SOFT X-RAYS FROM IRON

By Charles H. Thomas

Abstract

Critical potentials of iron to 900 volts, determined photo-electrically.—Soft x-radiation from a polished iron target bombarded by electrons from a filament heated by a current constant to .01 per cent, produced a photo-electric current from a platinum semi-cylinder which was so placed that all the radiation from the target fell on it and which was protected from stray electricity by a system of radially disposed nickel vanes charged alternately positively and negatively. A vacuum of 10^{-6}mm pressure or better was maintained. When the ratio of the photo-electric current to the thermionic bombarding current was plotted as a function of the exciting voltage a number of breaks appeared. From the similarity of the curves thus obtained to those obtained with gases, breaks at radiation potentials were distinguished from those at ionization potentials. The fact that radiation excited by 2.3 volt electrons produced a photo-electric current, can be explained by taking Einstein's complete equation $h\nu = e(V+\Phi)$ where Φ is the *work function* of iron whose value is calculated to be 5 volts. Correcting for this, about 23 *radiation potentials* were located at 7.3, 14.1, 16.5, 24.3, 28.8, 34.3, 48, etc. volts, and 9 *ionization potentials* at 11.1, 19.4, 41.2, etc., volts. The ionization potentials at 818.5, 704.3 and 54.6 volts are identified with the lines L_I, L_{III}, and M_{III}.

Introduction

A CONSIDERATION of the $eV = h\nu$ relationship, together with the known photo-electric properties of platinum, shows that radiation excited by 5 volt electron impacts is of sufficiently short wave-length to produce photo-electric emission from platinum. However, the observers[1-11] who used the general method of measuring the photo-electric current caused by the radiation from a metal bombarded by electrons, have failed to obtain any photo-electric emission from radiation excited by less than 12.5 volts and no definite results have been reported below

[1] Richardson and Bazzoni, Phil. Mag. **42,** 1015 (1921)
[2] Kurth, Phys. Rev. **18,** 461 (1921)
[3] Horton, Andrewes and Davies, Phil. Mag. **46,** 721 (1923)
[4] Lukirsky, Phil. Mag. **47,** 466 (1924)
[5] Rollefson, Phys. Rev. **23,** 35 (1924)
[6] Boyce, Phys. Rev. **23,** 575 (1924)
[7] Bazzoni and Chu, Jour. Franklin Institute **197,** 183 (1924)
[8] Hughes, Phil. Mag. **43,** 145, (1922)
[9] McLennan and Clark, Proc. Roy. Soc. A **102,** 389 (1923)
[10] Holweck, Ann. der Phys. **17,** 5 (1922)
[11] Holtsmark, Phys. Zeit. **23,** 252 (1923)

16 volts. Milliken[12] by spectroscopical methods has found lines in the spectrum which correspond to voltages even lower than 12.5 volts. Therefore it would seem probable that critical potentials should be observed in the low voltage region if sufficient radiation energy could be made to fall on the photo-electric detecting plate.

The ionization of residual gas in the experimental tubes has frequently led to difficulties and errors in the low voltage regions. Therefore any method for further investigation of this problem at low voltages must provide for the elimination of this error. A modification of the type of apparatus as used by Kurth was adopted because it seemed to offer the best possibilities of success.

Apparatus and Procedure

The essential part of the apparatus is shown in Fig. 1. The cathode source of electrons *F*, consisting of several turns of helically wound 15 mil

