XX. Cathode, Lenard, and Röntgen Rays.
By William Sutherland.

To explain the results of his experiments on cathode rays, and to account for the Hertz-Lenard apparent passage of cathode rays through solid bodies according to Lenard's wonderfully simple law, J. J. Thomson (Phil. Mag. [5] xlv., Oct. 1897) proposes the hypothesis, that the matter in the cathode stream consists of atoms resolved into particles of that primitive substance out of which atoms have been supposed to be composed. Before a theory of such momentous importance should be entertained, it is necessary to examine whether the facts to be explained by it are not better accounted for by the logical development of established or widely accepted principles of electrical science.

The chief facts which Thomson arrives at from his experiments are:—That the cathode rays travel at the same speed in different gases such as hydrogen, air, and carbonic dioxide; and that $m/e$, the ratio of the mass of the particles to their charge, is the same for the cathode streams in all gases, and is about $10^{-3}$ of the ratio of the mass of the hydrogen atom to its charge in ordinary electrolysis. These seeming facts have also been brought out with great distinctness in the experiments of Kaufmann (Wied. Ann. lxi. and lxii.)

Whatever proves to be the right theory of the nature of the cathode rays, the quantitative results which these experimenters have obtained (as did also Lenard), in a region, where, amid a bewildering wealth of qualitative work, the quantitative appeared as if unattainable, must constitute a firm stretch of the roadway to the truth.

Let us briefly consider the theories used by J. J. Thomson and by Kaufmann to interpret their experiments. For instance, Thomson considers $N$ particles projected from the cathode, each of mass $m$, to strike a thermopile, to which they give up their kinetic energy $\frac{1}{2}Nm^2v^2$ measured as $W$. Each of the particles carries its charge of electricity $e$, the whole quantity $Ne$ being measured as $Q$. Thus we have

$$\frac{1}{2}mv^2e = W/Q.$$  

But again, the particles, after being projected through a slit in the anode with velocity $v$, are subjected to a field $H$ of magnetic force at right angles to the direction of motion, so that the actual force tending to deflect each particle is $Hev$ at right angles to $H$ and $v$. The result is that each particle describes a circular path of radius $\rho$ with the centrifugal

* Communicated by the Author.

force $\frac{mv^2}{\rho}$ equal to $Hev$, and therefore our second equation is

$$\frac{vm}{e} = Hp \ldots \ldots \ldots \ldots (2)$$

By measuring $W/Q$ and $Hp$, Thomson is able to deduce values of $v$ and $m/e$ from (1) and (2), and these are the values which lead to his remarkable conclusions already given.

Thomson and Kaufmann control the results of this method by a second method of experimenting, in which deflexion of cathode rays was produced by electrostatic force, as well as by magnetic, the forces in Thomson's experiments being adjusted so that the deflexions in both cases were the same, and therefore, if $F$ is the electric force,

$$Fe = Hev \ldots \ldots \ldots \ldots (3)$$

Thus an independent measure of $v$ is taken, and as it confirms those made by the other method, the experimental evidence for the simplicity of the laws of cathode motion is greatly strengthened. But in the theory of these experiments there is one suppressed premiss, namely, that a charge $e$ must be associated with some mass $m$. Now in following up the ionic hypothesis as far as it will go, it is our duty to use this premiss as one of the links in the chain of reasoning; but when it leads us to a conclusion subversive of the ionic hypothesis, namely, that atoms are split up into particles having different charges from the atomic charge in electrolysis, then we are no longer bound by the ionic hypothesis. It may therefore be that free electrons can appear in the æther, and that in the cathode stream the greater part of the electricity travels as free electrons.

A systematic statement of the reasons for contemplating the possibility of the motion of free electrons through the æther will be given below; but in the present connexion it is of most importance to consider whether such electrons could give up to the thermopile the kinetic energy measured by Thomson. From the writings of Thomson, Heaviside, Searle, and Morton (Phil. Mag. [5] xi., xxvii., xxviii., xli., xliv.) we can form an idea as to what takes place when an electron is set in motion. These writings relate to electric charges on conducting spheres and ellipsoids, the charges being caused to move by the motion of the conductors; but in the case of the free electron we cannot say that its charge is on anything, unless a modified portion of the æther. Our simplest plan is to regard the electron as a spherical shell of electricity of total amount $e$, the radius being $a$.

