SOFT X-RAYS PRODUCED BY CATHODE RAYS OF FROM 200 TO 600 VOLTS VELOCITIES.

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SYNOPSIS.

Soft X-Rays, Examination of Method of Investigation Using No Window.—Previous results by the one author are briefly referred to, and a new experiment is described showing the difficulties in measuring a photoelectric effect due to soft X-rays produced in the same chamber as that which contains the photoelectric electrode.

Soft X-Rays Produced by Cathode Rays of between 200 and 600 Volts Velocity, Effect of Occluded Gases in the Anticathode on the Intensity.—The *method* used for estimating the radiation produced was to allow the soft X-rays to ionize the gas in a chamber separated from the discharge tube by a thin celluloid window. (*a*) A platinum anticathode was partially denuded of gas by glowing, and (*b*) the remnants of gas in the tube were displaced by hydrogen, the intensity of radiation was not notably altered. The *conclusion* is drawn that the radiation observed comes from the solid anticathode.

Variation of Intensity of Radiation with Voltage for Anticathodes of Brass, Platinum, Graphite, Aluminum, Lithium and for Gas Remnants, Air, Hydrogen, and Carbon Bisulphide.—After showing that the radiation is proportional to the cathode ray current, and that relative measurements could be fairly well repeated, even with different *pressures of gas in the ionization chamber*, the authors give details of the relative intensities and of the actual ionization current at 600 volts. The intensity at 300 volts was less than 2 per cent. that at 600 volts.

Characteristic and General X-Radiation.—From a comparison of (*a*) the radiation from different anticathodes, and (*b*) the intensity as measured by ionization and by the photoelectric effect, it is inferred that the radiation is largely general. There is evidence of a characteristic (K) radiation from carbon, and one observation suggesting a characteristic (L) radiation from aluminum. At the end of the paper are found *suggestions* of possible reasons for the similarity of behaviour of different anticathodes.

Soft X-Rays from 200 to 300 Volts.—It appears that the radiation in this region ionizes the gases used relatively less powerfully in proportion to its photoelectric effect.

X-Radiation below 190 Volts.—Tests are described showing that the effects thus far obtained by the authors were due to gas in the tube and not to a radiation from the solid anticathode.

THE following experiments have been done at odd times in the last three years in continuation of work previously published by one of us[1] on the X-rays produced by slow moving cathode rays. In the previous work it appeared among other results that X-rays were not obtained by the impact of cathode rays of less than 200-volt velocity

[1] Laird, Annalen der Physik (4), 46, p. 605, 1915.

on solid anticathodes, or else that such rays would not pass through a window of celluloid film to produce a measurable photoelectric or ionization effect, that above this voltage such rays were produced, the intensity of which seemed fairly independent of the anticathode used. The attempt to measure the wave-length by the velocity of the photoelectric electrons produced by the rays was not found very satisfactory, the method showing velocities up to not more than 100 volts when the cathode rays were of 500-volt velocity. In seeking to throw light on the questions raised by these results it was proposed (*a*) to make a further attempt to get on without a window, (*b*) to try other methods of ridding the anticathode of gas, supposing this might account for the similar behavior of the different anticathodes, (*c*) to examine more carefully the intensity of the radiation at different voltages, as measured by the ionization currents for comparison with the photoelectric effect and (*d*) to seek for characteristic radiations in the interval 200–600 volts.

The various researches on the emission of electrons from heated tungsten filaments led to the hope that by use of such, observations could be made at high vacuum on soft X-rays without use of a window. For this purpose after some preliminary experimenting on the use of such

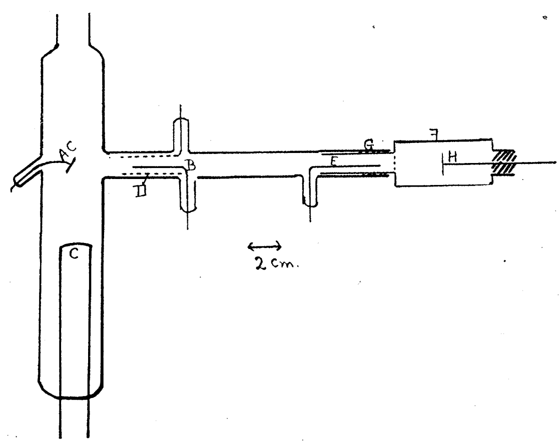

Fig. 1.

