SOFT X-RAYS.

By H. M. Dadourian.

SYNOPSIS.

Method.—Soft X-rays were produced by the impact of electrons from a hot-lime cathode against a platinum anode. Potentials of 20 to 1,000 volts were used to give the electrons the desired velocity of impact. The properties of the rays were studied by observing the velocity and number of electrons produced on a brass plate by a narrow beam of soft X-rays.

Experimental Results.—(1) Soft X-rays were obtained with as low potentials as 20 volts. (2) Radioelectric curves were obtained under different experimental conditions. These curves have the general shape of photoelectric curves but differ from them in several important particulars. (3) The velocity distribution of radioelectrons was studied and it was found that only a negligible fraction of the electrons have velocities comparable with the velocity of impact of the cathode electrons. (4) Evidence was obtained of the presence of characteristic L-radiations of copper and zinc of approximate wave-lengths of 15×10^{-8} and 13×10^{-8} respectively and of softer characteristic rays of platinum of approximate wave-lengths of 21×10^{-8} and 31×10^{-8}. (5) It is pointed out that the method used in this investigation, which is called the radioelectric method, lends itself to the study of characteristic radiations of elements of low atomic numbers.

INTRODUCTION.

THE term *soft X-rays* is used in this paper to denote roughly that region of general radiation which falls between the shortest known ultra-violet rays and the longest waves of characteristic X-radiation studied to date, that is, the region between the wave-lengths 600×10^{-8}, observed by Theodore Lyman, and 12.3×10^{-8}, the characteristic L-radiation of zinc. According to the well-known quantum equation, $Ve = h\nu$, this region represents, approximately, X-rays produced by cathode rays moving with velocities corresponding to a fall of potential varying from 20 volts to 1,000 volts.

A number of new terms are introduced in this paper which are conducive to conciseness and lucidity in descriptions of phenomena related to the production of electrons by X-rays. These phenomena are similar to photoelectric effect; therefore in introducing the new terms the author was guided by the terminology used in photoelectricity. Electrons produced by X-rays are called *radioelectrons*, while the phenomenon of the production of radioelectrons is called *radioelectric effect*. With these definitions the meanings of the terms *radioelectricity*, *radioelectric current*, *radioelectric curve*, and *radioelectric chamber* become self-evident. In order to differentiate clearly between radioelectrons and the electrons forming a beam of cathode rays which give rise to X-rays, the latter are called *cathode electrons*. Further, the potential through which the cathode electrons fall before they give rise to X-rays is called *cathode potential*, and the retarding potential necessary to bring an electron to full stop *halting potential.*

Relatively little has been published on the important region of radiation represented by soft X-rays; consequently a rapid review of the work done by other investigators is feasible.

Wehnelt and Trenkle[1] showed in 1904 that electrons from a hot-lime cathode give rise to X-radiation when they impinge against a metal target with a velocity corresponding to a cathode potential of 400 volts. Dember[2] found in 1911 that photoelectrons, moving with a velocity corresponding to a potential drop of 250 volts, produce X-rays when stopped by a metal obstacle. Later[3] he obtained evidence for the production of X-rays by photoelectrons moving with velocities corresponding to 18.7 volts. Dember also studied the velocities of radioelectrons produced by soft X-rays by applying retarding electrostatic fields to the radioelectrons and found that as the cathode potential was increased from 250 volts to 9,000 volts the halting potentials of the radioelectrons increased from 0.7 volts to 3.6 volts. Whiddington[4] showed in 1913 that the impact of electrons from a hot-lime cathode against air molecules gives rise to soft X-rays. He used potentials of 128 to 218 volts to accelerate the cathode electrons and found that the corresponding halting potentials ranged from 100 to 128 volts. In 1914 Sir J. J. Thomson[5] produced soft X-rays by slow moving positive rays and by electrons from a hot-lime cathode moving with as low velocities as that corresponding to a cathode potential of 10 volts. Miss Laird[6] studied soft X-rays produced by cathode electrons moving with velocities corresponding to potentials of 220 to 1,300 volts and showed that the rays are polarized. She was unable, however, to obtain evidence for the production of X-rays with cathode potentials of less than 200 volts and arrived at the conclusion, "various experiments make the results of previous observations of a Röntgen radiation produced by cathode rays of less than 200 volt-velocity appear doubtful." The four last named observers showed

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[1] A. Wehnelt and W. Trenkle, Sitz. Phys.-Med. Soc. Erlangen, 37, 1905.

