The Electrical Properties of Gases—I.*

Which Enable Important Problems in Physics to be Studied

By Sir J. J. Thomson, O.M., P.R.S.

I

IN opening his lecture Sir Joseph Thomson said that if the measure of the importance of a scientific subject lay in its power to come to close quarters with the fundamental bases of physics and chemistry, then the subject he had chosen for his course had strong claims to be counted as one of the most important in the whole range of physics. He would justify this claim by anticipating a little certain results, to be established later on. Two of the most fundamental questions of physics were: what was the nature of electricity? and what was the structure of matter? Now the study of the discharge of electricity through gases was responsible for the view now taken as to the nature of electricity. We now knew that electricity was, so to speak, atomic in structure, that every charge of electricity was made up of an immense number of smaller unit charges, and we differentiated sharply between positive and negative electricity. We knew that the atoms of negative electricity were extremely minute, having a mass less than anything else known up till a few years ago. They had, moreover, the power of moving with velocities which fell but a small percentage below those of light. The positive units were much more massive, having 1,700 times more mass than the negative particles. This view had been arrived at by the study of the electric properties of gases.

As for the other problem, concerning the structure of matter, the same study had shown that beyond the chemical atoms which made up the mass of ordinary bodies still smaller systems existed, each chemical atom being a little universe comprising many planets and suns. We knew that some of these atomic constituents were particles of negative electricity and we could count the number in any atom. In addition to these very small negative particles there was an equivalent amount of positive electricity. Moreover, by methods which the electrical properties of gases put at our service we could determine the magnitude of the systems inside the atom with an accuracy approaching that with which we could measure the size of ordinary bodies.

The study of the discharge of electricity through gases would, the speaker, proceeded, enable us to investigate problems of the greatest interest to the chemist. We wanted to know whether all the atoms of what chemistry recognized as elements were of the same kind. The evidence was that two atoms might show the same chemical properties and yet not be identical. One might, in fact, be more massive than the other. Since, however, the chemical properties were identical, it was impossible to separate the two by any chemical process. Hence in ordinary determinations of atomic weights we were not able to say whether we were dealing with anything but a mixture of two kinds of atom, although the weight of the one might not be the same as that of the other. The numbers given for the atomic weights might thus be vitiated by the fact that though similar in chemical properties the two were not identical as to mass. A sort of mean of the two atomic weights would thus be obtained.

An important question, raised long ago by Prout, was whether all the atomic weights were multiples of that of hydrogen. In the course of these lectures reason would be shown for believing that Prout was not very far wrong, after all, if we gave a wider interpretation to what he meant by the hydrogen atom. It was of course impossible to maintain this if the experiments on atomic weights were interpreted in the most straightforward way. The values found were certainly not integral multiples of the atomic weight of hydrogen. If, however, two atoms, chemically indistinguishable, had atomic weights of two and three respectively, a mixture of them might give an apparent atomic weight of anything whatever between the numbers two and three. Yet, nevertheless, the mixture would consist of units each an integral multiple of the mass of the hydrogen atom. It seemed possible, though in these strenuous times opportunity for proof had been lacking, that by a study of the electrical properties of gases new light might be thrown on this question of atomic weights.

In the foregoing he had, he hoped, said enough to justify the importance of his subject, and he would now show a few experiments. The first was perhaps hardly an experiment at all, but merely a matter of common observation, viz., the extreme difficulty of getting a gas to have anything to do with electricity so long as the gas was in its ordinary condition. To this end he would use the electroscope represented in Fig. 1. The essential parts were the plate H and the gold leaf G set edgewise to it and connected to the top plate D. If a charge was

given to H the gold leaf was attracted and touched H, and then was immediately repelled. So long as it held the charge acquired at the contact it stayed repelled, but if there was leakage from the top plate D it would on losing its charge be attracted again up to H and acquire a fresh charge. Hence with a steady leak the gold leaf would be set into a state of oscillation, alternately being attracted up to H and then repelled. The rate of oscillation was a measure of the rate of leakage.

