KATHODO-FLUORESCENCE OF CRYSTALS.

By Thomas B. Brown.

Part I.—A Quantitative Investigation of the Kathodo-Fluorescence of Willemite, Kunzite and Soda Glass. (A description of the results obtained by J. A. Veazey.)
Part II.—A Further Investigation of Willemite by the writer.

Introduction.

The intensity of the fluorescence excited by the impact of kathode rays upon a fluorescent substance depends, for a given substance at a constant temperature, upon the velocity of the rays, and upon their rate of impact. To a lesser degree it may be affected by other factors as yet undetermined.

The experimental study naturally divides into two parts:

1. A determination of the relation between the intensity of the fluorescent light L and the kathode ray current I at constant discharge potentials.

2. A determination of the relation between L and the discharge potential V at constant current values.

The earliest investigation was made by Lenard.[1] Lenard had only a secondary interest in the phenomenon, as a means of detection of kathode rays. He investigated several substances, making on each substance only a few observations through the limited range he was interested in; from the results he postulated the relation

$$L = CI(V - V_0),$$

where V_0 is a minimum potential *below which no fluorescence can occur.* No experimental proof of the existence of this minimum is given; and it seems, in the light of later investigation, an unjustifiable extrapolation.

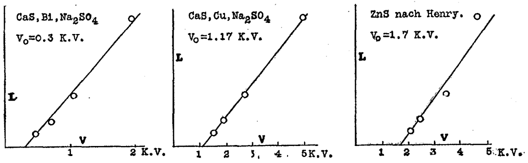

Fig. 1.

Plotted from data of Lenard. The lines drawn represent the equation he gives for them:

$$L = CI(V - V_0).$$

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[1] P. Lenard, Ann. d. Phys., 12, 1903, pp. 449–490.

The points plotted in Fig. 1 represent his observations on several substances, and the straight lines drawn, his interpretation of them.

The next observer in this field was Leithäuser,[1] who likewise wished to use the phenomenon as a means of detecting kathode rays. Working with calcium-sulphide, he found an exact proportionality between L and I at constant V, but found the non-linear relation between L and V at constant I which is given by Fig. 2, plotted from his data. It is to be noted that, curiously enough, this curve, if extended backward, would cut the *intensity* axis!

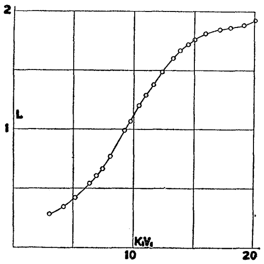

Fig. 2.
Intensity-potential curve obtained by Leithäuser for CaS.

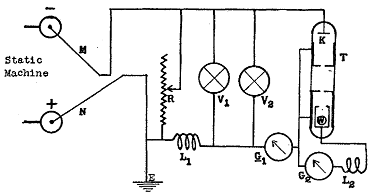

Fig. 3.
Diagram of connections.

Directly following a brief preliminary investigation by Nichols and Merritt,[2] in connection with a study of the spectrum of kathodo-fluorescence as influenced by the velocity of the exciting rays, J. A. Veazey took up, at their suggestion, an extended investigation of the problem. His untimely death in the summer of 1912 cut his work short. To the present writer, whose good fortune it had been to act as Veazey's assistant the previous year, fell not only the continuance of the work, but also the editing for publication of Veazey's work. This paper is accordingly in two parts, as indicated in the heading above.

PART I.—THE KATHODO-FLUORESCENCE OF WILLEMITE, KUNZITE AND SODA GLASS. (DESCRIBING THE MEASUREMENTS BY J. A. VEAZEY.)

After extended preliminary experiments which led to the elimination of several important sources of error, the apparatus was finally arranged as shown in diagram in Fig. 3.

Current is supplied to the discharge tube T through the high-tension reversing switch MN from the large Holtz machine H. An alcohol rheostat R in shunt with the Holtz machine regulates the current through the tube, and Kelvin electrostatic voltmeters V_1 and V_2, having over-

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[1] G. E. Leithäuser, Ann. d. Phys., 15, 1904, pp. 283–306.

[2] E. L. Nichols and E. Merritt, PHYS. REV., 28, 1909, pp. 349–360.

lapping ranges, measure the potential difference across the tube. A sensitive Sullivan galvanometer G_2 measures the current carried to the crystal by the kathode rays, and the galvanometer G_1 measures the total current passing through the tube. Ironless inductances L_1 and L_2 are inserted to prevent oscillations.

The tube is shown in section in Fig. 4. Kathode rays projected from the kathode *K* along the axis of the tube strike the crystal *W*, causing fluorescence. The cylindrical box anodes C_1 and C_2 shield off all but the central portion of the bundle of kathode rays, and receive all the current passing through the tube except that carried by this central portion of the rays. For reasons explained later, the lower box C_2 may , when desired, be maintained at a potential of -55 volts with respect to the inner box *M*, by throwing over the switch *S*. The crystal *W* is surrounded by the aluminum box *M*, whose purpose it is to receive the current carried to the crystal by the kathode rays and to conduct it to the galvanometer G_2.