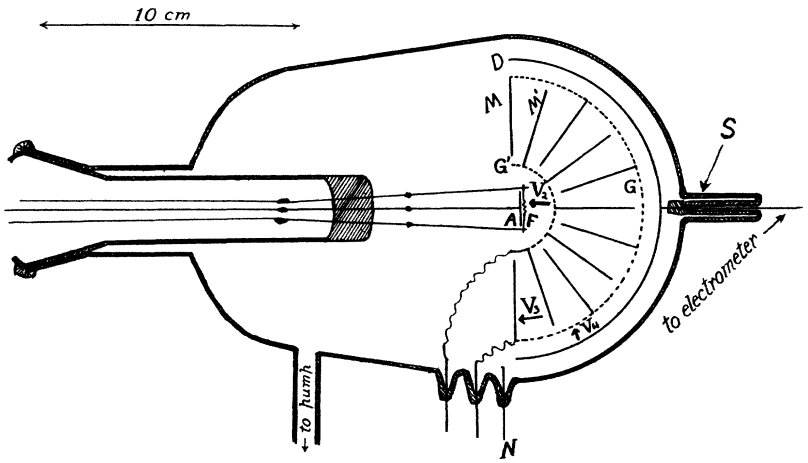

Fig. 1. Apparatus.

(0.375 mm) tungsten wire, was placed 1 mm in front of the anode target *A* which was a highly polished iron plate 8×12 mm in size. The anode and cathode were supported on tungsten leads through the glass stem, which was fitted to the tube with a ground glass joint and sealed with De Khotinsky cement. This ground glass joint was long and was kept free from cement except at the outside, where it was kept cool by water circulation. Thus, cement vapor pressure was reduced to a minimum and its presence in the experimental tube rendered inappreciable by the diffi-

[12] Milliken, Proc. Nat. Acad. Sci. **7**, 289 (1921)

culty of its diffusion through the ground joint combined with the rapid evacuation by the pump and liquid air traps.

The nickel vanes, M and M', in the form of a hollow semi-cylinder 8 cm in diameter and 8 cm high, were charged alternately positively and negatively, the negative ones being connected to a coarse gauze G', the positive ones M being connected to a coarse gauze G which acted as a receiver for the photo-electrons. The gauzes G and G' were made of fine platinum wire and were of such coarse mesh as not to intercept any appreciable amount of the radiation. These vanes, which were rigidly held together by spotwelding, were supported on two glass rods (not shown in diagram) from the stem S. These rods were carefully wound with a few turns of fine platinum wire which was connected to earth through N, in order to prevent any surface leakage of electricity to the detecting cylinder D.

This semi-cylindrical platinum detector D surrounded the vanes at a distance of 7 or 8 mm, and was supported on a tungsten lead which connected it to the electrometer through S.

A potential V_1 of from 0 to 1500 volts between anode and cathode, was supplied by a small direct current generator and was adjusted by the potentiometer method, using sliding rheostats. This voltage was measured on a 150 volt Weston Laboratory Standard Voltmeter fitted with suitable multiplying resistances to give the proper scale, on which the applied voltage could be measured to 1/30 of one per cent. A retarding potential V_2 of 8 volts was maintained between F and G'. This was found sufficient to keep all electrons from passing through G'. A potential V_3 of 145 volts between the vanes M and M' was furnished by dry cells, and was sufficient to prevent any ions, which might be present, from reaching D. A potential V_4 of 16 volts between D and G pulled off the photo-electrons from the detecting plate.

The filament cathode was heated by a current of 10 to 12 amperes, which was supplied by high capacity lead storage cells. The voltage drop across the cathode was 2 to 2.6 volts. In the early part of this work a carbon rheostat paralleled by a sliding wire rheostat was used to regulate the cathode current but this permitted a slight erratic variation which was sufficient to cause the results to be difficult to interpret, on account of the rapid variation of the thermionic current with small changes of temperature of the cathode. Later a resistance made by immersing in kerosene a nichrome ribbon with clamped contacts gave a current constant to at least one hundredth of one per cent. However, in order to obtain such a degree of constancy the cathode current was turned

on an hour before any readings were taken, to give ample time for the equalization of the batteries.

The thermionic current, varying from 0.5 to 4 milli-amperes, was measured on a Paul Universal Test Set.

The photo-electric current was measured by the constant deflection method on a Dolezalek electrometer with a sensitivity of 2300 mm per volt, shunted by a convenient set of India ink resistances.

