PHILIPP E. A. VON LENARD

On cathode rays

Nobel Lecture, May 28, 1906

I am pleased to fulfil my obligation as a Nobel Prize winner to talk to you here on cathode rays. I assume that you would prefer me to tell you what others could not tell you. I shall describe to you the development of the subject - which also embraces recent theories concerning electricity and matter - as it has appeared to me, on the basis of my own experience.* This will give me a welcome opportunity of showing on the one hand how my work has depended on that of others, and on the other how in one or two points subsequent, or more or less contemporary, work by other investigators is related to mine. Thus - using the simile which you, my esteemed colleagues of the Academy of Sciences, have used at the head of your member's diploma** - I shall now speak not only of the fruits but also of the trees which have borne them, and of those who planted these trees. This approach is the more suitable in my case, as I have by no means always been numbered among those who pluck the fruit; I have been repeatedly only one of those who planted or cared for the trees, or who helped to do this.

In the time at my disposal I can deal at length with only a few aspects of my work in the field under discussion.

The start takes me back 26 years to Crookes. I had read his lecture on "radiating matter" (5)*** - his term for cathode rays**** - and was greatly impressed by it. You are all acquainted with the tests he made. Here Fig. 1 is one as a reminder: the glass tubes with highly rarefied air; the negatively charged plate or cathode *(a)* on which the rays are produced; a cross *(b)* in the path of the rays, and here the shadow of the cross *(d)* thrown by the rays

* In this paper I have tried hard to put into their historical perspective all the publications which in my opinion have made basic contributions to knowledge, even if they came to my notice too late for them to influence my work.

** Coat of arms: gardener planting young trees, with the motto "For our descendants".

*** The numbers in brackets refer to the bibliography at the end; here "p." gives the page number in the case of voluminous publications.

**** After Faraday, Hittorf (2) and then Goldstein (4) had already produced and progressively studied "glow rays" or "cathode rays". But Crookes made more progress than these workers, because he carried out experiments at a higher vacuum.

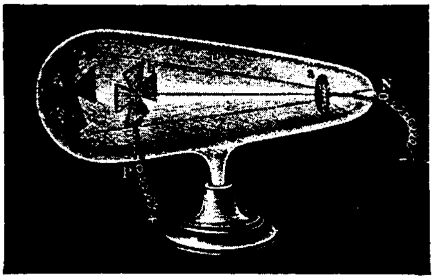

Fig. 1.

onto the phosphorescent glass wall. The shadow moves when a magnet is brought near; this is a sign that the cathode rays - unlike light rays - are bent in a magnetic field.

I have always attached great importance in my work to the problem of isolating the phenomenon being studied from interference sources, irrespective of the difficulties that this entails, an approach already adhered to by Crookes in his work. For it was he who produced these cathode rays in a pure form as never reached before, and showed that the phenomena concerned are of a very special type differing from other discharge phenomena through their attractive simplicity. The real nature of "radiating matter" or "the fourth state of aggregation", as he called it, was then beyond my comprehension, just as it must, we may now be sure, have been beyond his. But I readily shared his enthusiasm when he said: "Here, I believe, are the ultimate realities." And we were right: that is why I stand here today!

My interest in these matters found no direct expression during my student days. Electrical gas discharges were not considered a suitable object of study for beginners, and rightly so. But even mature investigators achieved nothing really significant in this field in the years following Crookes' work. They did not obtain any results that in themselves opened new vistas, and so far as purity of experimental conditions was concerned they hardly progressed beyond Crookes' work.

It was only later, when I was assistant to Quincke in Heidelberg, that I had the opportunity and the facilities for building a mercury air pump capable of giving very high rarefaction - then by no means a standard item of equipment in physics institutes - and for carrying out tests myself on cathode rays. I wanted to advance as directly as possible, and thought how fine it would be, in particular, to bring these rays from the tube out into the open air; it would then be possible to carry out direct experiments with them. To do this it was necessary to fit into the wall of the tube an airtight seal that would allow the rays to pass through. Now radiating *matter* would not readily pass through airtight seals, but might not Eilhard Wiedemann be right in assuming that cathode rays were a form of ultra-ultraviolet light? Finally, quartz appeared to me to be the most promising material, since it best transmitted all the radiations that were then known. Here (Fig. 2) is the tube I built at the time with the cathode plate, and at the top of it you will see the opening sealed by a quartz plate 2.4 mm thick. The test was unsuccessful, however; outside the quartz I found no phosphorescence nor even any electrical* effects that could be ascribed with certainty to the light issuing from the tube.

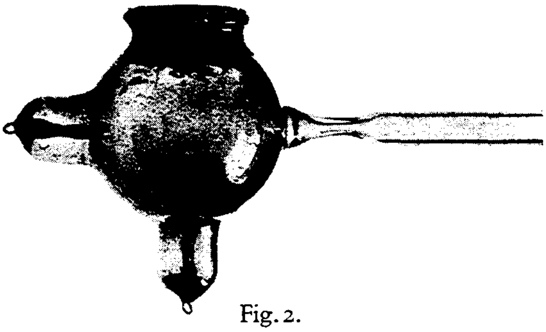

Fig. 2.

It was four years later, in 1892, that another opportunity arose. Hertz, whose assistant I then was, had found that thin metal leaf transmits cathode rays (15). He used quite thin, very soft and porous gold, silver and aluminium leaf used in bookbinding, but showed that the cathode rays not only pass through the holes but through the material itself, the metal of the leaf. One day he called me over - an event which to my great regret at the time did not occur often - and showed me what he had just found: uranium glass covered with aluminium leaf inside a discharge tube, glowed under the leaf when irradiated from above. He said to me: "We ought - and I might simply do this for he was prevented - to separate two chambers with aluminium leaf, and produce the rays as usual in one of the chambers. It should then be possible to observe the rays in the other chamber more purely than has been done so far and even though the difference in air pressure between the two chambers is low because of the softness of the leaf, it might be possible to completely evacuate the observation chamber and see whether this impedes the spread of the cathode rays - in other words find out whether the rays are

---

* Hertz' discovery of such effects of ultraviolet light had at that time just been made (8).

phenomena in matter or phenomena in ether." He appeared to consider this last question to be the most important one. I did carry out the test later; but I was primarily interested in my earlier question, that of cathode rays in the open air. I was not put off by the softness of the leaf used by Hertz. I laid more and more of such leaves on top of each other in a suitable tube and found that 10 and 15 layers still transmitted the rays fairly well. I then procured some pieces of aluminium foil of comparable thickness, to see whether they would withstand the air pressure. Such was the case, provided that a sufficiently small area of foil was used. Then, taking the old tube again, I replaced the quartz by a metal plate containing a small hole sealed with aluminium foil, spread a few small grains of alkaline-earth phosphor on this small aluminium window, excited the tube and, lo and behold, the grains glowed brightly! I then fixed them slightly above the aluminium window and they glowed brightly there as well! Thus not only had the cathode rays passed out of the interior of the discharge tube to which they had been hitherto confined, in addition - and nobody could have predicted this - they could pass through air of normal density. It thus became clear that a vast new field of investigation had opened up in front of me, a field that not only embraced hitherto unseen phenomena but also gave promise of a breakthrough into the unknown. Cathode rays, which had hitherto stubbornly eluded explanation, had yielded their secret and, more important, now for the first time tests of maximum purity could be carried out. Let us compare the position with that of another type of radiation, light: hitherto it was as if it had been impossible to study light except in the interior of furnaces and flames where it is produced, like the cathode rays in the tube. Where then would the great and detailed science of optics have stopped? ! A window had now been built in the furnace through which pure light only could emerge, freed from the complex and still unexplained processes of its formation. Such processes remain confined to the interior of the discharge tube and, as has since been found, could not be understood until a sufficient study had been made of the cathode rays themselves. As we shall see in our historical survey, this study has also provided a great deal of other information, some of which is now general knowledge, on X-rays and radioactivity, as well as a deeper understanding of electricity and matter.

