.8×10^{-27} gram.

Let me interpose here the remark that the method of determining the "atomic weight" of an electron does not differ in principle from the usual method of determining

atomic weights. The usual method is to ascertain the weight of the element in question which will combine with a known weight of some standard element the ratio of whose atomic weight to that of oxygen is known. This ratio is generally determined by the balance, and the result gives the equivalent of the element of which the atomic weight is required. With the electron the process is similar, except in the method of weighing; the "weight" is determined electrically. Indeed, the use of the word "weight" is not strictly permissible, for the attraction of the earth does not come into play; electric forces replace it. But there is now no doubt that the atomic mass of an electron is $\frac{1}{1830}$ of that of hydrogen. It is also certain that what is termed an electric current consists of a stream of such electric particles in motion; and that a negative electric charge consists in the surface of the negatively electrified object being covered with a film of such particles.

We see, therefore, that we have now to do with an element of known atomic weight which has been isolated from its compounds and is thus accessible in the free state. It may be pointed out here that this is not the first time that the existence of elements has been inferred before their isolation in a state of freedom. To quote a familiar instance, fluorine was defined as an element by Davy eighty years before Moissan prepared it by electrolysis of hydrogen fluoride, rendered a conductor by the presence of dissolved salts. The fact of the general resemblance of its compounds to those of the other halogens made the inference legitimate. But the electron possesses properties so remarkable that there is little wonder that its elementary nature was overlooked.

The first suggestion, which, nevertheless, fell short of the truth, was made in 1887 by Helmholtz in his Faraday lecture, when, having indicated that according to Faraday's law

each atom of an element, liberated on electrolysis, is associated with one or more units of positive or negative electric charge, he pointed out that the legitimate conclusion to be drawn was that each liberated elementary atom is associated with one or more positive or negative units of electricity, to which the term "electric atom" might legitimately be attached. It has only been slowly realized that a negative charge is due to the presence of atoms of electricity, or negative electrons, and that a positive charge is due to their absence. We are reminded by this of the long-exploded doctrine of phlogiston, the demolition of which by Lavoisier revolutionized the science of chemistry and gave it a fresh start. In it the absence of oxygen corresponded with the presence of phlogiston, a wholly imaginary conception; just as a positive charge was tacitly assumed to be the addition of positive electricity to matter, while a negative charge corresponded to the association of matter with negative electricity. It is as if the upholders of the phlogistic theory, having been convinced against their will that combustion implied combination with oxygen, had at the same time maintained that during such combination phlogiston is lost. Indeed, Scheele's ingenuity made him devise a somewhat similar hypothesis when he was confronted by the experimental fact that oxygen is produced by heating "mercurius precipitatus per se" in a retort. His explanation was that the heat which entered the retort, being composed of phlogiston plus fire-air, was decomposed by the calx of mercury; the calx, combined with the phlogiston, producing mercury, while the fire-air, or oxygen, the other component of "heat," escaped and could be collected. The reasoning is perfect as long as the use of a balance is excluded; and, as with the electron, it was only by careful weighing that the substantiality of oxygen could be demonstrated.

Similarly, it is now time to reject the old hypothesis that there are two kinds of electric fluid—one positive, one negative; the evidence is overwhelmingly in favor of the theory that electricity consists of an assemblage of electrons, or particles of negative electricity, and that compounds of electrons change their nature when the electrons are removed, just as mercuric oxide acquires the properties of a metal by removal of oxygen. Much confusion has arisen owing to the fact that electric phenomena are produced by ethereal waves. Indeed, the word "electricity" has a dual signification: firstly, it applies to congeries of negative electrons attached to what is generally termed matter, as one element is united to another—or, to use a more general expression, is attached to another, or to a compound; and secondly, it is made to signify vibrations in the ether, which arise when a current of moving electrons is started or stopped. It is also clear that a magnet is associated with electrons in circular motion, which keep the neighboring ether in a state of strain; if the lines of strain, or "lines of force," be cut by a moving wire, the electrons in that wire are set in motion and a current is produced. It is unnecessary to state that this fact that ethereal vibrations can start or stop electrons has proved of the very greatest service to mankind; to this is due the invention of the dynamo, of the motor, and of wireless telegraphy. But it is evident that such ethereal vibrations, transmitted as waves, are in no sense the material electrons, any more than the force applied by a horse to a rope is the canal-boat which it sets in motion.

