THE PROPERTIES OF SLOW CANAL RAYS.

By A. J. Dempster.

THE following paper contains an account of experiments with positive rays under more varied pressure conditions and of slower speed than those generally used. In the usual canal ray tubes the potential is limited very largely by the vacuum; for instance, if the pressure is about 0.005 mm. of mercury, the potential with ordinary tubes is of the order of 20,000 volts. In this investigation the subject was first approached from the side of the light emission and later the analysis by electric and magnetic deflection was made.

Light Emission.

The first to examine the light excited by slow positive rays was Stark.[1] He arranged a secondary cross field in the negative glow in a usual discharge tube; in this way he obtained a luminosity behind a hole in the secondary cathode, when the cross field was as low as 50 volts. Wehnelt[2] found that if a hole were made in a hot lime cathode, slow canal rays were obtained down to potentials of 50 volts. They were, however, so diffuse that no measurements could be made on them. In some experiments carried out by the writer[3] on the light excited by electrons, a Wehnelt cathode with potentials up to 4,000 volts was used, and it was observed that very strong positive rays passed backwards past the side of the platinum strip.

This method of ionizing the gas by means of electrons from a Wehnelt cathode was used in the present experiments and found to afford the following experimental advantages, namely, *the possibility of producing positive rays of any desired speed in a constant vacuum, and the possibility of changing the pressure over a wide range with constant speed of the rays.*

The cathode used in the following experiments had usually the shape shown in Fig. 1. The platinum strip 0.001 mm. thick and 1 mm. wide was clamped below the thin plates shown and the two halves of aluminum or brass were insulated by pieces of glass *a*, *b* fitted tightly into slots at

[1] J. Stark, Ann. d. Physik, 13, p. 390, 1904.
[2] A. Wehnelt, Ann. d. Physik, 14, p. 464, 1904.
[3] A. Dempster, Ann. d. Physik, 47, p. 796, 1915.

the edges. A plate P with a row of holes in it was screwed to the one half and insulated by the pieces of glass c, d. The heating current was brought in by the rods R, S.

In the first experiments to be described, an arrangement of cathode and anode similar to Fig. 2 was used. The whole fitted into a glass

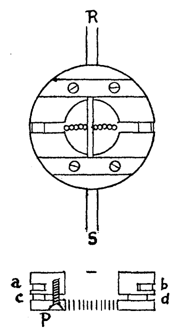

Fig. 1.

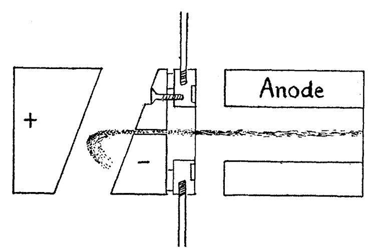

Fig. 2.

tube 4 cm. in diameter, and the rods leading in the heating current and brass caps to close the ends of the tube were made air tight by sealing wax. The cathode was made by heating a mixture of Ba, Sr and Ca nitrates on the platinum strip. By allowing hydrogen to stream in through a long fine capillary, while a Gaede pump was running, impurities were removed and pressure conditions were kept constant. To obtain the rays distinct it is important to remove mercury vapor and any other vapors present; this was done by means of a U-tube immersed either in liquid air or a mixture of solid carbon dioxide and alcohol.

The Positive Rays.

