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Sir J. J. Thomson and G. P. Thomson
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CHAPTER I

SOME PROPERTIES OF CATHODE RAYS

In Vol. I an account has been given of measurements of the mass of the cathode rays, and of their velocity. In this and the two following chapters we shall consider some of their other properties, leaving an account of the part which they play in the mechanism of the discharge till Chapter VIII.

The cathode rays were discovered by Plücker[1] in 1859; he observed on the glass of a highly exhausted tube in the neighbourhood of the cathode a bright phosphorescence of a greenish-yellow colour. He found that these patches of phosphorescence changed their position when a magnet was brought near to them, but that their deflection was not of the same nature as that of the rest of the discharge which he had carefully studied. Plücker ascribed the phosphorescence to currents of electricity which went from the cathode to the walls of the tube and then retraced, for some reason or another, their steps.

The subject was next taken up by Plücker's pupil Hittorf[2], to whom we owe the discovery that a solid body placed between a pointed cathode and the walls of the tube casts a well-defined shadow, the shape of the shadow depending only upon that of the body, and not upon whether the latter be opaque or transparent, an insulator or a conductor. This observation was confirmed and extended by Goldstein[3], who found that a well-marked, though not very sharply defined, shadow was cast by a small body near the cathode, whose area was much greater than that of the body: this was a very important observation, for it showed that the rays producing the phosphorescence came in a definite direction from the cathode. If the cathode were replaced by a luminous disc of the same size, no shadow would be cast by a small object placed near it; for though the object might intercept

1 Plücker, *Pogg. Ann.* cvii. p. 77, 1859; cxvi. p. 45, 1862.
2 Hittorf, *Pogg. Ann.* cxxxvi. p. 8, 1869.
3 Goldstein, *Berl. Monat.* p. 284, 1876.

the rays which came normally from the disc, yet enough light would be given out sideways by other parts of the disc to prevent the shadow being well marked. Goldstein, who introduced the term 'Kathodenstrahlen' for these rays, regarded them as waves in the ether, a view which received much support in Germany. A very different opinion as to the origin of the rays was expressed by Varley[1], and later by Crookes[2], who advanced many and weighty arguments in support of the view that the cathode rays were electrified particles shot out from the cathode at right angles to its surface with great velocity, causing phosphorescence and heat by their impact with the walls of the tube, and suffering a deflection when exposed to a magnetic field by virtue of the charge they carried. The particles in this theory were supposed to be of the dimensions of ordinary molecules; the discovery made by Hertz[3] that the cathode rays could penetrate thin gold-leaf or aluminium was difficult to reconcile with this view of the cathode rays; although it was possible that the metal when exposed to a torrent of negatively electrified particles acted itself like a cathode and produced phosphorescence on the glass behind. The measurements described in Vol. I of the mass of the particles carrying the charge show that though the cathode rays do consist of negatively electrified particles, the particles are not of the magnitude of even the smallest molecules, having a mass only about one-four-thousandth part of that of a molecule of hydrogen. We shall now proceed to describe the properties of the cathode rays in detail, beginning with that which led to their discovery, viz. the phosphorescence they produce when they fall on solids.

Phosphorescent Effects and Colour Changes.

The colour of the phosphorescent light they produce when they fall on glass depends upon the nature of the glass; thus with soda glass the light is yellowish-green, with lead glass it is blue. A very large number of bodies become phosphorescent when exposed to these rays; indeed, this phosphorescence often affords a convenient means for detecting the rays: as phosphorescence is very easily excited in potassium platino-cyanide, a screen of

1 Varley, *Proc. Roy. Soc.* xix. p. 236, 1871.
2 Crookes, *Phil. Trans.* clxx. pp. 135, 641, 1879.
3 Hertz, *Wied. Ann.* xlv. p. 28, 1892.