[2] H. Dember, Verh. Deutch. Phys. Ges., 13, p. 601, 1911.

[3] H. Dember, Verh. Deutch. Phys. Ges., 15, p. 560, 1913.

[4] R. Whiddington, Camb. Phil. Soc., 17, p. 144, 1913.

[5] J. J. Thomson, Phil. Mag., 28, p. 620, 1914.

[6] Elizabeth R. Laird, Ann. der Phys., 46, p. 605, 1915.

that soft X-rays are very absorbable but are capable of passing through extremely thin films of glass, celluloid, etc.

The present investigation was undertaken: (1) to confirm by an electrical method the results obtained by Sir J. J. Thomson who used a photographic method, (2) to determine the relation between the cathode potential of the electrons producing soft X-rays and the halting potential of the radioelectrons which the X-rays produce on a metal surface, and (3) to study the relation between the cathode potential and the saturation current of radioelectrons. A preliminary statement of some of the results obtained in this investigation was given in a paper[1] read before the American Physical Society at its eighty-eighth meeting.

APPARATUS.

The final form of the apparatus adopted and the scheme of electrical connections used are represented by the sketch of Fig. 1. The main part of the apparatus consisted of a brass tube 20 cm. long and 6 cm. in diameter, divided into three compartments by the two brass discs *D* and *D'*. The left-hand compartment formed the X-ray tube of the apparatus, the right-hand compartment the radioelectric chamber, and the middle compartment the electrostatic trap used to prevent the passage of electrons from the X-ray tube to the radioelectric chamber.

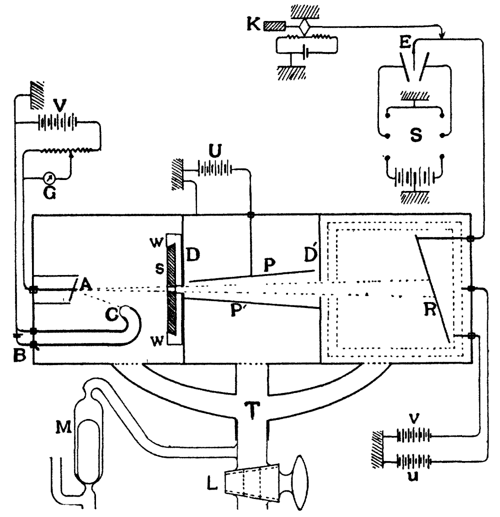

Fig. 1.

The X-ray tube is provided with a platinum anode *A* and a hot-lime cathode *C*. The latter consists of a thin strip of platinum foil with a

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[1] H. M. Dadourian, PHYS. REV., 9, p. 503, 1917.

small patch of barium oxide deposited on it by burning away a tiny speck of Bank of England sealing wax. The heating current for the hot-lime cathode is supplied by the battery *B*, and the cathode potential, which gave the cathode electrons the desired velocity, by the battery *V*. The cathode current is measured with the galvanometer *G*.

The partitions separating the compartments are provided with central windows to permit the passage of a narrow beam of X-rays from the anode, *A*, into the radioelectric chamber. To the partition *D* is attached a magnetic shutter of which two other views are shown in Fig. 2. The shutter proper, *s*, consists of a rectangular plate of soft iron with bevelled sides which fit in the bevelled ways of the piece of aluminum *WW*, and is free to slide back and forth between the pegs *p* and *p'*. The shutter is provided with two circular holes *o* and *o'*. When the shutter is in contact with the peg *p* the hole *o* is in line with the windows in *D* and *D'*. On the other hand, when the shutter is in contact with *p'*, the hole *o'* is in line with the windows. The hole *o'* is covered with a thin film of celoidin, while *o* is open. The shutter can be moved, by means of a magnet, from one extreme position to the other, or made to take a midway position, thus entirely closing the window in the partition. When the cylinder *c* is in the position indicated in Fig. 2 the shutter can be moved from one extreme position to the other but it cannot be made to take a midway position by means of a magnet. If the cylinder is pulled against *WW*, however, the shutter can be moved only from its extreme position on the right to its midway position. The upper half of the cylinder is made of soft iron and the lower half of brass so that it may be moved by means of a magnet without its "freezing" on the shutter.