The main effect of setting such an electron in motion by means of some source of energy, is that electric and magnetic
energy are spread into the æther with the velocity of light \( V \), so that when the electron has velocity \( u \) the total amount of such electric and magnetic energy is (Searle, Phil. Mag. xlv.)

\[
\frac{e^2}{2Ka} \left( \frac{V}{u} \log \frac{V+u}{V-u} - 1 \right).
\]

If \( u \) is small compared with \( V \) this is

\[
\frac{e^2}{2Ka} \left( 1 + \frac{2}{3} \frac{u^2}{V^2} + \ldots \right);
\]

and taking account only of the part of this energy due to motion, we have Heaviside's result:

\[
e^2 \frac{u^2}{3Ka} V^2 \quad \text{or} \quad \mu e^2 u^2 / 3a.
\]

Now if the process, by which some of our store of energy was converted into electric and magnetic forms on setting the electron in motion, is a reversible one, then on stopping the electron in a suitable manner the electric and magnetic energy ought to flow back to our source or to the stopping body, and if there are no arrangements at the stopping body suitable for storing this as ordinary kinetic or potential energy, it will appear as heat amongst the particles which take part in the stoppage. Thus, then, certain actions of a moving electron take place as if it had a localized inertia, just as in the theory of electric currents a large part of their behaviour is such as it would be if the moving electricity had localized inertia. According to Searle's expression, the inertia or effective mass of the electron becomes a function of its velocity, if we define it as the quantity which is to be multiplied by half the square of the velocity to give the kinetic energy. With Heaviside's expression for smaller velocities, we should have the inertia equal to \( 2\mu e^2 / 3a \). But apart from these details, we have only to assume that the energy imparted to an electron when it is set in motion (or the greater part of it) is given up as heat to the material particles which arrest its motion, and is equal to half the square of the velocity multiplied by a certain quantity characteristic of the electron and appearing by the symbol \( m \) in the equations of Thomson and Kaufmann. Then the experimental results are at once explained; for as the negative electrons are the same in all the experiments, \( m/e \) has the same value for cathode streams in all gases: the gas facilitates the electric discharge, but does not control it; as a steam-engine can give the same results with several lubricants, so the cathode stream can give the same stream of electric energy by means of its.
moving free electrons, whatever may be the gas used to facilitate its flowing.

We can use Thomson's and Kaufmann's value of $m/e$, namely, about $10^{-7}$ when $e$ is measured in electromagnetic units, to calculate the order of magnitude of $a$ the radius of the electron. With the relation $m/e = 2\mu e/3a$ and $\mu = 1$ and $e = 10^{-21}$ in the electromagnetic system of units, we then have $a = 10^{-14}$ nearly, while the radii of molecules are of the order $10^{-8}$ cm., so that the linear dimensions of an electron are about the millionth part of those of molecules. We must therefore concede to the electron great freedom of motion in the interstices between the molecules even of solid bodies.

A very remarkable fact about the equations of motion of the cathode stream used by Thomson is that, although the velocity attained is about one-third that of light, there is no sign of any necessity to take account of appreciable frictional resistance. The electrons stream through the æther with nearly the velocity of light and yet provoke no noticeable resistance. What wonder, then, that any æthereal resistance to planetary motion has remained beyond our ken!

The importance of the quantitative results in these experiments has necessitated their being discussed out of their historical and logical order in a train of thought on cathode and allied rays, which order we will now attempt to follow briefly.

Stoney's interpretation of Faraday's law of Electrolysis to mean that electricity exists in separate natural units, the electrons, as definitely as matter in atoms, is now generally accepted, after Helmholtz's independent advocacy of it in his Faraday lecture.

Many workers have investigated the general dynamics of electrons, but mostly on the supposition that the electron must be associated with an atom, so that they form in conjunction an ion. But if electric action in matter is to be explained only by the participation of electrons, it naturally follows that we should contemplate the existence of electrons in the æther to enable it to play its part in electrical action.

