The Structure of the Atom—III*

The Physical and Chemical Properties of the Atom Explained in the Light of Modern Theory and Experiment

By Sir J. J. Thomson, F.R.S.

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WE will continue with the consideration of the first fundamental problem involved in the atomic theory, namely the determination of the number of atoms in a given weight or volume of a body. At the end of my last lecture I described one method of solving this problem which physicists owe to Prof. Perrin, and it may be useful if I recall the fundamental principles on which this method is based. The most important theorem in the kinetic theory of gases is that the ratio of the pressure of a gas to the number of molecules in a given volume is the same for all gases. It is thus the same for hydrogen, a light gas, as for the vapor of mercury, which is the heaviest known. Were it possible to determine this ratio, then from the expression $p = \alpha N$, the value of N could be found for any gas, since α is independent of the nature of the gas. In the above, p denotes the pressure of gas, N the number of molecules in the unit volume, and α the constant in question. If Nature had provided us with a suitable gas in which we could both measure the pressure and count N , we should find α , and could then find N for any other gas in virtue of the relation that, at atmospheric pressure, p is equal to 1,000,000 dynes per square centimeter. Unfortunately, Nature has not provided us with a gas having molecules, on such a scale, that N can be determined by directly counting them. Perrin remedied this omission of Nature by producing artificial gases in which the "molecules" are 100,000,000 times as heavy as the molecules of air. With these artificial gases it is feasible to count the molecules in a given volume, and it is further possible to determine the pressure by the method described in my last lecture. Having found p and N , the problem is solved, provided that the kinetic theory can be trusted over so great a range as that between the molecules of hydrogen and a "molecule" 100,000,000 times as heavy as the molecules of air. The only thing that remained, then, was to make sure that this was the case. If the kinetic theory could be trusted for this range, α should come out the same, whatever the particles used by Perrin, whether they were of gamboge or of mastic, and this was found to be the case. Perrin also varied the liquids in which his particles were suspended, and again got the same value of α . He thus felt justified in concluding that his emulsions acted as gases, "within the meaning of the Act," and that his value of α , thus found, would "fit in" with any other gas. The difference of scale between his artificial gas and ordinary gases may be illustrated by the fact that it was necessary to go up as high as the top of the Matterhorn before the atmospheric pressure is reduced to one half its value at sea-level. In Perrin's artificial gases a rise of 1/20 millimeter (1/500 of an inch) was sufficient to halve the pressure.

From Perrin's results it appears that N , the number of particles in 2 grammes of hydrogen, or in 32 grammes of oxygen, or, in short, in a "gramme molecule" of any gas, is

$$N = 6.83 \times 10^{23}.$$

It is impossible to convey any idea of the vastness of this number, but a million $\times$ a million $\times$ a million $\times$ a million is equal to 10^{24} .

Perrin's method is the most direct one yet devised for determining this fundamentally important constant; but, historically speaking, it is not the first in the field. The earlier method depends on finding the charge-carried by the ions of an ionized gas. There is a very simple relation, which I shall give in a later lecture, between this charge and the value of N . As for the methods used to determine the charge carried by each electrified molecule, I shall only be able to set forth the general principles on which the method is based, and can not go into details as to the precautions necessary to get satisfactory results.

Suppose, then, that a pair of parallel plates are arranged in a closed vessel, the gas in which is ionized by Röntgen rays or otherwise. Then by establishing a strong electric field between these plates the positive ions are caused to go to one plate and the negative to the other, and the total charge carried can be measured without difficulty. This, however, is not what was wanted, which is the charge carried by each particle. To determine this charge it is necessary to count N , the number of electrified particles, and this constitutes a much more difficult problem. The method used depends on the fact that if damp air containing electrified par-

ticles is suddenly cooled, each particle becomes the nucleus of a drop of water, the mixture of moisture and electrified particles settling down as a fog.

To illustrate this fact, Prof. Thomson threw on a screen the shadow of a jet of steam issuing from a nozzle into the air. The nozzle was coupled up to a Wimshurst machine, and he showed that whenever the latter was operated the shadow of the jet became very much blacker than it was when the nozzle was unelectrified, the increase of blackness being due to a further deposition of water from the vapor.