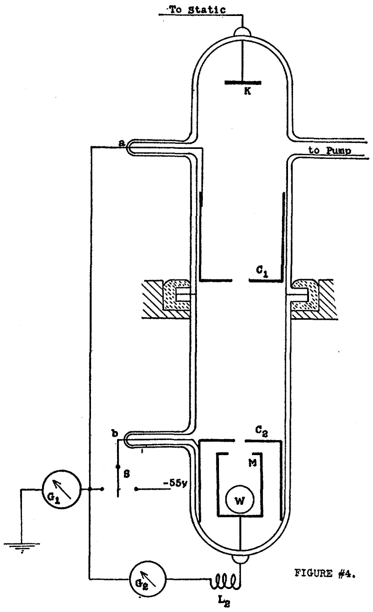

Fig. 4.

The tube is evacuated by a Pfeiffer-Wetzlar rotary mercury pump and a Fleuss oil pump in series. The vacuum system was so tightly closed and so free from vapor that pumping at intervals sufficed to maintain any desired potential difference across the tube.

Through holes in the sides of the boxes C_2 and *M* photometric measurements are made. The photometer used was designed especially for the work. A Lummer-Brodhun cube matches the illumination of two transmission-diffusion screens; one of these is illuminated by the fluorescence of the crystal, the other by a constant comparison source. By a suitable variation of these calibrated screens, any range of visible fluorescence may be measured. The small central portion of a large acetylene flame as seen through a circular hole in a diaphragm placed directly in front of it and covered with a suitably colored glass or liquid screen to give a visual color match with the fluorescent light, is used as the comparison source. The gas pressure was kept constant, and the outline of the flame, as observed in a flame gauge, remained constant. The distance from the crystal to its diffusion screen is fixed, while the comparison source is movable along a photometer bar. Since Nichols and Merritt[1] have shown that the spectral distribution for the substances examined is independent of the electrical conditions of the discharge (or indeed, of the method of excitation), ordinary photometric measurement is sufficient.

It was found upon trial with willemite that, for potentials below 1.5 K.V., with the box C_2 earthed, the galvanometer G_2 reads zero, and no light is given off by the crystal; but as the potential is raised, it began to deflect when the crystal began to fluoresce. At any discharge potential, a deflecting magnetic field reduced the galvanometer reading to zero at the same time as it stopped all fluorescence of the crystal. These tests seem to indicate that the current represented by the galvanometer reading is exclusively kathode ray current. They do not prove, however, that all of the impinging electrons contribute to the current read by this galvanometer; since the rays suffer reflection, a part of the reflected rays may escape through the openings in the box M and carry their charges to the cylinder C_2. But if the loss by reflection is independent of the potential and of the gas pressure, the data will still give the true relation between the intensity of the fluorescence, the current, and the potential. L. Austin and H. Starke[2] find the reflecting power of *metals* for kathode rays at normal incidence independent of the gas pressure and the potential within the limits of 3 to 30 K.V. No statement of work covering the case at hand has been found. Here the crystal is non-conducting, and the rays are incident at an angle of forty-five degrees. It will be assumed, however, that the reflecting power in this case also is independent of the potential and gas pressure.

Experiments with Willemite

The first crystal examined was a specimen of willemite (zinc orthosilicate) having an area of about one square centimeter ground smooth. A circular area about 0.80 cm. in diameter was bombarded by the kathode rays.

Curve 1, Fig. 5, represents data taken at the constant potential of 3.50 K.V., with the cylindrical box C_2 earthed. Curve 2 was taken with this box charged to a small negative potential (− 55 volts). These results seem to indicate that with C_2 earthed not all of the reflected electrons are caught by the box M; while with C_2 at a small negative potential, more if not all of the electrons are caught and their charge

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[1] E. L. Nichols and E. Merritt, PHYS. REV., 28, 1909, pp. 349–360.

[2] L. Austin and H. Starke, Ann. d. Phys., IX., p. 271, 1902.

measured by the galvanometer G_2. For all subsequent observations C_2 was kept at the potential of $-$ 55 volts.

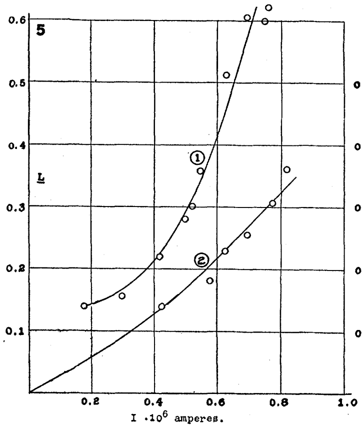

Fig. 5.

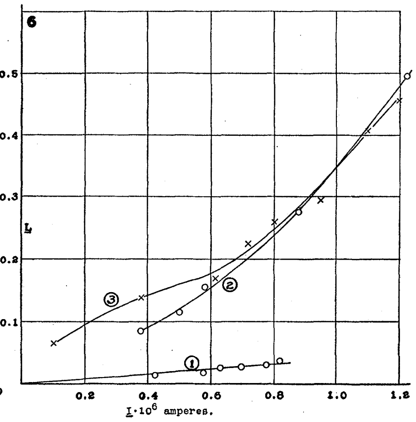

Fig. 6.

Potential constant at 3.50 K.V.
Curve 1. Cylinder C_2 grounded.
Curve 2. Cylinder C_2 at potential of $-$ 55 volts.

Potential constant at 3.50 K.V.
Curve 1. Taken March 4th. Pressure maintained low previously.
Curve 2. March 4th. After admission of air and reëxhaustion.
Curve 3. March 8th. Same conditions as No. 2.