And next we have to take account of the hypothesis advanced by Helmholtz in his Faraday lecture (Chem. Soc. Trans. xxxix. 1881) to explain Contact Electromotive Force, namely, that different atoms attract electrons with different amounts of force. This hypothesis may not be generally accepted yet, but we propose to follow out its logical consequences. If two things attract one another they must be entities of somewhat the same sort, and therefore the electron is
of essentially the same nature as an atom. But further, if two things attract one another, we must conceive the possibility of their being drawn apart, so that the ion can be split into an uncharged atom and an electron free of attachment to matter. Maxwell's ascription of inertia to electricity, in his theory of induced currents, bears out our conclusion that the atom and the electron are things of the same sort in many respects. If the electrons are distributed through the æther, we must suppose that in æther showing no electric charge each negative electron is united with a positive electron to form the analogue of a material molecule, which might conveniently be called a neutron. Of the existence of neutrons in the æther we have powerful evidence in Trowbridge's wonderful experiments ("The Electrical Conductivity of the Æther," Phil. Mag. [5] xliii., May 1897). He opens his account of them with a mention of Edlund's old contention that the æther is a conductor and J. J. Thomson's refutation of it, and closes it with the statement, "My experiments lead me to conclude that under very high electrical stress the æther breaks down and becomes a good conductor." Thus both Edlund's contention and J. J. Thomson's are happily reconciled; the æther is a perfect insulator until it is broken down, after which it is a conductor. According to the present theory, Trowbridge's result would be worded thus:—The æther insulates until the electric force at some point is sufficient to decompose the neutrons into electrons, whereupon it becomes a conductor of the same type as electrolytes. This principle should help practical electricians to construct a consistent theory of the hitherto rather intractable electric arc.

But to return to the cathode rays. The volume of experimental and theoretical work on the ionization of gases, which has been turned out from the Cavendish Laboratory, leaves no doubt as to the existence of ions in rare gases through which a current of electricity is passing: hence in the cathode stream there must be a certain number of ions flying along side by side with the electrons; but the experiments of Thomson and Kaufmann, according to our interpretation, prove that the stream of ions is of quite subsidiary importance to the stream of electrons. This is not always necessarily the case in the electric discharge through gases, and it seems to me that, for a satisfactory theory of the varied phenomena of electric conduction through gases, we must take account of the fact that we have two conducting media participating in the action namely, varying numbers of ions and also of free electrons.

Our theory of the cathode stream has the advantage that it
Mr. W. Sutherland on leads in a most natural manner to a theory of the Lenard rays. The cathode stream of electrons, moving with a velocity nearly that of light, possessing inertia, and yet of a size that is small compared to the molecular interspaces in solids, must be able to penetrate a solid that is thin enough, and to emerge on the other side, differing from the original cathode stream only in that the small trace of moving ions has been filtered out. Practically then Lenard rays are cathode rays. This is what experiment has abundantly proved. All the main properties of the cathode rays have been re-observed in the Lenard rays: thus Perrin proves that the cathode stream carries negative electricity, McClelland proves the same for the Lenard rays: Röntgen discovers that where the cathode stream strikes a solid it emits Röntgen rays; Des Coudres proves that where the Lenard rays strike a solid they also emit Röntgen rays: Goldstein discovered that the cathode stream colours salts, especially haloid salts of the alkalis, in a remarkable way; Des Coudres proves the same for the Lenard stream: and so on with such properties as magnetic and electric deflectability, power of exciting luminescence, and the like. The cathode and Lenard streams are the simplest forms of electric current known to us. Such a power as that of causing certain substances to emit light is only another form of our fundamental principle, that an electron in having its motion arrested imparts energy to the arresting molecules, and of course to their associated electrons. The colouring of salts discovered by Goldstein would be accounted for by the supposition that some of the negative electrons attach themselves to the electronegative atoms, thereby converting them into free ions, and liberating uncharged atoms of the metal, which cause the coloration. The experiments which have been made, with negative results, to detect the metal or the ion chemically do not decide anything, because of course the amounts produced are too small for ordinary methods of analysis to detect. The fatigue, which some substances show after fluorescing for a while under the influence of the cathode stream, may be accounted for in a similar manner by the lodgement of free electrons, which produce an opposing electromotive force and diminish the intensity of the cathode stream, while at the same time producing an analogous change to the change of colour in the salts studied by Goldstein, except that the change does not appear as visible colour, but as a lowering of fluorescent power. Fluorescence is known to be very sensitive to the presence of small traces of substances.