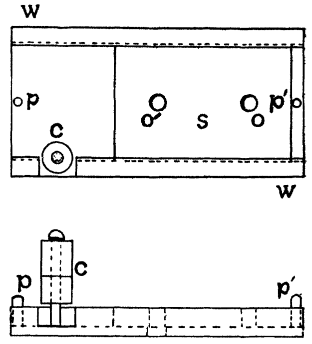

Fig. 2.

The radioelectric chamber is provided with a brass plate, *R*, and a cylindrical cage of bronze wire-gauze. (In some of the experiments the chamber was provided with two cages as indicated in Fig. 1.) A wire-gauze could not be obtained which had sufficiently small meshes and a considerable part of the area of which was not taken up by the wire itself. Therefore commercial wire-gauze of 1 mm. meshes was used in making the cages after the wire gauze was thinned down by dipping it in nitric acid until the wire of the gauze did not take up more than 25 per cent. of the total area.

The three-forked brass tube, *T*, connects each of the three compartments of the main apparatus directly to a charcoal-liquid-air bulb through a glass stop-cock with a bore one cm. in diameter. A ground glass valve *M* is placed between the liquid-air-charcoal bulb and the pumping system in order to reduce the distillation of mercury vapor into the charcoal bulb after the pump is stopped.

The measuring instrument was a gold-leaf electroscope, *E*, which could be given a sensitiveness of 5,000 divisions per volt with a fair degree of stability. A description of the electroscope has already been given by H. A. Bumstead[1] and need not be repeated here. The conditions under which this unusual sensitiveness was obtained, however, might be stated to advantage. The outside of the electroscope was covered with a thick coating by dipping it several times in molten paraffine. This made temperature changes within the electroscope slow and thus eliminated convection currents of air which disturb the gold leaf. The electroscope was provided with a milled head for raising and lowering the gold leaf in order to change its sensitiveness. It was found, however, that raising and lowering the gold leaf is invariably accompanied by slight rotational displacements of the gold leaf about its axis which often cause greater changes in the sensitiveness than the vertical displacement. Therefore after a fairly favorable position of the gold leaf had been obtained changes in sensitiveness were made by altering the potentials applied to the plates of the electroscope. The gold leaf was kept at the position of equilibrium by tilting the electroscope by means of a screw of fine pitch. The electroscope and the microscope were mounted upon a solid metal platform and a screw attachment was devised by means of which the microscope could be moved laterally without disturbing the electroscope in the slightest degree.

EXPERIMENTAL RESULTS.

I.

In the course of the experiments described in the following pages evidence was.obtained for the production of X-rays by electrons moving with velocities corresponding to a drop of potential of from 1,000 volts to 20 volts. There was nothing to indicate that 20 volts is the lower limit of potential with which an electron has to be made to impinge against an atom in order to give rise to X-rays. The fact that the effect observed did not disappear suddenly as the cathode potential was reduced, but its magnitude decreased gradually until it became equal to the magnitude of the errors of observation, indicates that 20 volts is not the lower limit in question if there is indeed a limiting potential.

[1] H. A. Bumstead, Phil. Mag., 22, p. 910, 1911.

It has been suggested that the discrepancy between Miss Laird's[1] negative results and the positive results of investigators who have been able to observe radioelectric effects with cathode potentials lower than 200 volts may be explained by assuming that the effects observed by the latter at these potentials might have been due to a diffusion of electrons from the X-ray compartment to the radioelectric chamber. In order to settle this point by testing the effectiveness of the electrostatic trap the following experiments were carried out.