An apparently perfect vacuum as indicated by a sensitive McLeod gauge capable of measuring 10^{-6} mm, was maintained by a mercury diffusion pump, backed by an oil pump, and a series of three liquid air traps, two of which contained charcoal. Before each series of runs the tube and charcoal traps were baked at a temperature of 450 to 500°C for a period of three hours by a system of electric heaters. At the conclusion of this baking out process the anode was brought to a bright red heat by bombarding it with electrons. In this manner the target was freed from occluded gases.

The tube and stem were wrapped on the outside by a few turns of fine platinum wire which was connected to earth. The heater coils were earthed during readings. The tube was further protected by a metal shield which covered the heating coil box. With these precautions the possibility of electrostatic disturbances or of surface leakage of electricity from the outside was negligible.

It was possible to get sufficient electrons from the cathode when it was heated to a temperature which should have caused little evaporation of the tungsten from the cathode. However, after ten or twelve hours use, there was a slight deposit on the polished anode. This did not affect the position of the breaks but it did decrease the sharpness of the breaks to a marked degree. When the anode was freshly polished the original intensity of the breaks returned. For this reason the anode was removed frequently and polished carefully, after which it was returned to the tube as quickly as possible and a vacuum obtained so that there would be as little time for oxidation as possible.

When a very hot cathode had to be used in order to obtain sufficiently large readings for accuracy, as at the lower voltages, an electrometer deflection of 15 to 20 mm in the positive direction occurred before the anode voltage was applied. At a lower cathode temperature and with a less sensitive electrometer shunt, with which most of the readings were taken, this effect amounted to only 2 or 3 mm. This deflection was constant for a constant filament temperature and could therefore be easily allowed for by shifting the zero of the electrometer scale. This effect was due to the photo-electric emission caused by the light from the filament.

The heating current through the filament was adjusted so as to give a maximum electrometer scale deflection for each run, which consisted of thirty or less readings over the desired voltage range. By following this plan it was possible not only to keep initial conditions constant for the short period necessary to take the readings but also to obtain greater accuracy by having the readings as large as possible.

When the ratio of the photo-electric current to the thermionic current was plotted as a function of the anode voltage, curves were obtained which show marked changes of slope at critical potentials. These breaks have been interpreted as indicating critical voltages at which new types of radiation set in and the frequency has been computed from the $eV=h\nu$ relation. In the study of iron only upward breaks due to increased radiation were noted.

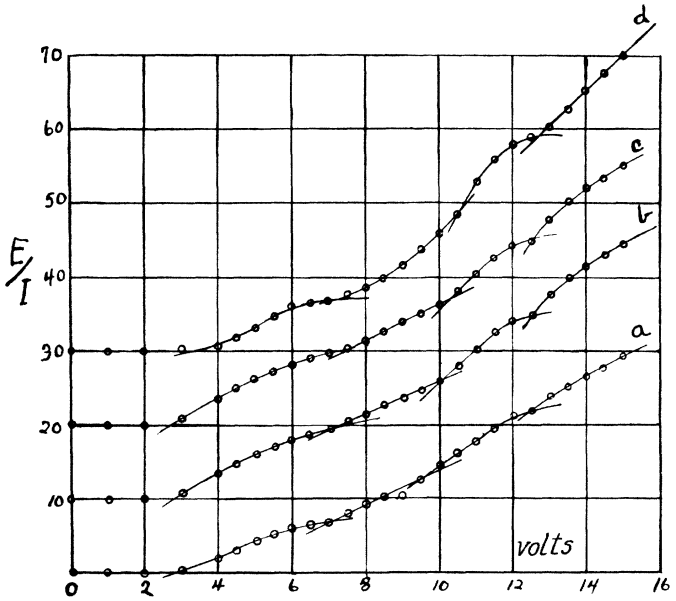

Fig. 2. Ratio of photo-electric current to thermionic current, as a function of anode voltage.