We do not know enough of the relations of atoms and
electrons to formulate \textit{à priori} what ought to be the law of
the resistance of bodies to the passage of a stream of electrons
through them; but fortunately we have the comprehensive
investigations of Lenard on the subject and can give a
reasonable explanation of his results. He found (Wied. Ann.
Ivi.) that for a great variety of substances of densities varying
from that of hydrogen at 3 mm. of mercury pressure (0.0368)
to that of gold (19.3), the resistance to the passage of Lenard
rays depended almost solely on density, the coefficient of
absorption being proportional to the density. Now we should
expect our electron being so small compared to atoms, and
moving with high velocities, to deform locally any atom
which it strikes, and to rebound before the deformation had
travelled far into the substance of the atom, so that after the
electron had departed the atom would be left with an increase
of vibrational energy, but no direct appreciable increase of
translatory energy; then, if the velocity of propagation of a
disturbance in all atoms is the same, and also the time of an
encounter between atom and electron constant, the energy
given up by an electron in an encounter with an atom will
be proportional to the density of the substance of the atom.
Now in the case of a solid, as an electron threads its way
through the molecular interspaces, the number of its encounters
will be proportional to the length of path, and therefore to
the thickness of the solid, and therefore the coefficient of
absorption, which will relate to unit thickness of all substances,
will be proportional to the density of the substance of the
atom, which is nearly the same as the density of the sub-
stance; thus for solids we interpret Lenard's law of the
absorption of cathode rays.

In the case of gases an interesting difference presents
itself. The electron is not now threading its way through
narrow passages, but has far more clear space than obstacle
ahead of it. As the electron is very small itself, we may say
that in passing through a gas the number of times it en-
counters a molecule is proportional to the mean sectional area,
and therefore to the square of the radius $R$ of the molecule
regarded as a sphere, and also to the number of molecules
per unit volume ($n$); and if $m$ is the mass of the molecule the
density of its substance is proportional to $m/R^3$, and thus the
coefficient of absorption for a gas is proportional to $nR^2m/R^5$
or $nm/R$; but $nm$ is the density $\rho$, so that the coefficient of
absorption of a gas is proportional to the density, but also
inversely proportional to the molecular radius. Now this
theoretical conclusion corresponds partly with one of Lenard's
experimental results, namely, that although the coefficient of
absorption for a large number of gases appeared to be proportional to the density within the limits of experimental error, the coefficient for hydrogen was exceptional to an extent decidedly beyond possible experimental error. In his experiments, Lenard showed that if \( J_0 \) is the intensity of a Lenard stream at its source, \( J \) that at a distance \( r \) from the source in a substance whose coefficient of absorption is \( A \),

\[
J = J_0 e^{-Ar/r^2},
\]

and determined \( A \) for various gases at a pressure of one atmo. As the densities of these gases are as their molecular weights, with that of hydrogen = 2, he shows the relation of \( A \) to the density of different gases by tabulating values of \( A/m \); while according to our reasoning \( RA/m \) would be expected to be constant. The following table contains Lenard's values of \( 10^3A/m \), and relative values of \( R \) as given in my paper on the "Attraction of Unlike Molecules—The Diffusion of Gases," Phil. Mag. [5] xxxviii., being half the cube-root of the limiting space occupied by a gramme-molecule of the substance and controlled by comparison with molecular dimensions as given by experiments on the viscosity of gases; the last row contains the product \( 10^3RA/m \):

<table>
<thead>
<tr>
<th></th>
<th>( 10^3A/m )</th>
<th>( R )</th>
<th>( 10^3RA/m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>237</td>
<td>1.025</td>
<td>243</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>124</td>
<td>1.47</td>
<td>182</td>
</tr>
<tr>
<td>CO</td>
<td>122</td>
<td>1.35</td>
<td>165</td>
</tr>
<tr>
<td>C(_2)H(_4)</td>
<td>132</td>
<td>1.75</td>
<td>231</td>
</tr>
<tr>
<td>N(_2)</td>
<td>113</td>
<td>1.415</td>
<td>160</td>
</tr>
<tr>
<td>O(_2)</td>
<td>126</td>
<td>1.34</td>
<td>169</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>115</td>
<td>1.56</td>
<td>179</td>
</tr>
<tr>
<td>N(_2)O</td>
<td>102</td>
<td>1.535</td>
<td>157</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>133</td>
<td>1.63</td>
<td>217</td>
</tr>
</tbody>
</table>