this substance is often used to detect the rays. The spectrum of the light given out by bodies when phosphorescing under bombardment by these rays is generally a continuous one. Sir William Crookes has shown that when the cathode rays fall on some of the rare earths, such as yttrium, the substance gives out a spectrum with bright bands; he has founded on this observation a spectroscopic method which is of the greatest importance in the study o the rare earths[1]. These earths are luminous when raised to a high temperature as in the mantles of Welsbach burners; there is, however, a marked difference between the incandescence produced in this way and that produced by cathode rays; thus in the Welsbach burner the addition of 1 per cent. of ceria to thoria increases the luminosity elevenfold as compared with that of pure thoria. Campbell Swinton[2] has shown, however, that it produces no appreciable change in the luminosity under cathode rays: again, in the flame pure ceria gives about as much light as pure thoria, while under cathode rays pure thoria gives a brilliant light, and pure ceria practically no light at all.

Among other convenient substances for the detection of cathode rays by phosphorescent action are the mineral willemite and preparations of zinc sulphide containing small amounts of various impurities. The light from the willemite is pale green, from the zinc sulphide it usually has a bluish tinge. While some samples of zinc sulphide are brighter than willemite, they have the disadvantage that the phosphorescence lasts for a considerable time after the cathode rays have ceased. This is inconvenient when one wants to observe changes in the distribution of the cathode rays. Willemite also shows some after-effect but not nearly so much. Zinc sulphide screens also are affected by the light they themselves emit, so that the contrast between the parts struck by the rays and the rest is not so great as for willemite.

In making a phosphorescent screen it is convenient to suspend the powdered willemite in water containing a little sodium silicate, and allow the solution to evaporate on a glass plate. The sodium silicate helps the willemite to stick to the glass. Calcium tungstate

1 Crookes, *Phil. Trans.* clxxiv. p. 891, 1883; clxxvi. p. 691, 1885.
2 Campbell Swinton, *Proc. Roy. Soc.* lxv. p. 115, 1899.

is often used for the screens in cathode ray oscillographs, it gives a blue light which is photographically active and shows little after-effect. Lenard (*Handbuch der Experimental-Physik*, xiv. p. 81) recommends the use of pentadecylparatolyketon. It is however only sensitive to electrons above 4000 volts energy, while willemite is sensitive down to one or two hundred. The luminosity of the keton is proportional to the intensity of the rays and it has no after-effect.

Lithium chloride gives a strong luminosity. If a beam of cathode rays is slowly moved over the salt by a magnet, the path of the beam traces out a coloured band over the surface of the salt. The light given out is blue, but if positive rays are used instead of cathode rays lithium chloride shines with the red light of a lithium flame. It is thus a useful indicator. The impact of the cathode rays produces in some cases very definite chemical changes; thus Goldstein[1] has shown that the haloid salts of the alkali metals change colour when exposed to the rays. For example, crystals of rocksalt acquire under the rays an amber tint which changes to blue on heating to 200° C.; this tint is not permanent, though under certain circumstances the rate of decay is exceedingly slow: thus there were at the Cavendish Laboratory some of these crystals which, corked up in a test-tube but not kept in the dark, retained a strong coloration for more than seven years: exposure to moisture causes the colour to fade away rapidly. The original amber tint disappears quickly, especially in the light. Similar changes in colour can be produced by chemical means; thus if sodium chloride is heated up with sodium vapour it gets coloured in much the same way as if it were exposed to cathode rays; the coloured salt is also produced at the cathode in the electrolysis of haloid salts. The blue salt also occurs native.

When naturally coloured blue rocksalt is examined by the method of electron diffraction (see below) it shows the structure of normal sodium chloride. Elster and Geitel[2] discovered that these coloured salts are very photo-electric, discharging negative electricity when exposed to light; behaving, in fact, as if they contained traces of the free metal. Pohl and his co-workers have shown that the blue colour is due to minute particles of metallic sodium dis-

1 Goldstein, *Wied. Ann.* liv. p. 371, 1895.
2 Elster and Geitel, *Wied. Ann.* lix. p. 487, 1896.

seminated throughout the crystal. Gudden and Pohl have made extensive studies of the conductivity of coloured rocksalt under the influence of ultra-violet light. (See *Die Lichtelektrische Erscheinungen*, Berlin, 1929.) The colour changes have been extensively studied by Przibram and his co-workers in Vienna. A general account of this work, with references, is given in a paper by Przibram, *Zeits. f. Phys.* xli. p. 833, 1927. The glass of a vacuum tube also acquires a violet tint after long use.