filaments, obtaining currents of .06 ampere with no luminosity that could be seen by a casual observer but which could be detected at the instant of putting current on and off, the apparatus shown in Fig. 1 was used. In this all seals were glass seals except at *G* where the metal chamber was sealed on with de Khotinsky cement. *C* was a tungsten wire, *AC*, a small brass anticathode, *D* a gauze, *B*, *E*, wires, *F* a metal cylinder, *H* an electrode connected to an electrometer. The pump used was a Gaede mercury pump. The tube was heated in an electric oven to 350° for some hours, while pumping, CO_2 and acetone were used on a charcoal tube to freeze out mercury vapor. The pressure while the electron current was going was in the neighborhood of .0001 mm.; observations were then made on electrometer deflections in a given time with a potential difference of 135 volts between cathode and anticathode. It was found that establishing a field between *B* and *D* changed the deflections obtained enormously, and that even when such a field was used so that changing the potential of *E* from 0 to 135 made very slight further change, yet if *F* were changed from + 5 volts to − 1.3 the sign of the electrometer deflection was changed. This might be due to photoelectric electrons from the edge of the opening into *F*, but the experience made it improbable that one could establish the existence of an X-radiation at low voltages by this method. This was in agreement with the observations made in the earlier experiments. In this connection it is interesting to note that Richardson and Bazzoni[1] using the method of magnetic deflection for measurement of the velocities of ejected electrons were not able to show the presence of a radiation of wave-length greater than 60 Å. (and did not try for smaller wave-lengths) from a solid anticathode in a high vacuum. Their method however would not be as sensitive as the more simple ones.

Having concluded from the experiments just described that more progress could be made with use of an airtight window, a return was made to the previous arrangement of apparatus and a Wehnelt cathode. The apparatus, which was originally set up by Miss Barton, is shown in Fig. 2. Slight changes were made in it from time to time. Both discharge tube *B* and measuring chamber *A* were of brass. The anticathode and plate electrode *P* were carried by side tubes. *P* was connected to an electrometer, with amber insulation throughout. The plate *P* was later changed for a long wire as indicated.

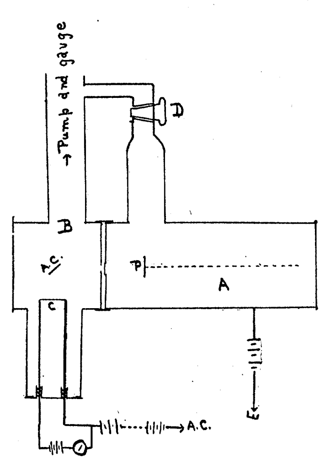

Fig. 2.

The cathode ray current up to potentials of 450 volts was supplied by a combination of dry cells and small storage cells, above this by the addition in the circuit of the line from a small dynamo. P.D. measurements were made at first with a high resistance voltmeter, which as

[1] Richardson and Bazzoni, Phil. Mag., 34, 285, 1917.

used would take about 2 milliamperes current. Later an electroscope clamped in place, the leaf of which was projected by a clamped lens on a scale formed a convenient and inexpensive electrostatic voltmeter. The scale was calibrated by groups of cells, in turn calibrated by a potentiometer. With this the potential on the tube could be read while taking readings with the electrometer. The current through the tube was read on a shunted Leeds and Northrup pointer galvanometer. The heating current on a Weston ammeter graduated to .1 ampere, graduations being about 3 mm. apart, it was furnished by storage cells. The electrometer needle was charged by a small set of cadmiun cells to 80 volts, its sensitiveness with the connections was 3.3×10^{-15} ampere per sc. div. per minute, and was very constant, one third of this was measurable in the best conditions.

Two methods were employed to test whether the X-radiation produced when slow cathode rays fall on the anticathode comes from gas occluded in the anticathode. The first was to introduce a thin platinum foil, which could be electrically heated, as anticathode. A set of readings were taken with air at a pressure of 4 mm. in chamber A, pumping on

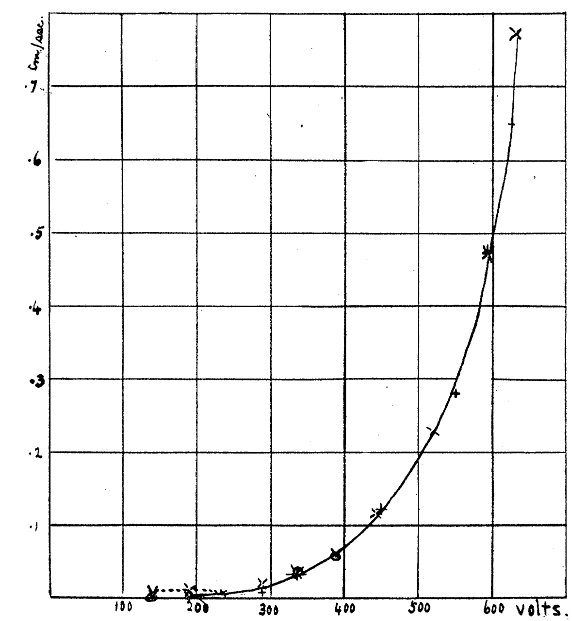

Fig. 3.