The shutter *s* was pulled to its middle position, thus closing the window in partition *D*, then the X-ray tube was operated at a number of different potentials. No effect was observed on the electroscope, showing that no electrical or electromagnetic communication could take place between the extreme compartments except through the window. The X-ray tube was then operated at a given potential and alternate readings of the deflection of the electroscope were taken with the shutter first at one extreme position and then at the other. During these experiments the walls and the wire cage of the radioelectric chamber were connected to earth, while the potential applied to the plate *P* was increased from zero to any desired value. The results obtained with three different cathode potentials are shown in Fig. 3, where the abscissas represent the potentials applied to the plate *P* and the ordinates the rate of deflection of the gold leaf due to positive charging of the radiator *R*. The continuous curves correspond to readings taken with the window open, while the discontinuous curves correspond to readings taken with the window closed by means of a thin film of celoidin. The cathode potential was 80 volts for

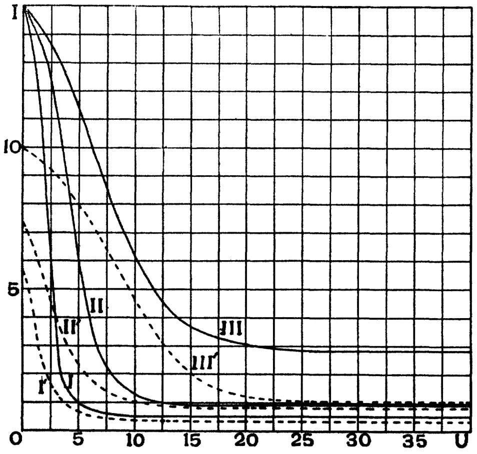

Fig. 3.

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[1] *Loc. cit.*

curves I and I', 190 volts for curves II and II', and 380 volts for curves III and III'. The continuous curves were plotted on different scales so as to make their initial points coincide, while each of the discontinuous curves was plotted on the scale of the corresponding continuous curve. It will be observed that every one of the curves becomes perfectly horizontal before the potential of the electrostatic trap attains one tenth of the value of the corresponding cathode potential. The electrostatic trap is therefore perfectly effective in preventing the passage of electrons from the X-ray compartment to the radioelectric chamber.

The celloidin film was prepared in the following manner. Celloidin was dissolved in a solution of equal parts of ether and absolute alcohol. A minute drop of the resulting solution was dropped on the surface of quiescent water by means of a glass pin point. The drop of solution spread over the surface forming a thin film. The shutter s was then removed from its ways, dipped under the film and lifted from the water so that the film covered one of the two holes in the shutter. The shutter was then set aside to dry. If the film was too thin it broke during the stretching process due to drying. After several attempts an unbroken film was obtained which was not much thicker than those which did break. The thickness of this film was estimated to be less than 10^{-5} cm. The film was examined with a microscope and was found to have no holes.

II.

A number of experiments were carried out in order to find a relation between the velocities of cathode electrons and radioelectrons and thereby test the validity of the quantum relation $Ve = h\nu$. In these experiments the radiator R, Fig. 1, was connected to the electroscope, the wire-gauze cage to a variable potential, and the walls of the radioelectric chamber to earth. This experimental disposition of the radioelectric chamber is indicated in the sketch inserted in Fig. 4. The current of electrons from the radiator to the cage was then measured for different accelerating and retarding potentials. The results were then plotted, with the radioelectric currents as ordinates and the potentials as abscissas. The radioelectric curves thus obtained for cathode potentials varying from 60 to 1,000 volts were all of the same general shape as that of curve I, Fig. 4, which corresponds to a cathode potential of 390 volts. It will be observed that curve I is similar to the typical photoelectric curve in its general form but differs from it in several particulars, namely, the radioelectric curve (*a*) attains its positive-saturation value at a higher accelerating potential, (*b*) intersects the potential-axis at a greater potential, (*c*) dips well below the potential-axis and (*d*) reaches a negative-saturation value. These characteristics of the radioelectric curve led the author to the conclusion that a part of the X-radiation incident upon the radiator was reflected and scattered by the latter and produced electrons on the wire-gauze cage and the walls of the radioelectric chamber. In order to test this conclusion certain experiments were carried out the results of which are represented by the curves of Figs. 4, 5 and 7.

