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ELECTRICITY RELEASED FROM MATTER[1]

By Dr. KARL K. DARROW

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In this situation I am reminded of something written a few years ago by Dr. Keen, the noted surgeon of Philadelphia. Dr. Keen was born in 1837 and he remembers men who were in their eighties when he was a child. Those men were born about 1760, and they in turn remembered men who were born around 1700 and whose lives therefore overlapped the life of Isaac Newton. So short is the history of physical science that three human lives suffice to span the entire time from our days back to the founder of modern physics! This is an extraordinary fact to think of, and no less extraordinary is the fact that *two* human lives suffice to cover almost the whole of the history of electrical science. One of these is the lifetime of our distinguished guest.

Try to think back, not 80 but 160 years, to the year 1773. Then, there was hardly anything deserving the name of electrical science—little more than an orderless assortment of quaint scraps of information about static charges, sparks and permanent magnets. Only one great electrician whose name we all remember lived wholly before that time; he was, of course, Gilbert. One other did most of his electrical work before that year, though he lived long past it; that, of course, was Benjamin Franklin. Now try to recall all the names of early electricians you possibly can. Unless you have lately been reading the history of electricity, I would wager that every one of them will belong to the 80 years following 1853. You will doubtless begin by running over the names of the electrical units. Well, Volta, Coulomb, Ampere, Gauss, Weber, Faraday and Henry all flourished in that period; and so did Galvani, Oersted, Cavendish and Davy.

[1] Address delivered at the Massachusetts Institute of Technology, March 29, 1933, in connection with the celebration of Professor Elihu Thomson's eightieth birthday.

These were the men who organized the science of electricity. They discovered the laws of attraction and repulsion of charged pithballs; the laws of attraction and repulsion of current-carrying wires; the laws of electrolysis. Above all, they achieved the synthesis of electricity and magnetism. Their work was so thorough and their results so extensive that one is amazed to-day to realize that they never had a chance of studying electricity outside of dense matter. Electricity to them was a mysterious and reticent entity which normally lurked in the depths of liquids and solids. It never seemed to want to come out into the open, and if it was forced into the open by the processes of thunderstorms or static machines, it hastened straight back into shelter with the utmost speed and violence.

Imagine a physicist who wants to study the nature and properties of water, but never has any at his disposal, except in damp sponges, moistened blotting-paper and crystals containing water of crystallization. Suppose him forbidden to squeeze the water out of the sponges, or steam it out of the blotting-paper, or distil it out of the crystals. This unfortunate person would be in somewhat the same position as the electrician of a century ago, except with regard to the spark. To find an image for the spark, we must concede him one more privilege: we must allow him to pump water out of a hidden reservoir through a pipe into a tank. He would like to be able to draw it off from the tank through a spigot in a small slow stream which he can easily observe and use. But, owing to some strange handicap, he can not do this; he can only pump water steadily into the tank until finally it gives way and bursts wide open and all the accumulated liquid rushes out in one terrific torrent, flooding all the neighborhood and threatening to drown the observer.

As usual, the simile is imperfect and has to be amended. We must suppose that the wall of the tank heals itself as soon as all the water has rushed out, and remains impervious until the internal pressure has mounted up again to a great height. Evidently what our physicist needs (since he can not have a spigot) is a tank which will crack open when there is only a little water in it, so that the outflow will be slow, and preferably just as slow as the influx of new water from the hidden reservoir which the pump is sending up. Now in my parable the tank is one of two metal electrodes which are connected to opposite poles of a battery. If the electrodes are separated by air of normal atmospheric density, the charge on the negative electrode can not burst out until it is built up to a hugely excessive amount. Then the wall of the metal is breached and the charge pours out with great violence until it is nearly all gone, after which the wall is closed and no more charge escapes until a new great excess is crowded into the electrode.

What can be done to persuade the charge to come out earlier? to come out gently and gradually and slowly, so that the flow can be steady, and easy to observe and to control? The answers to this question form all together one of the greatest achievements of the 80 years just past. I will recall them briefly to you.

The first answer was: form an arc in the open air between carbon or metal pole-pieces. This was given by Davy about 1815. It is not a convenient solution for one who wants to study electricity released from matter, because the electrical particles get badly tangled up with the molecules of the air almost as soon as they escape from the negative electrode.

