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THE REFLECTION OF CATHODE RAYS FROM THIN METALLIC FILMS.

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INTRODUCTION.

CATHODE rays after impingement upon a metallic surface may be considered from three standpoints: (1) Those rays which are reflected, (2) those which are absorbed or give up their charge to the metal, and (3) those which pass through if the metal is in thin enough layers. As to whether the rays reflected or those emerging from the rear side of a thin film are the identical ones which were incident upon the front surface is still an open question.

Among those having investigated the conditions of transmission and the properties of the transmitted cathode ray may be mentioned Hertz,[1] Lenard,[2] Leithaüser[3] and Des Coudres.[4] In a later research Lenard[5] studied the absorption of cathode rays in various media, on which subject Seitz[6] published some results at the same time. To our knowledge of the behavior of the reflected cathode ray, Swinton,[7] Starke[8] and Gehrcke[9] have made valuable contributions.

From these various researches two important conclusions may

[1] H. Hertz, Wied. Ann. 45, p. 28, 1892.
[2] Ph. Lenard, Wied. Ann. 52, p. 27, 1894.
[3] Leithaüser, Ann. d. Physik., 15, p. 283, 1904.
[4] Des Coudres, Physik. Zeitschr., 4, p. 140, 1902.
[5] Ph. Lenard, Ann. d. Physik., 12, p. 714, 1903.
[6] Seitz, Ann. d. Physik., 12, p. 860, 1903.
[7] Swinton, Proc. Roy. Soc., 64, p. 395, 1899.
[8] Starke, Ann. d. Physik., 5, p. 75, 1900.
[9] Gehrcke, Sitzber. d. k. Akad. d. Wissen. zu Berlin, 18, April, 1901.

be drawn: (1) With increasing potential, the transmission of cathode rays through a thin metallic film also increases; (2) the reflection coefficients remain constant for potentials ranging from 4,000 volts upward, if the reflectors are 1 mm. or more thick.

The transmission of cathode rays through thin metallic films shows that the rays penetrate the surface, but when we consider that the reflection coefficients of thick reflectors remain constant for varying potentials, the question arises, does reflection take place at the surface and thus remain constant in amount or do the rays which penetrate the surface suffer reflection from layers in the metal at depths which depend on the potential so that the amount reflected remains unchanged. If all reflection is from the front surface then reflection should be independent of thickness. If however deeper layers are also concerned it might be possible with increasing potential and very thin films to reach a critical point where a part of the rays would pass through and the reflection coefficient of the film be diminished. We might in the later case find for thin films a reflection coefficient diminishing with increasing potential.

To distinguish if possible between these two points of view of cathode ray reflection, the following study was undertaken at the suggestion of Professor E. Warburg and the experiments carried out in the physical laboratory of the University of Berlin.

Methods of Investigation.

From the various researches that have already been made on the reflection and transmission of cathode rays it is evident that there are two methods available for such an investigation: (1) The electrical method in which the charge carried by the reflected rays is measured by a galvanometer. (2) The photometric method in which the fluorescent brightness produced by the reflected rays is taken as a measure of the quantity reflected.

The electric method was first tried and the form of apparatus as used by Starke[1] was adopted in which the charge given up by the absorbed rays was measured instead of the quantity which the reflected rays carry. According to Starke, if a quantity of electricity,

[1] Starke, Ann. d. Physik., 3, p. 97, 100.

Q, transported by cathode rays, falls on a metallic reflector which is connected to earth through a galvanometer, the current which the galvanometer shows is

$$I = Q(1 - r)$$

where r is the reflection coefficient of the metal. Replacing one metal by another whose reflection is r' and the current is

$$I' = Q(1 - r').$$

Q remaining constant in both cases, we can write

$$I/I' = (1 - r)/(1 - r'),$$

whence follows

$$r' = 1 - (1 - r)I'/I. \tag{1}$$

Thus if r' be the reflection coefficient of a thin film and r that of a plate of the same metal, then any variation in r' would cause a change in I' by which if r was known r' could be determined. Here I' must include transmitted as well as absorbed charges.

In this way the reflection coefficient of a thin aluminum film about 1.5 μ was compared with an aluminum reflector, about 2 mm. thick, for the amount of cathode rays which they reflected. The reflection coefficient of the thick reflector was taken as 25 per cent., the value found by Austin and Starke.[1] Although comparisons were made at potentials as high as 18,000 volts no variations between the two currents I and I' could be detected. A d'Arsonval galvanometer with 10,000 ohms resistance being used to measure the currents. As higher potentials with the tube used gave inconstant readings, the results by the electrical method were in this case negative. These negative results however did not seem to be conclusive evidence. Since aluminum reflects 25 per cent., the other 75 per cent. given up to the reflector is measured by the galvanometer, hence a fairly large percentage variation in the amount reflected would have to occur before the variation would appreciably affect the galvanometer reading. Moreover this method offered no means of studying the loss in velocity of the rays reflected from thin films, which would be of especial interest here if any change in the amount reflected occurred.

[1] Austin u. Starke, Ann. d. Physik., 9, p. 292, 1902.

On those grounds the electrical method was given up and the photometric method tried since it seemed to offer as great a sensibility and had the advantage that it was possible also to investigate the loss in velocity of rays reflected from thin films.

