ing vessels many years ago; and, thirdly, by the Italian Sanzo, who in 1919 gave a figure of a specimen 2·8 mm. in length from the Straits of Messina. Richardson referred his—or rather Hooker's—specimen to the trunk-fishes, and termed it *Ostracion boops*; the other authors, however, realised that they were dealing with the young of sun-fishes, but were unable to make any closer determination of the species. Judging from the new material provided by the *Dana* expedition, I can now with full certainty state that all the specimens in question are larvæ of the oblong sun-fish (Ranzania). The tiny stages of the short sun-fishes (Mola), however, do not appear to have been figured or mentioned in literature up to now.

Electrons.[1]

By SIR WILLIAM BRAGG, K.B.E., F.R.S.

IN recent years the results of experimental research on the properties of electrons have accumulated with startling rapidity. As knowledge grows, the importance of the part played by the electron in the mechanics of the world becomes even clearer. There are all the right signs that progress is being made along a road that really leads somewhere; we are continually finding that, through some electron action, phenomena are linked together between which we had hitherto seen no connection. Precision is given to our views: we find ourselves able to express, quantitatively and with confidence, laws and relations which have been matters of vague surmise. Every experiment that is finished suggests others that are promising. The whole world of experimental physics is full of new life, and of the consciousness that after a period of hesitation the tide of discovery is sweeping on again. While knowledge grows by experiment, theory is also busy. The attempts to co-ordinate the new discoveries are of singular interest because of their daring, their width, and their strength: because they are so often fruitful in prediction: and, not least perhaps, because they seem so often to be irreconcilable with each other.

It helps to a right appreciation of the position as regards the electron if we observe its strong resemblance to the older state of things when first the atomic theory of matter was clearly defined. Just as chemistry has grown and prospered on its recognition of the unit of matter, so electrical science has already begun a new life, and, to all seeming, a most vigorous one, based on the understanding of Nature's unit of electricity. There are many different atoms of matter—nearly a hundred are distinguishable by their different chemical reactions; but the number of different kinds of electrical atoms is very much more limited. We have for some years been clear as to the existence of the electron, Nature's unit of negative electricity. More recently the work of Rutherford and Aston indicates that the nucleus of the hydrogen atom is to be regarded as the positive counterpart.

If the chemist has found so much profit in his recognition of the fact that Nature has just so many ways, and no more, of doing up parcels of matter, the electrician will surely gain in the same way when he grasps the fact that not merely is electricity measurable in quantity, but that there is already a unit of Nature's choice, possibly no more than one unit. We may say with justice that already the most wonderful advances in modern physics are the reward for our appreciation of this truth, and we may hope with equal justice that we are yet far from reaping the full benefit.

The first suggestion of the atomic character of electric charge came, it is well known, from observation of the laws of electrolysis. Since the movement of atoms or atom clusters or ions across the electrolytic cell was accompanied by a simultaneous transfer of electricity, in which each ion, of whatever nature, bore always the same charge or at least a simple multiple of it, there was a clear indication that this division of electricity into parcels of constant magnitude implied the existence of some natural unit charge. No progress, however, was or could be made so long as the charge could be observed only as an attachment to an ion: it was not even clear that it could ever have a separate existence. In the long series of researches which finally led to the isolation of the electron and the determination of its properties, there were certain that marked definite stages in the forward movement. Crookes examined the electric discharge in bulbs exhausted to a high degree by the new air pumps which he had succeeded in making; and he observed the so-called cathode rays streaming away from the negative electrode. He showed that they possessed the properties to be expected from a stream of particles projected across the bulb and carrying negative electricity with them; for on one hand they could heat up bodies on which they fell, and on the other they were deflected in crossing a magnetic field. Crookes spoke of a fourth state of matter and defended his view against the opposing hypothesis, held largely on the Continent, that the stream consisted of electromagnetic waves in some form or other. Hertz showed that the rays could pass through thin sheets of matter such as aluminium leaf, and Lenard took advantage of this to coax them outside the bulb and display their effects in the air outside.

In the later years of last century came the great experiments of Wiechert, Thomson, and many other well-known observers, who weighed the electron and measured its charge, and showed that there was only the one electron, though it was

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[1] The Twelfth Kelvin Lecture delivered before the Institution of Electrical Engineers on January 13.

to be found everywhere and in every body. Since then the measurements of these quantities have been repeated many times with increasing skill and understanding. They have reached their present high-water mark perhaps in the experiment of Millikan at Chicago, who gives as the value of the charge in electromagnetic units $e = 1{\cdot}591 \times 10^{-20}$, the mass being $0{\cdot}900 \times 10^{-27}$ gram, or 1/1850 of the mass of the hydrogen atom.