It was now necessary above all to widen the inroad already made into the new field of knowledge. It was important to increase the intensity of the rays coming out of the window, and to improve the conditions of their production compared with the first tube. This led to the construction of the tube

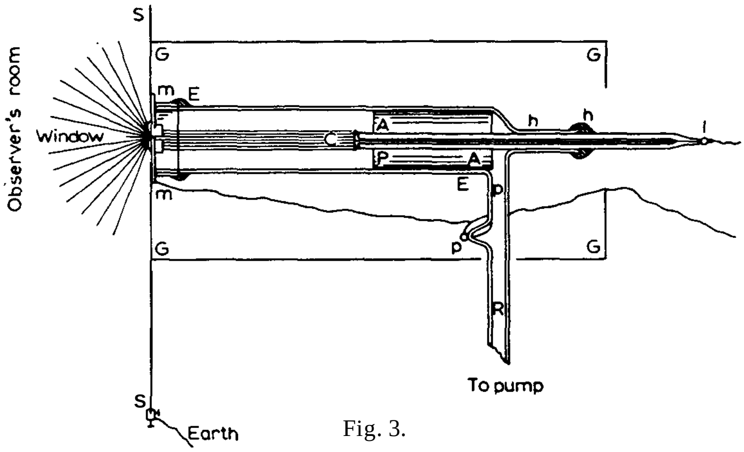

Fig. 3.

illustrated in Fig3, which was used in a large number of experiments (18). Here will be seen the production chamber with the anode *(A)* and the cathode (C), the seal (*m m)* with the window, and beyond it the observation chamber into which the rays emerge. The number of phenomena possible here is such that although the most obvious ones and also the slightly less obvious ones have probably now all been discovered, so far the consequences of all the phenomena have not yet been studied sufficiently.

It must be noted that the rays are not directly visible; it would be useless to put one's eye to the window, as this organ is not receptive to cathode rays. On the other hand, materials that are capable of becoming luminous without heat, phosphorescent materials as they are called, are suitable for making the rays visible. It is best to use sheets of paper coated with such materials, e.g. a certain ketone, platinum cyanide, or an alkaline-earth phosphor and to hold them as a screen against the rays. If the screen glows, it indicates that it has been hit by the rays. The rays can also be photographed directly. These are the same methods that are used to make visible ultraviolet light, at that time the only known example of such demonstrable invisible radiation.

When we use the phosphorescent screen, we find it glowing brightly close to the window; as the distance from the window increases, the intensity of the rays progressively diminishes until at a distance of about 8 cm the screen remains quite dark. Apparently air at full atmospheric pressure is not very permeable to cathode rays, certainly far less permeable than it is to light. But it was far more interesting to find that air is even a turbid medium for these rays, just as milk is for light. If we place an impermeable wall with a hole in it a suitable distance from the window and put the edge of the screen against it, we then get this view (Fig. 4). Here the dotted lines indicate the narrow pencil of rays that we should expect in the case of rectilinear propagation; but it is the broad bent bunch of rays that we really see on the screen in the open air, just as if we had passed light through the same hole into a tank containing slightly diluted milk. What clouds the air? In milk it is numerous small suspended fat particles that make it turbid to light. Pure air on the other hand contains nothing except molecules of the gases contained in it, suspended in the ether. These molecules are extremely small, 10,000 times smaller than the fat particles, far too small to act individually on light. But, as we see, the cathode rays are hindered by each of these molecules. Thus these rays must be extremely fine, so fine that the molecular structure of matter, which is minute compared with the very fine light waves, becomes pronounced in comparison with them. It may then be possible to obtain data by means of these rays concerning the nature of molecules and atoms.

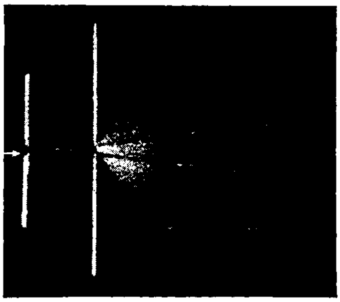

Fig. 4.

It is therefore particularly interesting to study the behaviour of a wide variety of materials relative to cathode rays. The first point to be studied was the permeability. Some idea of this can be obtained by holding a thin layer of the material being studied, between the window and the screen. It is abundantly clear that the permeability or impermeability of a material to light is is not even slightly related to its behaviour in relation to cathode rays. Here is an example (Fig. 5), a print of a direct photograph taken at the aluminium window. In the top half will be seen the deep shadow of a completely light-permeable ½ mm thick rectangular quartz plate, and in the left half, as a very mat veil, the picture of an ordinary aluminium leaf, impermeable to light and with somewhat irregular boundaries, laid over the whole of this

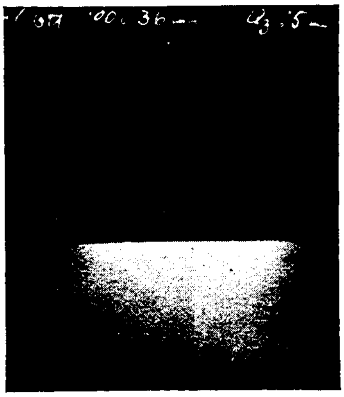

Fig. 5.

half. Great care must be taken in selecting the thickness of the layer throwing the shadow. Thus, for example, the quartz plate used in this experiment is impermeable simply because it is too thick, and the reason why metal leaf was found to be the only example of permeable layers in Hertz' tests lay in the thinness at which metal leaf is available. We shall soon see that most other materials, when of the same thickness, are even more permeable than gold and silver. It is soon evident that the absorption of cathode rays in any substance is a very gradual process, just as in the case of light, where as we know, gold is permeable when it is made sufficiently thin. Here (Fig. 6) we see the shadow of leaves of aluminium laid stepwise on top of each other; the numbers on the left give the number of leaves, those on the right their total thickness. Each increase in the number of leaves, and also any unevenness in

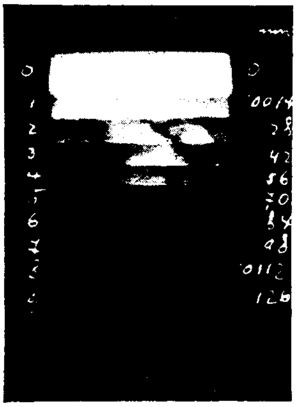

Fig. 6.

the thickness of the individual leaves, can be noted, and it will be seen how almost total permeability changes into almost total impermeability. Thus, with each material it was not a question of simply deciding between "permeable" and "impermeable", but of finding a numerical measure of the degree of absorption of cathode rays therein, of measuring its *absorptive power,* and I did this for a large number of solid and gaseous materials.