As for the mechanism by which ethereal waves effect motion in electrons, that is beyond the scope of these lectures. Indeed, of the rival theories which profess to explain it, not one is satisfactory. All that can definitely be said is that there is an evident gyroscopic action, for motion of

electrons occurs not in the direction of propagation of the ethereal force, but at right angles to it. We therefore deliberately confine our attention to the electron as a form of matter with a known atomic weight, viz., $\frac{1}{1830}$, and capable of forming compounds with what we commonly term matter. And here again we must draw a line. The question has been raised, Does matter consist of congeries of electrons in rotation, or in vibration, or exercising some form of relative motion? Or is there a material nucleus, composed of some entity different from electrons, with which electrons can combine, and from which they can separate? And is there only one such stuff—primordial matter? Or are there as many varieties of stuff as there are elements?

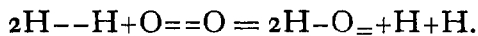
These speculations are of great interest; some of them have exercised men's minds for centuries. But answers to these questions are not yet forthcoming; they are the goals to which investigation is tending. As regards the question of the composition of matter, whether it consists wholly of electrons or not, that must be left open. It can and will be decided by experiments devised to test various theories. All we need say for the present is that most forms of matter, such as we know them, contain electrons as parts of their composition; we need not *yet* concern ourselves with the constitution of the residual matter after the removable electrons have been removed.

As for the unity of matter, I hope to be able to show that progress is being made in the direction of an answer to that question. It may, however, be stated at once that it is as yet absolutely uncertain whether or not matter will ultimately be found to be homogeneous—that is, consisting wholly of one kind, associated with more or with fewer electrons.

Having arrived, then, at the notion that in electrons we must recognize an elementary form of matter, let us next

consider the transference of electrons from one form of combination to another. This can be done most simply by reasoning on any simple electrolysis; and I will choose that of water, assuming, for simplicity's sake, that the change is the theoretical one, $2\text{H}_2\text{O} = 2\text{H}_2 + \text{O}_2$. The real change which occurs depends, of course, on the electrolyte which has been added to the water, and on the action of its liberated ions on the water; if it be sulphuric acid, for example, the hydrogen of the acid will be set free, and the sulphation group, SO_4 , will liberate oxygen by its action on water. We will neglect these actions, however, and will regard the action as expressed by the simpler equation.

Water, then, consists of molecules of some complexity, probably H_6O_3 , or H_8O_4 , or mixtures of these with even more complicated molecular groups; and along with them, mingled with the rest, are ions of hydrogen and oxygen. The hydrogen ions are those which lost electrons to the oxygen when the water was produced. It is reasonable to suppose that during the combination of the hydrogen gas with the oxygen gas (granting the water to have been so formed), the hydrogen, which as a gas consists of hydrions in union with electrons, $\text{H}-\text{H}-$, has, during its "union" with oxygen, which as a gas may be provisionally taken as $\text{O}=\text{O}$, given its electrons to the oxygen; so that on ionization the electrons, having already arranged themselves in the water-molecule in such a manner that they are no longer directly associated with the hydrogen, leave the hydrogen atoms entirely without removable electrons; it is often the custom to call these atoms of hydrogen devoid of electrons, "hydrions." Each electron which has left an atom of hydrogen associates itself with an atom of oxygen plus one of hydrogen, thus:



This equation requires consideration. A molecule of hydrogen is not $\text{H}-$, but $=\text{H}_2$. Now it is an open question how the electrons are attached; but it is to be presumed that an electron forms the bond between the two atoms. This may happen in two ways. First, the attachment may be $\text{H}-$; or, second, $\text{H}-\text{H}-$. The same reasoning applies to the molecule of oxygen; it may be $=\text{O}=\text{O}$ or $\text{O}==\text{O}$. In the first case one of the atoms is tetrad, according to the usual code of writing; but that need excite no surprise: oxygen is known to possess tetrad valency under suitable conditions. It may be remarked, however, that similar reasoning applied to the hydrogen molecule involves the assumption of dyad hydrogen, and that is an unlikely supposition. It need hardly here be insisted on that the actual practical valency of an element or group is equal to the number of electrons which it carries during electrolysis; that is the corollary of Faraday's law. Now hydrogen is invariably monovalent; hence the formula $\text{H}-\text{H}$ is preferable to $\text{H}-\text{H}-$. On the other hand, it may be objected that two electrons will repel each other, and it might with justice be asserted that for that reason $\text{H}-\text{H}-$ is preferable to $\text{H}-\text{H}$; and similarly that $\text{O}=\text{O}=\text{O}$ is preferable to $\text{O}==\text{O}$. This statement will be referred to again in the second lecture. Perhaps both formulæ are correct; tautomerism may occur in reference to atoms and electrons as well as between atoms considered independently of electrons; the formula of hydrocyanic acid appears to be both $\text{H}-\text{C}\equiv\text{N}$ and $\text{H}-\text{N}\equiv\text{C}$; and many similar instances will suggest themselves in more definite cases, as, for example, among the enols.

Leaving such questions for the present, let us see the effect of an electric current on hydrions and hydroxylions. They are to be regarded as separate and definite chemical entities intermingled with complex water-molecules—indeed, sur-

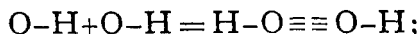
rounded by them; for it is in every way probable that the hydrions are attracted by spare electrons of the water-molecules. We have many instances of a similar directive action among compounds; the place of substitution in the benzene ring depends on the position of groups already substituted for nuclear hydrogen. We may therefore believe that the ions both of hydrogen and of hydroxyl are protected by a coating of non-ionized molecules of water. It is, indeed, probable that interchange of electrons takes place between the two, molecules and ions, so that it is not always the same hydroxyl group which retains its electron; the Williamson-Clausius hypothesis of interchange may well be applicable.

Into such a system of molecules and ions two platinum electrodes are plunged. We need not here consider the source of the current; suffice it to say that at the negative electrode the electrons are crowded on the surface, ready to escape on application of sufficient driving force—*i.e.*, of a sufficiently high potential; while from the positive electrode the electrons are subject to strain, for they are being sucked into the connecting wire by a corresponding electromotive force. In fact, we may consider the negative electrode as a region of electric pressure—a kind of electric force-pump; and the positive electrode as a partial electric vacuum—an electric suction-pump.

The hydrions, having no electrons attached to them, are attracted to the negative electrode, where electrons are present under electric pressure; they move thither at a rate depending on the mobility of the ion (and hydrions are the most mobile of all ions) as well as on the viscosity of the liquid, which is itself a function of temperature. Having arrived at the kathode, each ion absorbs an electron, and from a hydrion becomes an atom of hydrogen. Each atom

of hydrogen readjusts its newly found electrons so as to combine with its neighbor atom according to one of the schemes already set forth.

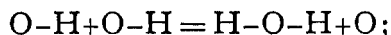
In an exactly similar manner, the kation, the hydroxylion, reaches the anode where electrons are under strain; from each hydroxylion an electron is removed, and the group OH is left without a free valency—*i.e.*, without an attached electron. It may under certain circumstances unite with another hydroxyl group, due possibly to the quadrivalence of the oxygen atoms; they may serve as bonds of attachment of the two groups to each other, thus:



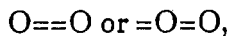
or only one of the three latent electrons may come into play, thus forming



the others being existent, though not in evidence. Or, as more generally happens, the molecules readjust themselves, forming water and free oxygen according to the scheme



and the atom O unites with a neighbor atom of O, forming



as explained before.