RESULTS

Fig. 2 gives four curves for the low voltage range over which the readings were taken at half volt intervals. Here, as in the following graphs, E/I is plotted on an arbitrary scale. These curves are the results of readings of different days. Each curve shows similar breaks and agrees well with the others except for the point on curve (a) at 9 volts. This discrepancy is assumed to be due to an experimental error. The first break occurs at an average of 3.3 volts. The second, at 7.1

volts, is of a different character because the curve shows no downward curvature or decrease of slope until it reaches the following break. Strong breaks occur at 10.1 and 12.5 volts.

Fig. 3 shows the results of eight runs over the range 38 to 90 volts or less. Curves (a) and (b) were taken from results obtained when the target had been used 12 hours without polishing. Therefore these curves do not show as strong breaks as the remaining curves. Each of these curves was taken under different conditions. These results were taken

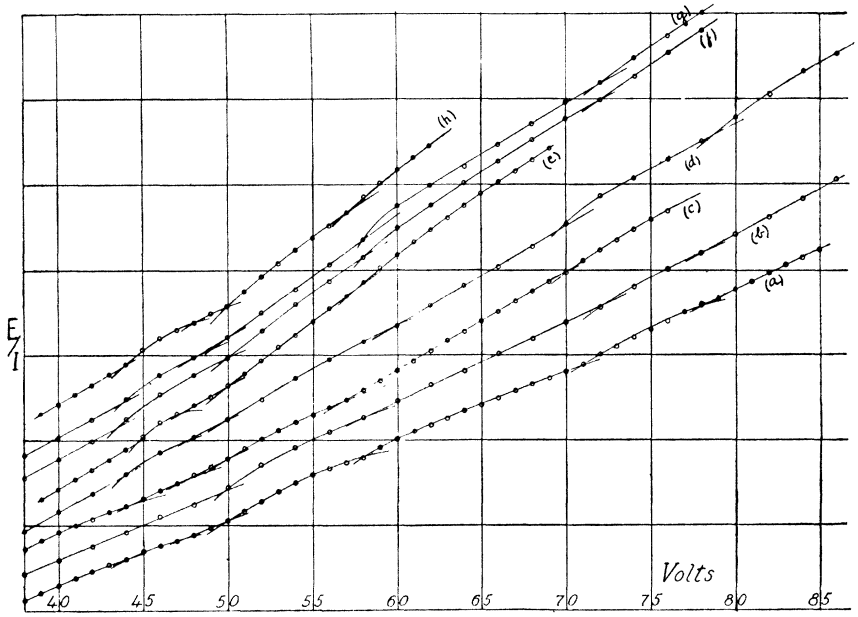

Fig. 3. Results for higher anode voltages, 38 to 87.

on five days, some with and some without fresh polishing of the target, and using three different electrometer shunts. However, their agreement comes within the limits of experimental error. A break occurs on 7 of the curves near 45 volts. Another break, which is shown on the best curves at smaller intervals, appears at 47.3 but this break is questionable because the late spring weather conditions would not permit of a final accurate check of this point.* At 50 volts a strong upward break occurs, also breaks at averaged values of 58.1, 71.3 and 78.7 volts.

Fig. 4 curve (a), the readings of which were taken at 3 volt intervals, shows breaks at 273, 285, 301, and 328 volts. Curve (b), readings at 2 volt intervals, shows breaks at 215 and 226 volts.

* Note added to proof: Since this was written the reality of this break has been verified by additional tests.