Prof. Thomson next showed that if a red-hot iron ball were brought near the jet, there was again a blackening of the shadow. In this case he pointed out that the high temperature of the ball would of itself tend to diminish the condensation and render the shadow fainter; this tendency was, however, overborne by the fact that such a red-hot ball emitted negatively-electrified particles which served as nuclei on which condensation took place. He also showed that a slight darkening of the shadow was produced by letting the fumes of nitric acid enter the jet.]

Reverting to the method used for counting the ions which carry the charges between the parallel plates mentioned above, as stated, this mixture of positive and negative ions could be converted into a cloud by having the air in which they are suspended saturated with water vapor. If such air is cooled suddenly, it can no longer carry the same amount of moisture in suspension; and if one knows to what temperature it was cooled, the weight of water deposited can be determined. It is well known, for instance, how much moisture air can carry when at a temperature of 15 deg Cent., and also what weight will saturate it at a temperature of 2 deg Cent. or 3 deg Cent. If these were the initial and final temperatures of the air in the experiment, the difference represents the weight deposited on the particles to form

Fig. 1.—Increase of Conductivity with Field Intensity.

a cloud. The most convenient way of cooling the air through a definite range of temperature is to expand it suddenly. This method is in principle the same as that by which air is liquefied in commercial work, by expanding it down from a very high pressure. Conversely, a sudden compression of the air will heat it. Although this effect is somewhat abstruse, it is one of the most remarkable facts about savage races that two distinct and independent tribes have discovered and perfected a method of getting fire by the sudden compression of air. The experiment is by no means easy to execute in a laboratory, and it is very difficult to conjecture the process by which these savages have been able to discover the method.

The cooling consequent on a given range of expansion is easily calculated, and from this the weight of water forming the cloud. If the size of each droplet in the cloud were known, the number present was readily obtained. The size of the droplets can be deduced by measuring the rate at which they sink down through the air. As the number of electrified particles is equal to the number of droplets, and the total amount of electricity carried is known, the amount carried by each is finally ascertained.

Knowing the charge carried by each electrified particle, it is possible to deduce the number of molecules present in a gramme-molecule of a gas. The value of N thus found comes out as 6.8×10^{23} , which is practically identical with that found by Perrin, though no two methods could be less alike.

A third method of finding N has become possible since the discovery of the radioactive particles. It depends on the fact that these groups of radioactive elements give off the so-called α particles which carry a positive charge.

If these particles are directed into a metallic vessel, they give up to this vessel their charge, and the total charge can thus be easily ascertained. If the number of particles can be counted, the charge on each can be found, and from this, as before, the value of N determined. The number in question has been counted in

two different ways. In the first, advantage is taken of the fact that when an α particle strikes against a suitable screen a phosphorescent spot was produced, as evidenced by the spinthariscopes. In this instrument a very great number of such particles are given off, and the whole screen is covered with twinkling stars of light. By cutting down the amount of radium used, however, the number of impacts can be reduced to two or three a minute, and these, of course, can be counted. This enumeration had been made by Dr. Geiger, who thus determined the number of α particles given off per hour by a known weight of radium.

Hence, by measuring the total charge emitted in the same time, the charge carried by each particle can be determined. The task of counting the spots is by no means an easy one, involving the fatiguing work of sitting for hours in a darkened room and recording each faint appearance on the screen. Even the most careful observer might be expected to nod occasionally, and it was therefore important to get some other way of counting these particles which did not involve the personal factor. This has been effected by Rutherford in a very ingenious manner. He arranged matters so that the α particles were discharged into a space between two parallel plates, which were connected to opposite poles of a battery. When an α particle rushed into the gas between these plates, it split up the molecules encountered into positively and negatively ions, thus for the moment rendering the space, between the plates, a conductor, and an instantaneous current resulted. Were this current big enough to be registered by a recording galvanometer, the discharge of each α particle would be registered by a kink in the trace. Though each α particle produced some 94,000 ions before its ionizing power was exhausted, this was not quite enough to operate a galvanometer, being just on the verge of what was measurable.