So we arrive finally at an accurate comparison of these unique and fundamental units of Nature with the units which we ourselves have chosen for our convenience, and without, of course, any consideration of the former. We infer from experiments such as those of Kaufmann and of Bucherer that the energy of the moving electron may be considered to exist wholly in the form of electromagnetic energy, such as is necessarily present when an electrical charge is in motion; and that its mass is in this way perfectly accounted for. But this conclusion sets a limit to the size of the electron, and we must assume that its radius, if its form is spherical, is very small compared with the radius of any atom. Also, as the velocity of the electron approaches that of light, its mass increases; imperceptibly at first, but in the end very rapidly.

Why, we may well ask, have these measurements of charge and mass never been made before? The electron is everywhere: the transfer of electricity from place to place consists always in the transfer of electrons. The electric current is a hurrying stream of electrons: all our electrical machinery concerns itself with setting them in motion, with giving them energy and again withdrawing it. In the processes of electrolysis the electrons are handed to and fro. Everywhere they fill the stage; why have we not hitherto noticed their qualities, which so far can be expressed so simply?

The answer is that we have never, until recently, been able to make them move fast enough in spaces sufficiently empty of air or other gases. It is only when an electron has a sufficient speed that it can escape absorption in the atoms which it must be continually meeting. Unless an electron has a speed exceeding about one three-hundredth of the velocity of light—that is to say, such a speed as it acquires in falling through a potential of a few volts—it sticks to the next atom it runs up against: even with ten times that speed it can move only a fraction of a millimetre through air at ordinary pressure before it loses its velocity, and, therefore, its power of going through the atoms. When Crookes first saw the cathode-ray stream in full course, it was because he had reduced the number of gas molecules in his bulb to such an extent that an electron could fly in a straight line from end to end of the bulb without going through more than a hundred atoms or so, and the induction coil had given it quite enough speed to do that without turning out of its course, no matter what sort of atoms they were. Incidentally, since atoms can be traversed in this way, we naturally think of an atom as a very empty affair.

Electrons flying still faster than in the discharge tube are found to constitute a part of the radiation from radioactive substances. Some of the β-rays have velocities nearly equal to that of light and can pass through millions of atoms before their energy is spent. In open air a β-ray may have a course of metres in length, though it is generally broken by encounters with traversed atoms into a path full of corners and irregularities.

It is speed which gives separate existence to the moving electron: and speed which also betrays its presence to us. For, on its way, the electron here and there chips away another electron from an atom which it is crossing and leaves behind it a separation of electricities which may afterwards influence chemical action, as in the case of the phosphorescent screen or photographic plate, or provide a current for the ionisation chamber. We do not know exactly how this removal of electrons is effected, nor why some atoms part with electrons more easily than others, so that the flying electron loses less energy as it goes through: there is much that is obscure in the whole process. But it gives us a ready means of observation, without which, indeed, our knowledge of the electron would be far less than it is.

These electrons which are so made manifest by speed form but a minute fraction of the whole number existing. They are to be found in every body, and in every atom of every body. They form one of the elements of construction of the atom, and it is one of the most immediate aims of present research to find in what way they are built into atomic structure. In every atom there are certain electrons of which one can be removed at the cost of an amount of energy of the order of 10^{-11} ergs. The potential through which an electron must fall so that it acquires this energy is of the order of a few volts. There are other electrons within the atom which are intrinsically far more difficult to remove. On the other hand, some atoms—for example, those of a metal in the solid or liquid condition—have each one or more electrons which are little more than hangers-on, and are, indeed, removed with very little trouble. A block of pure metal is full of such loosely bound electrons, so that if an electric potential difference is maintained across the block an electron flow or electric current is produced. The metal "conducts."

At sufficiently high temperatures all bodies become conductors; we must imagine that the violent thermal agitation shakes electrons free from their ties to the atoms even when at low temperature the bonds ordinarily remain unbroken. At a high temperature, too, the electrons acquire high velocities as they move to and fro with their proper share of heat energy. At the surface of the hot body the electrons may break away; and hence the "thermionic emission" investigated by O. W. Richardson. So copious is this supply of electrons at the surface of a hot body that if the latter is made negative in potential relative to its surroundings there is a current discharge which may sometimes be measurable in amperes. Of course, such a current can pass only one way, negatively from the hot body, or positively towards it. So we get the basic principle of the "valve," and so Coolidge provides the electrons for projection against the target in the X-ray bulb which he has designed. At this point we find already the adaptation of our new knowledge of electrons to apparatus of extraordinarily great use to mankind.