The next answer was: put the electrodes into a tube and pump out the air until what is left has only about a thousandth of the normal atmospheric density. This is an admirable solution. Faraday made a good beginning, but for some reason or other relinquished this field of research. It was not properly developed until the eighteen-sixties and the eighteen-seventies. We ought first to remember the name of the man who made the tubes, for in 1860 the injunction "seal the electrodes into a tube" was not so easy to obey as now. This man was an itinerant glass-blower who earned his living by wandering from college to college in Germany and blowing such glassware as the professors of chemistry and physics might happen to want; his name was Geissler. In Bonn he found a professor who wanted low-pressure discharge-tubes for spectroscopic purposes, as the science of spectroscopy was then just coming into being. Reserving the spectra for himself, this professor turned over the task of studying the electrical properties of the discharge to one of his pupils. This pupil, whose name was Hittorf, obtained the chair of chemistry and physics in a small and half-starved college, where he stayed for fifty years. In 1869 he published the first of his great papers; I will quote its opening sentence: "The darkest part of the science of electricity to-day is incontrovertibly the process by which current is conducted through gases." Nowadays we should say just the opposite, and for that we should thank Hittorf; and also Crookes, and others after them, but Hittorf first of all.

When the density of the gas in the tube is about a thousandth of atmospheric density, there is a very striking and lovely pattern of colored lights and shades, luminous clouds and intervening gulfs of darkness; but these are signs that the electrical particles are getting tangled up with molecules of the gas, as in the arc. When the density is ten or a hundred times lower, they disappear and opposite the cathode one may see a green fluorescence spread over the glass wall of the tube. This is due to electrical rays proceeding from the cathode. They travel in straight lines perpendicularly outward from the cathode surface, for if a metal emblem is put in front of the cathode one sees its shadow black and sharply bounded upon the green expanse. If the cathode is bowl-shaped they are focused at the center of curvature of the bowl, and here they will melt even a metal like platinum, which proves that they carry energy with them. If a negatively charged object is brought up close to the tube (with certain precautions) the green flare moves off, showing that the rays are pushed away by the negative charge. If a magnet is brought up, the rays are shifted as a wire would be if it were carrying negative charge straight outward from the cathode.

These cathode rays are therefore a stream of negative charges, pouring out of the cathode and acquiring such energy and such momentum that they hammer themselves against the opposite wall of the tube. So rarefied is the gas that many of them go clear to the opposite wall unimpeded and unintercepted. It is because of the haste of their flight and the tenuity of the gas that they are able to move in straight lines across the hollow of the tube, and reveal themselves by making the glass of the wall fluoresce, and respond to magnets and to distant charges in ways which make their nature manifest. It is because of the haste of their flight and the tenuity of the gas that they remain what they are when they quit the metal: free negative electricity, released from dense matter, disconnected from atoms, unburdened and discarnate.

Rarefied as the gas may be in these experiments, it is actually responsible for the escape of electricity from the cathode. To use my former metaphor, it is the gas which breaks down the wall confining the electrical corpuscles inside the metal. It is preferable, however, to change the metaphor and to say that the gas helps the electricity over the wall. It does this best when its density is neither too high nor too low; at atmospheric density we get only the violent sparks, at very low density, nothing at all. Why this should be so, and how the gas achieves the feat of helping the electricity out of the metal, are very intricate questions to which the answers are only just beginning to be clear. Fortunately it happens that there are two ways of persuading electricity to come out of a metal, which involve no gas at all and are easy to understand. Both of these were discovered in the eighties. You know the agents involved; they are heat and light.

As for the efficacy of heat: various early savants observed phenomena which we with our riper knowledge can explain by it, but there is strong reason for giving the honor of discovery to a man who, as chairmen say, "needs no introduction"—Edison. He in 1884 was working with his carbon-filament lamps, these pre-war "incandescent lights" which nowadays, I suppose, must look as quaintly old-fashioned to people in their twenties as a kerosene lamp to people in their forties. The filament of carbon, enclosed in a pear-shaped bulb evacuated to the degree then called "high vacuum," rose in a single fragile arch from its leads in the socket, and the current was meant to flow the entire length of the arch. Edison, however, noticed that a good share of the current was evading its duty, leaking out of the negative end of the arch and sneaking across the hollow of the tube to the positive end. This he proved by making lamps with an extra lead, connected inwardly to a metal plate projecting into the hollow space between the bases of the arch, outwardly through an ammeter to the positive filament lead; there was a flow of current through the ammeter.

This was one of the great observations of history. On its result repose essential portions of the art and science of telephony over long distances, whether by wire or wireless; broadcasting; many devices for remote control; a thousand ingenious feats of engineering, ten thousand delicate aids to detection of light and sound and electricity, to measurement and research. In the electric lamp a mere annoyance, this "thermionic effect" is the vital principle of those other dimmer lamps not meant for lighting, the tubes of the radio sets now almost as familiar as electric light itself.