It may be objected that views such as the above are very hypothetical; that they tend to complexity and not to simplicity; and that they are imperfect. To that it may be replied that it is certain that some ions are carriers of electrons, and that others—the positive ions—travel without manifest electrons; that the electron is certainly to be regarded as an element, and that its comings and goings, its entering and escaping from chemical compounds must therefore be chronicled in all complete equations; that the intro-

duction of a new element capable of reacting with other elements necessarily tends toward complexity; and that all first attempts to represent chemical changes are of necessity imperfect, as is witnessed by the enormous progress which has been made in the graphic notation of organic chemistry.

This example will serve to illustrate the electrolysis of any chemical compound; the processes which occur are similar in kind, although they may differ according to the nature of the electrolysis.

Let us next consider what goes on in a simple battery; and we may suppose a plate of platinum and a plate of zinc dipped in a bath of dilute hydrochloric acid and coupled by means of a wire, a galvanometer being inserted to show the direction and electromotive force of the current.

The solution contains chlorions and hydrions, each protected by water-molecules. The more dilute the solution, the more efficient the protection from mutual discharge of the anions and the kations, the greater the ionization of the solution. Concentration of the solution by diminishing the relative number of water-molecules decreases the number of ions of hydrogen and chlorine. These ions are to be supposed, before introduction of the platinum and zinc plates, as evenly distributed throughout the liquid.

The plates are now introduced but not yet joined by a wire. Now, zinc, for some reason which we cannot yet guess at, has a greater tendency to dissolve in water than has platinum. But metallic zinc, which is really a compound of a zincion with two electrons, is insoluble in water; to dissolve, it must lose its electrons. When placed in water which contains some few hydrions, a trace of zinc will doubtless dissolve as ions, while a trace of hydrogen will adhere to the surface of the zinc. But the pressure—the solution-pressure, as it may be termed—will soon cease, and no further action

will occur. On joining the zinc plate to the platinum plate by means of a wire (let us suppose of copper), the zinc begins to dissolve, while for every atom of zinc dissolved a molecule of hydrogen attaches itself to the surface of the platinum, and when the concentration is sufficient it escapes in bubbles.

In order that the zinc shall dissolve it must lose its electrons. These, however, require a channel of escape, which they find in the copper wire. Leaving for a moment the nature of the change which accompanies their transit, let us follow them to the surface of the platinum plate. Here they accumulate, with a pressure (that is, at a potential) equal in absolute measure to the solution-pressure of the zinc plate. The hydriions flock to the platinum plate, for they, lacking electrons, travel to where electrons are plentiful; each hydriion acquires an electron, unites with it, and, as previously explained, joins to a neighboring atom to form a molecule. When these attain a sufficient number to saturate the neighboring water, and the capacity of platinum for holding atomic or molecular hydrogen (probably atomic) is attained, the molecules of hydrogen escape in bubbles.

The chlorions—in the old nomenclature negatively charged, in the new conception containing each an active electron—are attracted to the spot from which electrons are flowing away through the wire. Although they are not otherwise changed, they concentrate in the neighborhood of the anode, from which zincions are being propelled into the solution. The rate of their flow to the anode depends on their specific mobility and on the viscosity of the liquid, a condition of concentration and temperature.

In short, the process taking place in a battery has considerable resemblance to that which causes the flow of a liquid due to osmotic pressure. A concentrated solution, in contact

through a semipermeable diaphragm with a dilute solution, tends to be diluted; the solvent from the dilute solution passes through the semipermeable membrane into the concentrated solution, and lessens its concentration. Now the electrons may be likened to the solvent of the dilute solution; they have alternative courses. The wire is permeable to electrons, but not to ordinary forms of matter; it acts thus as a semipermeable membrane. The pressure may, as in the case of osmosis, be regarded from two points of view: either as that of the solvent entering the concentrated solution through the semipermeable membrane, or as due to the bombardment of the walls of the vessel containing the concentrated solution by the molecules of the contained solute. So the pressure in the battery may be regarded from two points of view: either as the difference between the solution-pressure of the metallic zinc and that of the metallic platinum, or as the difference in the affinity of electrons for zinc and for platinum. It is, however, the property of the electrons to pass along the wire, which differentiates them from what we generally term matter; and, as already remarked, the phenomena in a battery afford a close analogy with those producible by means of osmotic pressure. We have in the battery a stream of electrons passing along the copper wire as long as there is zinc to dissolve in the ionic state, or as long as ions of hydrogen remain in solution to unite with the electrons on the surface of the platinum. This current of electrons may be made use of in several ways; first, it may be employed in electrolyzing an interposed solution—that phenomenon has already been considered. Second, it may serve to heat the wire; the conditions for a great rise of temperature are that the wire shall be thin, and that its conductivity shall not be high. Third, if the wire be coiled, and