The power of glass to phosphoresce is deadened by long exposure to cathode rays: this is very beautifully shown in an experiment made by Crookes[1]. The shadow of a mica cross was thrown upon the walls of the tube; after the discharge had been running for some time the cross was shaken down or a new cathode in a different part of the tube was used; the pattern of the cross could still be traced on the glass, but it was now brighter than the rest of the glass, instead of darker as before. The portions outside the original pattern got tired by the bombardment, and so in the second part of the experiment phosphoresced less brightly than the portions inside the original shadow which were now bombarded for the first time. Crookes[1] found that the change in the phosphorescence of the glass persisted even after the glass had been fused and again allowed to cool. All the substances used as phosphorescent screens also show a fatigue effect, and cease to function after long exposure.

Villard[2] found that cathode rays exert a reducing action; thus if they fall upon an oxidised copper plate, the part exposed to the rays becomes bright. In considering the chemical effects produced by the rays we ought not to forget that the incidence of the rays is often accompanied by a great increase in temperature, and that some of the chemical changes may be secondary effects due to the heat produced by the rays. Platinum after long exposure to the rays gets covered with platinum black.

Thermoluminescence.

In some cases, even when no visible coloration is produced, the behaviour of the body after exposure to the rays shows that it

1 Crookes, *Phil. Trans.* clxx. p. 645, 1879.
2 Villard, *Journal de Physique*, 3me Série, t. viii. p. 140, 1899.

has been changed. A very striking instance is the property called by E. Wiedemann[1] 'Thermoluminescence.' Some bodies, after exposure to cathode rays, are found to possess for some time the power of becoming luminous when their temperature is raised to a point far below that at which they become luminous when in their

Substance	Cathode phosphorescence	After-glow	Thermo-luminescence
$CaSO_4$	Faint yellowish red	None	None
$CaSO_4 + x\,MnSO_4$	Intense green	Strong green	Intense green
$SrSO_4$	None	—	—
$SrSO_4 + x\,MnSO_4$	Bright red	Perceptible	Perceptible
$BaSO_4$	Faint dark violet	—	—
$BaSO_4 + x\,MnSO_4$	Dark blue	Faint	Very faint
$MgSO_4$	Red	Perceptible	Feeble
$MgSO_4 + 1\,\%\,MnSO_4$	Intense dark red	Persistent	Intense red
$ZnSO_4$	Bright, white	Persistent	White
$ZnSO_4 + 1\,\%\,MnSO_4$	Intense red	Very persistent	Very strong red
Na_2SO_4	Bluish	Faint	Bright
$Na_2SO_4 + 0{\cdot}5\,\%\,MnSO_4$	Intense brownish yellow	Strong	Bright yellow
$CdSO_4$	Yellow	Persistent	Bright yellow
$CdSO_4 + 1\,\%\,MnSO_4$	Intense yellow	Very persistent	Intense yellow
$CaFl_2$	Faint bluish	Very faint	Faint
$CaFl_2 + x\,MnFl_2$	Intense green	Persistent	Intense green

normal state; they retain this property for weeks, and even months, after exposure to the rays. The substances in which this property is most highly developed belong to the class of bodies called by Van 't Hoff[2] 'solid solutions'; these are formed by precipitating simultaneously from a solution two salts, one greatly in excess of the other. The influence of a slight trace of a second substance on the phosphorescence produced while the rays are playing on the substance, on the after-glow, which lingers for a time after the rays are stopped, and on the thermoluminescence is shown by the preceding table, due to E. Wiedemann and Schmidt[3]. By the symbol $CaSO_4 + x\,MnSO_4$ is meant a 'solid solution' of a trace of $MnSO_4$ in a matrix of $CaSO_4$. Frisch (quoted by Przibram, *l.c.*)

1 E. Wiedemann and Schmidt, *Wied. Ann.* liv. p. 604, 1895.
2 Van 't Hoff, *Zeitschr. f. physik. Chem.* v. p. 322, 1890.
3 E. Wiedemann and Schmidt, *Wied. Ann.* lvi. p. 201, 1895.

finds that thermoluminescence is produced in rocksalt by electrons with energies down to 10 volts or even less.