Fig. 6 shows the effect of admitting fresh air into the tube. Curve 1 was taken after low gas pressures had been maintained for several days' use of the tube. Curve 2 was taken the same day after admitting air to the tube to atmospheric pressure, and reëxhausting. Curve 3 was taken a few days later, conditions similar to those of 2 having been maintained approximately in the interim. As a result of the admission of fresh air it is to be noticed that (*a*) for a given kathode ray current there is a marked increase of the intensity of fluorescence, and (*b*) with the same external circuit conditions, a much greater kathode ray current may be obtained. The first of these results may be due to some change in the surface condition of the crystal; perhaps to its oxidation by the freshly admitted air. The subsequent bombardment of the crystal, together with the removal of the gases of decomposition by pumping, may again reduce the surface. Villard[1] found in his experiments that the portion of an oxidized copper plate exposed to the action of kathode rays became bright, and he considered this a reduction of the surface due to the bombardment.

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[1] J. J. Thompson, Cond. of Elec. through Gases, p. 496.

The second result may be explained by assuming that the walls of the tube become conducting when bombarded with kathode rays. Many observations show that after low gas pressures and high potentials have been maintained for several days, the discharge is much less concentrated along the axis of the tube; a greater portion of it being deflected toward the wall of the tube above the anode, as is shown by the increased fluorescence of the glass walls, by the lower reading of the galvanometer G_2, and by the occasional snapping of sparks from the kathode to the nearest portion of the walls. With the tube freshly exhausted, the glass walls are but slightly fluorescent, and the path of the rays, as marked out by the blue glow, is along the axis of the tube.

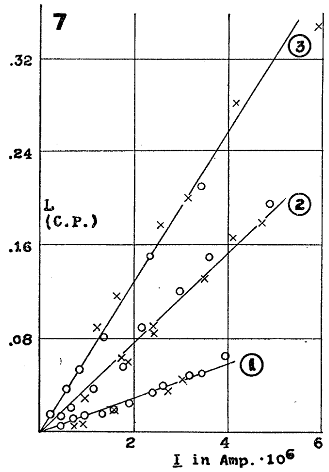


Fig. 7.

Constant potential curves for willemite, taken under conditions of maintained low pressures.

No. 1. 8.30 K.V.
No. 2. 12.20 K.V.
No. 3. 14.20 K.V.
Area bombarded, 0.5 cm.^{2}
O Ascending values.
× Descending values.

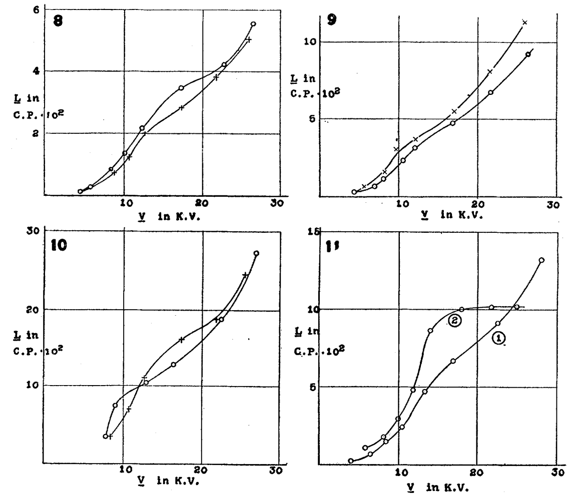
The curves shown in Fig. 7 are a part of a series of constant potential curves taken under conditions of maintained low pressures. These, as well as the others not shown, are all straight lines within the limits of experimental error, and show a direct proportionality between the intensity of fluorescence and the kathode-ray current. A great number of other curves, taken both before and since, likewise verify this linear relation.

This is so far in agreement with the Lenard formula

$$L = CI(V - V_0).$$

In order that complete agreement obtain, data taken at constant current should plot as straight lines for the intensity-potential relation, with an intercept on the potential axis equal to V_0. Figs. 8, 9, 10, 11 represent the data obtained for the constant current values indicated. None of these curves are straight lines, and all of them show decided hysteresis effects for increasing and decreasing potentials. These curves might possibly be considered straight lines with the superimposed effects of changes of temperature, of change of reflecting power with change of potential, and of fatigue and hysteresis. The lowest potential at which fluorescence of willemite could be detected was 1.40 K.V. The curves do not approach the axis close enough to determine an intercept accurately.

Curve 2, Fig. 11, illustrates another method of obtaining the relation between intensity and potential at constant current. It was plotted from the series of constant potential curves, a part of which are shown in Fig. 7, using values read from those curves corresponding to the current of $1.3 \cdot 10^{-6}$ amperes. It is to be recalled that this series of constant potential curves was taken under conditions of maintained low gas pressures, so that the bending of the upper part of this curve toward the horizontal may be due to a slow deterioration of the fluorescent power with time.



Constant Current Curves for Willemite.

Fig. 8.

Current value of $0.65 \cdot 10^6$ Amp.

Fig. 9.

Current value of $1.30 \cdot 10$ Amp.

Fig. 10.

Current value of $3.20 \cdot 10$ Amp.

Figs. 8, 9, and 10, illustrate different types of hysteresis.

Fig. 11.

Current value of $1.30 \cdot 10$ Amp.