if a magnet be suspended within the coil, it will set itself at right angles to the plane of the coil.

Let us first consider the heating of the wire, for that involves the theory of metallic conduction.

All material elements are capable of combination with electrons. Those which are termed bad conductors or insulators, however, do not readily combine; the electrons therefore form a layer on the surface. Such a layer can be produced by friction between two non-conductors—for instance, silk and sulphur. As has been known for a century and a half, “frictional electricity” can be produced by rubbing a silk pad on a cylinder of sulphur. Here the surface of the sulphur is “negatively electrified”—*i.e.*, electrons leave the silk and adhere to the sulphur. If a glass cylinder be substituted for one of sulphur, it is the glass which loses electrons and the silk pad which gains; hence the old names “vitreous” for positive and “resinous” for negative electricity. The rubbing of a metal object also effects the transfer of electrons; but in this case, unless the metal is supported by a non-conductor, the loss or gain of electrons is replaced by conduction from the earth. The electrons spread themselves all over the surface of the metal, instead of adhering in patches, as they do if non-conductors be rubbed.

When a salt is dissolved in water it is the metallic portion which loses its electron or electrons, and the non-metallic portion which gains them. We may therefore conclude that metals have less tendency to combine with electrons than non-metals, and that the more “metallic” an element, the less its tendency to hold electrons. It is therefore to be expected that in a metal wire, if electrons are introduced at one end, they will displace those in combination with the metal at the hither end of the wire, and that this process will go on con-

tinuously, so that if it is possible for electrons to escape at the further end, they will pass from one end of the wire to the other. This will also happen with rods or wires of poor conductors, but not with actual non-conductors. Transparent fused salts, or oxides, such as rock-salt, glass, or silica, are practical non-conductors. Their only method of conduction is an electrolytic one, and the mobility of their molecules and ions is so small that they cannot serve to convey electrons. But in a copper wire the transfer of electrons is easily effected.

The result of the passage of a current through a poor conductor of small section is to heat it. This heat corresponds quantitatively with the resistance which it offers to the passage of the current. It may be conceived that the electrons form relatively stable compounds with the atoms of the element of which the resisting wire is composed, and that in order to facilitate their passage the atoms are obliged to re-adjust their position relatively to each other; hence friction and heat. It would follow that the electrons do not flow as a stream through the interstices between the atoms, but that they form temporary and unstable compounds with the metal as they flow. It must, however, be acknowledged that this explanation lacks completeness, which further experiment will doubtless assure.

It is somewhat beyond the scope of these lectures to consider the action of a stream of electrons on the position of a magnet. The flow of electrons, it may however be remarked, produces a strain in the ether which interferes with the rotation of the electrons round the atoms of a magnetized bar. These set themselves at right angles to the plane of the wire carrying the current. Conversely, a forcible displacement of the magnet will cause a shift of electrons in the wire. But, as before remarked, owing to lack of definite-

ness in our ideas of the nature of the ether, no perfect picture has yet been made of the mechanism of its action.

We are more and more impressed with the necessity of a mechanical conception of things around us; all recent discovery shows that things much too minute for us to see are constituted in a manner not unlike the objects apparent to our senses. Hence we must regard the atoms of electricity—the electrons—as capable of taking up position in a chemical compound, just as we have imagined the atoms to do. It is true that we cannot maintain that the atoms are without motion. Far from it. But we can with fair probability determine the position of their centers of oscillation or rotation. The structure of compounds, viewed from the electronic point of view, will form the subject of the next lecture.