When cathode rays fall upon a fluorescent screen, the brightness of the illumination, H, will depend on the current density of the rays per unit area which falls on the screen, and some function of the potential under which the rays are produced, such as $H \equiv [I \times f(V)]$, where I represents the current density and V the potential. This dependence of the brightness of fluorescence on the current density and the potential under which they are produced has been carefully worked out by Leithaüser.[1] From his data it appears that the brightness is approximately proportional to the current density of the rays falling upon the screen, while on the other hand, the dependence of brightness on the potential with constant current shows that this relation is not a linear function, but that the ratio $\frac{\text{Brightness}}{\text{Discharge Potential}}$ at first increases with increasing potential while at still higher potentials, the ratio again decreases. Hence when comparing two fluorescent spots produced by cathode rays, the discharge potential must be taken into account. From these relations worked out by Leithaüser, we can compare the current densities of cathode rays from any two sources, by knowing the relative brightness of the fluorescence produced when they impinge upon a screen, for

$$\frac{H}{H'} = \frac{(I)f(V)}{(I')f(V')},$$

thus $H/H' = w$, a ratio which may be determined by means of a photometer. From these quantities we then have

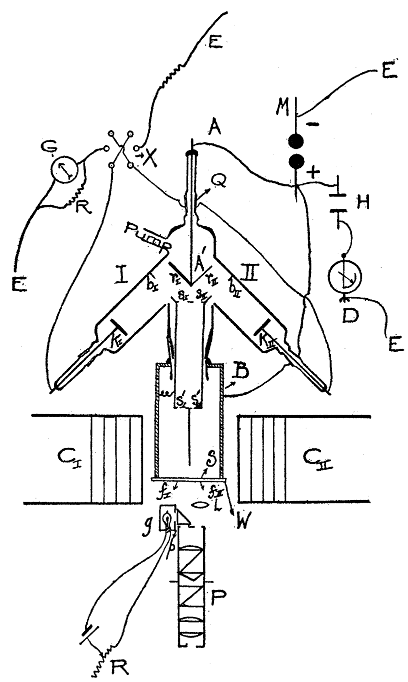
$$\frac{I}{I'} = w\frac{f(V')}{f(V)} \tag{2}$$

where the ratio $f(V')/f(V)$ may be obtained from Leithaüser's tables.

The two sources of cathode rays just mentioned may be two reflectors, one of which is a thin aluminum film, whose reflection coefficient is to be investigated, the other being a thick aluminum reflector, whose reflection coefficient is known.

[1] Leithaüser, Ann. d. Physik., 15, p. 283, 1904.

If then rays of the same intensity fall on both reflectors, by the equation just given, we can determine the ratio of the quantities reflected, by knowing the ratio of brightness of the fluorescence and by the data given in the tables of Leithaüser. By allowing the rays reflected from these two sources to pass through narrow apertures, side by side, narrow and sharply defined fluorescent spots may be obtained on the screen, which, by means of a magnetic field, can be drawn out into magnetic spectra, parallel to each other, and comparison of the amounts reflected be made.



Fig, 1.

The final form of the apparatus as used is shown in Fig. 1. In general the apparatus resembled that used by Gehrcke,[1] only with changes to suit the present problem. The most noteworthy difference is that Gehrcke studied the reflected rays which had struck the reflector at an angle of 45°, in this work the rays were incident normally upon the reflectors.

The apparatus consisted of a bronze box, *B*, 19 cm. high, 6 cm. broad and 13 cm. in depth, which allowed for space in which the rays might be drawn out into parallel spectra. The rear side of the box was closed by means of a thick piece of plate glass, *W*. This plate carried the fluorescent screen which was made by sprinkling calcium sulphide on the thinnest possible layer of grease, rubbed over the inner surface of the glass plate. The advantage of the calcium sulphide as a fluorescent substance is, that the fluorescent after-glow dies away rapidly after the bombardment of the cathode

[1] Gehrcke, Sitzber. d. k. Akad. d. Wissen. z. Berlin, 18, April, 1904.

particles has ceased, allowing measurements to be made in rapid succession on the same part of the screen. This property varies with the sample. Into a circular opening in the front side of the box, *B*, was sealed the discharge tube, which consisted of a main tube, 4 cm. in diameter, to which were joined two equal side tubes, *I* and *II*, 3 cm. in diameter, entering the main tube at an angle of 45°. These side tubes contained the cathodes K_I and K_{II}, the faces of which were parallel to the reflectors, r_I and r_{II}, and at a distance of about 8 cm. from them.