Thus while Lenard's approximate constant ranges from 102 to 237, the one to which we have been led ranges from 157 to 243, which is an improvement. The really striking point about Lenard's discovery, however, is that when \( A \) is divided by density, the range in value is from 2070 for paper to 5610 for hydrogen at one atmo; the results for many substances such as gold and hydrogen at 1/228 atmo falling between these extremes. The fact that the value of \( A/\rho \) for a rare gas is almost the same as for a dense solid, would seem to indicate that it is only when an electron strikes an atom almost in the direction of a normal that the most important part of the absorption of energy occurs; for if this is so, the chance of an electron's encountering an atom in a solid normally, while threading its way through the interstices, being the same as if it could pass through all the atoms which it does not meet normally, the absorption of energy from an electron by a number of atoms should be the same whether they are as close as in a solid or as wide apart as in a rarefied gas. Thus probably the coefficient of absorption for a solid
depends on its molecular radius, but the data hardly permit of an examination into this point. It should be remarked that, as the electron can probably pass easily between the atoms in a molecule, the absorption due to a compound molecule ought to be analysed into the parts due to its atoms; for instance, in Lenard’s table of values for $A$ in such gases as $\text{CH}_4$, $\text{CO}_2$, $\text{C}_2\text{H}_4$, the part due to the carbon, the hydrogen, and the oxygen, ought to be separated out, and then each part ought to be proportional to the atomic mass and inversely proportional to the atomic radius. If this is so, then the agreement in the values of $RA/m$ in our table could not be expected to be perfect.

A very characteristic property of the Lenard rays follows from our theory, for when the cathode rays fall on an aluminium window, such as Lenard used, they have a direction normal to it, whereas the Lenard rays issuing on the other side of the window are uniformly radiated in all directions; and this is exactly how our stream of small electrons would behave, because after they have threaded their way through the molecular interstices, they will issue with directions uniformly distributed in space, for it is to be presumed that the final directions of the intermolecular passages will be distributed at random.

As the cathode and Lenard streams are currents of electrons, and therefore form pure electric currents, we might expect a priori that the coefficient of absorption of substances for them would show some decided relation to the electrical resistance of the substances; but Lenard’s law proves that such an expectation would be futile, for the absorption of conductor and insulator alike depends almost entirely on density. This fact throws considerable light on the nature of metallic conduction. It would seem as if in the conduction of electricity in metals, both the positive and negative electrons, distributed through the metals, take part in the process of conduction, probably in the method of the Grothuss chain; by a process of exchange of partners both kinds of electron get passed along in opposite directions without anything of the nature of a great rush of one kind of electron at one time and place. When such a rush occurs in a cathode stream, the internal appliances of the best conducting metal can no more facilitate its passage, than can the obstructing appliances of the best insulator hinder it. In metallic conduction we have to do with a property of the metallic atom, whereby, with the aid of electromotive force, the local dissociation of the neutron into electrons is greatly facilitated; whereas in insulators the reverse is the case. This important field of the
relations of electrons and atoms must be nearly ready for important developments.

Two more of Lenard's facts are of special importance, namely, that cathode rays, when passed through a window from the vacuum-tube in which they are generated, travel as Lenard rays through gas of such a density as would prevent the formation of the cathode rays, if it prevailed in the tube, whether that density is great, as in the ordinary atmosphere, or very small, as in a vacuum so high as to insulate under the electric forces in the tube. These facts are explained by our theory: the properly exhausted tube furnishes a requisite facility for splitting up the neutrons and getting a supply of electrons to be set swiftly in motion; once that is accomplished, nothing will stop them until it offers enough resistance to destroy the momentum of the electrons, and ordinary lengths of dense or rare air in Lenard's experiments failed to do this. The action of the tube in generating the cathode rays may be likened in this connexion to a Gifford's Steam Injector.