The result was astounding. All the great multiplicity of properties that we associate with the different materials around us, disappeared. The sole determining characteristic was the *weight* of the materials (21). Everything of equal weight absorbed equally, anything heavier absorbed more, anything lighter absorbed less, and always in proportion to the weights or the masses. At a first approximation, the chemical composition of the materials, their state of aggregation and other properties, did not count at all - a quite unprecedented finding that was not valid for any radiation known at the time. * At a second approximation, on closer inspection it is seen that the chemical composition has a slight effect: thus, e.g. hydrogen, and anything containing hydrogen, absorbs slightly more than one would expect in proportion to its weight. I must forbear to discuss these deviations and their significance in detail here.** As an illustration of the law of proportionality between mass and cathode ray absorption, that is valid at a first approximation, let us see the direct photographs of the shadows of layers of aluminium, silver and gold of equal thickness (Fig. 7). It will be seen that the heavy silver absorbs more than the lighter aluminium, and that gold, which is the heaviest, absorbs the most. If on the other hand we take layers of equal weights of the three metals (Fig. 8), we also get equal shadows and equal absorption, and the result would

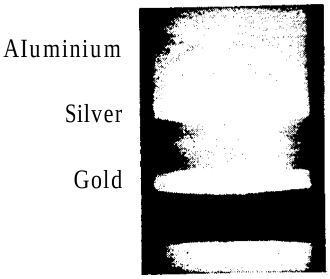

Fig. 7.

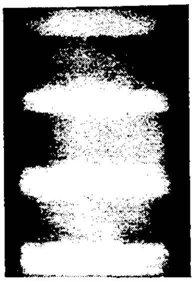

Fig. 8.

---

* Later X-rays were found to be a second example of radiation that is absorbed more or less in proportion to the mass.

** Compare (21, 47, 52).

be the same if we had taken any other materials in layers of equal weight.

In fact, in relation to cathode rays, not only the absorption, but also the turbidity, which I also studied in relation to a number of different materials (18*b* p. 257; 21, p. 265) was found to be related solely to the weight, the mass of the material in question, the *quantity* of matter - as Newton put it - and not the *quality* of the material.* If we now recall that cathode rays as they spread in matter are simply affected by the individual molecules of the material, we can conclude that the molecules of the most varied materials, and thus also the atoms of the different chemical elements vary, not qualitatively but only quantitatively, from each other, i.e. they all consist of the same basic material but contain different amounts of it. This old but because of the lack of valid data almost forgotten hypothesis of the alchemists was brought back vividly to our mind, this time however not to disappear again but to be proved; as evidence of this we can quote the recent results of Ramsay (54) and Rutherford (51) concerning the amazing transformation of radium** into other elements. But in order to use the law of proportionality between the mass and cathode ray absorption as a basis for drawing more detailed conclusions on the constitution of matter, it was first necessary to know something about the nature of cathode rays themselves. Let us now turn to this problem, which I have also borne in mind throughout my work.

Straightway we can decide whether cathode rays are phenomena that take place in matter or in the ether. When we completely evacuate a chamber by means of an air pump, it then does not contain any matter, only the ether, as present in the heavens. Now it has long been known for instance that sound cannot pass through such evacuated chambers, while light, and electrical and magnetic forces can. Thus there is no doubt that sound is a phenomenon in matter while light and electrical and magnetic forces are phenomena in the ether. We had been unable to carry out the corresponding test in relation to cathode rays in the ordinary discharge tubes, because once all the air is removed the production of the rays in such a tube ceases. But, without interfering in the least with production, we were able to completely evacuate our observation chamber on the other side of the window and see whether de-

* The diffuse reflection of cathode rays, which can be considered to be pronounced backwards-directed scatter, is also determined by the mass, as can be clearly seen from the measurements of A. Becker (52, p. 448).

** As evidence of the elementary nature of radium its spectrum and atomic weight are given (38, 39).

spite this the cathode rays spread in this chamber. We found that the propagation of the rays is particularly good in an extreme vacuum; all absorption and turbidity due to the gas molecules disappear, the rays attain lengths of several meters and are of such rectilinear sharpness as we are accustomed to find only in lightrays (18). Thus cathode rays are *phenomena in the ether. In* particular, on the basis of the hypotheses which we have mentioned, it could be stated that cathode rays were not radiating *matter,* nor emitted gas molecules, as they had come to be regarded, especially in England. * We were still not clear as to what type of phenomena in the ether they were. Many of my readers believed, very wrongly, that I had concluded beforehand that cathode rays were "waves in the ether"; I had no desire to say this or in fact anything unless it was shown to be so in my experiments and appeared to provide an explanation. I had the means available to discover new things daily from Nature herself, in further experiments. I hoped so or thought so, at least. I greatly regretted, therefore, that at this stage my experiments were interrupted for considerable time, first by a far-from-simple task that devolved unexpectedly on me through the untimely death of Heinrich Hertz - the publication of his *Prinzipien der Mechanik* (Principles of Mechanics) and then when I was appointed to a theoretical professorship.

It is barely worth mentioning, but not unimportant for the further development of our subject, that even before this interruption I had designed a new and far more convenient type of discharge tube. I had tested it as far as possible, and had recommended its use and made it generally available *(*18*b*, p. 228). Here (Fig. 9) the window seal is fitted to a platinum tube, which in turn is fused into the glass; this means the large amount of puttying which often made the tube very difficult to use, is avoided. This type of tube had however a special advantage that could not be foreseen at the time. In it the

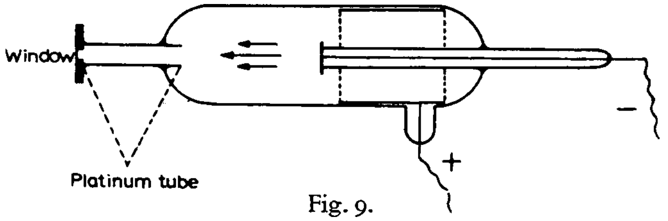

Fig. 9.

---

* Even after the experiments with the aluminium window had been reported, this theory continued to be held for some time, and it was suggested that molecular collisions actuated, via the window, the molecules of the outside air or molecules remaining in the vacuum.

intensive cathode rays impinge on the large area of platinum - the metal which, as we now know, is most effective in turning the rays into the - then undiscovered - X-rays. Thus X-rays are produced here in very large quantities, and they are also able to pass through the window, either mixed with or separate from the cathode rays, into the observation chamber. This was not possible in the earlier tube because of the large thick metal cover located in the path of the rays (27). The discovery soon after this of X-rays by Röntgen (22), the first investigator to use the type of tube described above, is generally considered to be a good example of a lucky discovery. But, given the tube, the fact that the attention of the observer was already turned from the interior to the outside of the tube, and the presence of phosphorescent screens outside the tube because of the purpose of the tube, it appeared to me that this discovery had of necessity to be made at this stage of development.

On resuming my experiments I soon occupied myself exclusively with an idea already put forward by Hertz *(7b,* p. 275) and Schuster (13), which in relation to the nature of the cathode rays had appeared to me to be very important right from the start, and which I had already begun to pursue in the first period of my experiments. It had been known since Hittorf's days that cathode rays are deflected by magnets (2) ; similarly the deflection of cathode rays noted by Goldstein (4) could be interpreted as being an influence of *electrical* forces on the rays. Now both the magnetic and the electrical deflection of the rays suggest that the cathode rays consist of emitted negatively charged masses. Moreover, from experiments made to measure the magnitude of the magnetic and electrical effects on a ray it is even possible to calculate the velocity of the supposed masses and also the electric charge per unit of mass (the charge / mass ratio). This is what Hertz and Schuster had done, but their results had contradicted each other. Hertz found that his observations refuted the theory of ejected gas molecules, while Schuster found that his fitted in with it, and thus he took them as support for this theory.

This contradiction did not surprise me. For both investigators had observed the interior of the discharge tube, and they might have been confused by the complications of the production process and the presence of the gas, as in fact they both admitted with reserve. It was now time to carry out these important tests under clearly-defined experimental conditions, i.e. outside the discharge tube and in a very high vacuum, and some excitement as to the result was permissible. For if we know already that the rays are ether, not material phenomena, it should be astonishing that their behaviour still resembled so deceptively that of ejected negatively charged gas molecules.