When the pressure is low, 0.001 mm. of mercury or less, the positive rays issue from the back of the cathode as a luminous bundle of bluish light at all potentials from 40 volts between the middle of the cathode and the anode up to 2,000 volts. As the potential is decreased below 100 volts the luminosity becomes gradually very faint and it is only with new cathodes that luminosity at the lowest potentials can be observed. As the cathode gets old and needs to be heated hotter, it is necessary to apply higher voltages up to perhaps 150 volts or more before the positive rays become visible. This is possibly due to the fact that when the cathode gets old the electron stream comes from a greater area of the strip instead of from a small point. This greater density of charge displaces the fall of potential to the neighborhood of the anode where the lines of force do not accelerate the positives in the proper direction. *The rays in these high vacua may be stopped entirely by an opposing field and may be completely deflected and bent into a parabola by an inclined field* as indicated in Fig. 2. It may be observed that in contrast to the behavior of electrons[1] the parabola is continuous up to its apex, indicating that the positive rays can excite light when slowed up to a speed of a few volts. This was tested by stopping 48-volt rays by directly opposing potentials. It was observed that, with 52 volts opposing, a dark space was just noticeable before the plate to which the potential was applied. We thus conclude that *positive rays can cause light when moving with a speed less than that corresponding to 5 volts.* Probably much slower rays also excite light, but it was not possible with the arrangement used to prove it. These positive rays at potentials of several hundred volts excite the hydrogen series lines, but, as they were too faint at the lowest speeds for a spectrum photograph, it is impossible to say whether or not the hydrogen series lines are excited or emitted by the slowest rays.

For fast rays (20,000 volts and up) the evidence is not conclusive. Koenigsberger and Kutchewski[2] find that the positive bundle deflected out by a magnetic field excites no light, although causing fluorescence on the wall. Dechend and Hammer[3] make the same observation. Baerwald[4] however deflected out a luminosity from the rays. The Doppler effect also shows that rays above a certain speed do not excite light. The fact that slow positive rays are able to cause light needs to be considered as a possible complication in experiments on the lower limit to the speed at which electrons excite light, especially if the vacuum used is not low and if any form of arc is used.

The Neutral Rays.

When the pressure is increased to about .005 mm. of hydrogen, the phenomena are more complicated. Instead of the striking sharp break in the luminosity when the positives are stopped and turned back by an opposing field, there is merely a sudden decrease in the light and a luminosity continues right up to the opposing plate. This luminosity could be due to negative particles, electrons or neutrals and to decide the matter a condenser was arranged to deflect the rays sideways as shown in Fig. 3. It was found that the positive bundle was deflected but there still remained an undeflected bundle of neutral rays. No negatively charged atoms were observed; if the holes were large, however, electrons

[1] E. Gehrcke and R. Seeliger, Verh. d. D. P. G., 14, p. 335, 1912.
[2] J. Koenigsberger and J. Kutchewski, Phys. Zeit., 11, 379, 1910.
[3] H. v. Dechend and W. Hammer, Sitz. d. Heid. Akad., 21 abh., 1911.
[4] H. Baerwald, Ann. d. Physik, 34, p. 883, 1911.

appeared as observed by Wien[1] for fast canal rays. A photograph of the tube showing the deflected and undeflected bundle is given in Fig. 3*a*. The appearance was the same at all potentials down to 50 v That the light is due to neutral rays which were neutralized be the condenser and not to resonance radiation caused by l electron discharge was proved by the fact similar sl was made in the anode and the trons wer eflected, no undeflected luminosity *These neu rays in hyd are still able to exc when movi with a speed sponding to a poten 50 volts.* This speed, acco g to my observation rather sha lower limit to the speed at which they excite light, for with rays a few volts slower the neu bundle could not be detected, although the positive bundle was unaltered.

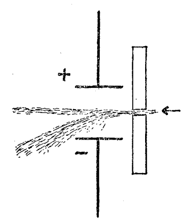

Fig. 3.

This behavior of the neutral rays offers a possible explanation of the dark space between the displaced and undisplaced lines in the Doppler effect in canal rays; the slow positive rays are soon neutralized and the slow neutrals are not able to excite light. The observed value for the minimum velocity in the Doppler effect is given by Stark as $1{,}07.10^7$ cm. per sec. for H_α, corresponding to a fall of the hydrogen atom through 57 volts, while the lower limit for excitation by the neutral rays observed above was 50 volts.