Fig. 5 curve (a), the readings of which were taken at 5 volt intervals, shows breaks at 636 and 698 volts. Because the break at 636 volts occurred on only half the curves taken, this break is questionable. Curve

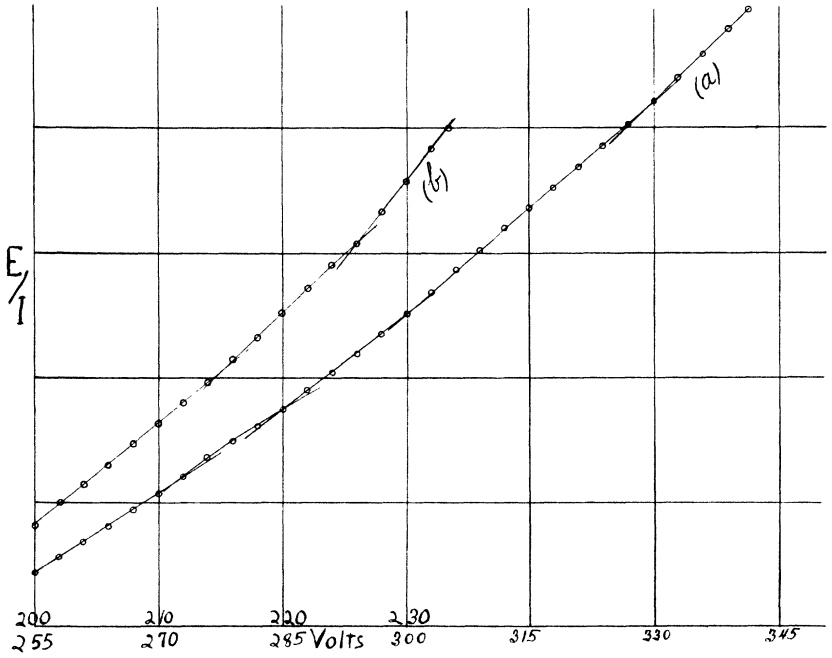

Fig. 4. Results for anode voltages 200 to 345.

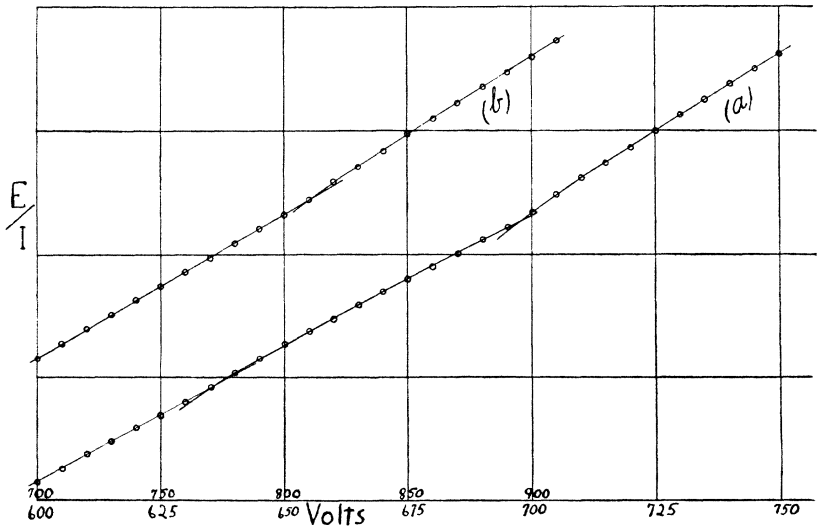

Fig. 5. Results for anode voltages 600 to 910.

(b) taken at 10 volt intervals shows a break at 812 volts. The experimental results from 812 volts to 1500 volts when plotted give an accurately straight line.