Curve *II*, Fig. 4, was obtained under the same experimental conditions as curve *I* with this exception—that in the experiment represented by curve *II* the walls of the radioelectric chamber were insulated and connected to the cage. Since at zero potential experimental conditions were identical for both curves they were plotted so as to make their points of intersection with the current-axis coincident. The result is interesting. Curve *II* has a greater negative saturation, rises to positive saturation more rapidly, and has the same value for positive saturation as curve *I*. Let us see how these facts fit in with the assumption that a fraction of the X-rays are scattered by the radiator. On this assumption the negative-saturation current of curve *I* represents the electron-current from the cage to the radiator, electrons produced on the walls of the chamber being driven back by the field between the walls and the cage. The negative-saturation current of curve *II*, on the other hand, represents the electron-current from the cage plus the current of electrons from the walls of the chamber which pass through the meshes of the cage. Taking into account the area occupied by the material of the cage we find that (in the experiment represented by curve *II*) about 30 per cent. of the X-radiation was scattered by the radiator *R* and that about one third of the electrons produced on the walls of the chamber passed through the cage. The relatively rapid rise of curve *II* to positive saturation indicates that for accelerating potentials of under 20 volts

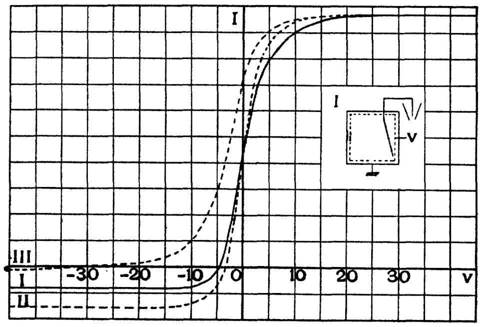

Fig. 4.

electrons produced on the walls of the chamber have a greater chance to be captured by the wire-gauze under the experimental conditions of curve *II*. In other words these electrons have a better chance to reach the radiator if they are accelerated before passing through the wire-gauze. When the accelerating field is high enough, however, all the electrons produced on the walls and the cage are prevented from reaching the radiator under the experimental conditions of both curves; therefore they have the same value for positive-saturation.

The negative saturation current may also be accounted for by assuming that the radioelectric chamber was not sufficiently free of gas molecules and that these molecules were ionized. But if the negative current were due to ions the condition of the surface of the cage and of the walls of the chamber would have no effect on the saturation current; on the other hand if it were due to electrons produced on the cage and the walls by scattered radiation the condition of these surfaces would have considerable effect. This fact was made use of to decide between the two hypotheses in an experiment in which the walls of the chamber and the cage were blackened with smoke from an asceteline lamp, the radiator *R* being kept polished. The result of this experiment, indicated by curve *III*, is decidedly in favor of the hypothesis that the negative current was due to radioelectrons produced by scattered radiation.

The curves of Fig. 5 were obtained with a cathode potential of 60 volts and with an experimental disposition of the radioelectric chamber indicated in the inserted sketch. In the experiments corresponding to both curves the outer cage was connected to a positive potential of 200 volts. In the experiment represented by curve *II* the walls and the cages were blackened, while in the case of curve *I* this was not done. It will be observed that curve *II* does not cross the potential-axis but approaches it asymptotically, indicating that the number of radio-

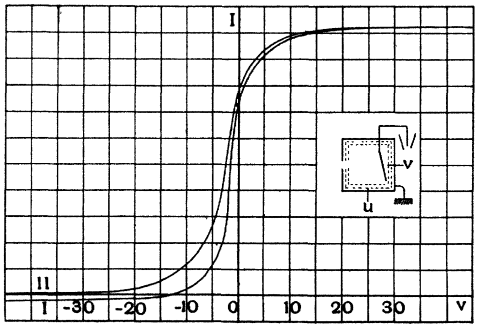

Fig. 5.