The changes that occur in hydrogen as the pressure is gradually diminished, while the potential is kept constant, are as follows: at high pressures (.05 mm.) there is a strong bundle which is quite unaffected by a deflecting electrostatic field, due probably to the fact that it consists mostly of neutrals. As the pressure is decreased the bundle becomes fainter and a positive deflected beam becomes visible. The two beams are of approximately equal strength at .005 mm. As the pressure is still further decreased, the neutral bundle becomes fainter till at the highest vacua only the positive remains.

The fact that the neutral rays excite light is not in agreement with the theory given by J. J. Thomson[2] or in fact with the ideas underlying Bohr's atom model. These theories regard the emission of light as taking place during the return of an electron to a positive center; the dark space in the Doppler effect is accounted for by J. J. Thomson by assuming that below a certain speed neutral particles are not ionized so that they can never act later as light emitters. On

[1] W. Wien, Wied Ann., 65, 446, 1898.

[2] J. J. Thomson, Positive Rays, p. 99.

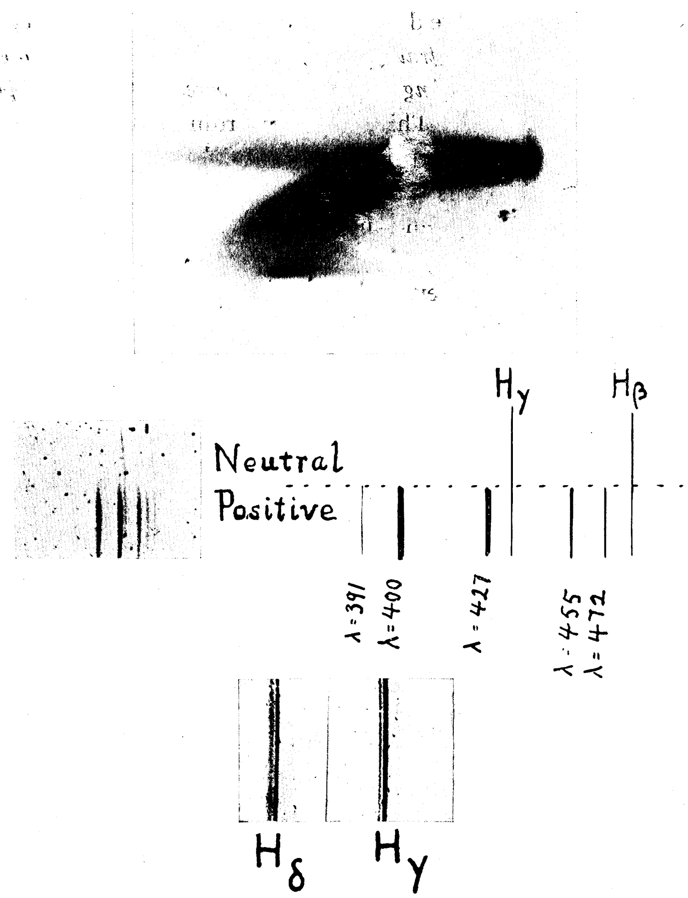

FIG. 3a.

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these theories, however, if we make the vacuum so high that changes take place slowly and then remove all the positives at one place, there should be no luminosity until more positives have been formed from the neutral bundle. This is not the case and the view is preferable that the collision of the neutral particles causes light directly.

Spectrum of the Two Bundles.

To determine whether the hydrogen series' lines were excited by the neutral or by the positive rays, photographs of the spectrum were made. The two bundles were projected across the slit one above the other so that the spectra of both could be taken simultaneously. A single large prism was used with large lenses of short focal length. With rays of 1,500 volts' speed, exposures of 2–4 hours were necessary. A reproduction and key is given on Fig. 3*a*. *The hydrogen series lines were found in both positive and neutral bundles.* In the positive bundle were five other strong lines or bands of which one is probably the strong barium line at $\lambda = 4,554$, the two at $\lambda = 472$ and $\lambda = 427$ agree with the strong positive bands shown in Fulcher's photographs[1] of electron excitation in air and the other two also agree with nitrogen bands. They are only excited by the positive rays and stop sharply at the neutral bundle while H_β and H_γ are equally strong in both.