In the first column of Table I are given the corrected critical potentials. The second column gives the relative intensities of the breaks estimated

TABLE I

Critical potentials of iron

Critical potentials					Other observations of voltages			
voltage	intens.	nature	λ	ν/R	Rollefson[5]	Kurth[2]	Horton et al.[3]	Stuhlman[17]
								3.3
7.3	2.5	R	1693.8A	.54				8.5
11.1	2.7	I	1112.1	.82				10.4
14.1	2.2	R	875.5	1.04				
16.5	2.9	R	748.1	1.22				
19.4	1.8	I	636.3	1.43	20.			
24.3	1.3	R	508.0	1.80	26.			24.3
28.8	2.5	R	428.6	2.14				
34.3	2.0	R	359.8	2.52				
41.2	2.5	I	299.6	3.04				
48.	2.4	R	257.1	3.53	46.8			45.8
51.3	1.6	R	240.6	3.78				
54.6	3.1	I	226.0	4.03		50		
62.	2.7	R	199.0	4.57				
75.3	2.2	R	163.2	5.56			73	
82.7	2.3	R	149.2	6.10	81.7			
94.8	1.3	R	130.1	7.00	95.4			
103.5	2.0	I	119.1	7.64				
112.2	1.7	R	110.	8.28	111.2			
131.8	1.9	R	93.6	9.72	130.4			
					140.9			
					147.1			
					153.4			
158.5	1.7	R	77.8	11.71	160.1			
169.4	2.3	I	72.8	12.51			166	
181.6	1.2	R	67.9	13.41				
192.	1.8	R	64.3	14.16				200
221.3	1.1	R	55.7	16.32				
228.1	2.8	I	54.1	16.83		227		
277.4	1.4	R	44.5	20.49				
288.6	1.1	R	42.8	21.31				
303.7	1.8	R	40.65	22.43				
331.	1.6	R	37.25	24.44				
					618			
639.(?)	.9	R	19.3	47.29	637			
704.3	1.5	I	17.52	52.01	697			
						757		
818.5	2.0	I	14.96	60.37				

by measuring the average change of slope at each break. Column three gives the nature of the effect producing the break; i.e. whether it is assumed to be a radiation potential R or an ionization potential I; in the

fourth column are the wave-lengths in angstrom units; in the fifth the values of ν/R where ν is the frequency and R is Rydberg's constant, and in the remaining columns are given the results obtained by previous investigators for iron. The potential in column 1 marked (?) is doubtful.

Discussion of Results

The designation R or I was made according to the nature of the break, following the analogy of the interpretation of corresponding curves for excitation of gases by electron impacts.[13,14] In gases the curve beyond a radiating potential is always concave downward, whereas beyond an ionizing potential it is straight or curved upward. It is not certain that the interpretation is the same in the present case, but at any rate, the designation will serve to differentiate between the two types of breaks.

The photo-electric current appeared when the excitation potential reached 2.5 or 3 volts and a definite break occurred at an average of 3.3 volts. Now if $eV=h\nu$ gives the frequency of the corresponding radiation, this radiation would be of too long a wave-length to produce any photo-electric emission from the platinum detector. Therefore it is necessary to seek some explanation for this discrepancy.

As an electron which has energy corresponding to the applied voltage V approaches the iron target, it is pulled in by the surface forces which give rise to the "work function." Thus the electron actually strikes the target with energy

$$\tfrac{1}{2}mv^2=e(V+\Phi).$$

This equation may now be written

$$h\nu=e(V+\Phi)$$

where the values of the factors except Φ are known. In order to compute a value for Φ it will be necessary to turn to the study of electron emission from some other metals because little is known of the electronic emission from iron.

Dushman[15] gives the ratio X_0/δ for tungsten, tantalum and molybdenum as about .56. In this ratio, X_0 denotes the distance at which an electron leaving the metal begins to be attracted by the charge induced on the surface in accordance with Coulomb's law. Schottky[16] gives

$$\Phi_0=(7.16\times10^{-8}/X_0) \text{ volts}.$$

[13] F. L. Mohler, Phil. Mag. **37**, 33 (1919)
[14] K. T. Compton, Phil. Mag. **40**, 553 (1920)
[15] S. Dushman, Trans. Amer Electrochem. Soc. **44**, 101 116 (1923)
[16] W. Schottky, Phys. Zeit. **15**, 872 (1914) and **20**, 220 (1920); Zeits. f. Phys. **14**, 63 (1923)

δ denotes the atomic diameter calculated from the atomic volume by the relation

$$\delta = (V/N)^{1/3} = 1.33 \times 10^{-8} V^{1/3} \text{cm}$$

where $N = 6.062 \times 10^{23}$ and V is the atomic volume. For iron this value is 7.1, which gives for δ the value 2.556×10^{-8} cm. From the above data Φ_0 for iron comes out 5 volts.