the other side to .002 while the discharge was going. The walls of the chamber were + 6 volts. The results are shown in the curve of Fig. 3 by points marked $\times$. The anticathode was then glowed for an hour and a half, the center being at white heat the last ten minutes, pumping all the time, during the last hour CO_2 and acetone were used on a charcoal tube. At the end of this time the pressure with the discharge going was still .001 mm., the observations taken at the end of this time are shown by the points marked ⊙ in Curve I., Fig. 3. It is seen that while below 200 volts the deflections are reduced nearly to zero, above 300 they are unchanged. With this same anticathode a set of readings were taken with the case $-$ *ve*; these were only half as great as with the case $+$ *ve*, and are shown in Fig. 3 on a scale twice as large as the scale for the other readings marked by $+$. Relatively there is fair agreement above 300 volts. Observations taken with the case at -6 volts do not include the photoelectrons, so that one would expect some slight difference, but we were unprepared for the great difference observed between the positive and negative currents amounting in a case observed by one of us to a ratio of 18 to 1 but variable. This when the back of the discharge tube was of gauze, and a brass electrode *P* was used. Finally when a small window was used, and a wire as collecting electrode the difference was reduced to one fifth of the whole. This would indicate that the difference was due to ions produced by the photoelectric electrons. Working with the case negative had the advantage of avoiding a possible error due to light in the tube.

More recently the second method of testing the effect of gas in the tube has been tried. Arrangements were made to wash out the apparatus thoroughly with hydrogen. As hydrogen is not believed to furnish any radiation of wave-length lower than 900 Ångstroms, it was supposed that this process might alter completely the X-radiation obtained. A fine capillary tube connected the discharge tube to a flask of about 1.5 liters capacity filled with electrolytically prepared hydrogen dried by passing over P_2O_5. No charcoal tube nor cooling was used. After the apparatus was pumped out, some hydrogen was admitted and pumped out, then more let in until the pressure was 19 mm. at which pressure the cock *D* was closed, and then the discharge tube pumped out and the admission of hydrogen controlled so that a pressure of about .003 mm. was recorded. A set of observations at 600, 500, 400, 300 volts gave values about 1/4 that with air. Cock *D* was then opened, the apparatus exhausted, and hydrogen introduced to 30 mm. pressure, the cock *D* closed, and observations repeated with a pressure .004 mm. in the discharge tube. This gave values differing only slightly from the previous ones. *D* was then opened, the apparatus exhausted, and hydrogen admitted to 3 mm., *D* closed, readings at .008 mm. gave values about 1/4 the previous ones, at .002 mm. about 1/3. 30 mm. pressure tried again in A restored the higher value, 17 mm. repeated gave values about 5 per cent. higher than the first. With D open, hydrogen at 30 mm. was left in the apparatus over night. The next day after pumping D was closed at 7 mm. pressure, and a stream of hydrogen passed through the discharge tube at pressures from .005 mm. to .2 mm. the discharge going all the while with currents from .3 m.a. up. Only .2 m.a. was being used for measurements. The electrometer currents were the same afterwards as before. These various observations made it seem probable that the diminution observed as compared with air was due partially to the somewhat higher pressure in the discharge tube, but more to the use of hydrogen in the ionization chamber. Hence another test was made by pumping out and letting in air to a pressure of 5 mm., closing D, exhausting, and taking a reading. Hydrogen was then pumped through for two hours, and for $1\frac{3}{4}$ hour the discharge passed. For the last half hour large currents were used at a pressure of .13 mm. At the end of this time the flow of hydrogen was stopped, and readings taken. The first was a little low, probably the pressure was still high. The second was somewhat higher than it had been at the beginning, but not sufficiently so as to suggest a real difference.