So long as the top plate was surrounded by ordinary air there was, the lecturer proceeded, no appreciable loss of charge, and the gold leaf remained away from the plate. Many, Sir Joseph proceeded, might ask why should any leakage be expected in such conditions. From the point of view of the nature of a gas its absence was, however, very remarkable. A gas consisted of a number of small particles, which were

continually hitting the charged surface of the plate D and going off again. If they carried electricity with them they would act as so many little proof planes, yet in spite of the fact that the plate was struck by the molecules of the air millions and millions of times per second there was no appreciable loss of electricity. Were these molecules able to take up a charge in the same way as a proof plane of the same size, the top plate would lose every vestige of its charge in $\frac{1}{300,000,000}$ of a second. Hence the retention of the charge was really much more wonderful than actual observation would induce us to believe.

The lecturer next showed that there was still no loss of charge when the plate was heated and ether poured over it. The ether evaporated off but left the charge behind it. The vapor, in fact, seemed, he said, incapable of receiving a charge, or at any rate resolutely refused to do so in the conditions of the experiment. This experiment had, Sir Joseph continued, been carried to a much greater pitch of accuracy. In some experiments the ether had been replaced by mercury, and the mercury evaporated off. The vapor still remained uncharged, although it was the vapor of a metal and came from a charged metallic surface.

This experiment showed one aspect of the behavior of gases to electricity. If, however, a gas were subjected to suitable treatment, then it was quite ready to take up a charge and to conduct electricity. There were various ways of achieving this end. It was, for example, sufficient to expose the gas to the radiation from a radioactive body. The lecturer showed this by directing on to the plate D of the electroscope a blast from a metal pipe at the entrance to which a little radium had been placed. A rapid leakage of electricity was thereby established, as shown by the vibrations of the gold leaf.

This proved, he said, that not only was it possible by proper treatment to put a gas into a condition in which it conducted electricity, but that it retained this condition for at least the time taken for it to pass down the tube. He next varied the experiment by connecting the outer wall of the tube to one pole of a battery, and a wire strung along the axis of the tube to the other pole. In this case he showed that the conducting power conferred by the action of the radium had been almost entirely lost before the blast reached the discharge end of the tube.

From this experiment it followed, he said, that the conductivity of the gas was due to something mixed with it which was charged with electricity, as only charged bodies would be moved by the electric force between the central wire and the wall of the tube. In fact the process of making a gas into a conductor consisted in ejecting negative particles from its molecules. This could be done, as shown, by exposing the gas to the action of radioactive bodies. The Rontgen rays were also effective, as was also exposure to certain kinds of light. The peculiarity of the light effect lay in the fact that for success the wave-length must be less than a certain definite value which depended on the nature of the gas experimented with. Only light belonging to the extreme ultra-violet section of the spectrum was effective, and there was a sharp line of demarcation between the effective and ineffective portions of the spectrum. Red light, even if concentrated by lenses till it was able to set things on fire, had no effect, whilst success was easily attained with ultra-violet light of quite feeble intensity.

Radiation of still smaller wave-length was, the lecturer said, also effective. This was shown by the apparatus represented in Fig. 2. On the right of this is shown a horizontal tube containing one plate connected to earth and an opposing plate coupled up to a charged electroscope. Any current between these plates will cause the gold leaf of the electroscope to oscillate. The end of this horizontal tube where it enters the vertical tube is covered gastight by a film of celluloid, so thin that it shows the colors of the soap bubble. The vertical tube is a special form of cathode ray tube, and on establishing a discharge between the upper and lower electrodes the lecturer showed that there was a current between the two plates in the right-hand horizontal tube, as was indicated by the motion of the gold leaf of the electroscope. The cathode discharge, he said, gave rise to radiations which passed through the celluloid window and rendered conductive the gas beyond it.

He had already, Sir Joseph continued, shown that ordinary air was an extremely good insulator. When, however, the test was made with the greatest delicacy and care, it was found that air did not definitely refuse to conduct, but would convey a little electricity. This remnant of conductivity was far too small to be shown in a lecture experiment, but had nevertheless given rise to an immense amount of work in every country and under every conceivable condition. The problem was to find what this residual conductivity was due to. The most natural view was to attribute it to the radium in the earth scattered through the rocks and soils.

