The action of Rëntgen and gamma radiations upon the electrical conductivity of selenium crystals

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THE ACTION OF RÖNTGEN AND GAMMA RADIATIONS UPON
THE ELECTRICAL CONDUCTIVITY OF SELENIUM CRYSTALS

by

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THE ELECTRICAL CONDUCTIVITY OF SELENIUM CRYSTALS

Historical Introduction

In 1873, fifty-five years after its differentiation by Berzelius(1), the element selenium was found by Smith(2) to have a much greater electrical conductivity in the daylight than in the dark. In his work this variation sometimes amounted to as much as one hundred per cent. Since this discovery many elements and compounds have been examined as to their light-electric properties. A number(3)(4) have been found which show similar changes though they vary notably in magnitude. Selenium is one of the substances which show the effect most prominently. The peculiarity must have considerable significance in the organization of our knowledge concerning matter.

Subsequent experiments using various preparations and forms of selenium have brought out many interesting facts connected with this distinctive property of the element. It has been found that the light sensitivity of the preparations used in investigation is due to the presence of crystals formed in their manufacture(5)(6). Amorphous forms of the element are not light sensitive. Many of the characteristics of types of selenium cells have been worked out. Recently, however, single crystals of metallic selenium have been obtained which are large enough to be studied separately(7). Consequently a more direct means of investigation is afforded. Some of

(1) Schweig. Journ. 23, p.309
(2) Am. Journ. Sc. (3) 5, p.301
(3) Anzel, Zeits. f. Elektrochem. 9, p. 695
(4) Case, Phys. Rev. 9, p.505
(5) Brown and Sieg, Phys. Rev. N.S. 4, p.48
(6) Dieterich, Phys. Rev. N.S. 4, p.467
(7) Brown, Phys. Rev. N.S.4, p.85
the most important of the results thus far secured are given as follows:

1. The change in conductivity is a function of the time, intensity, and character of illumination(8). Both cells and crystals have definite rates of response to and recovery from illumination. The total effect increases with the intensity. Beams of light of the same energy but of different wave-length produce different changes in conductivity. Thus wave-length-sensibility curves have been determined both for cells and for isolated crystals of various forms(5)(9)(et al).

2. The conductivity increases both with the pressure and potential applied. The sensitivity (absolute $\Delta \sigma$) increases with the pressure, being proportional to the initial conductivity in the dark(7)(20).

Other effects are known but it is with these that this thesis is chiefly concerned.

The forgoing summary of some of the principle facts contained in our knowledge of the action of light upon metallic selenium is necessary to a discussion of the object underlying this research. Recent investigations have shown that Röntgen and gamma radiations not only are similar but have many properties in common with light(10)(11). The fact that none of these radiations is deviated by electric or magnetic fields furnishes a strong beginning in the establishment of their relationship. Similarities between the phenomena of electronic emission from metals under the influence of ultra-violet light, Röntgen, and gamma rays, also bear out this theory. The most convincing argument of all, however, is that which follows upon the evidence obtained

(8) Brown, Phys. Rev. 33, p. 1
(9) Sieg and Brown, Phys. Rev. N.S. 4, p. 507
(10) Rutherford, "Radioactivity", p. 286
(11) Kaye, "X-Rays", p. 206
by Bragg(12) for the Röntgen rays, and by Rutherford and Andrade(13) for the gamma rays. By reflection from the planes of atoms in crystals they have been able to get effects explainable on the same assumptions ordinarily made in accounting for the diffraction effects of light. This has enabled them to measure the wave-lengths of constituents of the radiations. The one outstanding difference in the absorption of these rays does not seriously interfere with the theory that all three are transverse wave motions of some sort(14). It only requires a conception of the atom competent to explain the phenomenon. At present it seems an excellent working hypothesis to regard the gamma, Röntgen(or X-rays), Schumann, ultra-violet, visible, heat, and Hertzian, radiations as waves of a similar nature differing only in length.