Change of Neutrals into Positives.

Since the neutral rays emit the hydrogen series lines, it is of interest to see if the light emission is accompanied by a changing into positive particles. J. J. Thomson regards this phenomenon as taking place when the speed of the neutral particle relative to an electron at rest is greater than that required by an electron to ionize the particle and his experiments indicate that the neutral hydrogen atom does not change into positive unless its velocity is greater than that corresponding to a fall through 20,000 volts, the ionizing speed for electrons. Wien,[2] however, finds a formation of positive from neutral rays in oxygen and nitrogen; and also in hydrogen when the potential was only 3,500 volts.[3]

The arrangement shown in Fig. 4 was used. In a vacuum of .01 mm. of hydrogen, 800-volt rays entered at S_1. E_1 deflected out the positives while the neutrals passed on through a second slit S_2. If any neutrals changed into positives, they were deflected by E_2 up into the chamber F and detected by an electrometer. It was found however that F always

[1] G. S. Fulcher, Phys. Zeit., 13, p. 1137. 1912.
[2] W. Wien, Ann. d. Physik, 39, p. 529, 1912.
[3] W. Wien, Ann. d. Physik, 27, p. 1030, 1908.

gained a positive charge, due either to slow positives diffusing in or to electron emission from F. This was avoided by raising F to a positive potential of 258 volts above the metallic chamber; it then gained a negative charge, and only fast positive rays would be able to enter it and charge it positively. As the potential of E_2 was increased F still gained a negative charge till E_2 became 180 volts. From 180 to 300 volts it gained an increasing positive charge, while further increase to 470 volts decreased the positive charge to zero, and, with higher potentials

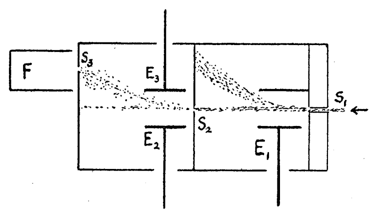

Fig. 4.

on E_2, F gained a negative charge again. This is what would happen as rather diffuse fast positive rays were deflected past the slit and so it is probable that neutral rays of 800 volts' speed are able to turn into positive rays. In view of the possibilities attending such changes, such as the absorption or emission of quanta of energy by a neutral in the brief period of its flight, the ejection of fast electrons, or the splitting up of the molecule, and the dependence on the speed of the rays it is hoped to investigate the matter further.

Doppler Effect.

Five photographs were taken of the Doppler effect in the hydrogen series lines H_β, H_γ, H_δ with rays of 3,000–4,000 volts and various pressures above .004 mm. A single Rutherford prism was used with lenses of 4 cm. aperture and 34 cm. focal length. No difference could be detected in the appearance of the undisplaced and displaced lines from that obtained with the usual method of exciting the rays. A reproduction of H_γ and H_δ is given in Fig. 3*a*, showing the Doppler effect to the left of the undisplaced line.

Ionization.

Ionization curves were made with an apparatus the same as in Fig. 4, except that the Faraday chamber and opening S_3 were opposite S_2. E_2 was connected to an Edelman electrometer and brought to various potentials relative to E_3 and the chamber. Positive rays or neutral rays of various speeds were allowed to enter through S_2 and the ions they made driven to E_2. With the positive and neutral rays together, curves similar to that in Fig. 5 were obtained, where the abscissæ give the potential in volts forcing the ions formed to the electrode E_2, and the ordinates the numbers of negative ions obtained. Here the rays were 480-volt rays in hydrogen of .003 mm. pressure. There is an apparent saturation at about 30 volts but the continuation of the curve in Fig. 6 shows a second rise with final saturation at about the same potential as that used to give the rays their velocity.