The conductivity of a gas, he went on, arose from the ejection of negative particles from the molecules. This residual conductivity of ordinary air showed that about eight molecules were thus affected per cubic centimeter per second. Since one cubic centimeter contained 2.75×10^{19} molecules, and only eight became conductors per second, it followed that if any particular molecule "wanted" to be split up, it might have to wait ten-million-million years before its time came. It was this extremely small effect which had given so much trouble, and occasioned such heart-burnings and discussions in scientific societies throughout the world. As stated, it might be due to the radium in the soil, and accordingly tests had been made with vessels in ordinary rooms, or sunk ten to twelve feet below the surface of a pond; in the middle of the Atlantic, and over the ice covering frozen lakes. In all cases this residual conductivity remained. The idea arose that it might be intrinsic to the air itself—that some of the molecules split up spontaneously like those of radio-active bodies. Just before the war, however, McLellan, of Toronto, taking advantage of the climatic conditions, replaced the zinc vessel commonly used in the experiments with one constructed of ice, and found that the value of the conductivity was reduced to one-quarter of what it was when zinc vessels were used. It was now thought, therefore, that the effect was due to some trace of radio-activity in the zinc, either on the part of the metal itself, or of some impurity in it. The question had, the lecturer said, given more trouble

than some of the most celebrated problems in the history of physics.

The nature of the conductivity of gases was at one time much misunderstood. With any ordinary conductor, if the length were increased the resultant current was enfeebled. This result was so familiar as to seem a truism. With gases, however, just the opposite happened. The thinner the layer of gas across which conduction occurred the less the current, and in fact the conductivity was only appreciable when the thickness of the layer was substantial. This peculiarity was at the outset misunderstood. It arose from the fact that when a gas was rendered conductive by, say radium, every ion generated was made use of. By doubling the thickness twice as many were produced, and the greater the number of these particles the greater the rate of leakage, provided always that the force between the plates was sufficient to make all come up to the plates in the time available.

II

In the opening remarks at his second lecture, Sir Joseph Thomson observed that in his last lecture he had given reasons for concluding that when a gas conducted electricity, this electricity was carried by charged particles. In this respect the phenomenon resembled that of electrolysis, as to which the ordinary view was the current was conveyed by positively charged particles, such as hydrogen atoms, moving in one direction through the liquid, and by negatively charged particles going the opposite way; the mechanism at work, therefore, was very analogous to that which, we were led to believe, was responsible for the passage of a current through a gas. The phenomena in the latter case was, however, characterized by some strange features not normally exhibited in electrolysis. In the first place, an increase in the thickness of the slab of gas through which the current passed gave an increase of current, whilst with electrolytes such an increase of thickness enfeebled the current, and in this respect the behavior of a gas was at variance with the known behavior of electrolytes. Moreover, with the latter the effect of doubling the potential difference responsible for the flow was to double the current. With a gas, on the other hand, up to a certain stage there might be very great differences in the voltage drop without materially affecting the strength of the current, which, after a certain potential difference was reached, became practically constant. The reason for this peculiarity of gases lay in the fact that the number of carriers available for conveying the electricity from one electrode to the other was small, whilst in a liquid electrolyte the number was practically unlimited. In the gas not more than one molecule in a million-millions was ionized, whilst in the case of a liquid electrolyte the number of ions was an appreciable fraction of the whole number of molecules present.

As an analogy he might observe that in the transport of troops it was useless marching up men to a railway station in greater numbers than the trains available for taking them away could carry. The rate of transport to the other end would be limited by the train service available, and until this limit was reached the number carried over the rails would be governed by the rate at which the troops reached the station. When this rate equalled that for which carriage could be provided, no further crowding up the station would increase the number transmitted to the farther end of the line. In the case of a gas conducting electricity a point was soon reached at which the whole of the carriers available were used up, thus fixing a limit to the strength of the current, while in normal electrolysis there was practically an unlimited supply of carriers, and the current accordingly increased proportionately to the potential difference. Some liquids were, however, very bad conductors, and with these a stage was reached, just as with gases, in which an alteration in the potential difference had no effect on the current, so few carriers being available that a comparatively small current used them all up.