At this point of the narration almost any layman would assume that Edison himself went onward and discovered all these things. Not so! this was one of the occasions when the race was not to the swift, nor the battle to the strong. The keen inventor thought so little of this thing which had lain across his path that he showed it to a traveling British electrical engineer named Preece, and not only showed it to him but made up some extra tubes for him to take home and study at his leisure. Preece and Fleming studied the effect with care; but, so foreign to the human mind was then the idea of free electricity, they could not shake off the idea that the carbon filament must be projecting its own substance forth into space, with negative charges clinging to the atoms. Crookes entertained the same idea about the cathode rays in his low-pressure discharge-tubes. There are animals which are obliged to live successive stages of their growth in different media, first water and then air. Somewhat the same destiny was imposed on the thermionic effect as a division of human knowledge; born in the workshop of an inventor, started in life by electrical engineers, it attained to maturity in the academic world.

J. J. Thomson fostered the study of the effect at the English Cambridge, but turned it over in the main to his pupil, Richardson, as in an earlier generation Plücker had entrusted the low-pressure discharge to Hittorf. Richardson discovered the major laws of the effect and showed that they permit a beautifully lucid theory. We are to think of the metal as populated by a swarm of corpuscles of negative charge—henceforth I will no longer avoid the word "electrons"—which rush about in thermal agitation and beat in an incessant patter against the wall of the metal. This "wall" is a metaphor for the force of attraction whereby the positive charges moored to the atoms of metal pull back on the electrons which are trying to escape, and which is in fact confined to a thin region along the surface of the metal. Some of the electrons are moving rapidly enough to overcome this pull, and they climb over the wall; but at room temperature their number is imperceptibly small. As the metal is warmed up, its heat is shared by the electrons, and the fraction which is able to escape increases steadily. Eventually the outflow becomes a perceptible current which rises rapidly with further rise of temperature. Its law of increase is like that of the vapor pressure of a liquid or a solid, and thus we are justified in saying that electrons evaporate out of a metal.

To expel electrons from a metal by heating the entire bulk is an effective way, but in a sense it is crude; we lavish quantities of energy on the atoms of the metal in order that the particles of electricity also may receive some. It would be neater to impart the energy directly to the electrons without wasting any of it upon the atoms. A distant approximation to this ideal is attained by sending a beam of light against the metal. It consists of corpuscles of energy, the so-called "photons"; and every now and then one of these will dive through the surface and yield up its total energy to an electron. This is the so-called "photoelectric effect."

The energy of the photons is greater, the smaller the wave-length of the light, and is calculable from the wave-length. With light of the visible spectrum, what the electron receives is not sufficient to help it over the wall unless the metal is one of those which have walls abnormally low—the alkali metals and their alloys, and a few others. With light of the remote ultra-violet, the photons have energy enough to enable electrons to climb out of any metal whatever. The necessary energy, or (to preserve the metaphor) the height of the wall, can be determined by observing the wave-length of the light which is just able to release electrons from the metal; for the energy of the photons of this light is the same as the quantity in question and it is calculable from the wave-length. The height of the wall can also be estimated from the rate at which the thermionic current increases with rise of temperature. The estimates by the two methods agree very well and this contributes very much to our confidence in the theoretical picture. The establishment of this picture by the study of the photoelectric effect is largely due to a happy alliance of the insight of Einstein with the experimental skill of Richardson, K. T. Compton and Millikan.

Now a few words about the qualities of negative charge when it has been released from matter and is available to our experimental arts. You are of course aware that it consists of corpuscles, the electrons of which I have already spoken, of which the charge and mass are definite and known. The exact evaluation of this charge and this mass, e and m as they are familiarly called, has been a great experimental problem of the early twentieth century. To be precise, its period overlaps slightly with the nineteenth century (J. J. Thomson having made the earliest fairly good estimates, towards 1895), and also with the future, since measurements are still being made; but probably the first quarter of the twentieth century will always be remembered as the time of the achievement. Both e and m are very small by ordinary standards; upwards of 10^{19} electrons are required to make up the charge which passes per second through the filament of an incandescent lamp, and upwards of 10^{27} to make up the mass of a gram. The eighteenth-century savants who spoke of electricity as a "subtle fluid" were well inspired, in so far as they meant negative electricity; its particles are the most nimble, agile, penetrating and insinuating of all that are known, except perhaps the corpuscles of light, which belong to another category of existence altogether.

