RETROGRADE RAYS FROM THE COLD CATHODE.

By Orrin H. Smith.

J. J. THOMSON,[1] as early as 1897, showed that a system of rays of an entirely different character from the cathode rays accompanies the cathode beam. He found that these rays proceed normally from the face of the cathode, that they are not appreciably deflected by a permanent magnet, and that they possess very little, if any, power of producing phosphorescence.

In 1906 Villard[2] gave an account before the French Academy of the rays accompanying the cathode beam which are not so readily deflected as the cathode beam but which were deflected in such a direction and by such an amount as would be expected of the "kanal strahlen." He noticed that in a mixture of oxygen and hydrogen (or water vapor) the cathode rays produced a luminescence characteristic of oxygen, but when these were deflected aside by a magnet there remained rays which produced a luminescence characteristic of hydrogen. He explained their presence by saying that they were the positive canal rays which fall against the cathode and rebound. To explain their rebounding beyond the limits of the cathode dark space, he assumed that the potential fall underwent rapid variations or was even discontinuous. A stroboscopic test showed this to be true; however, this was to be expected since he used a transformer to produce the discharge.

The following year Thomson[3] showed, independently, that these rays were deflected by strong electric and magnetic fields and that they possessed considerable mass. In a later work he observed that they were very feeble under the most favorable conditions of vacuum, discharge potential, etc., and were exceedingly feeble when the gas pressure in the discharge tube was very low. In this latter respect they were quite different from canal or positive rays. Employing a tube having an opening of about .5 mm. in diameter he obtained a photograph which showed that these rays contain (*a*) positively electrified atoms and molecules of hydrogen, (*b*) positively electrified atoms of oxygen, and (*c*) negatively electrified atoms of hydrogen and oxygen. The photograph

[1] Proc. Camb. Phil. Soc., IX., p. 243, 1897.
[2] Comptes Rendus, CXLIII., p. 673, 1906.
[3] Phil. Mag., XIV., p. 359, 1907.

showed the intensity of the lines corresponding to the negative ions to be greater than that of the positive ions. With the ordinary positive rays the positive lines are the more intense.

The conditions under which retrograde rays are produced are quite different from those that obtain for the ordinary positive rays and for this reason it seemed worth while to repeat and extend Thomson's investigations.

Thomson does not find the molecule of oxygen with the negative charge while in this investigation the molecule of oxygen and the molecule of hydrogen are the only carriers obtained with a negative charge, no atoms appearing at all. The presence of helium in the discharge chamber apparently makes no difference in the photographic result.

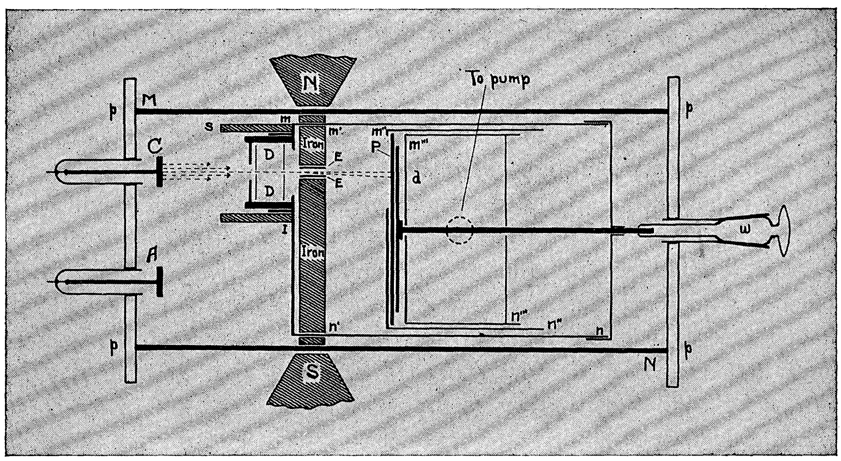


Fig. 1.

Top View. *MN*, containing vessel of glass; *pp*, glass end plates; *mn*, large brass cylinder; *m'n'*, magnetic field extensions; *EE*, electrostatic field plates, connections to which are not shown; *m''n''*, plateholder; *P*, photographic plate mounted on disc *d*, supported by telescoping cap *m'''n'''*, and turned by winch *w*; *DD*, aluminum diaphragms; and *SI*, iron shield.

It appears that Thomson was unable to use a tube of less than .5 mm. bore, while in this investigation traces were obtained with a tube and set of diaphragms having openings of about .05 mm. thus producing sharp lines on the plate which made possible more accurate measurements.