For the production of the discharge current a 20-plate influence machine, *M*, of the Toepler type, was used. Its negative pole was earthed, while the positive pole was connected to the anode, *A*. The rod on which the reflectors, r_I and r_{II}, were fixed, served as anode and since the metal cylinder containing the slits, s_I, s_{II}, s_I' and s_{II}', and the screens, b_I and b_{II}, were within about 2 cm. of the reflectors, they were charged to the same potential as the reflectors, by metallic connection with the side of the box, *B*, and positive pole of the machine as shown. To work with high potentials, the box, *B*, was insulated on heavy glass plate to prevent leakage to earth through platform on which the apparatus was placed. The cathodes, K_I and K_{II}, were then earthed to complete the circuit. The potential at the cathodes being almost zero, allowed the measuring of the cathode discharge with a galvanometer, *G*, without the disturbing influences of static charges under high potentials. The two cathodes were connected to a six-pole reversing switch, *X*, in such a way that first one cathode and then the other could be connected to earth through the shunted galvanometer, *G*, while simultaneously the other cathode was earthed through a resistance, *R*, equal to the resistance of the shunted galvanometer. If the current was the same in both side tubes, then the deflection of the galvanometer should be the same in both cases, a condition obtained in all final readings. Thus cathode rays passing out from the two cathodes, K_I and K_{II}, fall on the reflectors, r_I and r_{II}, respectively after having passed through horizontal slits 1 by 15 mm. in the screens, b_I and b_{II}. From the two reflectors the rays are reflected diffusely in all directions and part of the rays from r_I pass through the two horizontal slits, s_I and s_I' (1 by 6 mm. in size and in the same plane as the slit in b_I), and finally fall upon the fluorescent screen, S, producing the fluorescent spot, f_I. Similarly the rays from r_{II} produce the fluorescent spot, f_{II}. f_I and f_{II} are then drawn out into magnetic spectra by means of the solenoids, C_I and C_{II},[1] and the spectral distribution of the rays measured.

It is at once apparent that this method will not give correct results unless the intensities of cathode discharge from K_I and K_{II} are equal. The elimination of such inequalities from the preliminary measurements was the cause of so much trouble that it may be useful to mention the precautions finally taken to prevent errors of this sort.

As may be seen from Fig. 1 the apparatus is symmetrical about an axis running through the anode, A, and the photometer, P. In putting the apparatus together, unless each part was symmetrically placed, inequality of the two currents in the side tubes occurred. Also when the two reflectors, r_I and r_{II}, were of different metals, the currents were not the same. This was to be expected, as the reflector having the largest reflection coefficient produced a greater ionization in the discharge space and so more current passed through the side-tube which carried the reflector of largest reflection coefficient. In comparing copper and aluminum, for example, the reflection coefficient of copper is 45 per cent. and that of aluminum 25 per cent., a larger current always passed through the side-tube facing the copper reflector. This error was eliminated by placing between the cathodes and the reflectors the screens, b_I and b_{II}, with narrow slits in them which prevented rays from the reflectors being thrown back into the discharge space to any appreciable amount.

An inequality of cathode discharge in the two branch tubes due to unavoidable dissymmetry of construction was still present and to eliminate this from the results the two reflectors, r_I and r_{II}, were mounted on a shaft, A', which could be rotated by means of the ground-glass joint, Q, through which the shaft passed. Any inequality of cathode discharge in either one of the branches could be eliminated by taking readings from both branches with the mirrors in one position and repeating with the mirrors reversed. This gave a mean which was free from errors of this sort. Any in-

[1] S. Simon, Wied. Ann., 69, p. 595, 1899.

equalities of size or position of the slits, or lack of uniformity in the fluorescent screen was also eliminated at the same time, as measurements were made of each reflector under exactly the same conditions as the other. A further inspection of the symmetry of the apparatus shows that the fluorescent spots, f_I and f_{II}, could be compared directly with each other by means of the photometer [1] or by inserting a right-angled prism, p, over one opening of the photometer the brightness of either spectrum could be compared with the constant brightness of an incandescent lamp. The direct comparison of the two spots, f_I and f_{II}, worked very well until high potentials were reached and then discharge would take place first through one side-tube and then the other in quick succession. For high potentials only one cathode was used and first one reflector and then the other was turned into position and the brightness of the spectra compared with the standard lamp, the current being held constant as shown by the galvanometer during the rotation of the reflectors.

A Sprengel pump was used in exhausting the tube. As soon as an adequate vacuum was reached the pump was cut off and the occluded gases, driven from the cathodes by the discharge, were absorbed by cocoanut shell charcoal in a bath of liquid air according to Dewar's method.[2] This gave most satisfactory and constant results. By varying the opening between the tube and the receptacle holding the charcoal almost any pressure could be maintained for some considerable time, so that with the influence machine giving constant current very steady conditions were obtained.

The spectra formed on the fluorescent screen, when a magnetic field was produced, were focused by means of a lens, L, on the openings of the photometer, the image being natural size. By means of a faintly illuminated scale, the amount of deflection and dispersion, and the position of the photometer openings in the spectra were easily and quickly determined. Only those readings were accepted in which constant current conditions were maintained.

For convenience of observation, the length of spectra were divided into four regions and for each of the four positions of the photometer ten readings were made, during which both current and

[1] F. F. Martens, Phys. Zeitschr., 1, p. 299, 1900.
[2] J. Dewar, Compt. Rendus, 139, p. 261, 1904.

potential were held constant. The fourth region was generally too faint in illumination to be measured. Thus sixty readings were necessary to determine one reflection coefficient for a single potential, as the two spectra had to be separately compared, region by region, with the standard lamp. On repeating such a set of readings it was found that from 6 to 7 per cent. accuracy could be obtained.

Having the apparatus to all appearances free from errors it was of interest to compare this method with the electrical method used by Starke.[1] Accordingly a comparison of the reflection coefficients of copper and aluminum was made. The reflection coefficients of these two metals Starke determined by direct methods and afterwards verified his results by a comparative method, hence their values were pretty well fixed.

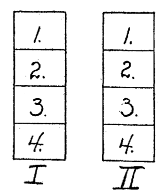


Fig. 2.