Thermal Effects produced by the Rays.

The cathode rays heat bodies on which they fall. If the rays are concentrated by using a concave cathode the effect is very intense and even refractory substances such as platinum may be melted. In an X-ray bulb elaborate precautions have to be taken to cool, usually by a stream of water, the target which the cathode rays strike. It is easy to calculate the heat produced on the assumption that all the energy of the cathode rays is concentrated into heat. In this case the rate of production is Vi/J, where i is the electron current and V the potential difference between cathode and target. Actually a small proportion, of the order of 1 per cent., will be transformed into X-rays. In addition some energy may be lost in the form of reflected rays (Chap. v). These however will carry their full charge but less than their full energy, so that if i is the net current measured at the target the effect of reflection will be to make the heat produced greater than Vi/J. Any secondary electronic emission will have an effect in the same direction.

Mechanical Effects produced by the Rays.

A secondary result of the thermal effects produced by the rays are the very interesting mechanical effects which have been especially studied by Crookes[1] and Puluz[2]. A typical example of these is afforded by the well-known experiment due to Crookes represented in Fig. 1, where the axle of a very light mill with a series of vanes is mounted on glass rails in a vacuum tube; when the discharge passes through the tube the cathode rays strike against the upper vanes and the wheel rotates and travels from the negative to the positive end of the tube.

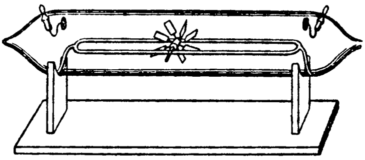

Fig. 1.

A simple calculation will show that we cannot ascribe the rotation to the momentum communicated to the vanes by the

1 Crookes, *Phil. Trans.* clxx. p. 152, 1879.
2 Puluz, *Radiant Electrode Matter.* Physical Society's Reprint of Memoirs, p. 275.

impact of the electrons against them; for, take the case when the rays are so powerful that they carry the very large current of 10^{-5} ampere, and that they move with the very high velocity of 10^{10} cm./sec.: if N is the number of electrons striking a surface in unit time, m the mass of the electrons, then even supposing the electrons to rebound from the surface with a velocity equal to that with which they impinge against it, the momentum communicated to the surface in unit time is $2Nm.10^{10}$; if e is the charge carried by an electron, then Ne is the current carried by the rays, in our case 10^{-6} in absolute measure; hence the momentum communicated to the surface per second is equal to $2\frac{m}{e}10^4$ dynes, or as $m/e = 6 \times 10^{-8}$, to $1{\cdot}2 \times 10^{-3}$ dyne: this is equivalent to a difference of pressure on the two sides of a vane 1 sq. cm. in area of one-seven-hundred-millionth part of an atmosphere; an effect altogether too small to explain the movement of a body such as that represented in Fig. 1. This movement is probably due to an effect similar to that observed in a radiometer, as the impact of the cathode rays will make one side of the vanes much hotter than the other. Starke[1] has shown that when the vanes are arranged so that the radiometer effect is eliminated, the mechanical effect is exceedingly small—in his experiments, where the current carried by the cathode rays was 10^{-7} ampere and the potential difference 10,000 volts—certainly less than 10^{-4} dyne.

Electric Charge carried by the Cathode Rays.