Rutherford therefore multiplied the effect of each α particles by making each ion itself the parent of an enormous number of other ions. This he did by establishing an enormous electric field between the two plates. This field gave the ions such a velocity that they were themselves capable of producing further ions. In this way Rutherford magnified the effect of each α particle, so that it could be automatically registered by a recording galvanometer. The increase of conductivity consequent on an increase of the electric field is well shown by Fig. 1, where it will be seen that the current shot up very rapidly when a certain intensity was exceeded. In this way Rutherford obtained the following value:

$$N = 6.2 \times 10^{23}.$$

A modification has been made by Dewar, who determined how much helium was produced in a certain time by a stated weight of radium. Since helium is nothing but the converted α particles, the amount of helium is equal to the quantity of α particles, and in this way Dewar got $N = 6.4 \times 10^{23}$, and the same figure is given by a method based on the theory of radiation.

All the values found are, it will be seen, in good agreement, and we have thus much confidence that we do know with considerable accuracy "Avogadro's constant," which is the number of particles in a gramme molecule of a gas. The number of molecules in a cubic centimeter of a gas at atmospheric pressure and at 0 deg. Cent. is 2.35×10^{19} .

By the above methods a complete census has been obtained of the number of "systems" present in a given weight of a gas, and I shall now pass on to discuss a more difficult problem—viz., to find the population of the individual atom. I have shown that from each atom negative particles can be obtained, and it is important to know how many of these corpuscles there are present in each case. Such a census constitutes, however, a much more difficult problem than that of counting the molecules. At a previous lecture I have shown that in the case of mercury it was possible to remove as many as eight of these corpuscles from the atom, and in this case, therefore, the total number present must be considerable. Two methods have been employed to find the corpuscular population of the atom. One of these is dependent upon a certain property of the Röntgen rays. If a cathode particle is suddenly started or stopped, it gives rise to Röntgen rays. We know that these rays are a form of electric wave quite analogous in its nature to light. If such rays are allowed to fall on a corpuscle, they set it in motion, and this corpuscle itself then produces Röntgen rays on its own account. The rays thus

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given off by a mass of gas could be measured, and it is known that they are practically entirely produced by the negative particles, since the positive electricity in the atom is so heavy and big that it is not moved enough by the incident rays to generate fresh rays on its own account. The secondary radiation comes, therefore, wholly from the negative particles.

A connection has been found between the intensity of this secondary radiation and the number of negative particles present. Barkla has measured this intensity, and thus deduced the result that the number of negative particles in a molecule of a gas is proportional to the atomic weight. It is thus sixteen times as high in oxygen as in hydrogen, and 200 times as much in mercury as in the gas last named. The ratio between the number of particles present and the atomic weight is not a large one, the number of corpuscles present in the atom being between two and three times the atomic weight.

An objection to the above method of making the estimate is that if any of the negative particles were held in the core of the atom by very strong forces, the incident radiation would be unable to set them in motion, and these particles would, therefore, not be counted, which would result in too low an estimate of the corpuscles present. Another method has therefore been tried in which the importance of such firmly-held corpuscles is exaggerated. A negative particle, if shot

through an atom, would be deflected by each corpuscle it came near. This deflection would sometimes be to one side and sometimes to another, but the sum of these deflections would not generally balance, just as, if a coin were tossed up 1,000 times, the total number of heads and the total number of tails would practically never be exactly equal. Hence a cathode particle passing through a collection of negative particles would not, on its final exit, be found to be moving in exactly the same direction as it had originally. A fine pencil of such rays would thus be rendered fuzzy by such a passage and come out as a sort of brush in place of a parallel pencil. By measuring the spread of the brush, it is possible to calculate the number of particles which have acted. This method, as stated, will exaggerate the importance of firmly-held particles, since these will not "give," as the cathode particle rushes past them, and a weak point in the Röntgen ray method, of arriving at the number of particles present, is thus made good. Estimated in this way, the result is again that the number of particles present in the atom is between two and three times the atomic weight, and this is about as far as it was now possible to go.