If we divide the two magnetic spectra to be compared into sections as shown in Fig. 2, by knowing the ratio of the brightness of the various sections we can determine the relative current densities of cathode rays producing the spectra, from the equation,

$$\frac{I_I}{I_{II}} = \frac{n_1 + n_2 k_1 + n_3 k_2 + n_4 k_3}{1 + k_1 + k_2 + k_3} + \cdots \tag{3}$$

where the n's represent the ratios of brightness between sections having the same deflection, here indicated by sections having the same number. These ratios are read directly from the photometer as we are comparing cathode rays of the same potential and the brightness in such a case Leithaüser has shown is directly proportional to the current density of rays producing the fluorescence. The k's are ratios of the intensities of the cathode rays between 1 and 2, 1 and 3, 1 and 4, etc., determined by equation (2). The k's were always measured in the brightest spectrum which in this case was that of copper. If

$$n_1 = n_2 = n_3 = n_4$$

then the distribution throughout the two spectra is the same and

[1] Starke, l. c.

$$I_I / I_{II} = n.$$

This means that the ratio of brightness of the two undeflected spots for the condition of equal distribution in the two spectra is the same as the ratio of the reflection coefficients.

The undeflected spots, f_I and f_{II}, were 5 mm. wide and somewhat longer and when the magnetic field was on, these were drawn out into spectra a little over 15 mm. long. The width of the photometer openings were also 5 mm. so that lengthwise of the spectra there were three sections 5 mm. wide that could be measured. Increasing the magnetic field lengthened the spectra but decreased the brightness, so that a spectrum 18 to 20 mm. in length was found the most advantageous in use.

The distance from the centers of the undeflected spots to the centers of the various sections was taken as the deflection of that section. The potential of section 1, was taken as the potential at which the rays were produced since rays which come direct from cathode without reflection would be deflected by this amount as shown by Gehrcke.[1] Of course with such wide photometer openings as those used in the present work the rays producing the fluorescence on the two sides of the opening would of course correspond to different potentials, but by considering the brightness observed in each region as that belonging to the center, we get a fair average, although not an absolute value. Any such error was still further reduced when two equally deflected sections of neighboring spectra were compared.

In a magnetic spectrum the deflection, z, varies inversely as the velocity of the rays, v. But the velocities stand in the same ratio as the square roots of the potentials, so that we may write $z^2 \propto 1/V$. For the various sections of the spectra, z, could be measured, and the potential and deflection of section 1 being known, the corresponding potential for the others could be determined.

Since the reflection coefficients of massive metal plates remain constant for varying potentials, to compare the coefficients of aluminum and copper, a potential of 16,500 volts was chosen, as at this potential a very steady current could be maintained. The

[1] Gehrcke, Sitzber. d. k. Akad. d. Wissen. z. Berlin, 18, April, 1901.

data obtained in this photometric comparison are given herewith and graphically shown in Fig. 3, where the current densities are plotted as ordinates, and abscissas as distances from center of section 1, z_0 being the magnetic deflection of section 1.

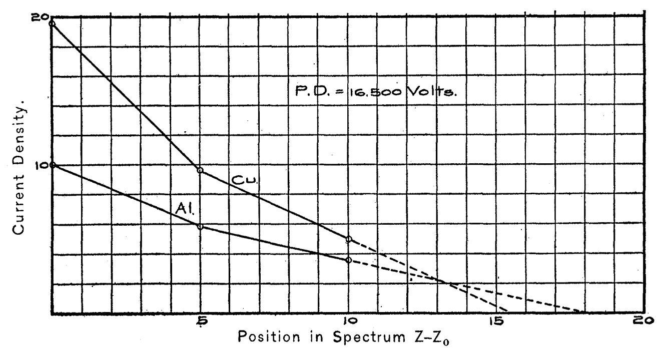


Fig. 3.

Deflection of section	(1) 1.7 cm.	(2) 2.2 cm.	(3) 2.7 cm.
Voltage " "	(1) 16,500	(2) 9,850	(3) 6,550
Corresponding brightness	(1) 182.6	(2) 110.1	(3) 56.4

(Interpolated from the tables of Leithaüser.)[1]

Measured brightness	(1) 0.601	(2) 0.178	(3) 0.044

$1_{al}/1_{cu} = n_1 = 0.518.$ $2_{al}/2_{cu} = n_2 = 0.616.$ $3_{al}/3_{cu} = n_3 = 0.787.$

(These ratios were also photometrically measured.)

$$\frac{0.178}{0.601} \times \frac{182.6}{110.1} = k_1 = 0.491, \quad \frac{0.044}{0.601} \times \frac{182.6}{56.4} = k_2 = 0.337.$$

$$\frac{I_I}{I_{II}} = \frac{n_1 + n_2 k_1 + n_3 k_2}{1 + k_1 + k_2} = \frac{0.518 + (0.616 \times 0.491) + (0.787 \times 0.237)}{1 + 0.491 + 0.237}$$

$$= \frac{1.006}{1.728} = 0.58,$$

the ratio of the reflection coefficients of aluminum and copper. Austin and Starke[2] found as the value for this ratio, 0.56 which, considering the accuracy of 6 to 7 per cent. which this method afforded, is a fair agreement. The results showed that the apparatus was in working order and free from large errors. The copper reflector was replaced in succession by a series of thin aluminum

[1] Leithaüser, Ann. d. Physik., 15, p. 296, 1904.