The fact that the cathode rays carry a negative charge of electricity was proved in a very direct way by Perrin[2]. Fig. 2 represents a modification of his experiment. The rays start from the cathode A and pass through a slit in a brass rod B, which fits tightly into the neck of the tube; this rod is connected with the earth and used as an anode; the rays after passing through the slit enter the spherical vessel C. In this vessel there are two coaxial metal cylinders, the outer one D connected with the earth, the inner one E carefully insulated and connected with an electrometer. The cylinders are placed so as to be out of the direct line

1 Starke, *Ann. der Phys.* iii. p. 101, 1900.
2 Perrin, *Comptes Rendus*, cxxi. p. 1130, 1895.

of fire of the rays. When the discharge passed through the tube and the cathode rays passed horizontally through the vessel *C*, the inner cylinder *E* received a small, but only small, negative charge. The cathode rays were then deflected by a magnet; their path could be inferred from the position of the phosphorescent patch on the walls of *C*; when the deflection was increased, so that the position of the patch showed that the rays had fallen on the opening of the cylinders, there was a very great increase in the negative charge received by *E*; when the rays had been so much

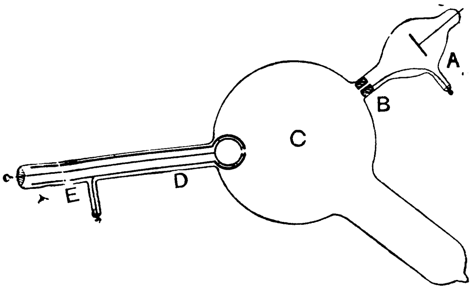

Fig. 2.

deflected that the phosphorescent patch fell below the slit, the negative charge in the cylinder *E* again disappeared. This experiment shows that the rays carry a negative charge, as it proves that the negative electrification follows exactly the same course as the rays producing the phosphorescence on the glass.

This experiment also shows that the cathode rays make the gas through which they pass a conductor of electricity; for if in the experiment the discharge is kept continuously passing through the tube and the cathode rays deflected until they pass into the cylinder, the negative charge on the cylinder will rise to a certain value, beyond which it will not increase however long the discharge may be kept running; this shows that the gas round the cylinder is a conductor, and the steady state of the cylinder is reached when it loses as much electricity by conduction through the gas as it gains from the cathode rays. The same thing is shown when the cylinder is given a negative charge before the discharge through the gas begins; if this charge is less than a certain value the cathode rays will increase the charge; if however it is greater than this value, the cathode rays will diminish the charge until it falls to this critical value.

An interesting way of showing the deviation of the cathode rays under an electric field is to produce a narrow pencil of the rays from a spot of lime on a strip of platinum foil heated to redness by an electric current; if this strip is used as a cathode a thin sharply defined pencil of rays will start from the patch of lime; if, as in the

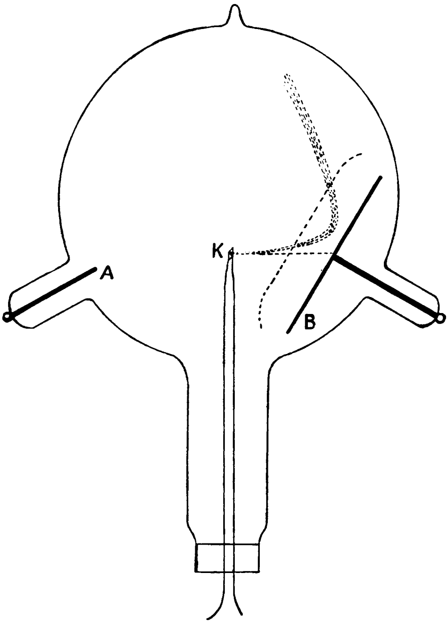

Fig. 3.

arrangement shown in Fig. 3, a metal plate *B* is placed near the path of the rays, then if this is charged negatively the cathode rays will be bent from the plate as in the figure and their path can readily be traced by the luminosity they produce in the gas. The hot lime enables us to produce rays with a smaller potential difference than could be used with a cold cathode, so that the velocity of the rays is smaller and their deviation in a given electric field larger than is the case for rays produced in an ordinary vacuum tube.