electrons which have velocities comparable with the velocity of the cathode electrons producing the X-rays is vanishingly small. This is in agreement with results obtained by Duane, and Hunt[1] who have shown for hard X-rays that energy due to the maximum frequency of hard X-rays given by the quantum equation $Ve = h\nu$ is infinitesimal for a given cathode potential V. This result is to be expected if transformation of energy from radiant energy to energy of motion of electrons and vice versa is not a perfectly reversible process. When the cathode electrons impinge against the anode only a small fraction give up their entire energy to an X-ray pulse in their first collision with an atom. Therefore the primary pulses produced by the original cathode electrons contain many wave-lengths. A fraction of this radiant energy is absorbed by the anode and the inner walls of the X-ray tube, thereby giving rise to radioelectrons and these in their turn give rise to softer X-rays. As the result of this process of progressive exchange of energy between radiation and radioelectrons the beam of X-rays which enters the radioelectric chamber becomes anything but monochromatic. The process of degradation of energy is continued in the X-ray chamber and results in a pseudo-maxwellian distribution of velocity among the radioelectrons, with a maximum velocity determined by the quantum equation. A rough idea of the relative number of electrons having a given velocity may be obtained from Fig. 6, where the abscissas denote accelerating and retarding potentials and the ordinates the corresponding values of the slope of curve *II*, Fig. 5. In view of foregoing considerations it is easy to see why Whiddington[2] was able to obtain halting potentials comparable with the cathode potentials he used, while the other investigators

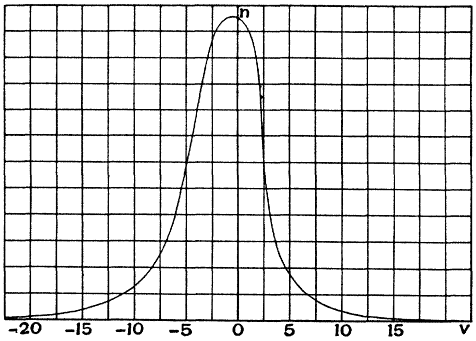

Fig. 6.

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[1] Phys. Rev., 6, p. 166, 1915.

[2] *Loc. cit.*

[3] Irving Langmuir, Phys. Rev., 2, p. 450, 1913.

of soft X-rays did not. In Whiddington's experiment X-rays were produced by the impact of cathode electrons with molecules of air at low pressure. Therefore the rays were more nearly monochromatic than the rays produced by the impact of cathode electrons against metallic targets.

It should be noted that a considerable accelerating potential is necessary to obtain positive saturation even when the electron current from the walls of the radioelectric chamber and the cage are eliminated, as was the case in the experiment represented by curve *II*, Fig. 5. This lag in saturation can not be accounted for by contact difference of potential, especially in view of the fact that both the radiator and the wire-gauze cage were both brass. Two possible factors suggest themselves which may have contributed to the lag. One of these is the negative gradient due to space-charge effect caused by the radioelectric current, and the other is the infiltration of the accelerating field into the depressions on the surface of the radiator. The part played by the first of these factors must have been relatively small because the radioelectric currents involved in these experiments were not large. Therefore the lag must have been due in a large measure to the second factor. Experiment as well as theory shows that electrons produced by a beam of X-rays may have initial velocities having any direction. There can be no doubt that there are electrons among those liberated from atoms on the surface of the radiator which are captured by neighboring atoms and which would leave the radiator if a slight impulse could be given to them in the proper direction. This is especially true when the surface of the radiator is not perfectly smooth and consequently some of the surface atoms are in depressions relative to their neighboring atoms. The accelerating field infiltrates into the depressions on the surface of the radiator and pulls away from the radiator electrons whose velocities make small angles with the plane of the radiator and which without this impulse would have been just barely captured by neighboring atoms which project out on the surface. All the electrons which, in the absence of an accelerating field, would have been captured by a projecting atom after crossing a depression on the surface are pulled away from the radiator when the accelerating potential equals the saturation potential.

On the infiltration hypothesis the value of the saturation potential will depend upon the distance across which the accelerating potential acts and upon the condition of the surface of the radiator. It is possible therefore to give it a further test by obtaining radioelectric curves with different distances between the radiator and the gauze, and with radiators of the same material but with different surface conditions.