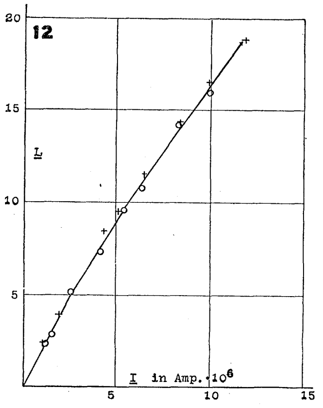
Curve 1 was taken directly.

Curve 2 was obtained from the series of constant potential curves of which the curves in Fig. 7 are a part.

Experiments with Kunzite.

A crystal of kunzite (a variety of spodumene, $LiAl(SiO_3)_2$) was next examined. Kunzite is fluorescent only under spark or kathode ray excitation, with an amber or reddish yellow fluorescence. This crystal was less permanent under kathode ray bombardment than willemite, giving off decomposition vapors much more rapidly, and exhibiting other fatigue or decomposition phenomena to be described later.

The curves for kunzite are very similar to those for willemite in form, but the relative intensity is considerably less. The constant potential curves, of which Fig. 12 is an example, all show a good proportionality between the intensity of fluorescence and the current; while the constant current curves, of which Fig. 13 is an example, are non-linear, much resembling the corresponding ones for willemite, and show a considerable hysteresis between the ascending and descending values.



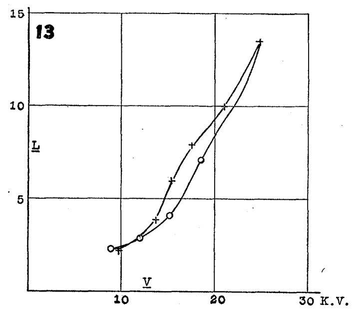


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Fig. 12.

Kunzite. Potential, 17.15 K.V. Area bombarded, 0.2 cm.^{2}

Fig. 13.

Kunzite. Current, $3.88 \cdot 10^{-6}$ Amp.

Fig. 14.

Kunzite. Appearance of bombarded area. *A*, Low potentials. *B*, High potentials.

Direct observation of the fluorescing crystal discovered that the fluorescing area was not uniformly bright, but appeared as a luminous ring surrounding a darker central area, with a very dark spot near its center. At low potentials this ring grew to greater diameter, but became narrower, and scallops appeared, extending into the ring from the center. Fig. 14 illustrates this. These phenomena lead to the supposition that the kathode ray bundle incident upon the crystal is not homogeneous, but is more or less hollow, depending upon the potential. Such a hollowness has been reported by Swinton.[1]

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[1] C. Swinton, Proc. Roy. Soc., LXI., p. 79, 1897.

Examination after removal from the tube found the surface of the crystal to be discolored where it had suffered bombardment; there being a dark spot near the center surrounded by a discolored ring. Several hours' heating at several hundred degrees Centigrade completely removed this discoloration, together with the natural lilac color of the crystal, so that it now appeared as clear glass. The fluorescent properties were but little changed, as Fig. 15, taken after heating, shows. The noticeable change is the absence of any hysteresis effect. For these observations the distribution of the rays was rendered more uniform by placing a plate of aluminium drilled full of fine holes over the opening in the cylinder C_2.

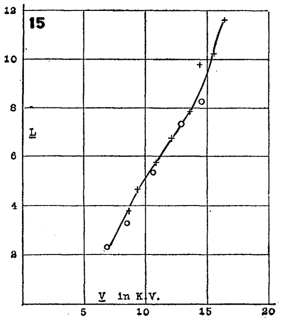

Fig. 15.

Kunzite, after heating. Current value, $0.634 \cdot 10^{-6}$ Amp.

Experiments with Glass. (Soda glass of German manufacture.)

A piece of glass taken from a broken discharge tube was next examined. The fluorescence is a greenish color, and much weaker than that of either of the substances previously examined. The results obtained, shown in Figs. 16 and 17, indicate the same general relation between the variables

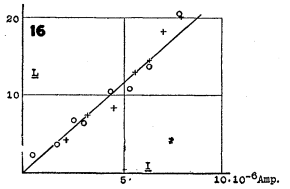

Fig. 16.

Glass. Potential, 19.1 K.V.

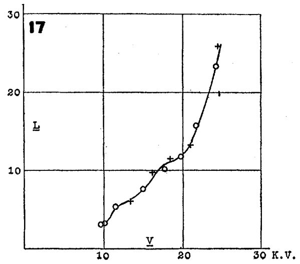

Fig. 17.

Glass. Current, $3.88 \cdot 10^{-6}$ Amp. Area bombarded, 0.2 cm.^{2}

as holds for the other substances: a direct proportionality between intensity and current at constant potentials, and a non-linear relation between intensity and potential at constant currents. There is little if any hysteresis. Direct observation discovered the same phenomena of non-uniform luminosity as observed for kunzite, when the opening in the top of the cylinder C_2 was uncovered.

Conclusions.

1. For potentials not too small, the constant potential curves obtained for willemite and kunzite show a direct proportionality between the intensity of fluorescence and the kathode ray current, and so far verify the relation postulated by Lenard

$$L = CI(V - V_0).$$

The single curve for glass agrees approximately.

2. If precautions are taken to prevent loss of charge by reflection, the curves obtained for willemite and kunzite for small discharge potentials likewise show this proportionality; except that, for the same potential, a much steeper line is obtained in a freshly exhausted tube than is obtained after the vacuum has been maintained at a low gas pressure, and discharge passed at a high potential, for some time previously.