He had dwelt on this point, Sir Joseph continued, because this difference in the behavior of a conducting gas and a normal electrolyte had long been urged as a difficulty in accepting the idea that the current was carried through a gas by means of charged particles. It would be seen, however, that the explanation was perfectly simple, the special features of the flow being a mere matter of the number of carriers available.

In general, whether a gas were rendered conductive by the action of radium, by Röntgen rays, or other agents, the conductivity was very small. By applying to such a gas a suitable electric field it was, however, possible to make each charged particle "breed"—becoming thus the ancestor of a very numerous family. Under such conditions we might, in fact, get from the original particle a million of descendants. Suppose, for example, that we had two parallel plates, the one charged positively and the other negatively, with a conducting gas between. Each negative particle in the 'tween space would be

pushed along from the negative plate towards the positive one, and its speed would depend on the force applied. So long as it moved slowly it passed through the gas without splitting up the molecules encountered. If, however, it moved above a certain pace, or rather, with more than a certain amount of energy, it would, on encountering a molecule, split it up into a negative particle and a positive one. The negative particle thus freed would also be pushed along like its progenitor, and when, under the action of the field, it acquired a sufficient speed, it would in its turn ionize another molecule. Each negative particle thus set free became accordingly the parent of two charged particles, and hence, before the original particle had moved very far, the total number of charged particles present would be increased to a very large extent.

Hence, when the potential between the two parallel plates was steadily increased, starting from a low value, a stage was at length reached at which the current increased with very great rapidity. The change came in quite sharply, and the gas suddenly became quite a good conductor, comparable with the best solution of sulphuric acid in water. This the lecturer demonstrated by showing that the energy absorbed by an exhausted bulb (containing a little residual gas) placed within a coil which was traversed by a very rapidly alternating current was as great as if the bulb had contained a mixture of sulphuric acid and water.

In experiments of this kind, the lecturer proceeded, although the gas showed very considerable conductivity, there was no indication of any approach to an unstable state. Nothing, in fact, comparable to what happened on the discharge of a Leyden jar. The discharge through the gas was quite orderly, and not comparable in intensity with the discharge of a jar, or of a lightning flash. The difference was due to the fact that in the orderly discharge in the bulb the negative particles alone acquired sufficient energy to ionize the molecules of the gas passed through. The current, it was true, increased rapidly, but this increase was finite, depending on the distance between the plates and the number of negative particles produced by the original ionizing agent. Matters became different if, in addition to the negative particles producing fresh ions, the positive particles also began to ionize the gas.

So long as the negative particles were alone able to split up molecules, the whole of the negative particles, parent and progeny, were chased along to the positive plate, where the whole were finally got rid of. If, however, the positive particles also began to ionize the gas, these, as they moved towards the negative plate, liberated fresh negative particles behind the original ones, and everything began over again, with the difference that the supply of negative particles available for ionization was greater than that at the start, and would continue to increase indefinitely. An enormous current could thus be built up, starting at the outset with but one or two charged particles. Two stages could, then, be recognized—one in which the negative particles alone acted as ionizers, and a second stage in which the positive particles also acquired sufficient energy to act.

A similar condition might also, the lecturer said, be produced in other ways. What was necessary was that fresh negative ions should be liberated near the negative plate. The Röntgen rays produced by the striking of the negative particles against the anti-cathode could therefore serve, generating fresh ions near the negative plate and producing an instability in which the current mounted up to an enormous value.

The most conspicuous example, and the most important, of this kind of discharge was afforded by the lightning flash. Although lightning was the oldest electrical phenomenon known, there was, until very recently not much precise information about it. Indeed, it was only within the past four or five years that we had any reliable measure of the amount of electricity which passed in a flash or any reliable estimate of the length of the flash. Nothing was known, moreover, as to whether the discharge carried to the earth a positive or a negative charge. There had, however, been a great number of general observations on lightning and its associated phenomena. A great number of these reports were difficult to believe, but amongst these the lecturer did not, he said, include statements as to balls of fire running about the ground and finally exploding with a sulfurous smell.

The researches of Mr. C. E. T. Wilson at Cambridge had, he proceeded, given us some definite measurements as to the order of the quantities with which we had to do in a lightning discharge. Fortunately, or unfortunately, England was not a very good place for the study of lightning. Mexico, where thunderstorms occurred daily, would be better. In England they were sporadic, and it commonly happened that when the storm occurred the would-be observer had not got his instruments ready.