The observed critical potentials must be further corrected for the potential drop across the cathode, for the contact difference of potential between cathode and target, and for the initial energy of emission of the electrons from the cathode. Taking the value of Φ as 5 volts, a final correction factor of 4 volts is obtained which is believed to be correct to $\pm .2$ volts, exclusive of the uncertainty in the value of Φ.

A tabulation of the critical potentials for iron by the different observers has been made in Table I. The uncertainty of the value of the correction factor especially when a cathode of large potential drop is used, together with the failure of the other observers to take into account the work function, leads to discrepancies which make the comparison of results uncertain, especially at lower voltages. However, the results for iron of previous observers agree with the results of the writer within the limit of the correction factor (4 volts), except for the potential at 757 volts by Kurth, those at 140.9, 147.1, 153.9 and 618 volts by Rollefson and those at 3.3 and 200 volts by Stuhlman[17] who used a method of investigation different from that of the others.

Rollefson[5] tested his results for iron by an application of the combination principle to his critical potentials in order to calculate the voltages corresponding to lines of the spectrum which Milliken[12] studied spectroscopically, and he obtained values which agreed within 1 volt with Millikan's values. Because there are 83 lines of intensities 1 to 9 within the range 10 to 42 volts in the Millikan spectrum for iron, any arbitrary value from 10 to 42 would agree within .2 volt with one of these lines if they were equally spaced. This seemed to warrant further investigation. Therefore, the wave-lengths of the lines attributed entirely to iron and having an intensity of 1 or greater, were changed to corresponding volts and from these the probability that an arbitrary value would agree with the voltage of some line, was estimated. If 32 consecutive integers beginning at 10 are assumed to be results of the application of the combination principle, 90 per cent of these values will agree within 1 volt with voltages corresponding to lines found by Millikan, 80 per cent will agree within .5 volt and 50 per cent will agree within .2 volt. Unless

[17] Stuhlman, Science **56**, 344 (1922)

experimental results show much greater precision than those outlined above, the agreements obtained would not seem to have any particular significance.

The ionization potentials at 818.5, 704.3 and 54.6 volts can be identified as corresponding to the lines, L_I, L_{III} and M_{III} with ν/R values of 60.37, 52.01 and 4.03 respectively. Mohler[18] has computed from x-ray data the ν/R value of L_{III} for iron to be 52.2 and of M_{III} to be 4. He has also computed the value of L_I, using $\sqrt{L_{II}} - \sqrt{L_{III}} = .65$, to be 63. The value of L_I cannot be computed with the same accuracy as those for L_{III} and M_{III}. The values just given seem to be the only available data for the prediction of the levels for iron.

Undoubtedly some of the lower voltages correspond to lines of the N series but there is no apparent gap between the M and N series as between the L and M series. Even though the value for ν/R of 16.8 be assigned to M_I, critical potentials apparently belonging to the M series appear above this value. No definite attempt will be made at the present time to assign definite critical potentials to definite series because this work is now being continued with other metals. It is hoped that by a comparison of the results of different metals more definite conclusions may be drawn.

In conclusion the writer wishes to express his thanks to Prof. K. T. Compton, at whose suggestion this work was undertaken, for his encouragement and ever ready assistance during the course of this experiment. He also wishes to thank Dr. S. Dushman for suggesting a method of evaluation of the work function for iron.

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October 17, 1924

[18] K. T. Compton, and F. L. Mohler, Bull. Nat. Research Council, **9**, part I, No. 48, p. 105 (1924)