Nothing known so far had made solving this dilemma of the streaming molecules and the ether phenomena possible; these experiments would do this, and in any case therefore they would reveal something quite new.

While I was still doing the preparatory work for the experiments* I heard that others were already convinced of their importance. J.J. Thomson was the first to publish a detailed publication on the subject (25). His experiments, like those of Hertz and Schuster, were carried out in the discharge tube. He sought to avoid the danger of confusion as a result of interaction of the production discharge, by means of shielding devices, and to compensate the lack of reliability due to the presence of the gas by greatly varying the test conditions. It was clear to me that all that followed would have to rest on this pillar which I had learned to distrust from the discrepancy between Hertz and Schuster. It seemed to me that before it was made a part of the structure of science it should be tested as directly and rigorously as was possible with the means at our disposal. I therefore concluded my experiments, the results of which were as follows (28).

The velocity of the supposed masses was about one third the velocity of light, and the ratio of the charge to the mass was about 1,000 times that of a hydrogen atom in electrolysis, which atom is the lightest material carrier of electricity known to us. So, if the rays were streaming hydrogen atoms, their charge would have to be taken as being 1,000 times that in electrolysis. This possibility had however been excluded by my previous tests, which had shown that the rays are not material bodies. It seemed evident that I had discovered hitherto unknown parts of the ether, representing electric charges and moving like inert masses. The smallness of the inertia determined - 1/1,000 of the inertia of the hydrogen ion, at an equal charge - and the other behaviour (30) of these parts of the ether, made it easier to identify them with what had long been known as the "electrical fluidum". The solution to the dilemma was therefore as follows: The rays are not emitted electrically-charged molecules but simply streaming *electricity*. Thus, in cathode rays we have found under our very noses what we never believed we should see: electricity without material, electrical charges without charged bodies. We have, in a sense, discovered *electricity itself*, a thing whose existence or non-existence and whose properties have puzzled investigators since Gilbert and Franklin. Earlier workers, even Coulomb, had referred naively to electric-

---

* These were resumed at Aix under the direction of and with a grant from Wüllner's Institute (1896), and they had again been interrupted when I was appointed to another professorship elsewhere.

ities as something that existed and could almost be grasped. But the number of electrical phenomena known grew steadily without anybody being able to state that they had seen anything of the supposed electricity itself. Thus it was that - about a generation after Coulomb - Faraday (1) and then Maxwell (3) turned their attention completely away from the electricities to concentrate on the *electrical* forces that could be observed. These forces - thought of as states in the ether - appeared in fact in the famous experiments of Hertz (9) to be so likely to exist independently that from then on one felt increasingly inclined to forget their centres, the electricities, that had formerly been regarded as indispensible. Now - again about a generation after Faraday and Maxwell - the picture has changed somewhat: it has become more complete. We have found in cathode rays just as good a way of studying electricity as we found earlier for the electrical forces alone; we can follow the motion of electricity to and fro in these rays over distances stretching several meters, at will and directly with our senses - without any intermediate theoretical conclusions; we can see how electricity behaves under different conditions, and what its properties are; we are now in a position to give to the old term "electricity" a new content based on experience.

This new content, of which we now know a great deal, appears quite different now in many ways from what could have been supposed earlier.

Here it should be noted that all our remarks concerning electricity apply only to *negative* electricity, not positive electricity, about which even today little can be said that is concrete. We cannot claim to be acquainted with it; we can only recognize positively-charged material, whether it be atoms, molecules or groups of molecules.* We thus use the unitary means of expression, and say that a piece of material is positively charged when it has lost negative electricity.

Let us now therefore consider negative electricity, as it appears in our tests. Here we are amazed by the freedom of its motion, which we hitherto believed was only present inside metallic conductors. Already in the discharge tube, in the centre of the gas, we set this electricity in accelerated motion through the voltage applied to the electrodes, and immediately its velocity becomes one third that of light, 100,000km / set, and it represents a cathode ray. Now it impinges on the aluminium window. "It will adhere to it and flow to earth" one would have said on the basis of previous knowledge. Far

---

* Thus, for instance, canal rays and, so far as they have been studied, also the α-rays of radium, have been found to be emitted positively charged molecules.

from it: it passes through the metal plate (28, p. 28) and, as I was able to check, its velocity does not diminish appreciably (19; 46, p. 479). Beyond the window it can enter a more or less total vacuum, in which it continues its course linearly, representing an electric current in the empty ether, a phenomenon which we had earlier also thought to be impossible. When it finally hits a piece of metal of sufficient thickness, it penetrates it and sticks there; finally, after following such unusual courses it appears as an ordinary charge on the surface of the metal (28).

The problem of whether electricity fills space continuously or not, of whether it has a structure, is of particular interest. I have seen two cathode rays pass through the same chamber in opposite directions, and found in a quantitative investigation of the phenomena that the two rays did not interfere with each other in the slightest (44, p. 165). This indicates that the electricity of these rays consists of discrete and very small parts separated by a large volume of free space. We can represent the parts themselves as being more or less impenetrable to each other, because according to Coulomb's law, as soon as two of the parts come very close to each other they must exert enormous repulsive forces on each other. But the best indication of the structure of electricity comes from quite a different source, and is much older.

Here we come to the connexion between our findings and earlier knowledge. Such knowledge was very scanty, and was related to phenomena taking place in and on individual atoms, i.e. phenomena that could not be studied directly, but the connexion was a very good and fruitful one.

Years earlier, Helmholtz in his lecture in memory of Faraday had noted that electrolysis phenomena would suggest that electricity is split up into pieces of constant size, just as matter is split up in atoms (6). This was the indication already available concerning the structure of electricity, the existence of electrical atoms, *electrical elementary quanta* , as Helmholtz called them.*

In the field of optics moreover, the theory already firmly supported by Hertz' famous experiments (9), that each luminous atom be regarded as an electrical oscillator, had suddenly been given a tangible form by the discovery of Zeeman, who in conjunction with Lorentz concluded from his observations that it is *negative*** - not *positive* - electrical mass that oscillates in the lu-

---

* I recall hearing him use this expression many times in his demonstration lecture in the summer term of 1885.

** It is interesting that in Zeeman's first publications the word "positive" - not "negative" - was printed (24, p. 18), so that there was some delay in recognizing the relationship between his discovery and cathode rays.

minous atoms of a sodium or other metal flame, and that there is a definite ratio between the charge and mass of the oscillating material (24). The ratio was of the same magnitude as that found shortly afterwards, in the way described, for cathode rays.

It seemed likely that in all these cases, in the ions in electrolysis, in the luminous metal atoms and in the cathode rays, and perhaps everywhere where electricity plays a part, we might be concerned with the *same* electrical elementary quanta, the existence of which had first been indicated by Faraday's electrolysis law and which might be further elucidated by means of cathode rays. This theory has been proved, so much so that it has engendered a new branch of physics, so fruitful and already so vast that in this paper, which is devoted primarily to my own work, I cannot say any more in general on the subject. I would simply like to mention three points.

First, as an important initial quantitative check on our conclusions, the direct experimental measurement of the velocity of cathode rays carried out by Wiechert, in which the figure obtained was the same as that obtained from the electrical and magnetic deflections (see above) - about one third of the velocity of light (29).