In the logical development of the present line of thought, an attempt at an explanation of the cause of the Röntgen rays must find a place. Already J. J. Thomson, in his paper on a Connexion between Cathode and Röntgen Rays (Phil. Mag. [5] xlv., Feb. 1898), has worked out in some detail the electromagnetic effect of suddenly stopping ions moving with high velocity, the main result being that thin electromagnetic pulses radiate from the ion. He believes that these pulses constitute the Röntgen rays, in agreement with a surmise of Stokes. Thomson's reasoning would apply to our free electrons just as to his ions, but there would be this important distinction, that while Thomson's hypothesis involves the condition that the greater part of the energy of the cathode stream consists of the kinetic energy of the atoms, in our hypothesis the energy belongs almost entirely to the moving electrons, and when these are stopped the energy appears as heat at the place of stoppage. Thus Thomson's electromagnetic pulses appear only as subsidiary phenomena in connexion with the conversion of the kinetic energy of the electrons into heat; indeed, we cannot be sure that they exist, because their existence has been suggested only in accordance with the particular assumptions in Thomson's hypothesis which correspond to only a limited portion of the complete electrodynamics of such an action as is contemplated in this paper, causing the conversion of all or almost all the kinetic energy of an electron into heat. Moreover, in tracing the relation of Lenard rays to cathode rays we have been led to picture the stoppage of the moving electrons as nothing
like so sudden as that which Thomson has to contemplate for his charges: this of course only makes a difference in the degree of intensity of the phenomena resulting from the stoppage. There has as yet been no systematic proof that the properties of a train of impulses would be the same as those of the Röntgen rays in the matter of the absence of refraction and reflection. Again, it is recognized that the Röntgen rays and the Becquerel rays from uranium are very similar, but it would be hard to imagine the Becquerel rays to be due to thin impulses. On these grounds it seems to me that Thomson's suggestion as to the cause of the Röntgen rays, although exciting one's admiration by its clear consistency, does not lead to the desired end; and therefore I will try to follow out the premisses of this paper to such conclusions as may relate to phenomena like those of the Röntgen rays.

To the electrons we have assigned inertia and size, and we must therefore ascribe to them shape; but a general conception of shape involves also the notion of deformability, which, therefore, we must consider as a possible property of the electron. The electron is therefore to be supposed capable of emitting vibrations due to the relative motions of its parts; as light is supposed to be due to the motion of electrons as wholes, we see that the internal vibrations of electrons will have this much in common with light, that they are transmitted by the same aether, but they need have nothing else in common. We propose, then, to identify the Röntgen rays with these internal vibrations of our electrons. It might be expected that the electron, in executing the motions which cause light, would get strained and thrown into internal vibration, so that Röntgen rays would accompany ordinary light; but the fact that Röntgen rays cannot be detected in association with light shows that the motion of the electron occurs either so that it is very free from shock and strain, or so that atoms promptly damp any internal vibrations of adjacent electrons. The way in which matter absorbs the energy of Röntgen rays shows that we may rely on atoms to suppress any small amount of Röntgen radiation that might tend to accompany ordinary light as emitted by electrons. Thus, then, appreciable Röntgen radiation is to be looked for only when free electrons are thrown into vigorous internal vibration. Internal vibrations should originate where cathode or Lenard
rays are absorbed, and most powerfully where the absorption is most powerful: this corresponds with all the facts as to the place of origin of Röntgen rays.

As to what must be the order of magnitude of the length of the waves in the æther produced by the internal vibrations of the electrons, we can form no à priori estimate, but under the circumstances we are at liberty to assume that, like the size of the electron, it is small compared to that of atoms, and small also compared to molecular interspaces. We shall then have to do with systems of waves, which, when they fall on a body, can travel freely in the molecular interspaces, but are liable to absorption near the surfaces of molecules. The propagation of such a system of waves would take place almost entirely in the æther of the interspaces, as sound travels through a loose pile of stones mostly by the air-spaces; the molecules cause absorption, but do not act as if they loaded the æther. Therefore when our system of waves enters a body it experiences no refraction. As to reflexion at the first layer of molecules which it encounters, we must remember that our wave-length is small compared to the radius of a molecule or atom, and that therefore in studying reflexion it suffices to study that from a single molecule; whereas, with ordinary light, where the wave-length is large compared to atomic radius, we have to take the effect of a large number of contiguous molecules, if we are to reason out results comparable with those observed in ordinary reflexion. Now the reflexion of our small waves from a single molecule will be of the same nature as reflexion from a sphere, and will be similar to diffuse scattering, a good deal of the scattering being towards the neighbouring interstices. Thus the attempt to reflect these waves from a material plane surface will be similar to that of attempting to reflect ordinary light from a large number of smooth spheres whose centres lie in a plane. If we take the average effect of a large number of molecules whose centres are by no means in a plane, as must be the case with our best reflecting surfaces, we see that a diffuse scattering of our small waves must take the place of reflexion, and this is the experimental result with the Röntgen rays.