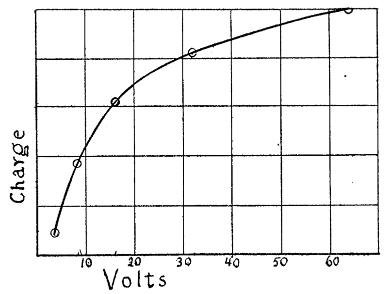

Fig. 5.

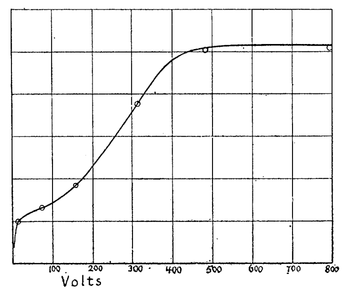

Fig. 6.

When the positives were deflected out by E_1, and only the neutrals and any newly formed positives allowed to enter the condenser, curves similar to Fig. 7 were obtained. This curve was for 480-volt rays in hydrogen at .0057 mm. pressure, and shows the positive charge obtained on E_2 as the potential difference was increased. The curve for the negative charge obtained was almost identical; the negative charge was, however, much greater, but could be reduced to approximate equality by a magnetic field. This indicates the presence of electrons, but a reason for the slow saturation can not be given at present. With fast canal rays an absence of saturation has been observed by Seeliger[1] and Baerwald[2] and ascribed to ionization by collision.[3]

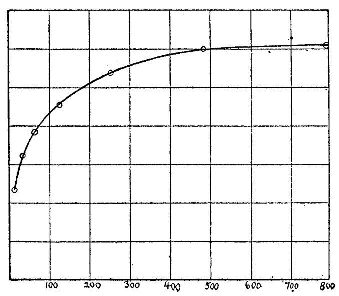

Fig. 7.

[1] R. Seeliger, Phys. Zeit., 12, p. 841, 1911.

[2] H. Baerwald, Verh. d. D. P. G., 16, p. 790, 1914.

[3] The assumption that the impact of positive rays can cause the emissions of fast electrons of the same energy would account for the form of the curves and agree with the conclusion recently reached by A. W. Hull (PHYS. REV., 7, p. 16, 1916), since it was found above that positives excite a radiation when their energy is of the order of magnitude of that required for electrons to excite light, we could assume that electrons are ejected under the influence of radiation excited by the impact of the positives, the maximum frequency of the radiation being given by, $h\nu$ = energy of the positive particle.

Deflection in Electric and Magnetic Fields.

The electric and magnetic deflection of slow positive rays from gases have been examined thus far only by J. J. Thomson[1] and by Knipp. In J. J. Thomson's experiments the rays after falling through a potential difference of from 160 to 420 volts, were deflected in a magnetic field and m/e computed from the measured deflection and the volts. The result of these experiments was to detect the presence of hydrogen atoms and of particles for which m/e was from 25 to 44 times as large. Knipp[2] examined the rays from a Wehnelt cathode and found that 150-volt rays were not fast enough to affect a photographic plate without being accelerated by about 1,500 volts. These slow rays were therefore accelerated and then analyzed by electric and magnetic fields and values of m/e which corresponded to hydrogen atoms, hydrogen molecules, and doubly charged carbon atoms were found.

The method employed in the present experiments was to deflect the original slow rays by both electric and magnetic fields and to detect the deflected rays by the charge they carry. This method of detection has been previously used for fast canal rays by J. J. Thomson.[3] The apparatus is shown 4/10 actual size in Fig. 8. The analyzing chamber was

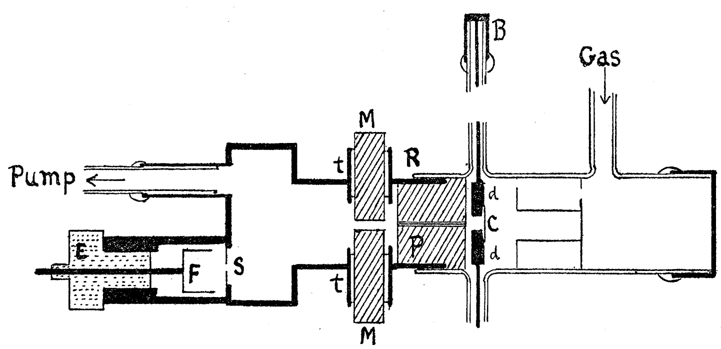

Fig. 8.