Air was then let into the main apparatus and the anticathode which had been brass dusted over with graphite was removed, cleaned, polished and replaced. The flask of hydrogen was pumped out and refilled, and the experiments repeated. Hydrogen was left standing in the apparatus two hours, and for two hours the discharge was passed with hydrogen flowing through, with the same result as before. During this run it was found that at a pressure of .024 mm. and 2 m.a. current one had the same electrometer currents for 400 and 300 volts as for 0.1 m.a. at a pressure of .0016 mm. This is just the sort of change found with pressure conditions such that only a small portion of the rays striking the anticathode have the full velocity. These two sets of experiments make it rather sure that the X-radiation under observation is from the solid anticathode rather than from a gas.

In the earlier experiments no constancy had been found in the ionization currents produced by the radiation on different days, nor any relationship between the ionization and the pressure of the air. This was ascribed to two causes, the lack of a saturation current, and the presence of vapors in the air due to the use of a charcoal tube. Similar variations were found in the course of these experiments, but as this last year no charcoal tube was used, and no vapor introduced for other reasons, more uniform currents were obtained. The result of a trial with air at different pressures is shown in Table I. The air was let in through a $CaCl_2$ drying tube and the pump, and was room air from near a window. The figures give electrometer deflections per minute for

Table I.

(Case − 6 volts.)

P. D.	2 Mm.	7.5 Mm.	15 Mm.	29 Mm.
600	90 (100)	126 (100)	133 (100)	126 (100)
500	43 (47.7)	62.7 (49.5)	65 (48.9)	63.2 (49.7)
400	15.4 (17.2)	23.2 (18.4)	22.5 (16.9)	24? (19.2)
300	2.1 (2.4)	2.8 (2.2)	2.6 (2.0)	2.1 (1.7)

constant cathode ray current at the different pressures. There is seen a decided increase from 2 mm. to 7.5 mm., a slight one up to 15 mm. and beyond what appears like a slight decrease. Increasing the potential on the case to − 12 volts did not alter the current. Nevertheless it is probable that at the higher pressure a saturation current was not really obtained. The relative ionization at the different voltages is shown by the figures in brackets, and does not vary markedly. The ionization current increased proportionately with the cathode ray current over a wide range tested from .007 to .3 milliampere.

Table II. shows in extended form the relative values of the ionization currents for different potential differences on the discharge tube under a variety of circumstances. The headings of the columns give the anticathode used, date, gas pressure in the chamber A when known. At the foot of each column is given the cathode ray current in 10^{-4} amperes, and the electrometer deflection per minute at 600 volts. The measurements are shown divided into four groups. The first group includes those where the voltages were measured electrostatically, in the others it is estimated that error if present would be in the direction of making the lower voltage readings relatively too low. In the groups after the first a number of the values have been interpolated between adjacent readings, indicated by brackets about the number at the head of the column. The second group contains two sets of measurements with an anticathode that had been soaked in a strong solution of lithium chloride. The first measurements given were made six months after the salt had been put on, and after the anticathode had been used considerably. The plate electrode P used in the first part of the first group, the second group and the first four sets of the third group was of aluminum, in the last five sets given it was of brass. In these five sets also the back of the discharge tube was of brass gauze, instead of a solid brass piece with a central opening. The fourth group are three sets of observations made

TABLE II.