Even so limited a population as this, however, gives rise to some intricate problems. In mercury there must be at least 200 particles present, all repelling each other, so that the problem to be faced lies in discovering in what

conditions they would be in equilibrium. Hints for its solution may be obtained by experiment, and these experiments have an important bearing upon the significance of what chemists termed "valency." In these experiments he uses little magnets to represent the negative particle. These consist of needles, each run through a fragment of cork so that it will float. By arranging that poles of the same kind are in all cases at the top, these magnets will repel each other if a number are placed in a basin of water; but by arranging over the center of the water a powerful pole of suitable sign the floating magnets will be attracted in, and arrange themselves in states of equilibrium.

Thus three floating magnets will arrange themselves at the corners of a square, and five at the corners of a pentagon. On adding a sixth, however, the set does not form a hexagon, but a pentagon with a single magnet at the center. With this magnet in the center, the addition of another magnet will lead to the formation of a hexagon with a central magnet, and a ring of seven is also stable, with one magnet at the center. The addition of still another cause, however, a second magnet to pass to the center. The sudden changes in the grouping which occur at certain critical numbers, when additional magnets are added, throw a good deal of light on the question of valency, and with this I shall deal later.

(To be continued)

Some Indirect Causes of Imperfect Interchangeability*

The Fit of Machined Parts Often Disappointing

By A. Whitehead

MUCH attention has been given to the establishment of systems of tolerances or limits of error in machined work during recent years, with a view to obtaining interchangeability and to reduce the amount of hand-work. The utility of such systems for this purpose is obvious, and many have been invented and employed with more or less success. But when it is considered how accurate the product of our modern machine-shop appears to be when tested in the usual way by limit-gages appropriate to the particular tolerance system in use, the amount of subsequent adjustment frequently found necessary in the fitting or erecting-shops must seem extraordinary. Ingenious and expensive appliances are made in order that interchangeable work may result, yet the outcome may be disappointing in that respect. Clearances cannot be exaggerated in high-class work; moreover, the interchangeability, to be perfect, should be of that degree when parts will not only assemble, but will run well together without any alteration or selection. This condition is attainable, for it has been reached in certain branches of manufacture, branches somewhat removed, however, from ordinary engineering practice by reason of the size and quantity of the evolved product, which enable special manufacturing means to be adopted. Such means must have been wisely chosen and consistently employed to be successful.

There is rarely need for intricate or elaborate methods, although these are sometimes justified. An exact knowledge of the function of the piece to be made, governed by common-sense, will often enable the very best quality work to be produced—though not very expeditiously, maybe—with the aid of special tools, few in number and simple in character. At the same time parts may be made with the aid of a most elaborately equipped plant which, although they pass inspection readily, do not deserve to do so, and could not under a better system. The more searching tests of assembling or running will reveal faults: rotating pieces will not run true, or parts will fail to align or to match, until some adjustment is made. The causes are always to be found on investigation, but, unfortunately, an inquiry is rare, because the magnitude of the defect in any particular case is seldom large enough to force one. Besides, it appears absurd to suspect any defect in machinery which is known to be correct within a very minute fraction of an inch; it is easier to attribute it to some unknown evil influence. With the exception of certain aspects, such as cost accounting, card systems, and the like, the science of manufacturing has received an unjustifiably scant attention from educated engineers. A few weekly papers are devoted to the subject, it is true, but on the whole the treatment is far from what it ought to be. There is a real need for men who can arrange and direct manufacturing processes in just the same manner that design is controlled by the drawing office; that is, minutely to the smallest detail, yet with breadth of judgment and certainty. But such men as have acquired that almost instinctive perception of difficulties and troubles likely to attend cer-

tain procedure which comes from long shop experience, rarely have had the advantage of undergoing the discipline of a good education and training in physical science. They have instinct with little understanding or powers of expression. On the other hand, the man of limited shop experience, and therefore superficial knowledge of processes, is frequently superabundantly blessed with powers of expression. His efforts to direct will result in delay, expense, and ill-feeling, until in time his knowledge increases, or, crushed at last, he meekly yields entirely to the shop foreman. The right man will rapidly become guide and counsellor to foremen and draughtsmen too. His rule over shop processes will be absolute, but not despotic. What follows illustrates the kind of trouble he will constantly have to meet and overcome, anticipating when possible all manufacturing needs.