Second, Kaufmann's experimental result, obtained on the basis of the work of J.J. Thomson and Heaviside (10), and concerning electrical elementary quanta, namely that their mass and inertia are of a purely electromagnetic nature (55), a result that we can interpret as follows : We have no evidence that (negative) electricity is a special *material* with inertia; it appears to be simply a *state,* the state of the ether which we were accustomed, after Faraday (1), Maxwell (3), and Hertz (9), to denote as the electric force field in the environment of electrified bodies, a state which according to Hertz (20) and Bjerknes (33) might consist of latent motion of the ether. Thus, even with the pure elementary quanta of electricity nothing else has been discovered except this ether state in their area. These elementary quanta themselves appear to us in Maxwell's sense to be the probably empty and only purely geometric centres of the electrical forces, except that we can now claim to be able successfully to observe these centres individually, follow their courses and study the geometric proportions of their size and shape. According to this finding, cathode rays, the streaming centres of state, appear to us, more than ever, to be what they seemed to us to be from the beginning, pure ether phenomena.

Thirdly, we must list the names given to these parts of electricity, or centres of state: I have called them *elementary quanta of electricity* or for short *quanta,* after Helmholtz; J.J. Thomson speaks of *corpuscles,* Lord

Kelvin of *electrions;* but the name preferred by Lorentz and Zeeman *electrons* has become the everyday term.

So far we have spoken of cathode rays as such; we shall now discuss their modes of formation, their generation.

The oldest, and for a long time the only known method of generation and the one which we have hitherto used to the exclusion of all others, is the discharge tube. Here, as their name suggests, the rays originate at the cathode. The gas molecules which are under the influence of the prevailing electrical forces have an effect - the proximity effect as I call it (53) - on the electrode metal, whereby quanta are withdrawn from the latter. Immediately they are free they are subjected to the accelerating forces of the field between the electrodes and thus move with increasing velocity away from the cathode; the ray is complete. The ultimate velocity at which we allow it to leave the tube through, say, a window is given by the size of the voltage used; and the very fact that in effect this whole voltage and not just a fraction thereof is determinative for the ultimate velocity proves that the origin of the ray must be sought at the cathode surface and not, say, in the centre of the gas.* By the magnitude of the voltage we can thus produce faster or slower cathode rays and when we previously spoke of 1/3 the speed of light that applied only to one particular voltage about 30,000 V, which I used generally throughout my experiments.

How would faster or slower rays behave? Some predictions could be made on the basis of my first experiments in which the voltage, and hence the velocity, was slightly varied (18*b*, p. 266; 19; 21, p. 261). Very fast rays could be expected to have extremely slight absorbability (high penetrating power) ** ; the slow rays on the other hand appeared best suited to yield information on the forces of atoms, the constitution of matter. For a long time, however, it seemed impossible to carry out pure tests over a sufficiently wide

---

* To start with this was an arbitrary assumption made in many previous studies on cathode rays; the proof of its correctness was supplied with increasing accuracy as time went on, with most accuracy probably by A. Becker (52, p. 404).

* * When X-rays were discovered this expectation of them appeared to be fulfilled; their first properties to become known agreed with those to be anticipated from my tests for the fastest cathode rays (27). It was just at first Righi's convincing observation that the X-rays do not carry with them a negative charge (23) that had shown the untenability of the theory that they were extremely fast cathode rays. They are nowadays considered to be short, transverse impulses in the ether, a kind of ultra-ultraviolet light. The fact

range of velocities since the glass of the discharge tube could not withstand the heavy voltages needed for the very fast rays, and the slow rays, although easy to produce in the tube, failed to emerge through the window; they were too absorbable. Other arrangements failed, too.*

Both problems, that of the slowest and that of the fastest rays, were finally solved in quite novel ways.

A discovery by Hertz as early as 1887(8) completed shortly afterwards by Hallwachs (11), had shown that by mere exposure to ultraviolet light metal plates give off negative electricity to the air. This remarkable fact - nowadays usually referred to as the photo-electric effect - immediately captured my interest at that time and has also continued to do so since. Experiments carried out in collaboration with the astronomer Wolf showed me first of all that ultraviolet light roughens substances or pulverizes them (12; 46, p. 490). Subsequent experiments, however, caused me to think it unlikely that metal particles carried the negative charge off the plate. At the time I conducted my first experiments on cathode rays, when I had discovered that the air in front of the aluminium window becomes conductive (18) I formed the idea that cathode rays could be driven from the plate into the air by ultraviolet light. Both then and later I made repeated vain attempts to detect possible rays in the vacuum on fluorescent screens. Only my decision - based on Righi's work (14) - to use the electrometer instead of the fluorescent screen revealed the existence of the rays. The apparatus used is illustrated in Fig. 10. U is the plate to be irradiated and is in a complete vacuum; the quartz seal at B admits the ultraviolet light. The cathode rays start from U and a narrow beam is separated out by the hole in the counterplate E. This beam impinges on the small plate α which collects the negative charge brought by the beam and thereby indicates the existence of the radiation on the electrometer. We bring a magnet or the coil indicated by a broken line close to the tube in a suitable manner and then find the charge on the plate β instead of on α, in-

---

that such impulses can actually occur side by side with heavy absorption of cathode rays, such as e.g. in heavy platinum, follows, as first put forward by Heaviside, from Maxwell's theory (10). The fact that extremely short-wave ultraviolet light will pass unrefracted through prisms was foreseen by Helmholtz in his dispersion theory (17*c*, p. 517). The low-absorbability cathode rays forecast first became a reality in the rays emitted by radium.

* Amongst other measures I had tried inserting, instead of the window, narrow channels between generating chamber and completely evacuated observation chamber, but they allowed too much gas through.

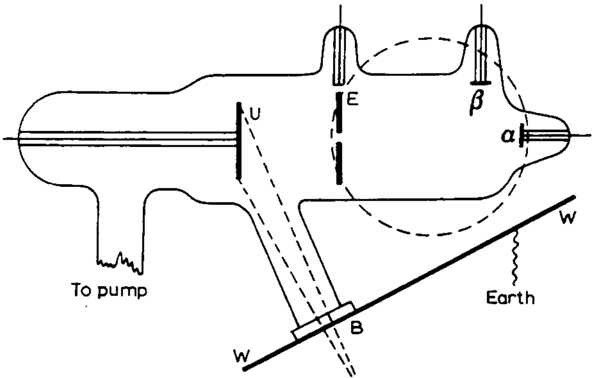

Fig. 10.

dicating that the invisible ray is actually deflected by the magnet and in the appropriate direction for cathode rays. When carried out quantitatively, the experiment showed that the deflection is also of the correct degree, and that the same ratio obtains between charge and mass of the quanta as in the case of the rays generated in discharge tubes (32; 44, p. 150; 46).

Immediately it had been established beyond doubt in this way that cathode rays are produced by ultraviolet light and that their behaviour had become sufficiently well known, I was soon able to detect them on fluorescent screens (44), then follow them further and use them. I shall refer to those aspects later. The following should be noted as regards the actual generation.

Firstly - an important point for pure experiments - it also occurs in a complete vacuum where the usual method fails. A gas need not be present but it does not interfere with the generation of the rays. What is involved is the direct action of the light on the metal of the plate. The initial velocities with which the quanta leave the plate are so slight that a negative charge of only a few volts on the counterplate is sufficient to compel the rays to reverse before reaching it. They then return to the irradiated plate in the same way as a stone thrown upwards falls black to the ground (32; 44).*

---

* My first detailed communication on the subject (32) appeared in the *Sitzungsberichte der Kaiserl. Akademie der Wiss. zu Wien* for 19th October 1899. In the December issue of *The Philosophical Magazine* of the same year J. J. Thomson published studies "On the mass of the ions in gases at low pressures" in which the photo-electric effect is involved although its centre is still sought in the gas adjacent to the irradiated plate, as the remarks on p. 552 indicate. In the same author's book *Conduction of Electricity through Gases,* 2nd. ed., 1903, p. 109, my publication is dated one year later than that just mentioned since a later reprint *(Ann. Physik,* 2 (1900) 359, where it is expressly marked as a reprint), and not the original is cited.