3. The constant current curves for willemite, kunzite, glass, and the heat-treated kunzite, do not agree with the Lenard formula, although they come closer to it than do the results of Leithäuser. The constant-current curves for willemite and native kunzite show marked hysteresis effects, while the glass and the colorless (heat treated) kunzite do not.

4. The crookedness of the constant current curves may be due to the effect of changes of temperature upon the fluorescent power of the crystal, or to changes of the reflecting power of the crystal, with changes of potential.

Some means must be provided to insure these conditions are constant before the exact relation between the intensity of fluorescence and discharge potential can be found.

PART II.—A FURTHER INVESTIGATION OF WILLEMITE.

If L is known to be a function of I and V, and it is found that for V constant, L is directly proportional to I, then it follows that the ratio L/I is a function of V alone. The results of all investigators agree that, at a constant discharge potential V, the intensity of fluorescence L is directly proportional to the kathode-ray current I. Particularly conclusive evidence seem the abundance of curves verifying this relation obtained by Veazey. This continuation of the work is concerned with, first, checking the apparatus used by determining whether or not it will give this same relation between L and I at constant potential, and then determining the form of the relation between L/I and V.

Willemite was chosen for further investigation as typical of these substances and also as being the most brilliantly fluorescent of them, and the most stable under the kathode-ray bombardment. The specimen was used in powdered form, the crystals being chipped away from the quartz with which they occurred, powdered, and then heated to redness to drive off any volatile or gaseous impurities present. After heating the color was almost white, but the fluorescent properties remained unchanged. This specimen never gave evidence of the hysteresis and tiring effects found by Veazey in his specimen; and this fact is probably due to the preliminary heating.

It is to be recalled that for these substances at room temperature the spectral distribution is the same for all discharge potentials.[1] The effect of temperature upon the spectral distribution has been investigated by Nichols,[2] and is found to be inappreciable in the range of ordinary room temperatures.

The discharge tube used is shown in vertical section in Fig. 18. This tube is similar to the one used by Veazey, but much larger. The upper part of the tube *A* is about 13 cm. in diameter and stands 24 cm. high. The height over all is about 55 cm. and the volume approximately 3.3 liters. The kathode *K* is 2.7 cm. in diameter. The anode, the two concentric cylindrical aluminum boxes *M* and *N*, occupies a major portion of the tube. The distance between the top of the box *M* and the kathode is 2.4 cm. The outer box *M* is earthed and receives all the discharge except that part carried by the central portion of the kathode stream which enters the inner box *N* through the circular openings *a*, *b*, and *c*, and bombards the fluorescent powder at *d*. *N* is insulated from *M* by the glass plate which supports it, and the charge carried to *d* by the rays is conducted through *C* to the galvanometer *G* and thence to the earth. The area of powder surface bombarded is about one centimeter in diameter. The upper opening *a* was covered with a multi-perforated plate, as this was found desirable by Veazey. A sixty-degree prism *o*, sheathed with aluminum except for openings as shown, reflects the fluorescent light through holes in the sides of the boxes *M* and *N*, and

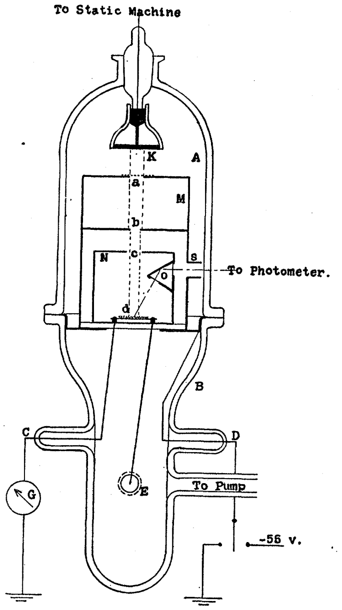

Fig. 18.
Vertical section of discharge tube.

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[1] E. L. Nichols and E. Merritt, Phys. Rev., 28, 1909, p. 349–360.

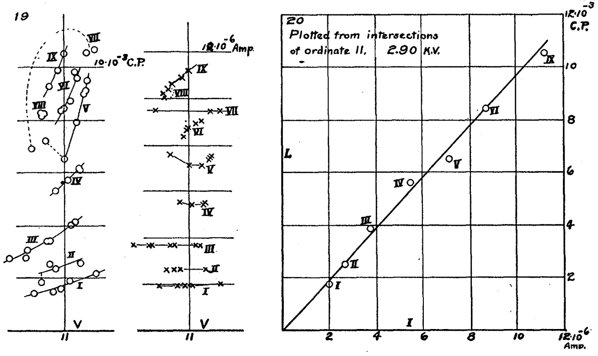
[2] E. L. Nichols, Proc. Amer. Phil. Soc., 196, 1910, pp. 267–280.

the tube *s* (placed here to prevent any stray discharge reaching *N*), and thence into the photometer. In this form of anode the possibility of loss of charge due to reflection is very much smaller than in the form used by Veazey, and it was unnecessary to give the outer anode a negative potential to prevent loss.

The pumping system is the same as that used by Veazey, and the electrical system likewise (see Fig. 3), except for a few minor connections, and the addition of a third static voltmeter, built by the author, to cover a lower range of potentials than the others. All permanent connections are soldered. The voltmeters were calibrated and checked against an attracted disc electrometer. The photometer used is a modified form of the one used by Veazey, with an entirely new set of calibrated comparison screens. By means of a contrast photometer comparison was made with a laboratory standard, so that the intensity values are given in approximate visual candle power.