[2] Austin u. Starke, Ann. d. Physik., 9, p. 292, 1902.

films and the properties of the rays reflected from them compared with the reflection from a thick aluminum plate. The first film used was 0.53 μ thick, the thickness being measured with a Zeiss Dickenmesser. Ten and twenty thicknesses of the aluminum leaf were laid together and the total thickness divided by the number gave results agreeing to 0.01 μ. The thickness was not over 0.53 μ although it might possibly have been thinner as some allowance must be made for the air layers between the leaves. This error was made as small as possible however by pressing the films firmly together in measuring.

On comparing the brightness of fluorescence produced by the rays reflected from a thin and a thick aluminum reflector at higher potentials, viz., about 20,000 volts, the difference was so great as to be readily observed with the naked eye.

Since the reflection coefficient of the films varied for potentials above a critical potential, it was necessary to measure the entire spectrum for each potential used. The first film was measured at the potentials 11,000, 16,500, 21,800 and 27,750 volts. For these high potentials it was necessary to connect a condenser in series with the Braun electrometer, *D*, as shown in Fig. 1, as the range of the electrometer, was from 4,000 to 10,000 volts only. This worked satisfactorily as long as the atmosphere in the room was dry. If it was not, whenever the influence machine was short-circuited, a charge would remain on the electrometer due to leakage over the glass supports.

The observations were made in the same order as in the comparison of aluminum and copper already described and the results are given in the following tables and curves:

Potential = 11,000 volts.

Deflection of section	(1) 2.3 cm.	(2) 2.8 cm.	(3) 3.3 cm.
Voltage of section	(1) 11,000	(2) 7,400	(3) 5,350
Corresponding brightness	(1) 129.0	(2) 66.6	(3) 43.6
Measured brightness	(1) 1.83	(2) 0.478	(3) 0.197

$$n_1 = 1.021, \quad n_2 = 0.958, \quad n_3 = 0.949.$$

$$\frac{0.478}{1.83} \times \frac{129.0}{66.6} = k_1 = 0.505.$$

$$\frac{0.197}{1.83} \times \frac{129.0}{43.6} = k_2 = 0.318.$$

I_I = total quantity in spectrum from thin film.

I_{II} = total quantity in spectrum from thick film.

$$\frac{I_I}{I_{II}} = \frac{n_1 + n_2k_1 + n_3k_2}{1 + k + k_2} = \frac{1.021 + (0.958 \times 0.505) + (0.949 \times 0.318)}{1 + 0.505 + 0.318}$$

$$= \frac{1.807}{1.823} = 0.991 = \frac{x}{25},$$

where 25 per cent. is the amount reflected by the thick reflector. That is, 0.991 is the ratio of the reflection coefficients of the thin

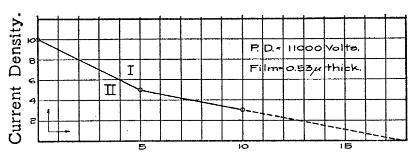


Fig. 4.

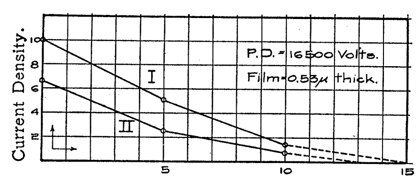


Fig. 5.

and thick aluminum reflectors at a potential of 11,000 volts. This means that within the accuracy of the method the two reflectors are equal. (See Fig. 4.)

Potential = 16,500 volts.

Deflection of section	(1) 2 cm.	(2) 2.5 cm.	(3) 3 cm.
Voltage of section	(1) 16,500	(2) 10,550	(3) 7,350
Corresponding brightness	(1) 182.6	(2) 122.2	(3) 66.0
Measured brightness	(1) 2.65	(2) 0.868	(3) 0.130

$$n_1 = 0.656, \quad n_2 = 0.517, \quad n_3 = 0.451.$$

$$\frac{0.868}{2.65} \times \frac{182.6}{122.2} = k_1 = 0.489.$$

$$\frac{0.130}{2.65} \times \frac{182.6}{66.0} = k_2 = 0.135.$$

$$\frac{I_I}{I_{II}} = \frac{0.656 + (0.517 \times 0.489) + (0.451 \times 0.135)}{1 + 0.489 + 0.135}$$

$$= \frac{0.970}{1.624} = 0.597 = \frac{x}{25}.$$

$x = 14.9$ per cent. reflected at a potential of 16,500 volts. (See Fig. 5.)

Potential = 21,800 volts.

Deflection of section	(1) 1.8 cm.	(2) 2.3 cm.	(3) 2.8 cm.
Voltage of section	(1) 21,800	(2) 13,350	(3) 9,000
Corresponding brightness	(1) 195.0	(2) 161.5	(3) 95.8
Measured brightness	(1) 3.57	(2) 0.98	(3) 0.25

$$n_1 = 0.518, \quad n_2 = 0.274, \quad n_3 = 0.216.$$

$$\frac{0.98}{3.57} \times \frac{195.0}{161.5} = k_1 = 0.331.$$

$$\frac{0.25}{3.57} \times \frac{195.0}{95.8} = k_2 = 0.142.$$

$$\frac{I_I}{I_{II}} = \frac{0.518 + (0.274 \times 0.331) + (0.216 \times 0.142)}{1 + 0.331 + 0.142}$$

$$= \frac{0.640}{1.473} = 0.434 = \frac{x}{25}.$$

$x = 10.8$ per cent. reflected from the thin reflector at a potential of 21,800 volts. (See Fig. 6.)