Here, therefore, we obtain extremely slow cathode rays; faster ones can be produced merely by charging the counterplate positively. The velocity of the rays can be controlled freely by the level of the voltage of the counterplate.

Secondly, considering the effect of the ultraviolet light on the plate, we must imagine that the light waves cause the interior of the metal atoms in the plate to vibrate. We have previously mentioned that Zeeman's discovery has proved atoms to contain negative electricity capable of vibration. If the co-vibration of a negative quantum in the atom with the light waves becomes too violent, the quantum escapes from the atom* and so from the plate; we have a cathode ray.

The velocity at escape we have already mentioned as very low. I have also found that the velocity is independent of the ultraviolet light intensity (M), and thus concluded that the energy at escape does not come from the light at all, but from the interior of the particular atom. The light only has an initiating action, rather like that of the fuse in firing a loaded gun. I find this conclusion important since from it we learn that not only the atoms of radium - the properties of which were just beginning to be discerned in more detail at that time - contain reserves of energy, but also the atoms of the other elements; these too are capable of emitting radiation and in doing so perhaps completely break down, corresponding to the disintegration and roughening of the substances in ultraviolet light. This view has quite recently been corroborated at the Kiel Institute by special experiments which also showed that the photoelectric effect occurs with unchanged initial velocities even at the temperature of liquid air.

We cannot regard the action of the light as restricted only to the solid state of aggregation. The molecules, or atoms of gases undergo a completely analogous effect under the action of ultraviolet light (35; 40); it is reasonable to assume that quanta escape from them (49, p. 486); the gas thus becomes electrically conductive in a manner which we shall discuss in detail later. If the gas contains oxygen like the air, ozone is formed as a by-product (35).**

---

* This is a process which was earlier anticipated in Helmholtz's comprehensive dispersion theory (17*c*, p. 518).

** In the light of subsequent studies by Warburg it can be assumed that the most productive of current methods of producing ozone, i.e.those using what are termed "silent electrical discharge" are wholly or largely effective owing to the ultraviolet light of these discharges (48). The rich sources of ultraviolet light obtainable nowadays, e.g.electrical mercury quartz lamps, propagate such a noticeable odour of ozone in their environment that this effect of ultraviolet light has now became a commonplace.

This same action of light, namely the production of cathode rays, the vibration of atoms and the releasing of quanta therefrom, is also involved in phosphorescence (50, p. 671) and hence probably also in fluorescence, perhaps, too, in all photochemical effects. Bearing in mind that we have detected transformation of energies from the interior of the atoms associated with the photoelectric effect, we should not be surprised if in future perhaps we encounter phenomena of the same type acting as sources of energy not introduced from outside.

It should also be mentioned that the research carried out by Curie and Sagnac (37) as well as that by Dom (42) indicates that in common with ultraviolet light, X-rays too have the effect of generating cathode rays. This is consistent with their ability to make gases electrically conductive and induce phosphorescent and photochemical effects.

Scarcely had ultraviolet light been shown suited for the generation of the slowest rays when the solution was found to the problem of how the fastest rays originate. The rays emitted by uranium and radium were already known; Becquerel, P. and M. Curie were engaged in pursuing further these discoveries of theirs. By applying to these new rays the methods developed as described for the cathode rays from discharge tubes, it was shown that the new rays are partly cathode rays (34; 36; 41)*, and amazingly cathode rays of almost or entirely the speed of light (43). What no discharge tube could withstand is thus achieved by the radium atom - and quite spontaneously - although admittedly not without being completely broken down in the process (51; 54).

Once the entire range of velocities from rest to the speed of light was thus available it was worthwhile re-examining in more detail the behaviour of matter to irradiation.

From the turbidity of all substances, including e.g. air, to cathode rays, we had concluded that each molecule or atom acts as a separate obstacle to the rays, an obstacle which deflects them from their path to a greater or lesser

Nevertheless, the meteorological significance of the action of ultraviolet sunlight in the upper layers of the atmosphere (35, p. 504) still does not appear to have been sufficiently appreciated. Whether the ionization by cathode rays first found at the aluminium window (18) is also an effect of the light which occurs there, or else the direct effect of the cathode rays, is still obscure.

* This is the part of the uranium or radium radiation normally designated as β.

extent. How should we visualize this deflection? Let us first examine whether perhaps the quanta of the rays are reflected from the molecules of the substance in the same way as the molecules of a gas are reflected on one another when they collide. Were that so a cathode ray in the gas would be restricted to that length which can readily and accurately be calculated as the mean free path of very small particles between the gas molecules from the data of the kinetic gas theory. These path lengths are, however, very small; in hydrogen at 40 mm pressure, for example, about two hundredths of a millimeter. Beyond this short length, a ray would not be able to develop at all in this gas, that is to say almost instantaneous diffusion would ensue. However, gases are by no means so turbid as my observations published in diagrammatic form had earlier shown *(*18*b).* Even the air at full atmospheric pressure proved much clearer, as we have already seen (Fig. 4), and the lighter hydrogen rarified to the specified pressure of 40 mm is much clearer still; Fig. 11 illustrates the path of the ray in hydrogen as observed on the fluorescent

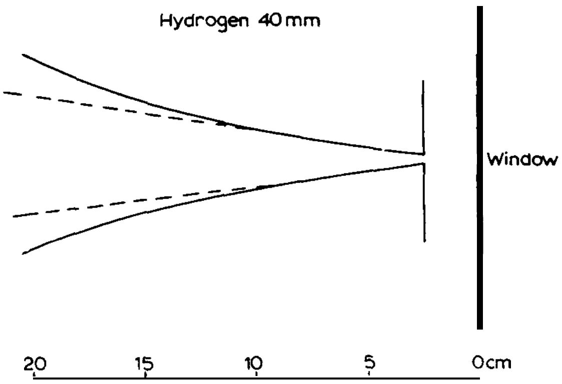

Fig. 11.

screen. The broken lines show the extent to which rectilinear light would propagate under the same conditions. It will be seen that over a length of 10 cm the cathode ray still scarcely deviates from this rectilinear propagation, and it becomes distinctly broader only beyond that length. The length of 10 cm is, however, 5,000-fold that of the free path length of 0.02 mm. It thus follows that here the radiant quanta must have traversed 5,000 hydrogen molecules before undergoing the first noticeable change of direction. We are amazed to see that we have transcended the old impermeability of matter. Each atom in the substance occupies a space which is impermeable to the other atoms*; but vis-à-vis the fine quanta of electricity all types of atoms are highly permeable structures as if built up of fine constituents with a great many interstices.

What are these fine constituents of atoms? That in all atoms they are the same, only present in varying numbers, we have already concluded from the law of proportionality between mass and absorption. We can now learn further details. We can use the quanta of the cathode rays as small test particles which we allow to traverse the interior of the atoms and thus provide us with information thereon.

The first and most noticeable thing to happen to them during this traverse, i.e. deflection from the rectilinear path, we have just discussed as *diffusion of the rays.* As far as we know, cathode rays experience such a deflection owing only to electrical and magnetic forces. To assume magnetic forces within the atoms would imply the assumption of mobile electricity in the atoms, thus again electrical forces. We must therefore regard the diffusion of cathode rays in matter as proof for the *existence of electrical forces in the interior of the atoms.* The magnitude of these forces can be estimated by considering the extent of the deflection together with the transit time, which latter depends on the velocity of the quanta and, of course, on the size of the atoms. If we take progressively slower rays, the transit times will become longer and correspondingly the diffusions occurring will be stronger (19, p. 30; 46, p. 480). In this way we find for the interior of the atoms electrical field intensities of unusual magnitude such that we can never produce by any means known to us owing to lack of sufficient resistance in even the best insulators: field intensities compared with which those occurring during the most violent storms are insignificantly small (47). The force effects of the radium atom then cease to seem so surprising but we should be more amazed that most of the atoms around us behave so placidly, only revealing something of the force stored within them when subjected to the photoelectric action or through other similar causes.