Voltage.	Plate Electrode. Brass Aug. 7, Air 7 Mm.	Plate Electrode. Brass Aug. 12, Air 15 Mm.	Wire Electrode. Brass Aug. 18, Air 12 Mm.	Wire Electrode. Brass Aug. 19, Air 32 Mm.	Wire Electrode. Graphite Aug. 19, Air 14 Mm.	Wire Electrode. Graphite Aug. 20, Air 18 Mm.	Wire Electrode. Graphite-H_2 Aug. 22, H_2 19 Mm.	Wire Electrode. Aluminum-H_2 Aug. 27, Air 16 Mm.	Licl Jan., '19, Air 4 Mm.	Licl Aug., '19, Air 9 Mm.	Platinum Aug. 1, '18, Air 4 Mm. Case + *ve*.	Platinum Aug. 3, '18, Air 6 Mm.	Pencilling on Brass Aug. 6, '18.	Pencilling on Brass Aug. 7, '18. Case + *ve*.	Larger Window. Brass July, '18, CS_2, Air.	Larger Window. Brass July, '18, CS_2, Air.	Brass May, '17, Case + *ve* Air.	Brass May, '17, Air.	Brass May, '17, New Window.	Cu and Pt, '14, Vacuum (d).	$\frac{d \times \text{Voltage}}{600}$.
600......	100	100	100	100	100	100	100	100	(100)	(100)	(100)	(100)	(100)	(100)			(100)	(100)		100	100
550......					73	69.7		70.2	67	57	63		78	61				65	(65)	76	69.8
500......	43	48.9	52	46	55.8	50.3	49.4	48.2	35	22		42.5	52.3	42	(45)	(45)	44.5	42.8	42.5	52	41.6
450......					38.7	34.3		30.1	18.5	9.4	23.8	23.2	32.5		27	25	27	24	24	34	25.5
430......					37	28.7									19	21	23	20	20		
413......					27.7	24.5				4.4					16	19	19	15	17		
400......	12.3	16.9	19.9	19.2	23	21.1	19	18.6			13.4	14.4	20.3		14	15	15	13	14	22.2	14.8
390......	9.3				21.8	18.6					10.7				12.7	12.4					
370......	6.0				15.4	13			4.2											14.3	8.8
350......	4.5		9.2		8.9	8.7		8.4		1.0	7.6		12.4		6.4	5.5				10.8	6.3
330......			5.5		6.8	5.6						2.2		2.9							
320......	2.9		2.85			4.7	2.9	2.9					2.4	1.7			1.4	3.8	5.2		
300......	1	1.98	1.69		3.4	1.68	1.5	1.1	.0				1.2		2		.7			5.6	2.8
280......			.37			0.51	.7	.7		.0		.55	.5				.4	2.3			
260......			.18			.19		.3													
220......	.3		.0		.0		.0	.2							0.3		.1	.1		.9	.3
200......								.2		.0	.39	.03		.3	0.1			.0		< .2	.1
..	4	<3	1.1	0.8	0.8	1.1	1.8	1.3	3	4	3	2	3	2.9	2	2.3	30	30	13		
r																					
e.	75	133	331	204	234	385	76	312	40	68	308	152	980	618	2,440	1,860	7,200	330	830		

by Miss Barton with two windows of different thickness and size. Finally is given the relative measurements on the photoelectric current produced by the radiation at high vacuum, and the result obtained by multiplying these numbers by the corresponding difference of potential divided by 600.

If the radiation were a characteristic radiation of definite wave-lengths, only the intensity of the lines increasing with the voltage, then the ionization current would be proportional to the photoelectric current. On the other hand if it were purely a general radiation in which the wave-length varies inversely with the voltage of the cathode rays, and if the energy of the ejected photoelectrons were proportional to this voltage, and capable of producing ions in numbers roughly proportional to the energy, then the relative ionization would approach the numbers in the last column. A first glance at the table is not encouraging for a definite decision, as the numbers in the rows differ even for the same anticathode. The first given for a brass anticathode, those for platinum, for brass with some carbon bisulphide, and Miss Barton's observations agree approximately between 600 and 320 volts with the last column. The others for brass, and the one for aluminum lie in between.

The only known difference between the first set of observations given for brass and the others of the first group, in addition to the difference in pressure as shown, is that in the first set the cathode ray bundle was diffuse, in the others it was a definite pencil appearing to come from one point of the cathode. In each case when graphite was used, in the one instance as powder dusted on, in the other as pencil marks, the first set of readings gave values markedly larger between 350 and 550 volts than these given by the other anticathodes, or by the graphite later. This suggested a change in the anticathode when used, but gives some grounds for supposing that one had here the K characteristic radiation of carbon which might be expected in this neighborhood. The actual deflections with the lithium chloride anticathode were smaller than with the other materials, and fell more rapidly with decreasing voltage. The surface was rough, and there was possibly a local higher pressure, so that it is not felt that this indicates surely a real difference. Below 300 volts it is safe to say that the ionization is relatively smaller than that computed by either method from the vacuum phenomenon. The ionizing power must be diminishing either as a result of diminished velocity of the ejected electrons produced by it, or of diminishing power to ionize the air directly. In the previous experiments one set of observations was recorded where there was an enormous increase in the radiation at about 400 volts. This happened after liquid air had been removed from a charcoal tube, evidently releasing various vapors. In the hope of producing a similar effect, the vapors of ether, carbon-bisulphide and turpentine, were introduced into the apparatus, but there was no marked result. Below 200 volts especial search was made for a radiation from the lithium chloride anticathode as a characteristic X-radiation from lithium might be expected. In the first trial, not shown in the table since the cathode ray current was inconstant, effects were found down to 100 volts. This could not be repeated with the case $-$ *ve.* however. With the case $+$ *ve* an effect was found which increased with diminishing voltage down to about 170 volts and then slowly diminished. A similar effect was found however with a brass anticathode, and, as indicated in Fig. 3, with a platinum anticathode before being glowed. It evidently did not represent a radiation capable of producing ionization as there was no effect with air in the chamber when the case was negative,