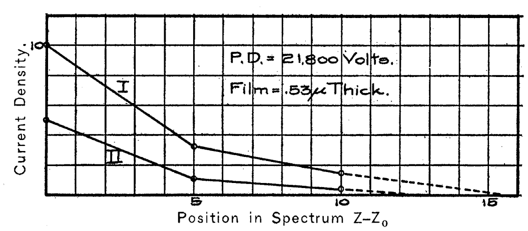


Fig. 6.

Potential = 27,750 volts.

Section (3) of the spectrum from the thick reflector was so faint in intensity that no measurements could be taken, as were also (2) and (3) of the spectrum from thin film.

Deflection of section	(1) 1.5 cm.	(2) 2 cm.
Voltage of section	(1) 27,750	(2) 15,600
Corresponding brightness	(1) 225.5	(2) 179.4
Measured brightness	(1) 3.06	(2) 0.239

$$n_1 = 0.329.$$

$$\frac{0.239}{3.06} \times \frac{225.5}{179.4} = k_1 = 0.096.$$

$$\frac{I_I}{I_{II}} = n_1 = 0.329 = \frac{x}{25}.$$

$x = 8.22$ per cent. reflected at the potential of 27,750 volts from a thin film. (See Fig. 7.) From the above results the reflection coefficients of an aluminum film, 0.53 μ, may be plotted as a function of the potential. (See Fig. 12.)

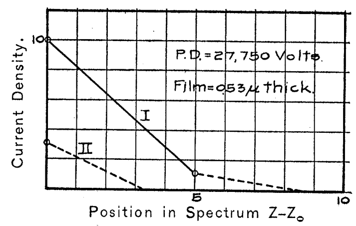


Fig. 7.

Next the reflection of an aluminum film, 1.90 μ, was measured as described above. The results follow:

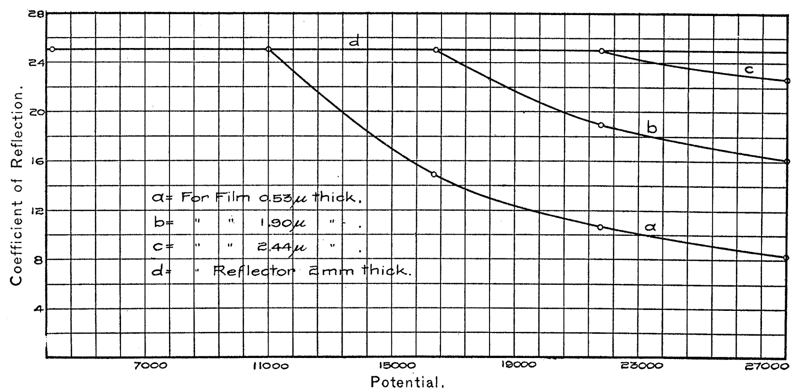


Fig. 12.

Potential = 16,500 volts.

Deflection of section	(1) 2.1 cm.	(2) 2.6 cm.	(3) 3.1 cm.
Voltage of section	(1) 16,500	(2) 10,750	(3) 7,600
Corresponding brightness	(1) 182.6	(2) 125.2	(3) 69.7
Measured brightness	(1) 2.99	(2) 0.736	(3) 0.245

$$n_1 = 1.023, \quad n_2 = 0.978, \quad n_3 = 0.934.$$

$$\frac{0.736}{2.99} \times \frac{182.6}{125.2} = k_1 = 0.358.$$

$$\frac{0.245}{2.99} \times \frac{182.6}{69.7} = k_2 = 0.214.$$

$$\frac{I_I}{I_{II}} = \frac{1.023 + (0.978 \times 0.358) + (0.934 \times 0.214)}{1.572}$$

$$= \frac{1.572}{1.572} = 1.00 = \frac{x}{25}.$$

$x = 25$ per cent. reflected from film $1.9\,\mu$ thick at a potential of 16,500 volts. The reflection is the same as a thick reflector. (See Fig. 8.)

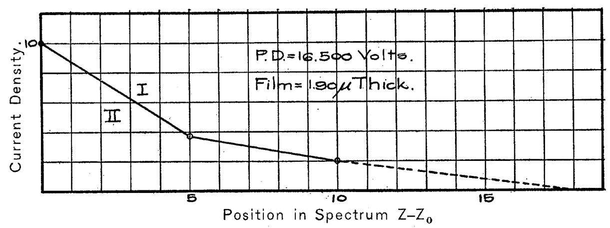


Fig. 8.

Potential = 21,800 volts.			
Deflection of section	(1) 1.8 cm.	(2) 2.3 cm.	(3) 2.8 cm.
Voltage of section	(1) 21,800	(2) 13,350	(3) 9,000
Corresponding brightness	(1) 195.0	(2) 161.5	(3) 95.8
Measured brightness	(1) 4.58	(2) 0.574	(3) 0.225

$$n_1 = 0.796, \quad n_2 = 0.710, \quad n_3 = 0.555.$$

$$\frac{0.574}{4.58} \times \frac{195.0}{161.5} = k_1 = 0.151.$$

$$\frac{0.225}{4.58} \times \frac{195.0}{95.8} = k_2 = 0.099.$$

$$\frac{I_I}{I_{II}} = \frac{0.796 + (0.710 \times 0.151) + (0.555 \times 0.099)}{1.250}$$

$$= \frac{0.958}{1.250} = 0.767 = \frac{x}{25}.$$

$x = 19.2$ per cent. reflected at potential of 21,800 volts. (See Fig. 9.)