The curves of Fig. 7 represent the results of experiments in which the experimental disposition of the radioelectric chamber was further altered as indicated by the inserted sketches. In the experiment represented by curve *I* a positive potential of 200 volts was applied to the outer cage.

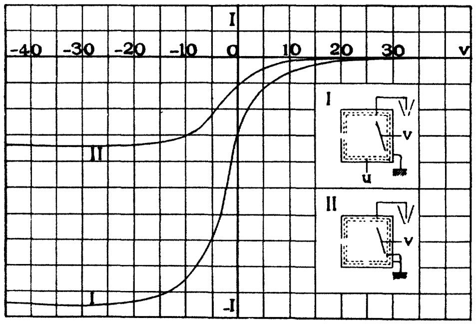

Fig. 7.

The cathode potential was 200 volts for both curves. The general character of these curves is in agreement with the results of the experiments described in the foregoing pages.

III.

The relation between the cathode potential and the radioelectric current was investigated and the results indicated by curves *I* and *II* of Fig. 8 were obtained. In these curves the abscissas denote the cathode potential in the X-ray compartment and the ordinates the positive saturation current of electrons from the radiator to the wire-gauze cage. In the experiment represented by curve *I* the window in partition *D*, Fig. 1, was open, while in the case of curve *II* it was closed with a thin celloidin film. The readings for these curves were taken alternately, that is, a reading for a given cathode potential was taken for each curve before altering the potential for another pair of readings.

Both curve *I* and curve *II* show the presence of characteristic X-radiations. In curve *I* there are three well-defined peaks at 400, 580 and 800 volts. The first two of these peaks are shifted to the right in curve *II* indicating that the rays responsible for these peaks have suffered partial absorption in passing through the celloidin film. They must therefore be due to characteristic radiations from the platinum anode in the X-ray compartment. The third peak is, in all likelihood, due to L-radiation of copper, which forms with zinc the two elements in the brass radiator. The potential at which this peak appears is near enough the computed value of the potential at which L-radiation of copper is to be expected. Using

Kossel's[1] formula $L_\alpha = K_\beta - K_\alpha$, the quantum relation, and the known values of K_α and K_β for copper this potential is found to be 778 volts. The corresponding potential for zinc is 930 volts; therefore the sudden rise of both curves in the neighborhood of 950 volts may be due to L-radiation of zinc.

It may be stated here parenthetically that the radioelectric method described in this paper lends itself very readily to the detection of K- and L-radiations of elements of low atomic numbers, and the lower series of characteristic radiations of elements of high atomic numbers. In the usual spectrometer method the beam of X-rays has to pass through absorbing matter before entering the ionization chamber where the effect to be observed is produced. In the radioelectric method there need be no absorbing material in the path of the beam before entering the radioelectric chamber where the observed effect is produced. The author hopes to use this method in studying characteristic radiations of low frequency using a modified apparatus especially adapted for the purpose.

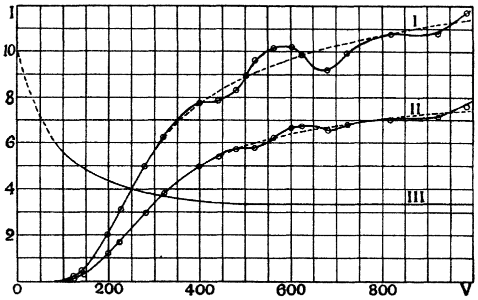

Fig. 8.

Curve *III*, Fig. 8, shows the absorption of soft X-rays by the celloidin film. The ordinates of this curve represent a coefficient of absorption defined by

$$\alpha = \frac{I_1 - I_2}{I_1}$$

where I_1 and I_2 denote, respectively, the ordinates of curves *I* and *II*. It will be observed that the coefficient of absorption is greater at lower potentials.

I wish to thank Sir J. J. Thomson for suggesting this investigation and for placing the facilities of the Cavendish Laboratory at my disposal during the preliminary stages of the investigation. The experiments described in this paper were carried on in the Sloane Physical Laboratory while I was still a member of the Physics Department of Yale University.

NEW YORK CITY, April, 1919.

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[1] Kossel, Deutsch. Phys. Gesell. Verh., 16, p. 953, 1919.