If now we plunge a little deeper into our subject we come to certain most fascinating regions of it, where exploration is still in full progress. In one of these we find the most remarkable connection between moving electrons and electromagnetic waves. One, it seems, can always call up the other, and the action obeys certain precise numerical laws.

Let us take as an example the production of X-rays in a Coolidge bulb. A plentiful supply of electrons is provided at the cathode by heating a fine spiral of tungsten wire to a high temperature. A high potential difference between cathode and target is provided by some approximate means, and the electrons are hurled at the target, each possessing an amount of energy equal to the product of the electron charge and the applied potential. Where the electrons strike, some of their energy is converted into electromagnetic waves of very high frequency, the so-called X-rays. Suppose that we measure the energy supplied to each electron—not an easy matter with the usual arrangements, but very easily done if, as in certain experiments of Duane and Hunt at Harvard University, the potential is derived from a great storage battery of 40,000 volts. Suppose, further, that we analyse by the X-ray spectrometer the X-ray radiation that issues from the target. We find that the frequencies of the emitted rays may have a wide range of values, but that the upper limit of the frequencies is always proportional to the energy of the electron, and, therefore, to the potential imposed on the tube. This ratio remains the same no matter what the intensity of the electron discharge, and no matter what the nature of the target. This ratio of electron energy to maximum frequency is a number which has turned up in previous cases where the emission of radiation energy has been measured: it is known as Planck's constant, and denoted by "h." Its value is $6{\cdot}55 \times 10^{-27}$. Although the constant has been met with before, there is probably no instance where the transformation of energy which it governs is so simply displayed or so easily measured as in the case just described.

In certain measurements made by Duane and Hunt and illustrated in Fig. 1, the X-ray spectrometer was set to observe the presence of a certain frequency as soon as it appeared. The potential on the tube was then increased by degrees. The rays of the given frequency appeared as soon as the energy supplied to the electron was equal to the frequency multiplied by h. As the potential was increased still further these rays increased in intensity, as the figure shows.

It is to be observed that the production of X-rays is no aggregate of individual efforts by separate electrons: each electron produces its own train of X-rays when it strikes the target. There is no sign of any combined action, as, indeed, is evident from the fact that the intensity of the cathode-ray stream is without influence on the frequencies of the X-rays produced.

The crucial point is that when the energy of an electron is handed over in whole or in part, the frequency of the X-ray waves that take over the energy is determined by the quantity of energy handed over. This explains why there is a limit to the frequency of the X-rays: it is because there are some electrons, though only a fraction of the whole number, which give up all their energy to the formation of X-rays at the moment of striking, before they have lost energy in collisions. The rest of the rays, all those which have lower frequencies, will come from electrons that have lost speed in this way, or possibly have transferred only part of their energy. The atom of the target is playing the part of a transformer, and does not determine the frequency, so far as these effects are concerned.

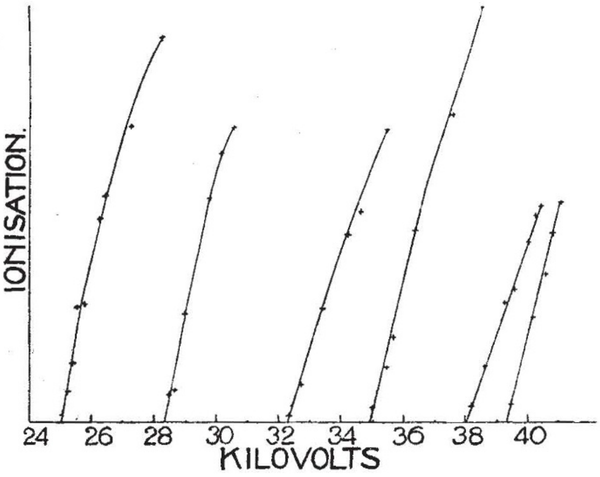

FIG. 1.—From Duane and Hunt, *Physical Review*, 1915, p. 166. Each curve represents the growth in intensity of a certain wave-length as the voltage applied to the X-ray bulb is increased. The wave-lengths are: left to right, 0·488, 0·424, 0·377, 0·345, 0·318, 0·308, all in Ångström units (10^{-8} cm.).