First to be considered is the relation between the intensity of fluorescence L and the kathode ray current I at constant potentials; *i. e.* testing for this apparatus the relation $L = kI$ at constant potential, where k is a function of the potential V.

Figs. 19 and 20 show the way in which the results were plotted. Since in most cases it was difficult to hold the potential absolutely constant, and since in the same cases the change of L for a small change of V is relatively great, readings were made of a series of corresponding values of L, V, and I in the neighborhood of the desired potential; this data is plotted as in Fig. 19. Then by interpolation from these curves corresponding values of L and I at a constant potential are obtained and plotted as in Fig. 20. Fig. 21 shows the collection of curves obtained



Figs. 19 and 20.

Method of plotting intensity-current curves.

to show the relation between L and I at constant potentials; they are all straight lines within the limits of experimental error. They cover fairly well the range of potentials investigated hereafter, and are considered a satisfactory agreement with the relation $L = kI$ at constant potential, which has already been pretty exactly verified by Veazey and others.

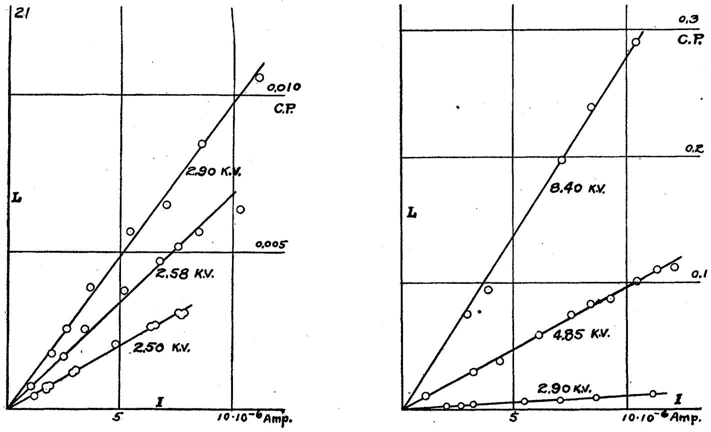


Fig. 21.

Intensity-current curves for different potentials.

Having established the direct proportionality between L and I at constant V, *i. e.*, the relation $L = F(V)I$, it is now possible to proceed to investigate the form of the relation $F(V)$ between L/I and V. Typical results of this investigation are shown in Figs. 22, 23, and 24. Because of the great range of intensities, it was necessary to plot the results

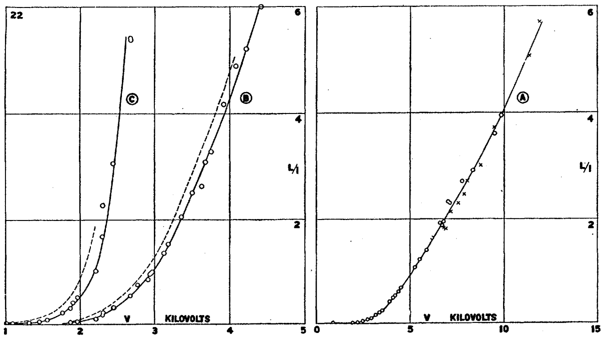


Fig. 22.

April 1. To read the values of L/I in candle power per ampere, multiply the ordinates of curve A by 10^4; of curve B by 10^3; and of curve C by 10^2. O indicates increasing values; ×, decreasing values.

of a single run (often around a hundred observations) on two sheets, and to three different scales of intensities. The results as represented by these curves are in general agreement with the results obtained by Veazey, and with those obtained by Leithäuser, with the exception pointed out heretofore. In addition, in the present work, successive observations have been made much closer together than in any previous work, and the results present a greater degree of uniformity and extend the investigation to a region of much lower potentials. The results are not in agreement with the conclusions of Lenard *i. e.*, that the relation would be a linear one, with a minimum potential existing below which no fluorescence could occur, but seem to be in good agreement with his data. Comparing Figs. 1 and 23, Curve *A*: It is easy to see how Lenard, having only a few observations in a region of potentials corresponding to the nearly straight portion of Fig. 23 (between 4 and 13 K.V.) could conclude them to represent a linear relation. It is very evident from the present work that the relation is not linear. Fig. 24 shows better than the others the marked curvature at the foot of these curves. As low down as the fluorescence could be observed the curve is bending nearer and nearer towards the horizontal. There was measurable fluorescence at 0.75 K.V.; and at even lower potentials fluorescence could be detected by viewing the crystal directly. A transverse magnetic field would stop it, and at the same time bring the deflection of the galvanometer to zero, thus proving that the excitation was by the bombarding kathode electrons. However, the fluorescence for the low potentials is so faint that the results obtained below 1.00 K.V. are not accurate; especially as a small amount of light from the now luminous discharge in the top of the tube

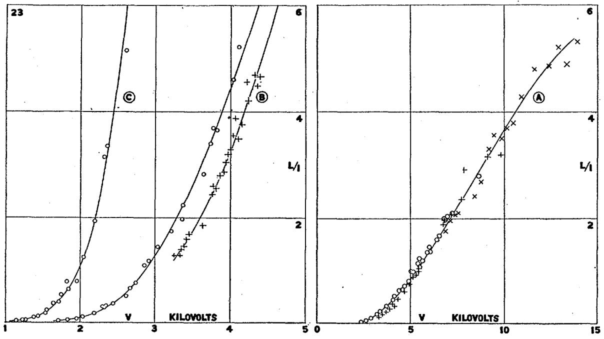


Fig. 23.