The further quantitative study of cathode-ray diffusion in the various materials promises to yield valuable information on the precise nature of the electrical fields of atoms. For the present we must turn to a second phenom-

---

* In any case at the normal velocities of the molecules. For very high velocities such as occur with the α-particles of radium, mutual penetrability of even whole atoms, although probably accompanied by their destruction, would not be impossible in the light of the concepts which we have arrived at regarding the constitution of atoms. Recent studies by Bragg and Kleemann promise to throw light on this subject.

enon, somewhat more easy to determine numerically, which is apt to occur in the course of such atom traverses. It can easily happen that the quantum, after successfully passing thousands of atoms, finally stops in an atom and does not emerge at once. This is the *absorption of cathode rays.* I have determined this effect quantitatively for the entire scale of available ray velocities and found the following (47).

The absorption increases with decreasing ray velocity, in common with the diffusion. This is also to be expected if the absorption, like the diffusion, is an effect of the electrical fields of force within the atoms and if these fields of force concentrate about certain centres in the atoms in the vicinity of which their intensity is greater than at longer range, in the same way as the intensity of a magnetic field of force concentrates about the two poles. A radiation quantum which traverses such fields with mobile centres is only stopped when it enters sufficiently intense parts of these fields along its particular path; otherwise it will pass through and be deflected to a greater or lesser extent. The entire cross-section of the atom, the area which the atom presents to a ray, thus consists of two parts, an absorbing and a transmitting part, and the former - which I refer to briefly as the absorbing cross-section - is known in square centimetres from my measurements. It affords a measure for the size of those parts of the force fields of the atom, the intensity of which is greater than the relevant level which is just sufficient to arrest the particular velocity of the quantum. The slower the quantum, the larger the parts of the atom’s force field which act as absorbing cross-sections. For the slowest rays I have found that the absorbing cross-section not only becomes equal to the entire cross-section of the atom or molecule - which entire cross-section was known from the kinetic theory of gases - but even slightly larger. This is tantamount to direct proof for the existence of electrical fields of forces both within the atoms and molecules and also for a certain distance around them. It is probably correct to identify these external electrical forces of the molecules with the forces of strength, elasticity, cohesion and adhesion, in short with the *molecular forces* in general which have long been known although not immediately regarded as of an electrical nature. Berzelius’ view that the *chemical forces* of atoms are of an electrical nature will now be held with all the more reason and as the research in progress continues it is to be hoped that concepts of the electrical force fields of the atoms will emerge which give a better and more complete picture of their chemical behaviour than the simple concept of a number of fixed valency positions equipped with electrical charges.

Of equal interest to the transition to the lowest velocities was that to the highest. As the ray velocity increases, the absorbing cross-section contracts; ultimately only those quanta are stopped whose path lies through the highest intensity parts of the internal force fields close to their centres. For that very reason the fastest rays are also capable of supplying the answer to the question whether perhaps these centres have a special, impenetrable proper volume, or in more general terms: whether apart from the force fields there is something else in the atoms which holds back our test particles. What happens when the test is carried out with the fastest rays can best be illustrated by means of an example. Let us imagine a cubic metre block of the most solid and heavy substance known to us, say, platinum. In this block we find altogether not more impenetrable proper volume than at most one cubic millimetre. Apart from this pinhead-sized portion, we find the remainder of our block as empty as the sky. We ought to be astounded at the insignificant degree to which the space in matter is actually filled! What we have found in the space occupied by matter have only been fields of force such as can also form in the free ether. What are then the basic constituents of all atoms to which we have been led by the mass dependence of cathode-ray absorption? Clearly they too are in the main only fields of force in common with the whole atoms. I have therefore termed these basic constituents of all matter "dynamids".

As constituents of electrically neutral atoms the dynamids will also be regarded as electrically neutral, and hence possess the same amounts of negative and positive electricity as the centres of their fields. We may then state : matter - all the tangible, ponderable substances around us - consists ultimately of equal quantities of negative and positive electricity. The previously mentioned findings derived from the Zeeman phenomenon, the photo-electric effect and the secondary cathode radiation, which will presently be discussed, show that the negative electricity is contained in the atoms as precisely the same quanta which we found in the cathode rays, and which the research worker has since variously encountered in their own right, separate from matter. The positive electricity, on the other hand, appears to be something much more specifically proper to the atoms of matter; as has been previously stressed they have not been found with certainty other than in atoms. From our findings on the packing of space it follows that for negative quanta the proper volume, impenetrable for things of the same kind, must then be extraordinarily small. This is consistent with the previously mentioned experiments by Kaufmann. The probable proper volume of the positive electricity, provided it too were not extremely small, should be regarded as completely penetrable for negative quanta.

With this constitution of matter, the third phenomenon occurring during atom traverses, and one which has still to be referred to, can readily be understood. Owing to the repelling force which it exerts on the other negative quanta proper to the atom the traversing ray quantum will be capable of setting up a tremendous disturbance within the atom and as a result of this disturbance a quantum belonging to the atom can be flung out.*
The process is termed *secondary cathode radiation.* We have allowed one cathode ray - the primary - to penetrate into the atom, against which two emerge, the primary and the secondary** (46, p. 481).

The *velocity* of the secondary rays - in common with that of the photoelectrically generated cathode rays - is very low, even when that of the primary rays is high. The *amount* of the secondary radiation, i.e. the probability of quanta emission from atoms during traverse, is largest at a given optimum of the primary velocity; both faster and slower primary rays are less effective and at quite a low primary velocity - below 1/200th of the speed of light - the secondary radiation is absent altogether (44, p. 188 et seq.; 46, p. 474 et seq.; 49). This is quite understandable for if the primary quantum approaches too slowly, it has too little energy to cause adequate disturbance of the interior of the atom, and if it approaches too quickly it will generally remain for too short a time in the atom to have that effect.

At its low velocity the secondary radiation must succumb to strong absorption in the surrounding molecules of the material. In gases where the molecules are free, a molecule which has absorbed a secondary quantum will act as a *mobile carrier of negative electricity,* while the molecule from which the secondary quantum has escaped has an excess of positive electricity and is thus a *positive* electricity carrier. The migrations of such carriers, however - for which knowledge we are indebted to the unremitting efforts of Arrhenius and after him to J. J. Thomson in particular - constitute the electrical conductivity in gases*** and in the secondary cathode radiation we have thus

---

* Two and more quanta can also escape from the atom (46, p. 485).

** It seems often to be assumed that the secondary radiation is an exclusive result of the absorption of the primary radiation; but this is not the conception which I have formed from observation (46, p. 474 et seq.).

*** Three consecutive steps seem to me to substantiate the belief that molecules or groups thereof carry the electrical conductivity in gases, notably: (*i*) the thorough study of one of the first cases of gas electrification in which dust - which at first was regarded found and, as I believe, adequately ascertained by thorough observations, the mechanism whereby cathode rays cause a gas to become electrically conductive (46, p. 474).* This case of conductivity induced and maintained by cathode rays must also be a factor in all gas discharges where sufficiently fast cathode rays occur; hence also in the normal discharge tube which we took at the outset as our first generator of cathode rays.

In other cases as well where gases become electrically conductive the mechanism appears to be the same: escape of quanta from molecules, and reabsorption by other molecules; this occurs under the influence of ultraviolet light on gases, as aforementioned, and also in flames (45) but the cause underlying the escape of quanta is apt to vary from case to case (53, p. 242).