made completely of brass to avoid any static charges since the slow rays are very easily deflected. The Faraday chamber *F* was supported by an ebonite plug *E* which was made airtight by picien. The entrance to the Faraday chamber was through a parabolic slit *S* about 9 mm. long and 1 mm. wide, the minimum electrostatic deflection being about 7 mm. The iron pole pieces *M* fitted tightly into glass tubes and were sealed by De Khotinsky cement. The glass tubes, which did not pro-

[1] J. J. Thomson, Phil. Mag., 16, p. 673, 1908; Phil. Mag., 18, p. 838, 1909.
[2] Knipp, Phil. Mag., 22, p. 926, 1911, Phys. Rev., 34, p. 215, 1912.
[3] J. J. Thomson, Phil. Mag., 24, p. 245, 1912.

ject into the chamber, were similarly sealed into tight-fitting brass tubes t soldered into the walls of the chamber. The canal 0.7 mm. in diameter and 3.5 cm. long was a drawn copper tube set in an iron plug P. The cathode C was at first made as in Fig. 1 and 2, but, later, one has been used which is more easily made; the two brass pieces d were held in place and insulated by means of two dowel pins of glass not shown in the figure. The heating current is led in by rods soldered to brass caps B, which are made tight by sealing wax. It was found that the soldered joints in the chamber soon leaked after being warmed and cooled a few times during the removal and resealing of the glass tube

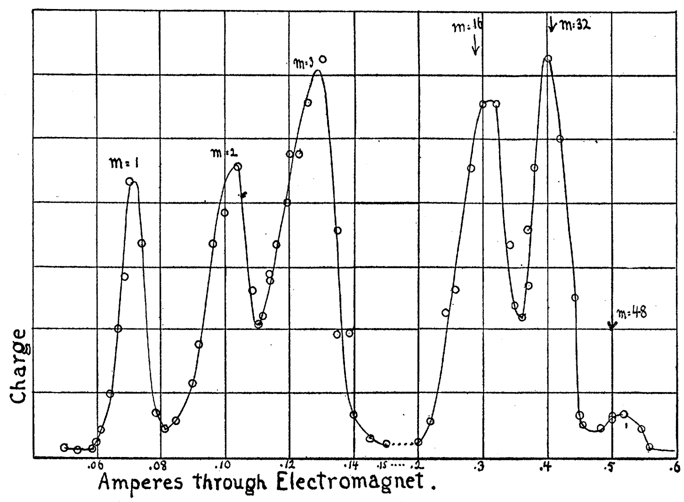

Fig. 9.

at R, the joints were then coated with shellac. It would, however, be an advantage to have the analyzing chamber half as large and the whole enclosed in a glass tube.

The magnetic field was produced by an electromagnet whose poles were brought against the iron pieces set in the chamber, and the PD necessary to deflect the parabolas electrostatically was applied to the iron pieces. The electron stream in front of C was shielded from the poles M by a screen at the iron plug consisting of 6 plates of transformer iron at right angles to the tube, also by several pieces bent around the tube itself. As the current through the electromagnet was increased bringing successive constituents of the rays into the Faraday chamber, the charge obtained was measured by a sensitive Dolezalek electrometer. A magnet placed near the Faraday chamber was sometimes used to turn back secondary electrons, for with fast rays they may cause a great distortion of the curves. The resolution was sufficient to separate the first three constituents of the rays quite sharply but was not sufficient to distinguish with certainty between atomic weights of the ratio 6 to 7 or less. The first three parabolas are easily determined by their maxima coming at currents proportional to the square roots of the numbers.