Any polarization that our system of waves might possess could not be detected by the ordinary optical appliances, because these depend on actions exercised by the molecules on the vibrations of light, whereas, as our small waves travel by the interstices between the molecules, their character is not controlled to any appreciable extent by the molecular structure. This result also agrees with the experimental one
that polarization of the Röntgen rays cannot be detected by ordinary optical apparatus for the purpose.

These negative properties have been explained chiefly by the assumed smallness of the wave-length, and have, therefore, little direct connexion with our theory of the Röntgen rays beyond indicating the probability of a small wave-length for the Röntgen rays for similar reasons to those usually urged. We must, therefore, proceed to properties that our short waves must possess by virtue of their origin in vibrating electrons. In the first place, we should expect the electrons forming the neutrons in the æther to be set vibrating by our waves; but if they produce no dissipation of the energy, they will not cause any absorption, but will simply participate in the general æthereal operations of propagating the waves. But when the waves get amongst the electrons associated with atoms, and set them vibrating internally, there is called forth that resistance to the vibration which constitutes the damping action already spoken of. One of the probable results of such an action would be the setting of the acting and reacting atom and electron into relative motion, so causing the absorbed Röntgen energy to appear as some form of radiant energy congenial to the atom and electron. In this way our waves could give rise to fluorescent and photographic effects in the manner of the Röntgen rays. If an electron absorbs enough of the energy of our small waves, it may be set into such vigorous motion as to escape from the atom with which it is acting and reacting, and appear as a free electron, or it may associate itself with an electron* to form an ion. At the foundation of our theory we suppose our small waves to be produced by the deformation of an electron during a vigorous transfer of energy from electron to atom; and now we suppose this to be a reversible action, so that an electron set vibrating near to an atom can convert enough of its vibrational energy into translational kinetic energy to escape from the atom. With this legitimate dynamic assumption of reversibility, we can deduce from our hypothesis the production of free electrons or ions in a dielectric traversed by our small waves, which is in agreement with the remarkable property possessed by the Röntgen rays of making gases conduct electricity well. The presence of scattered ions in a solid dielectric does not necessarily make it conduct. An experimental method of testing our theoretical conclusion, that Röntgen rays ought to have the same effect on solid dielectrics as on gases, would be to heat one till it gave decided signs of electrolytic conduction, and then test as to

* [Atom?]
whether conductivity is increased by radiation with Röntgen rays. Experiments on liquid dielectrics should be easy enough. One of Röntgen's observations is of special importance. He found that air, through which Röntgen rays are passing, emits Röntgen rays; and this is exactly what our theory would indicate, because, as we saw in discussing reflection, each atom scatters our small waves as a reflecting sphere distributes ordinary light.

The remaining important positive facts concerning Röntgen rays relate to their absorption in passing through different substances. Our short waves in passing through a unit cube of substance in a direction parallel to one of the edges, while passing along the molecular interspaces, will be falling at intervals directly on opposing surfaces of atoms; and if \( n \) be the number of atoms per unit volume, and \( R \) the radius of each, the quantity of surface encountered by unit area of wave-front will be proportional to \( nR^2 \), and the number of encounters in passing unit distance will be proportional to \( nR \), so that as regards amount of encounter of wave-front with atoms the energy absorbed by the atoms will be proportional to \( nR^2 \). But if the effectiveness of a collision in causing absorption from a given area of wave-front in a given time is also proportional to the density of the matter in the atom, that is to \( m/R^3 \), as we had to suppose in discussing the collisions of electrons and atoms, then the absorption of energy from our short waves in passage through unit length of different substances will be proportional to \( nm/R \), that is to the density and inversely to atomic radius as with Lenard rays. The fact that Röntgen rays produce powerful fluorescence in certain substances shows that there are special resonance phenomena that must be expected to produce decided variations in absorption from the simple form just discussed; but the fact remains, as discovered by Röntgen, that by far the most important factor in the absorption of Röntgen rays is density. Benoist (Compt. Rend. cxxiv.) has found that the absorption of Röntgen rays by certain gases is proportional to the density, the factor of proportionality being nearly the same as for solids such as mica, phosphorus, and aluminium, though rising to a value six times as great in the case of platinum and palladium; density is the prevailing, but not the only, property which determines the absorption of the Röntgen rays. But under different circumstances Röntgen-ray apparatus gives out rays of very different absorbability; or, as it is usually expressed, of different penetrative power. Thomson's theory of the Röntgen rays, as thin electromagnetic pulses, does not seem to offer any feasible ex-
planation of this fundamental fact. The theory of vibrating electrons requires that, in addition to the fundamental mode of vibration, we must contemplate a number of harmonics associated with it; various combinations of fundamental and harmonics will be associated with different conditions of generation of the vibrations, and these will correspond to the Röntgen rays of different penetrative power.