Everybody knows that turned work is never symmetrically disposed with respect to one axis unless it is completely machined at one setting or finished all over on centers; but a very close approximation to perfect symmetry can be arrived at by taking special precautions. The operation of turning is not presented as the only faulty one, but as a very fair example. The turner, be he foreman or journeyman, is mainly interested in the maximum quantity of work he can get satisfactorily through the view room. Naturally, therefore, he tends to study his own convenience and to sacrifice aught that tells against rapid production. Experience and tradition will be his guides when engaged on parts, the purpose of which he fully understands (or the inspector fully understands), and lead him to preserve to the best of his ability true relationship between essential features, and to sacrifice, if necessary, those less important. But what is there to indicate a right selection on new and strange pieces whose exact purpose it may be troublesome for him to discover, or possibly beyond his comprehension?

It would be absurd to insist on perfectly true relationship between every part of every piece, because the expense would increase out of proportion to the improvement. But experience proves that it pays to be over-exacting, if anything, even if it involve operations which, on the surface, appear less economical than an alternative series. Left to themselves the shop foremen will generally contrive at last to arrange processes so that a satisfactory result ensues. But at what a cost. And when a critical examination is made of the means they have adopted, it will be found too frequently that they have forsaken economical methods needlessly.

It might be a gain if draughtsmen would recognize the difficulty, and would assist to overcome it by stating which features they required to be perfectly in right relationship, and if they assigned limits to permissible departures from perfection. For example, suppose some small wheels were being turned from bar stock for a purpose which allowed the periphery to be somewhat eccentric with the bore with no evil result. The drawing might stipulate that the eccentricity should never exceed 0.002 inch, say. Unless the inspec-

tor were informed by some means of this tolerance, he might reject perfectly satisfactory wheels; on the other hand, he might never dream of testing the relationship, assuming it needless to do so.

Although completed at one setting, many pieces made from the bar are by no means free from irregularities such as that instanced, due very often to an improper choice or application of tools. It is better to recognize the fact and legalize it than to ignore it and lose control. Should it happen that much scrap resulted from the adoption of a tolerance, the right policy would not be recourse to an extra "truing up" operation on another machine, but to careful revision of the tools on the turret lathe. This effect on the methods of machining by the addition of a tolerance in this simple case is worthy of note.

There might be objections to a universal application of this extension to tolerance systems; it might prove complex and unwieldy. But, generally, a short note on a drawing could be made to convey vital information of this character. Unhappily, few draughtsmen could be depended upon to know when it was desirable or what was the most convenient form in which to present it.

Whereas a few years ago a piece would have been completely machined, perhaps, in two operations on an engine lathe, the same piece might now have two or more operations on a semi-automatic turret lathe, another or two on a screw-miller, and be finally ground. Anything from ten to twenty distinct operations may often be found necessary to obtain economical production. On the other hand may be seen splendid manufacturing machines used in a way best described as "poking," and justified by the phrase "Our work is so very fine." There are extremely few cases, however, in which speed and essential accuracy of production cannot be combined, providing the determining factors of each process are designed by one mind—a critical mind cognizant of the fallacy of the popular belief that a system of jigs merely accurate in construction is bound to produce accurate work.

Science in Postage Stamps

POSTAGE stamps do not often afford material for scientific discussion, but an interesting point is mentioned by Mr. Sam S. Buckley in his book on the marginal varieties of the Edwardian stamps of Great Britain (published by Oswald Marsh, London), in connection with a change that was initiated in the autumn of 1911 in the mode of perforating the new English issues. Until then the horizontal and vertical perforations were at the same distance apart, namely 14 in 2 centimeters. It was found, however, that the stamps would not tear well along the horizontal lines, and the explanation was that in machine-made paper the fibers have a tendency to lie in certain directions, thus making the resistance to tearing unequal in different directions. A remarkable result of experiments was the conclusion that resistances could be equalized by using fifteen perforations horizontally to fourteen vertically, the extra perforation making all the difference.—*Nature*.

* Reproduced from *Engineering*.