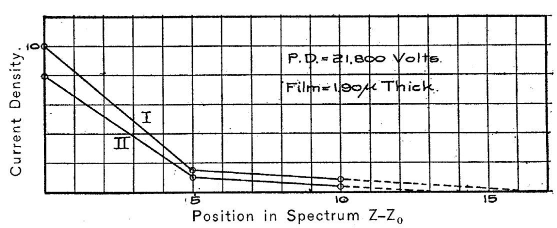


Fig. 9.

Potential = 27,750 volts.

Deflection of section	(1) 1.5 cm.	(2) 2.0 cm.
Voltage of section	(1) 27,750	(2) 15,600
Corresponding brightness	(1) 225.5	(2) 179.4
Measured brightness	(1) 4.41	(2) 0.441

$$n_1 = 0.671, \quad n_2 = 0.510.$$

$$\frac{0.441}{4.41} \times \frac{225.5}{179.4} = k_1 = 0.125.$$

$$\frac{I_I}{I_{II}} = \frac{0.671 + (0.510 \times 0.125)}{1.125} = \frac{0.735}{1.125} = 0.653 = \frac{x}{25}.$$

$x = 16.3$ per cent. reflected at this potential of 27,750 volts. (See Fig. 10.) Just as for the previous film, so here we can plot the reflection coefficients as a function of the potential. (See Fig. 12.)

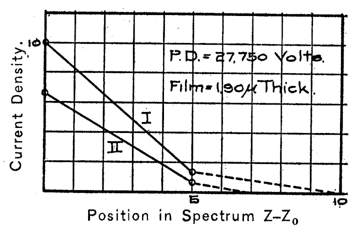


Fig. 10.

Finally the reflection of an aluminum film 2.44 μ thick was compared with a massive plate for potentials of 21,800 and 27,750 volts. At the lower potential, plate and film reflected equally. The results for 27,750 volts follow:

Deflection of section	(1) 1.5 cm.	(2) 2.0 cm.
Voltage of section	(1) 27,750	(2) 15,600
Corresponding brightness	(1) 225.5	(2) 179.4
Measured brightness	(1) 3.61	(2) 0.640

$$n_1 = 0.947, \quad n_2 = 0.756.$$

$$\frac{0.640}{3.61} \times \frac{225.5}{179.4} = k_1 = 0.222.$$

$$\frac{I_I}{I_{II}} = \frac{0.947 + (0.756 \times 0.222)}{1.222} = \frac{1.114}{1.222} = 0.911 = \frac{x}{25}.$$

$x = 22.7$ per cent. reflected from a film 2.44 μ thick at a potential of 27,750 volts. (See Fig. 11.) For the curve of reflections plotted as a function of the potential, see Fig. 12.

Having thus found a variation of reflection with thickness for aluminum, it seemed of interest to measure the reflection coefficients of thin films of other metals. In place of the aluminum reflectors a thick copper reflector and a copper film 0.66 μ thick were compared. For the highest potential, viz., 27,750 volts no difference in reflection was found. Since the gradient of brightness in a

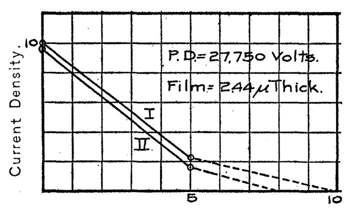


Fig. 11.

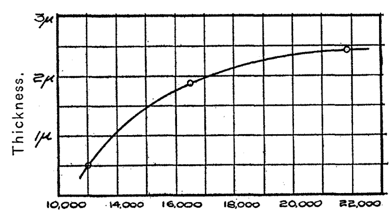


Fig. 13.

spectrum reflected from copper is large as compared with aluminum, the spectra were so short that measurements could only be made in the first section, so that

$$\frac{I_I}{I_{II}} = 1.002 = \frac{x}{45}, \quad x = 45.0$$

for a copper film 0.66 μ thick and at a potential of 27,750 volts. Thus there is a marked difference in behavior of thin aluminum and thin copper films.

If we plot as shown in Fig. 13 the thickness of aluminum films used, as a function of the potential at which the reflection begins to diminish we find that the curve rises quite rapidly to a point between 1.90 μ and 2.44 μ and then becomes more nearly parallel to the axis of abscissas. It thus appears that for reflectors 1 mm. thick it would take an infinite potential before any of the reflected rays would be lost by transmission. In other words this would be saying that whatever the potential, the reflected rays are never from a depth greater than 1 mm.

Discussion of Results.

From the data just given, we are in a position to discuss some of the conditions under which the reflection of cathode rays take place, especially when reflected from thin films.

The question as to whether the reflection of cathode rays from metals occurs at the surface or whether there is penetration and then reflection has been answered by the results in such a way as to leave no doubt but what the rays penetrate to various depths, depending on the potential, and are then reflected. In the beginning it was assumed that a part of the cathode rays, which would be reflected from a thick film, would in the case of a thin one be lost by transmission after a critical potential was reached and so a thin film would not show as large a reflection as a thick one. The results substantiate this view in that a difference in the quantities reflected, depending on thickness and potential, was found. This dependence of reflection upon potential and thickness will here be discussed more in detail.