Owing to the short range at which these rays were obtained on the photographic plate, the increased sharpness of the lines, and the restricted range of their velocities due to a restricted cathode dark space, it was possible to obtain some evidence on the question as to whether the power of a particle to affect a photographic plate is a function of its velocity, momentum, or kinetic energy. This evidence seems to indicate that it is a function of the kinetic energy and that the mean value is about 7.4×10^{-9} ergs.

The apparatus, shown in Fig. 1, and the manipulation is essentially the same as that described by Knipp[1] except that a cold cathode was used instead of the Wehnelt cathode and the discharge was produced by an induction coil. The cathode was just like the anode and similarly placed facing the line of the tube and the diaphragms.

A large Leeds induction coil was operated on ten storage cells. The vacuum was maintained with the aid of a large charcoal bulb dipping into liquid air. In general the vacuum improved with sparking. After a few runs it was found that the liquid air could be removed after about ten minutes from starting, and, as the sparking and pumping continued, it could be dispensed with altogether. Finally the vacuum was so easily maintained that it was necessary to keep the pump itself turned off for about three fourths of the time.

There is a point of interest in connection with the charcoal bulb. It was left on the apparatus for weeks after its use was found unnecessary, remaining all the while at the nearly constant room temperature. The pumps were unable to produce a vacuum of .005 mm. in fully three hours' time when starting from atmospheric pressure, and this was the case whether the bulb was heated for an hour during that time or not. However, if it was pumped to a pressure of one or two mm. and left to stand for ten to fifteen hours then upon starting the pumps a vacuum of .005 mm. could be attained in twenty to thirty minutes. This, strangely, was true even when the vacuum had been let down for a very few minutes and then the pumps started again immediately.

The photographic plate used was Seed's Yellow Label lantern slide plate. This plate is very slow and hence produces great contrast which is the thing desired. Thomson[2] points out that the large ions affect only the surface of the film and do not penetrate like the faster moving electrons, into the film. Hence the plate best suited for this work is one that is slow and that has a thin film with a high percentage of silver. The best traces that could be gotten in this investigation were in many instances so thin that they could hardly be seen. They were obscured easily by the slightest fogging. For this reason a fast plate could not be used. Seed's Gilt Edge Number Twenty-seven plate was tried but in every instance fogging obscured the lines. The Double Coated Cramer Crown plate was tried and found to be entirely too sensitive. Some

[1] Phys. Rev., XXXIV., p. 215, March, 1912.

[2] Thomson, Rays of Positive Electricity, p. 4.

experience by another member of the department obviated the necessity of trying the Cramer X-ray plate. As an instance to show that these carriers affect only the surface of the film, the author gently stroked the film under water with a fine camel's hair brush to remove foreign particles and it was found that, in some cases, the lines were entirely obliterated. Further, after the negative had dried the lines could be obliterated by breathing on the film and wiping it gently with a soft cloth. In both cases, other than erasing the lines, no further change could be detected in the film. It was found advantageous to put some alum in the fixing bath to harden the film. The developer used was ordinary hydrochinon, the time of development being from six to twelve minutes.

The time of exposure varied from thirty minutes for the small to three hours for the larger deflections. There seems to be a limit to the intensity that is obtainable, for after a certain length of exposure the intensity of the lines did not apparently increase with further exposure. This was true for long or short development or even when they were exceedingly dim. This is in agreement, however, with the theory that they affect only the surface of the film.

Thomson found that the retrograde rays were best obtained when the gas pressure was not too low. The present photographs bear out that fact very well. If the vacuum was kept about .002 to .004 mm. scarcely any trace of the rays could be found on the plate. The best pressure for their production seems, from this investigation, to be between .015 and .008 mm.