Electrons in their passage through vacuum are of course invisible; they are perceived only when their flight has come to an end, as, for instance, by striking upon a fluorescent screen or a photographic plate or entering a metallic collector. Unimpeded flight is like a dreamless sleep, perceived only because it was unperceived while it lasted, known only when it is over. Nevertheless we can trace the paths of electron-streams through vacua with confidence, by noting where they end. It is interesting also to know that the paths of electron-streams may be made visible by using a suitable small density of gas. Occasional corpuscles elicit flashes of light from atoms which they strike, and these mark out the path which the main body of unimpeded corpuscles is following, as the path of an army through a hostile country by night could be marked by the flashes of shots fired by natives on whom occasional troopers happened to stumble.

The most pleasing feature of these corpuscles is that, in large-scale electric and magnetic fields such as we can make in the laboratory, they behave just in the way they should in order to account for the fundamental laws of electricity in dense matter discovered in the eighty years preceding 1853. Electrons repel one another like negatively charged pithballs; electrons dashing past a magnet are displaced like a current-carrying wire. (Indeed it is only because of this that we are able to define and measure the charge and mass of an electron). Perhaps this sounds self-evident, hardly worth the verifying, let alone the saying. However, there is no law of nature to the effect that things which seem self-evident are necessarily found to be true. I will tell you of a case where something not self-evident occurred.

Suppose we send a beam of electrons against a crystal. The crystal is an assemblage of atoms regularly arranged. Each atom is a collection of electric particles roaming in vacant space. The sizes of these particles are so small compared with the spaces between them that each atom may be regarded for the present purpose as a narrow empty region where there is an electric field (and also a magnetic field) varying rapidly from point to point. The crystal is an assemblage of these narrow concentrated fields, tens of millions of them to the linear inch. We might say that it is a region of space occupied by a rhythmic pattern of field strengths. This is traversed by the electron-stream, which behaves in a most remarkable way, as Davisson and Germer found. It behaves as though it were attended by a train of waves, and the crystalline pattern seized upon these waves and guided them according to the well-known laws of wave motion, while the corpuscles trailed along after them.

This is a notion difficult to admit, for we are not accustomed to water-waves or sound-waves dragging massive bodies with them, although there is a striking analogy to be found in the phenomena of light. One immediately inquires whether the concept of the waves would serve in the cases of electron-streams traversing large-scale electric and magnetic fields, such as we know so well in the laboratory. So it does; the deflections of electron-streams in such fields as these can be explained by supposing that the fields act directly upon wave-trains, which accompany the corpuscles and steer them. In these cases by themselves the idea of waves would be superfluous, since we can explain the phenomena as well without them. But when electrons pass through crystals the waves are necessary to account for the phenomena, and this obliges us to imagine them always. It is by no means easy to adapt one's thought to the conception of corpuscles guided by waves, nor to the further and highly abstracted refinements which this notion has undergone in the last few years. But I came here with the intention of speaking to you not of the perplexities of theory, but of the clarities of experiment; and I must not continue to impair your memories of these.

THE ELECTRON THEORY OF METALLIC CONDUCTION[1]

By Professor J. C. SLATER
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ELECTROMAGNETIC theory may be broadly divided into two parts: the theory of electric and magnetic fields and the theory of the electrical structure of matter, of conductors, insulators, magnetic bodies, charges, currents. Both branches have undergone profound changes since the time of Maxwell. The electromagnetic field has been of interest particularly in cases of very rapid oscillations, the waves of light and x-rays. There, from the photoelectric effect and other similar phenomena, has arisen the idea that in some respects light seems to behave in a corpuscular way, its energy being concentrated in particles of energy or photons. The electromagnetic waves of Maxwell and Hertz have but a statistical connection with the motion of these photons. The discreteness of the photons is shown beautifully by such a device as a Geiger counter, which can be made to register each photon as it comes along. In weak radiation of high frequency, as x-rays or gamma rays, no one after seeing the experiment can doubt the corpuscular nature inherent somewhere in the phenomenon. But the photons get smaller and smaller as the frequency decreases, the energy of a photon being proportional to the frequency, according to Planck's famous equation

$$\text{energy} = h\nu.$$

Thus by the time we reach the frequencies with which practical electricians deal, frequencies which even in these days of short wave radio are only about 10^{11} cycles per second, the photons are so excessively small that any electromagnetic field of reasonable strength contains enormously many photons, so many that their individual effect is entirely lost. We deal with them only statistically, and we may without error replace the discrete photons by the continuous field of Maxwell. For this reason, unless he is dealing with photoelectric cells or some such device, the electrical engineer need hardly come in contact with the theory of photons.

The developments of the other side of electrical theory, the electrical structure of matter, on the other hand, are, and even more promise to be, of great

[1] Address delivered at the Massachusetts Institute of of Technology, March 29, 1933, in connection with the celebration of Professor Elihu Thomson's eightieth birthday.