April 7. Values of L/I are read as indicated under Fig. 22. O indicates ascending values, and ×, descending values, taken in the morning. + indicates ascending values taken in the afternoon.

illuminates the specimen enough to introduce between five and twenty per cent. error for observations below one kilovolt potential. Above this, the effect becomes inappreciable, since most of the luminous discharge is then driven from the tube, and its illumination becomes a negligible amount of the total brightness, which increases rapidly.

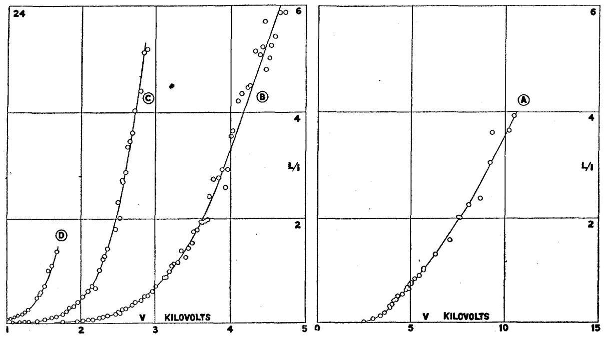


Fig. 24.

April 8. Values of L/I for curves A, B, and C are read as indicated under Fig. 22. Multiply ordinates of curve C by 10.

The lower values of L/I are undoubtedly too low; due to absorption, by the relatively greater amounts of gas present, of a part of the measured energy of the exciting electrons, and to scattering, by the same agent, of a part of the electrons, whose charges are measured, but which do not strike the crystal. There is nothing about the results obtained to indicate that, if this absorption, etc., could be eliminated, the fluorescence would not be present for all potentials down to zero potential. Certainly, if there exists a minimum potential below which no fluorescence would be produced, it is *below* the lowest value investigated here, and the data gives no evidence of its existence. If the fluorescence of such substances as willemite may be compared to the "characteristic" X-radiation of metals, computations based upon the conclusions of Duane and Hunt,[1] who found that the minimum potential for that radiation is given by the equation $eV_0 = h\nu$ (where V_0 is the minimum potential for X-radiation of frequency ν, and e and h are the electronic charge, and the Planck radiation "quanta" constant, respectively) give about 4 volts as the minimum for the middle of the fluorescent spectrum. It is doubtful if that value can be reached experimentally.

A slight change of temperature occurred during the bombardment, and was measured during some of the later runs. For example, in the case of the data of April 7, a temperature change of 19° C. occurred. This is hardly sufficient to affect the phenomena.

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[1] W. Duane and F. L. Hunt, Phys. Rev., N.S., VI., Aug., 1915, p. 166.

The results of the different runs, when compared (Fig. 25), instead of coinciding, as might have been reasonably expected, scatter considerably; but in general, they fall into two groups, represented by the two lines drawn in the figures. These two lines correspond to the data of April 7, and of April 8, which are typical of the two groups respectively. A key to the cause of these two groups of values is found in the results of April 7 (Fig. 23). The longer curve was obtained in the morning; the vacuum was poor, and the potential was raised by pumping, running up to a maximum. After being once thoroughly exhausted, the tube had an excessively slow rate of leak, so that after lunch hour the potential was still up to 3.25 K.V. and rose steadily, due to the discharge alone and *without pumping*, to 5.45 K.V., when pumping was begun. Throughout the region where the potential rise was automatic the points representing these data fall considerably below those obtained in the morning; approaching them after pumping is begun. The next day the potential had fallen to 0.78 K.V., but the rise of potential was slow and automatic up to 5.45 K.V., where pumping was begun. This curve also falls below the first of those taken the day before, but it *coincides* with the second. Examination of the data reveals that all those of the second (lower) group of values (those of Jan. 21, Apr. 7 (P.M.), and Apr. 8) were taken under conditions of automatic potential rise; and that all those of the first (upper) group were obtained by pumping to raise the potential. The January 21 values start out in good agreement with the lower group, but fall increasingly below them above 3.3 K.V. Since this case is a

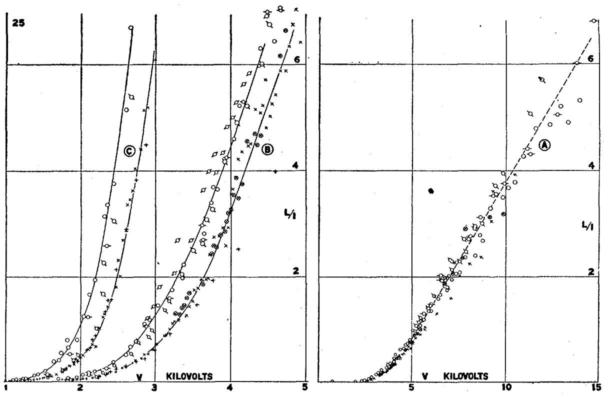

Fig. 25.

Combined results. Values of *L/I* are read as indicated under Fig. 22. Different runs are ndicated as follows: January 21 +, February 10 ρ, March 18 -○-, April 1 , April 7 ⊙ ⊗ iand April 8 ×.