For the film 0.56 thick at a potential of 11,000 volts the reflection coefficients of the thin and the thick reflectors are the same. At 11,000 volts then the critical potential has not been reached. On increasing the potential however, a difference occurs, and the only way the decrease in the amount reflected from the thin film can be accounted for is that a part has been lost by transmission. This indicates then that the reflection is not all taking place at the surface of the reflectors, but that there is penetration and then reflection for some of the rays. Although at 11,000 volts the thin film did reflect as much as a thick one, this is not saying that none of the cathode rays passed through the thin film, for behind the film a fluorescence on the walls of the tube showed that some of the rays were coming through, thus some rays penetrate even farther than those reflected from the greatest depths. At the same potential, viz., 11,000 volts, and with a film 1.8 μ thick, Leithaüser[1] still found some transmission.

Again the data and the curves show that there is a decrease in the quantity of rays reflected as one goes from rays of less to those of greater deflection in the magnetic spectrum, further the difference in brightness of corresponding sections of the two spectra is greatest in the most deflected portions, *i. e.*, from equation (3) $n_3 < n_2 < n_1$. This is in accord with what has just been said concerning the reflection of rays which have penetrated to greater depths and which

[1] Leithaüser, Ann. d. Physik., 15, p. 305, 1904.

have been slowed down in consequence. Take a case where a difference in reflection from the two reflectors occurs. Those rays which are penetrating farther into the thick film than the thickness of the thin one are being thrown out and form a large part of the most deflected portion of the spectrum. Consequently the difference in brightness of the most deflected portion of the two spectra will be greater than in the less deflected part, because in the case of the thin film the larger part of those rays which form the most deflected part of spectrum have been lost by transmission, and so we find there the greatest difference in brightness between the two spectra. Fig. 11 illustrates the point in question. The difference in brightness of the least deflected portions of the two spectra is so small that it might pass as an error in the reading. In the next section of the two spectra however a much larger difference occurs, showing that for that part of spectrum from the thin film, a part of the rays has been lost by transmission.

The penetration of cathode rays into copper is interestingly shown by the results given on page 18 where a thin and a thick copper reflector are compared. Here the penetration of the reflected rays is very much less than in aluminum. For a potential of 27,750 volts the penetration of the reflected rays in copper must be less than 0.66 μ as this thickness reflected as much as a plate 2 mm. thick. With an aluminum film and the same potential, viz., 27,750 volts, the penetration of the reflected rays was about 2.5 μ as curve 9 shows. Fig. 3 and the results given in the comparison of the amounts reflected from thick reflectors of aluminum and copper, show that the reflection, in the case of copper must take place nearer the surface of the reflector as the difference in brightness between corresponding sections of the spectra measured was greatest in the least deflected portions, for $n_1 < n_2 < n_3$, that is, the larger part of the rays from the copper reflector were being reflected without appreciable loss of velocity. The spectrum from the copper reflector was also noticeably shorter in length than the one from aluminum. As one approached the more deflected portions of the spectra therefore, the ratio between the brightnesses approached unity. The values given also indicate this, viz.,

$$n_1 = 0.518, \quad < n_2 = 0.616 < n_3 = 0.787.$$

That Gehrcke[1] did not find so great a difference in the spectra of the rays reflected from copper and aluminum is quite likely due to the fact that he was not using normal incidence of the rays in his work.

Sufficiently thin films of other metals with known reflection coefficients could not be obtained, but from the data given above for copper and aluminum, and the fact that Starke[2] found an increasing reflection coefficient the greater the density of the metal, would lead one to infer that the denser the material of the reflector, the less the penetration of the reflected rays.

Summary of Results.

1. The reflection of cathode rays does not all take place at the surface of a metal, but there is penetration and then reflection for a large part of the reflected rays.

2. From a critical potential on, a thin metallic film of aluminum reflects less than a thick one since a part of the rays have been lost by transmission.

3. This decrease in the amount reflected from a thin film appears first in the most deflected rays and with increasing potential will also be found in the least deflected portion.

4. The critical potential depends on the thickness and the nature of the film. For aluminum this critical potential for thicknesses $0.56\,\mu$, $1.90\,\mu$ and $2.44\,\mu$ is 11,000, 16,500 and 21,800 volts respectively. For a copper film of thickness $0.66\,\mu$, the critical potential has a value greater than 27,750 volts.

5. The foregoing data has shown a fair qualitative agreement with the theory deduced by Professor E. Warburg,[3] although the values given do not show the desired agreement with those calculated.

In conclusion the writer takes pleasure in acknowledging his indebtedness to Professor E. Warburg, under whose direction the foregoing work was undertaken, for many kindnesses and helpful suggestions throughout the course of the experiments.

[1] Gehrcke, l. c.

[2] Starke, l. c.

[3] Theories on the reflection of cathode rays have been given by Professor E. Warburg, Verhandl. d. Deut. Physik. Gesell., VI. Jahrg., Nr. 1; J. Stark, Phys. Zeitschrift, 3, p. 161, 1901; J. J. Thomson, Conduc. of Elec. Through Gases, p. 509.