All this is wonderful enough; but the marvel is greatly increased by the discovery that the effect is reciprocal. Just as the swiftly moving electrons excite X-rays, so X-rays when they strike any substance lose their energy, which now appears as the energy of moving electrons. And, again, we find the same variation in the result and the same limit to that variation. Among the electrons so set in motion we find, examining them as soon as possible after their motion has begun, every variety of energy-content up to a certain critical value which is equal to the frequency of the X-rays multiplied by the same constant h. It is to be observed that we cannot measure all the electron velocities as soon as they exist because some of the motions begin in the body of the substance, into which the X-rays have penetrated, and have lost speed on the way out. Again, therefore, there is nothing against the hypothesis that the energy of every electron set going by waves of given frequency is originally the same, and is determined by the standard condition already given.

Not only in the case of X-rays are these effects observed, but also in the case of light. The only difference is that the frequencies of light vibrations are some 10,000 times less than those of X-rays, and the electron energies correspondingly smaller. When the light waves produce the electrons we have what is known as the photo-electric effect. The production of light by electrons has been much studied recently in experiments to find "resonance-potentials"—that is to say, the magnitudes of potentials which must act on electrons so as to give them enough energy to excite certain particular radiations from atoms on which they fall.

Exactly how this strange transfer of energy from one form to another takes place we do not know: the question is full of puzzles. The magnitudes involved are hard to realise; it helps if we alter their scale of presentment. Suppose that the target of the X-ray bulb were magnified in size until it was as great as the moon's disc—that is to say, about a hundred million times. The atoms would then be spheres a centimetre or so in diameter. But the electrons would still be invisible to the naked eye. The distance from earth to moon would correspond roughly to the distance that ordinarily separates the bulb from an observer or his apparatus. We now shoot the enlarged electrons at the moon with a certain velocity; let us say that in every second each square yard or square foot or square inch, it does not matter which, receives an electron. A radiation now starts away from the moon which immediately manifests itself (there is no other manifestation whatever) by causing electrons to spring out of bodies on which it falls. They leap out from the earth, here one and there one; from each square mile of sea or land, one a second or thereabouts. They may have various speeds; but none exceed, though some will just reach, the velocity of the original electrons that were fired at the moon. That, reduced again to normal size, is the process that goes on in and about the X-ray bulb: which is part of a universal natural process going on wherever radiation, electron or wave, falls on matter, and which is clearly one of the most important and most fundamental operations in the material world.

(*To be continued.*)

Obituary.

THE RT. HON. LORD MOULTON OF BANK, F.R.S.

THE news of the sudden death of Lord Moulton on March 9 came as a shock to all who had been associated with his many activities. Notwithstanding his advanced age—he was in his seventy-seventh year—he was so full of vigour that all his friends had looked forward to some further years of activity for the good of the country he loved so well, and for which he rendered such magnificent services. He died in the midst of his work; the very day before his death he was engaged in hearing an appeal at the House of Lords. A short time before, he delivered a speech on behalf of the chemical industries of the country with all his customary lucidity and vigour, and again on February 19 he showed his delightful personal charm as chairman of a "Saturday Evening" at the Savage Club. These random incidents might almost be taken as typical of the outstanding qualities of the man—the brilliant judge and lawyer, the man of science and patriot, and the genial companion whose sympathy and humour helped to brighten many a life, and never more than in the dark days of the war, when he was always ready to cheer and inspire those around him and to lead the way in meeting one difficulty after another.

After his brilliant career previous to the war, in which he had shown himself an adept at science, classics, law, and politics, as well as an athlete and a linguist, Lord Moulton might well have been content to rest upon his laurels, but unquestionably his greatest achievements were for the cause of his country, when, at the age of seventy, he took up a burden which would have taxed the endurance of the strongest man, and set himself to organise the resources of the country to obtain the explosives necessary for the war. Looking back upon his earlier career, it might almost seem that his numerous activities were directed by destiny towards the great climax of his life. Certainly they formed a unique training which fitted him for his supreme task in a way which could scarcely have been paralleled.

Lord Moulton was born on November 18, 1844, at Madeley, his father being the Rev. James Egan Moulton, a Wesleyan minister. After passing through the Wesleyan school at New Kingswood, near Bath, he entered St. John's College, Cambridge, and had a brilliant career as a student. In 1868 he became Senior Wrangler and first Smith's prizeman, and took a gold medal at London University. He was elected a fellow and lecturer at Christ's. His academic career was not of long duration. In 1874, at the age of about thirty, he was called to the Bar, and speedily became famous as a specialist in patent cases. His scientific training gave him a great advantage in dealing with such subjects, and he was entrusted with many cases involving very large