" freak "; *i. e.*, it has occurred in the data but the once, it will have to be disregarded until some later work may throw some light upon it.

It seems more probable that the difference in these two sets of curves, which seems to correspond to the difference that Veazey observed as a difference between a freshly obtained vacuum and a long maintained one, is not due to the causes he suggests (an oxidation or other change of the surface of the specimen) but to a difference in the state of the residual gas in the tube; either a difference in the pressure under the different conditions of discharge, or a difference in the character of the gas, due to vapors, or to formerly surface occluded gas, or both. The differences are most marked in the lower range of values, where the difference of absorption and scattering of the electrons due to the differences of the gas state might be sufficient to account for the lowering of the values in the case of the second group.

At the time, no observations were made of the gas pressure conditions, except those indications gotten by observation of the discharge; and these were not reliable, since the form of the tube was so different from the usual one. Since then, a McLeod gauge has been attached and the gas pressure observed under the conditions of taking the first group of values (potential raised by pumping) and the characteristic pressure-potential curves were obtained. Between the potentials 1.00 and 13.00 K.V. the pressure varied between outside limits of 100 and 10μ (thousandths of mm. of mercury). To a crude approximation, the pressure is inversely proportional to the potential through this range. The seal of the new vacuum system was not sufficiently perfect to obtain the conditions of the second set of values. *Indications* of the pressure conditions of this set were obtained, however, in that a measurable *rise* of potential was observed during an appreciable *rise* of pressure. The suspicion is that the " automatic " rise of potential occurred with at the most only a slight decrease of pressure. The greater gas density would cause a greater absorption of energy, etc., and this would explain why the curves obtained in this manner lie below the others.

Only fragmentary data concerning absorption and scattering of kathode rays are available. Extrapolation of values from a table given by Lenard indicates that for the values obtained in group one (upper), L/I at 1 K.V. is about seven times too small, while L/I at 4 K.V. is about 11 per cent. low, and above 4 K.V. the losses are negligible. This does not affect the conclusions drawn from the shape of the curves: As seen in Fig. 22, where the values based on the extrapolation are represented by the dash line, the curvature is just as pronounced, and the existence of an appreciable " minimum " potential is still less evident. Also, the magnitude of the losses is such that, taken together with the assumption that the "automatic" rise of potential is accompanied by but a slight change of gas pressure, it could quite well account for the difference between the two groups of curves. Later work with this apparatus may be undertaken to obtain more complete data on the absorption and scattering losses. But a much simpler method of obtaining the exact relation between the variables is to use a modern hot kathode discharge tube, since in such a tube the gas density is so small as to cause but an immeasurable amount of loss. This work is now under way.

There will still be present another cause of error to consider; namely, the static potential which accumulates on the specimen and results in causing a reduction of the velocity of the electrons as they approach it. Since the $L - I$ curves at constant V are straight, this static potential would seem to be dependent only upon the gas pressure, if indeed it is a variable. So that in the new apparatus it should be a constant. It seems probable that the appearance of the fluorescent area, reported by Veazey and illustrated in Fig. 14, is due to this static potential. It would be naturally greater at the center, where the chance for leakage is the less, and hence cause a greater decrease in the velocity of the electrons striking there, and also deflect some of the approaching electrons towards the outer annular ring.

The processes of fluorescent radiation are too complex and too little understood to permit the derivation of any theoretical equation against which to check these results. The results themselves suggest vaguely a number of qualitative theoretical explanations, and several empirical (expotential) equations have been tried in an attempt to arrive at some definite conclusions. But the net result of it all is the conclusion that further work is necessary, along lines suggested by the experimental results and by these theoretical speculations, before any definite theory can be developed that will stand rigid scrutiny.

Conclusion.

This investigation of the kathodo-fluorescence of willemite has had as its purpose a determination of the relation between the intensity of fluorescence L, the rate of impact of the kathode electrons (measured by the kathode ray current I), and the electronic kinetic energy (measured by the discharge potential V).

A direct proportionality is found between L and I at constant values of V, confirming the results of previous investigators.

The relation between L/I and V (which corresponds to the relations obtained by Veazey and others between L and V at constant values of I)

is found to be non-linear, of the form shown by the curves plotted; these curves having an increasing slope as the potential is raised, which approaches a constant value for higher potentials, and possibly falls off for values still higher (as indicated by Veazey's results, which are in fair agreement with the present ones). There is no indication of a minimum potential below which no fluorescence would be produced.

The results have been shown to be in general agreement with the *data* obtained by Lenard for similar substances, but to be not in agreement with the empirical relation postulated by him. Indeed, they may be considered as a very definite disproof of that relation.

Certain discrepancies observed by Veazey have been observed in greater detail, under conditions that permit them to be explained as most probably due to the effects of absorption and scattering of the energy of the kathode electrons by the residual gas in the tube.

Static potentials acquired by the specimen are suggested as explaining the uneven appearance of the fluorescence, noticed by Veazey.

Sources of error are recognized in the two paragraphs above: losses due to absorption and scattering, and to static potentials on the specimen. Means for their elimination are being considered.

While the present work has furnished some very promising germs for a theoretical explanation, yet it is but idle speculation to attempt to develop them into any concrete form without first planting them in a very much more fertile soil of experimental investigation. Suffice they now to point the way to that investigation.