Mr. Wilson had, however, made a systematic study of the matter. His plan of procedure consisted in installing recording instruments at two stations some considerable distance apart. The charged thunder-cloud produced at places in its neighborhood an electric force, the intensity of which was recorded by the instruments at the two stations. If the cloud discharged, the part of the force due to this loss of electricity disappeared and the instruments recorded a kink, the magnitude of which differed at the two stations. Its size depended upon only two variables, viz., the quantity of electricity discharged and the distance of the cloud from the station. Hence the two simultaneous observations served to determine both the quantity of electricity passed and the height of the cloud, that was to say, the length of the flash. In this way Wilson found that the length of an ordinary flash was 10 km., or about six miles, whilst the quantity of electricity passed was about 30 coulombs. He further found that even at his stations, which were not immediately under the flash, the increase of potential was at the rate of 2,000 volts per meter of vertical height, and it was no doubt much greater immediately in the line of the discharge. Taking this value as a minimum, the actual value of the potential difference between the cloud and the earth at the moment the spark passed was therefore 20,000,000 volts. Hence, as the electricity passed was 30 coulombs, the energy expended was 6×10^{16} ergs, or about 600,000 ton-meters. It was not surprising, therefore, that lightning flashes were so destructive; it was, in fact, rather remarkable that they did so little damage. Fortunately the greater part of their energy was not spent in destructive purposes.

Thunder was due to an impulsive wave produced all along the track of a flash. This was apparent with even a comparatively short spark, as he demonstrated with an apparatus consisting of a bulb containing air and provided with a water-gage of fine bore. On discharging a spark through the bulb a wave of high pressure was produced, which was indicated by the motion of the water in the gage. Lightning, he stated, produced the same effect, but on an infinitely greater scale.

[TO BE CONTINUED]

Physico-chemical Considerations on Benzol Recovery from Coal-Gas

THE author deals with the effect of viscosity, temperature, and composition on the efficiency of creosote as a washing medium for extracting benzol from coal gas. In the case of washable products of coal gas dissolved in creosote, each dissolved body exerts a fraction of its own maximum vapor pressure equivalent to the percentage in which it occurs in the creosote. From a series of vapor pressure curves given, the percentage of these constituents which the gas could carry if saturated may be ascertained. From further data the author deduces the fact that creosote can remove the toluene from 3.55 times the quantity of gas which saturates it with respect to benzene, and solvent naphtha from 10.7 times the same amount. The effect of temperature on the rate of solution, using 100 and 50 gallons of creosote per ton of coal respectively, is shown in a series of curves. A suitable wash oil for benzol extraction should not give off any large proportion of light oils when steam distilled, must take up heat quickly and cool quickly, must flow or spray readily at the washing temperature, must not emulsify with water, and must not give up naphthalene to the gas. The influence on viscosity of various factors, is indicated by curves, showing effect of temperature naphthalene content, distillation tests, etc., and the author sums up his observations in the following conclusions: (1) Efficiency of washing is improved by using a cold oil. (2) The lighter oils in creosote help the washing process by lessening the viscosity, but are readily distilled out by steam and contaminate the benzol. (3) Naphthalene tends to lower the viscosity but under certain conditions may pass into the gas. (4) Creosote fractions boiling above 300° C. greatly increase the viscosity. (5) A good creosote should be as fluid as possible at 10° to 15° C., give little oil distillate when steam distilled, and contain a minimum amount of naphthalene. (6) Much improved cooling is obtained by using a creosote of which the viscosity rises very little when cooled to 10° to 15° C., and the benzolized oil is more readily heated. (7) Efficiency of washing is improved by increasing the intimacy of contact between oil and gas. Washers on the spraying or atomizing principle appear to offer the best field for development in this direction. (8) Specific gravity is no criterion as to whether a mixture of blast-furnace and coal-tar creosote is "spent" or not, viscosity being the best test. (9) Sufficient creosote should be in circulation to prevent the removal of light oils leaving a creosote of high viscosity. —*Note from the Jour. Soc. Chem. Ind. in a paper by T. F. E. Rhead in Gas. J.*