The hydrogen which was prepared from zinc and hydrochloric acid could be allowed to stream from a reservoir into the tube through a fine capillary while the Gaede mercury pump was running; in this way pressure conditions could be kept constant. Liquid air was used on a U-tube to remove mercury and other vapors. An example of the curves obtained is given in Fig. 9. This curve was with 800-volt rays and a rather high pressure (about .01 mm.). H_1, H_2 and H_3 are present and other constituents which are probably O_1, O_2, O_3. The amount of H_3 obtained with these slow rays when the vacuum is not very high is apparently much greater than that obtained by J. J. Thomson by the usual method.

Effect of Decrease of Pressure.

One advantage of this method of producing the positive rays is that the rays may be made and examined in the highest vacuum. With the usual arrangement the vacuum in the analyzing chamber may be made high, but if the pressure in the discharge tube is much below .001 mm., the discharge refuses to pass or cracks the tube. With the present method the pressure may be varied over wide limits keeping the speed

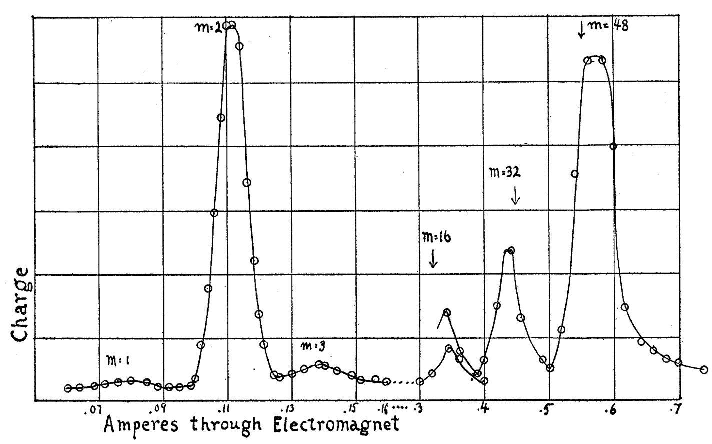

Fig. 10.

of the rays the same, and the change in the constituents of the rays examined as the pressure is altered. It was found that when the pressure was taken very low, using a charcoal bulb in liquid air connected to both the discharge chamber and the analyzing chamber curves similar to that in Fig. 10 were obtained. The curve shown was obtained with 800-volt rays and the highest vacuum. Here the hydrogen atoms and H_3 are negligible in comparison with the hydrogen molecules. They regain, however, in relative intensity as the pressure is increased by admitting small amounts of hydrogen. At the low pressures, the free path is very large, so that the positive rays are analyzed in the condition in which they are just after being formed by the impact of the electrons from the Wehnelt cathode. The electrons thus ionize the gas merely by detaching a single elementary charge from the neutral molecule as concluded by Millikan[1] for ionization by β-rays and X-rays. The electrons cannot dissociate the molecules into atoms, but, when the pressure is taken higher so that the positive molecules make collisions, they dissociate the hydrogen.[2] That H_3 is not present when the gas is

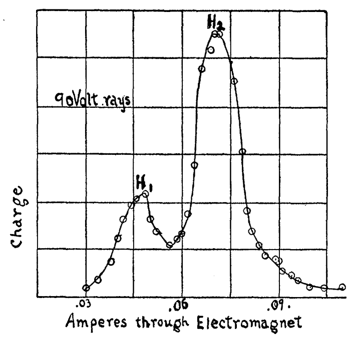

Fig. 11.

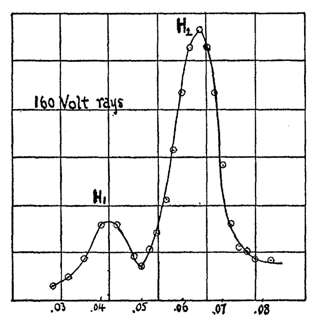

Fig. 12.

not dissociated shows that it is an unstable complex formed in the discharge tube itself, probably a neutral hydrogen molecule to which a charged hydrogen atom has attached itself. It is possible that with slow rays the formation of the complex is favored. There may also be an influence of impurities on the formation of H_3 at the higher pressures, but this matter and the change in the rays with the speed at constant pressure has still to be investigated.