There is always a central spot that is undeflected which is probably due to neutral carriers that were negative originally but which lost one electron before they got into the deflecting fields. It would seem from this that a moving particle need not be charged in order to affect a photographic plate. It is quite evident that the velocity of an uncharged particle must be above a certain value otherwise a plate would be affected by exposure to the air in a dark room due to no other agency than to the velocity of the air molecules produced by ordinary heat agitation. The mean of this velocity at 0° C. for the hydrogen molecule is about 2×10^5 cm./sec. and for the oxygen molecule about 4.5×10^4 cm./sec. Whether the ability of a moving particle to affect a photographic plate is due to its momentum or its kinetic energy, or simply to its velocity, is not definitely known. It seems reasonable to expect, however, that it should be a function of one of these. On a number of the plates the lines were distinct enough to locate approximately the place where the slowest ions would strike, *i. e.*, those that had just sufficient velocity to affect the plate. These points were found, in every case, to be well within the limits of the field, *i. e.*, so far as the limits of the apparatus are concerned the lines might have extended farther from the origin. It occurred to the author then to assume that there were particles which struck beyond the last points of the visible trace but whose velocity was not sufficient to cause them to affect the film. If the coördinates of the last visible point in each line be measured and v and e/m determined, then, for all such points, we should get a constant, showing whether this minimum effect on the plate is a function of the velocity, the momentum, or of the kinetic energy of the moving ion. Table I. shows values which are proportional to the velocity, momentum, and kinetic energy for the points in question on sixteen different lines. It can be seen that the values for the kinetic energy are nearly constant while the values for the velocity and the momentum are not constant. It thus appears that the power of a particle to affect a photographic film probably depends on its kinetic energy. The mean of these values of the kinetic energy is, from Table I., 7.4×10^{-9} ergs which is the minimum required. This value would probably be different for an electron because of its size. It is somewhat larger than the energy required to produce an ion which is 1.63×10^{-11} ergs. The above value (7.4×10^{-9}) was calculated from data obtained from this investigation, except for the value of e, by the formula

$$\text{kinetic energy} = 1/2 \cdot m/e \cdot e \cdot v^2.$$

The value of e was taken as 1.55×10^{-20}.

Table I.

Photographic Plate.	Line.	Constant × Velocity.	Constant × Momentum.	Constant × Kinetic Energy.
75	Upper	6.04	18.36	111.0
76	Upper	6.54	17.99	117.6
76	Lower	1.36	87.18	118.6
85	Upper	6.37	12.50	79.0
85	Lower	1.52	52.50	79.7
86	Upper	6.23	12.71	79.2
86	Lower	1.53	52.48	80.4
87	Upper	7.27	19.40	102.5
87	Lower	1.69	60.50	102.3
88	Lower	1.37	61.70	84.5
94	Upper	5.55	10.71	106.4
94	Lower	1.77	36.28	100.4
95	Upper	7.41	15.03	91.1
95	Lower	1.64	51.50	84.47
96	Upper	6.35	17.70	112.5
96	Lower	1.42	59.36	84.26

It can be seen from Table I. that, even though the values of the kinetic energy vary somewhat, the values for a given plate as a rule are more nearly alike. Plate ninety-six furnishes the greatest variation from this rule. It might be reasonable to expect that different emulsion numbers would reveal slightly different kinetic energies required to affect the film. Several emulsion numbers are represented in these data.

The photographs taken with the apparatus in the last refinement, while clear and capable of accurate measurement, do not lend themselves to reproduction and hence are omitted. The important dimensions are as follows:

Length of electrostatic field	1.10 cm.
Length of magnetic field	1.10 cm.
Distance from point of emergence to plate	1.58 cm.
Length of triangular test coil[1]	2.52 cm.
Base	.63 cm.
Number of turns	19.

The negative lines show distinctly the parabolic heads which are not in evidence on the positive lines. It was evident from nearly all the plates exposed that the negative carriers are in preponderance over the positive ones. This seems reasonable to expect since the distance to the plate is, for the lower pressures, within the limits of the mean free path and it is necessary to assume that every positive carrier has lost two electrons between the outer limits of the dark space and the deflecting fields. If this is true we should expect that the lines due to the positive carriers would not be as sharp as those due to the negative carriers, the ions being deflected somewhat from their true path in the process of losing an electron. Most of the photographs bear this out. It is somewhat surprising, in consideration of the foregoing, that this preponderance is not greater than the photographs seem to indicate unless the negative ion is more unstable than the positive ion. An additional suggestion in the same line comes from a study of Thomson's photographs of positive rays, in a great many of which the negative counterpart is very weak or cannot be seen at all on the prints when the positive lines are very pronounced. The positive lines do not have the distinct parabolic head that the negative lines have. They are also broader and more diffuse. Joining the parabolic head to the center is a line due to the secondary rays of Thomson. This is shown particularly in one exposure where the electric field overlapped the magnetic so that the secondary line does not join straight on to the head of the parabola. The data for exposure number eighty-five, are given in Table II. This

[1] Thomson, Rays of Positive Electricity, p. 10.

indicates that the carriers which produced the two lines are the molecules of hydrogen and oxygen respectively. The measurements of the coördinates were made with an ordinator composed of a frame to which the plates could be fastened so that there was a movable point above the plate capable of being carried in either of two directions perpendicular to each other by micrometer screws. A Grassot fluxmeter was used to determine the strength of the magnetic field.