An interesting observation of Swinton's, that two colliding cathode streams do not give rise to Röntgen rays, is explained by our hypothesis, because the electrons are so small and so far apart that an appreciable number of collisions between the electrons of two colliding streams cannot occur.

Some consequences of our line of reasoning, to which as yet no corresponding experimental results have been obtained, may now be indicated. The difference between cathode and anode is due to the fact that the attraction of metallic atoms for positive electrons is stronger than for negative ones, so that under a given electrical stress negative electrons break away as a cathode stream more easily than positive ones as an anode stream. But still, under strong enough electric stress at the anode, it ought to be possible to get an anode stream or anode rays similar to the cathode rays, but carrying positive electricity. These on encountering atoms, especially the atoms of a solid body, should cause the emission of rays similar to the Röntgen, but possibly very different in detailed properties, such as wave-length. It is possible that the Becquerel rays may be examples of what we may call positive Röntgen rays, because, while we have seen that, in the majority of cases, electrons move relatively to atoms in the production of light, in such a manner that they do not experience shocks throwing them into internal vibration, the uranium atom may be so formed that it periodically collides with its satellite electron or electrons, in which case the atoms of uranium would be a source of radiation analogous to the Röntgen.

According to our theory the velocity of the cathode stream is not a physical constant like the velocity of light through the æther, but ought to vary greatly according to the history of the stream, which starts with zero velocity and ends with the same. The velocity of the Röntgen rays should be of the order of that of light: we cannot assert that it should be exactly equal to that of light, because to waves of so short a length the neutrons may act as if they loaded the æther, so that Röntgen rays may suffer a refraction in æther in comparison with light. The fact that the experimental velocities found for the cathode rays are of the order of the velocity of
light is a striking one, to be compared with the fact that in the *vena contracta* of a gas escaping from an orifice the maximum velocity attainable is nearly that of the agitation of the average molecule in the containing vessel or of sound in the gas.

It appears as though a complete theory of electricity would be a kinetic theory, in which the place of the atoms or molecules of the kinetic theory of matter is taken by the electrons. The ion appears as a sort of molecule formed by the union of an atom or radical to an electron. But such large questions can hardly be opened up in the present connexion. We may summarize the contentions of the preceding pages in the two propositions:

- The cathode and Lenard rays are streams, not of ions, but of free negative electrons.
- The Röntgen rays are caused by the internal vibrations of free electrons.

Melbourne, Nov. 1898.

---

**XXI. Properties of Liquid Mixtures.—Part III.* Partially Miscible Liquids.** By R. A. LEHFELDT, D.Sc.†

The phenomena of complete mixture between two liquids, about which so little systematic knowledge is yet in existence, are connected with the phenomena of ordinary solution by an intermediate stage, that in which two liquids dissolve one another to a limited extent only. The study of such couples seems a promising field of investigation, on account of the intermediate position they occupy; it seems to offer the chance of extending some of the laws arrived at with regard to simple solution to the more complicated cases; I have therefore attempted to get some information on the equilibrium between incomplete mixtures and the vapour over them, and especially at the “critical point,” i.e., the point at which incomplete miscibility passes over into complete. A recent short paper by Ostwald ‡ draws attention to the importance of that point in the theory of mixtures.

**Choice of Liquids.**

The first point is to obtain suitable pairs of liquids for experiment. In order to study the properties of the critical point with ordinary vapour-pressure apparatus, it is necessary

† Communicated by the Physical Society: read Nov. 25, 1898.