The slowest rays thus far analyzed by the apparatus in Fig. 8 were with 90 volts between cathode and anode and at a pressure of hydrogen of about .0005 mm. Fig. 11 shows the two lightest constituents. The rays are diffuse and the pressure is so low that any H_3 is not apparent. Fig. 12 shows 160-volt rays under the same conditions of pressure.

My thanks are due to the members of the physics department and

[1] R. Millikan, Phil. Mag., 21, p. 753, 1911.

[2] J. J. Thomson, Phil. Mag., 24, p. 234, 1912.

especially to Professor Millikan for their readiness in assisting in every possible manner.

SUMMARY.

Positive rays excite light down to a speed less than that corresponding to a fall through 5 volts. They may be completely deflected by an electrostatic field.

Neutral rays in hydrogen excite light down to a speed corresponding to 50 volts. The theory that light is excited only during the return of a corpuscle to a positive center does not cover this case of light excitation.

The light caused by both the neutral and positive rays contains the hydrogen series lines.

Neutral rays of 800 volts speed change into positive.

Saturation curves are given for ionization by positive and neutral rays.

An apparatus for analyzing positive rays down to 90 volts' speed by the electric and magnetic deflection method is described.

At high vacua H_1 and H_3 are negligible in comparison with H_2, indicating that electrons ionize by detaching a single elementary charge from the neutral molecule, that the impact of positive rays is necessary for dissociation, and that H_3 is formed only when the gas is in a dissociated state.

RYERSON PHYSICAL LABORATORY,
UNIVERSITY OF CHICAGO.

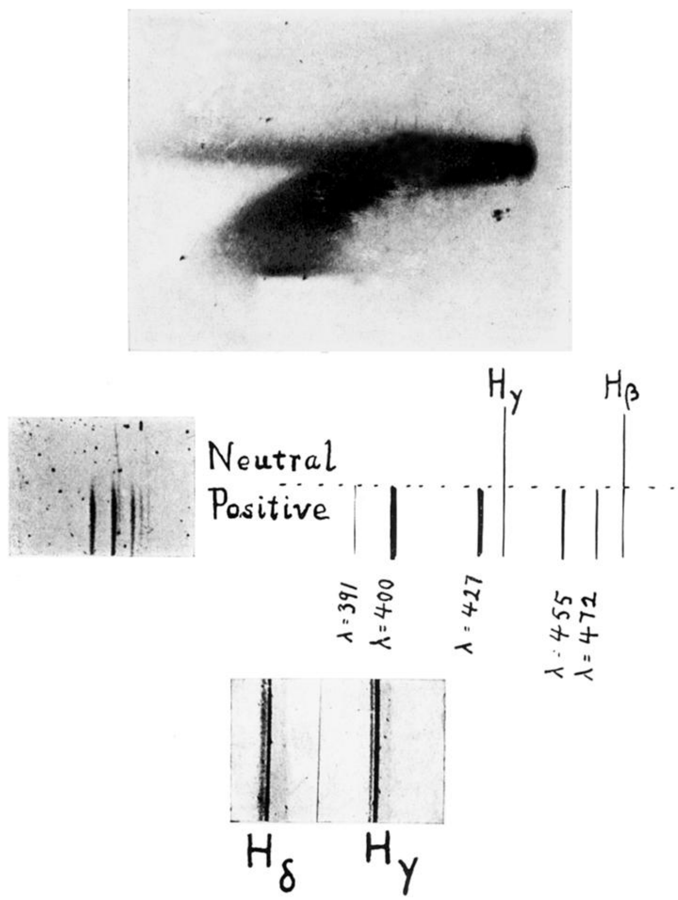

FIG. 3a.