TABLE II.

Photographic Plate Number 85.
Measurements for the Upper Line.

Position.	z in mm.	y in mm.	$v \times 10^{-7}$ cm./sec.	$e/m \times 10^{-4}$	Electric Atomic Weight.	Carrier.
1	3.34	6.42	6.37	.509	1.97	H_2
2	2.46	5.48	7.39	.504	1.99	"
3	1.88	4.77	8.96	.500	2.00	"
4	1.12	3.51	10.38	.458	2.18	"

Measurements for the Lower Line.

1	3.34	1.53	1.52	.029	34.5	O_2
2	2.46	1.31	1.77	.0288	34.8	"
3	1.88	1.16	2.04	.0296	33.8	"
4	1.12	.84	2.50	.0260	38.5	"

Time of exposure, 3.25 hours.
Gas pressure varied between .008 and .018 mm.
Electric deflecting field, 965 volts.
Magnet current, 4.25 amperes.
$A = 8{,}040$, $B = 267 \times 10^9$

All the photographs were exposed with residual air in the discharge chamber except number 88. In this instance it contained some helium but no traces appear in the photograph, in fact in no case does anything appear in any of the photographs except the lines due to the molecules of hydrogen and oxygen. In some cases the positive rays are not visible.

The data show very well how the velocity varies for the carriers striking at the various points along the parabola, that it decreases with increase of distance from the undeflected spot. The value of v and e/m obtained for the smaller values of the electric field are in general less reliable than for those for which the deflection is larger. The "electric atomic weight" of a carrier Thomson[1] has defined as the ratio of m/e for that carrier to m/e for the atom of hydrogen.

[1] Phil. Mag., XXI., p. 234, Feb., 1911.

It was noticed in connection with these experiments that the discharge in the chamber passed more easily with the presence of a transverse magnetic field. Earhart[1] has shown that this is true for a longitudinal field.

Summary of Conclusions.

The results of this investigation may be summarized briefly as follows:

1. When obtaining retrograde rays in residual air the molecule of hydrogen appears on every plate accompanied by a heavier carrier which in most cases is the molecule of oxygen. The velocities obtained by the author are smaller than those obtained by Thomson. This is due to the position of the cathode with reference to the small canal through which the carriers pass, the dark space extending beyond the near end of this tube and hence the carriers not attaining their maximum velocity.

2. The negative lines are clearer and sharper than the positive; probably because of the disturbance to the path of the positive particles in the process of becoming positive.

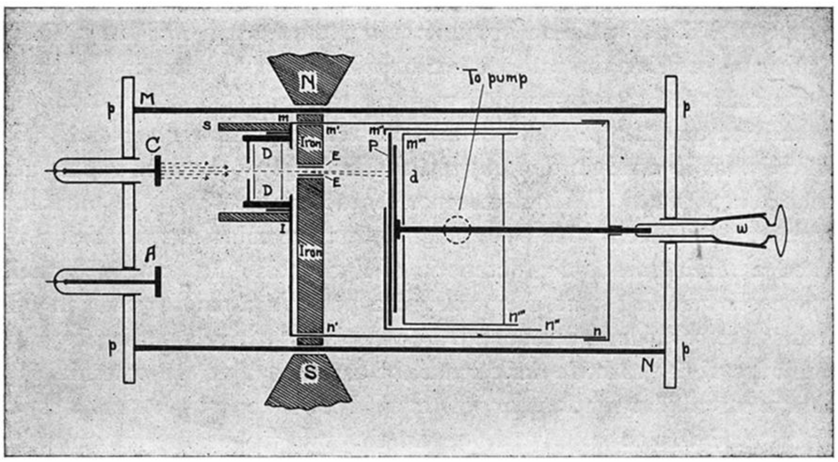
3. Retrograde rays can be obtained with a canal having a bore of about .05 mm. diameter. The best range of pressures for their production is between .008 and .015 mm. of mercury.

4. The power of a moving particle to affect a photographic plate seems to be a function of its kinetic energy. The minimum required for the heavy carriers is of the order 7.4×10^{-9} ergs, which is larger than the energy required to produce an ion, however, there is evidence in favor of the view that this value may depend somewhat on the emulsion on the plate.

In conclusion I wish to express my thanks to Professor A. P. Carman for the excellent facilities placed at my disposal and to Dr. C. T. Knipp for his interest and help in carrying on the investigation.

Laboratory of Physics,
University of Illinois.

[1] Phys. Rev., Feb., 1914.



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