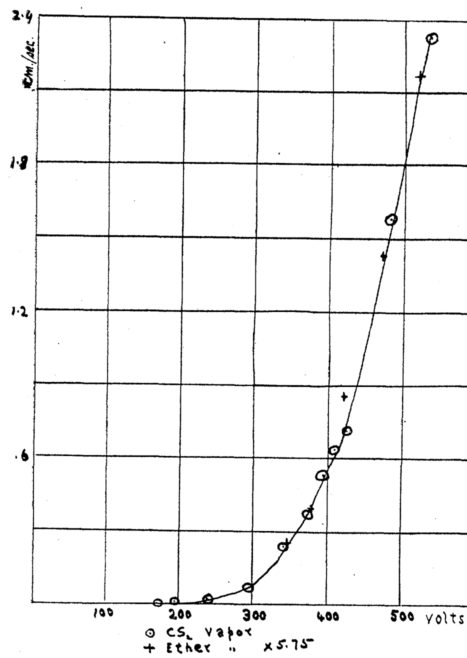

Fig. 4.

nor was it a radiation from the solid anticathode since it was removed by the ridding of the anticathode of gas in the case of the platinum. Occasionally as low as 190 volts electrometer deflections slightly greater than the natural leak were obtained, hardly enough to demonstrate surely an X-radiation from the solid anticathode. The electrometer was however not pushed to its greatest sensitiveness. Examining the results it was noted that in the case of aluminum larger relative values at 200 and 220 volts were obtained than in any other set of this most recent group, and larger than in any other instance with the case − *ve*. Unfortunately this was not repeated nor was an attempt made to continue below 200. The observation is of interest as aluminum would supposedly have its L radiation at this point, but this was not in mind at the time. Some sets of observations are shown graphically in the curves of Figs. 4, 5, 6.

There seem to be three possibilities of explanation for the fact that

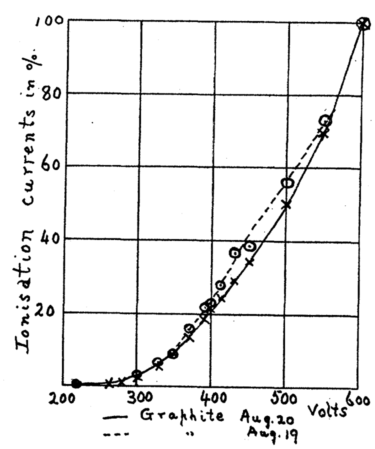

Fig. 5.

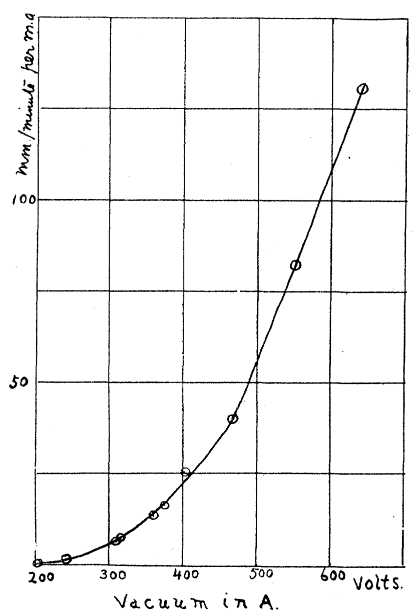

Fig. 6.

varying the anticathode changes the radiation produced so slightly. First all the anticathodes may give off so many radiations in this region that the method fails to distinguish between them, second they may all become sputtered from the cathode in the same way, or third the radiation may be largely a general radiation. This latter is probably true in any case as seen from Table II. The common classification of spectra ascribes bright line spectra to gases and vapors, in the case of the ordinary X-rays the wave-length is so small that the distances between atoms is larger than the wave-length, or a solid is relatively a thing with holes in like a gas, but in the case of these soft X-rays the wave-length is greater than the atomic distances, so that one might well expect the relative intensity of lines to diminish unless one could produce a layer of vapor close to the anticathode. As further experiments with this particular method are being halted in the intention of trying out new methods of attack, it was thought best to publish these results as they are. A closer examination of the variation of the radiation with shorter steps in the potential difference might still bring more accurate results, with greater means at hand of keeping the heating current for the cathode constant over a long range of time.

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SEPTEMBER, 1919.