In conclusion, I wish to thank you for your attention.

---

as the sole or at any rate the main carrier of electrical discharges in gases - was found definitely not to be involved. This was the case of waterfall electricity (16); (*ii*) the first measurements of the migration speeds of gas carriers in various cases of conducting gases, performed in rapid sequence by a number of different observers, first of all by Rutherford (26) ; *(iii)* J. J. Thomson's essentially irreproachable first measurements of the absolute electrical charge of the individual gas carriers in different cases (31). - In the light of simple considerations of gas kinetics the size of the gas carriers was calculated from *(ii)* and *(iii)* as equal to that of molecules or groups of molecules.

* This mechanism differs from that of ion formation in liquid electrolytes where it consists in the splitting of electrically neutral molecules into two oppositely charged atoms or groups of atoms. In other respects, too, the analogy between the conduction of electricity in gases and in liquids breaks down precisely in the most characteristic points. Magnitude and sign of the charge on a gas carrier are - quite unlike the case with the ions in liquid electrolytes - not determined by the chemical nature of the carrier, and electrolysis proper - that so typically chemical mode of decomposition - hence does not occur at all in gases (53, p. 236). I therefore considered it better to emphasize this analogy no longer, notwithstanding its heuristic usefulness at the outset, and for that reason I have always avoided applying the name ions to the gas carriers, and calling the conduction of electricity in gases electrolytic.

Röntgen rays" *Phil. Mag.*, Ser.5, Vol.46. (Published in December issue.) Continued and subsequently corrected in *Phil. Mag.*, December issue 1899, and March issue 1903.

(1899) 32. P. Lenard, "Erzeugung von Kathodenstrahlen durch ultraviolettes Licht" (Production of cathode rays by ultraviolet light), *Sit.z.-ber. Kaiserl. Akad. Wiss. Wien* for 19th October. Reprinted in *Ann. Physik*, Vol.2.

(1900) 33. V. Bjerknes, *Vorlesungen über hydrodynamische Fernkräfte nach C. A. Bjerknes' Theorie* (Lectures on the hydrodynamic distant forces in accordance with C. A. Bjerknes' theory).

- 34. H. Becquerel, "Contribution à l'étude du rayonnement du radium" (Contribution to the study of the radiation from radium), and "Déviation du rayonnement du radium dans un champ électrique" (Deflection of radium radiation in an electrical field), *Compt. Rend. (Paris)* for 29th January and 26th March, respectively.

- 35. P. Lenard, "Über Wirkungen des ultravioletten Lichtes auf gasförmige Körper" (Effects of ultraviolet light on gaseous substances), *Ann. Physik*, Vol. I. (Received 6th February.)

- 36. P. and M. Curie, "Sur la charge électrique des rayons déviables du radium" (The electrical charge of deflectable radium rays), *Compt. Rend. (Paris)* for 5th March.

- 37. P. Curie and G. Sagnac, "Électrisation negative des rayons secondaires produits au moyen des rayons Röntgen" (Negative electrification of secondary rays produced by means of X-rays), *Compt. Rend. (Paris)* 130, for 9th April.

- 38. E. Demarcay, "Sur le spectre du radium" (The radium spectrum), *Compt. Rend. (Paris)* 131, for 25th July.

- 39. M. Curie, "Sur le poids atomique du baryum radifère" (The atomic weight of radiferous barium), *Compt. Rend. (Paris)* 131, for 6th August. Also "Sur le poids atomique du radium" (The atomic weight of radium), same journal 21st July, 1902.

- 40. P. Lenard, "Über die Elektrizitätszerstreuung in ultraviolet durchstrahler Luft" (Scattering of electricity in air irradiated with ultraviolet light), *Ann. Physik*, Vol.3. (Received 17th August.)

- 41. E. Dorn, "Elektrostatische Ablenkung der Radiumstrahlen" (Electrostatic deflection of radium rays), *Abhandl. Naturforsch. Ges. Halle*, Vol.22.

- 42. E. Dorn, "Versuche über Sekundästrahlen" (Experiments on secondary rays), *Arch. Néerl. Sci. (Haarlem)*, Ser.2, Vol.5.

(1901) 43. W. Kaufmann, "Die magnetische und elektrische Ablenkbarkeit der Becquerelstrahlen und die scheinbare Masse der Elektronen" (The magnetic and electrical deflectability of Becquerel rays and the apparent mass of electrons), *Nachr. Kgl. Ges. Wiss. Göttingen*, Vol.8, for 8th November.

(1902) 44. P. Lenard, "Über die lichtelektrische Wirkung" (The photoelectric effect), *Ann. Physik*, Vol.8. (Received 17th March.)

- 45. P. Lenard, "Über die Elektrizitätsleitung in Flammen" (Electrical conductivity in flames), *Ann. Physik*, Vol.9. (Received 18th August.)

(1903) 46. P. Lenard, "Über die Beobachtung langsamer Kathodenstrahlen mit Hilfe der Phosphoreszenz und über Sekundärentstehung von Kathodenstrahlen" (The observation of slow cathode rays by means of phosphorescence, and the secondary occurrence of cathode rays), *Ann. Physik*, Vol.12. (Received 28th June.)

- 47. P. Lenard, "Über die Absorption von Kathodenstrahlen verschiedener Geschwindigkeit" (The absorption of cathode rays of various velocities), *Ann.* Physik, Vol.12. (Received 30th July.)

- 48. E. Warburg, "Über die Ozonisierung des Sauerstoffs durch stille elektrische Entladungen" (The ozonization of oxygen by silent electrical discharges), *Sitz.-ber. Berl. Akad.* for 11th November.

(1904) 49. P. Lenard, "Über sekundäre Kathodenstrahlung in gasförmigen und festen Köpern" (Secondary cathode radiation in gaseous and solid substances), *Ann. Physik,* Vol. 15. (Received 22nd August.)

- 50. P. Lenard and V. Klatt, "Über die Erdalkaliphosphore" (The alkaline-earth phosphors), *Ann. Physik,* Vol.15. (Received 22nd August.) Extracts also published in the *Mat. Naturw. Ber. Ungarn,* Vol. 22.

- 51. E. Rutherford, "Slow transformation products of radium", Phil. *Mag.,* Ser.6, Vol.8. (Published in November issue.)

(1905) 52. A. Becker, "Messungen an Kathodensstrahlen" (Measurements on cathode rays), *Ann. Physik,* Vol.17. (Inaugural dissertation submitted to the Kiel Philosophical Faculty on 1st March.)

- 53. P. Lenard, "Über die Lichtemissionen der Alkalimetalldämpfe und Salze und über die Zentren dieser Emissionen" (The photo-emissions of alkaline metal vapours and salts, and the centres of these emissions), *Ann. Physik,* Vol.17. (Received 13th April.)

- 54. F. Himstedt and G. Meyer, "Über die Bildung von Helium aus der Radiumemanation" (The formation of helium from the emanation of radium), *Ber. Naturforsch. Ges. Freiburg i.B.,* for May. Also *Ann. Physik,* Vol.17.

(1906) 55. W. Kaufmann, "Über die Konstitution des Elektrons" (The constitution of the electron), *Ann. Physik,* Vol.19. (Received 3rd January.)

It is not without interest to see from *this list how, during the years 1887-1894, the subject under discussion has suddenly, as it were, become the field of more abundant and more successful activity. The years prior to that period, with the exception of the fundamental work by Faraday and Maxwell, are marked by only sporadic and isolated symptoms of that activity, the years thereafter and down to the present by its increasingly fruitful pursuit.*