Since the discovery of the light effect(2) a number of experimenters have been led to investigate the action of Röntgen rays and of the rays of radium upon the electrical conductivity of selenium. A brief summary of the results obtained by each will next be given.

We are indebted to Giltay(15) for our first knowledge of the action of Röntgen rays upon selenium. In 1896 he tried for the effect but failed owing to the poor operation of his induction coil. Not wishing to wait he wrote Prof. Haga of Groningen University, Holland, describing the experiment and asking him to perform it. A Bidwell cell shielded from light and potential effects was found to increase 19.6% in conductivity with a one minute exposure. The return

(12) "X-Rays and Crystal Structure"
(13) Phil. Mag. 27, p.554
(14) Kaye, "X-Rays", p.129
(15) Nature 54, p.109
to the initial conductivity \((3.16 \times 10^{-5})\) was slow twenty minutes being necessary for 60% recovery. One minute exposure to diffuse daylight produced a change of 106.5% in the conductivity of this cell.

Perreau (16) obtained a 17.6% increase in conductivity with a Mercadier cell placed five centimeters from his Crookes tube. With diffuse light the same cell showed a change of 21.2%. He found that its initial conductivity \((2.5 \times 10^{-5})\) was regained slower than after illumination with light.

Himstead (17) found that Bequerel rays from a Giesel radium preparation increased the conductivity of his cell about 1%. Röntgen rays from a focus tube produced fifty times this effect. The initial conductivities are not given.

Bloch (17) has determined the effect of a sample of Ba CO₃ of radioactivity one thousand upon the conductivity of a Semens cell. The increase amounted to 3.9%. Two hours were required for recovery to the initial conductivity \((3.32 \times 10^{-5})\). Light from an incandescent bulb increased the conductivity of this cell 101%. The author offers these results as indications that Bequerel rays are a mixture of cathode and Röntgen rays.

Brown (19), using a radium sample of from two to three million activity found an increase of conductivity for both Ruhmer and Giltay cells varying from 30% to 0%. The rate of recovery to an initial conductivity of \(1.6 \times 10^{-5}\) was one-fifth that from light exposures of short duration. The effect was thought to be due to the \(\alpha\) rays chiefly.

(17) Ann. d. Phys. 4, p.531  
(18) Compt. Rend. 132, p.914  
Athanasiadias (20) finds that the effect of Röntgen rays on a cell follows the same law which he discovered to hold for light in regard to variation with the distance, viz.: \( i = k(k - a)b \), where \( i \) is intensity, \( k \) conductivity, and \( a \) and \( b \) constants.

McDowell (21) has studied the action of Röntgen rays upon Bidwell cells of \( 2 \times 10^{-5} \) to \( 2.5 \times 10^{-6} \) conductivity. The form of the recovery curve from this effect is identical with that from illumination. The difference occurs in the rate of recovery, cells requiring a much longer time to regain their initial conductivity when the change is produced by Röntgen rays. Actual values are not compared.

Guilleminot has studied the effect of Röntgen rays upon the conductivity of an Ancel cell. With a four minute exposure to rays from a Villard tube an increase of 25% in conductivity was obtained. The initial value varied from 7 to \( 4 \times 10^{-7} \). Several minutes were required for the conductivity to reach a final value. Mention is made in his paper of experiments with radium rays but no measurements are given.

In a later article (23) by the same author the use of selenium cells in the radiometry of Röntgen rays is discussed. Data given show that such measurements, though of a delicate nature, are capable of a remarkable precision. The chief difficulty is found in the variable nature of the initial conductivity. An unknown portion of the change produced during an exposure to the rays is due to other factors.

Voltz (24) is of the opinion that selenium cells are unsuit-

(21) Phys. Rev. 30, p. 474
(22) Compt. Rend. 156, p. 1155
(23) Archives d'El. Medicale 23, p. 168
(24) Phys. Zeits. 16, p. 209
able for ready measurement of X-ray intensities, chiefly because of variations with the time of exposure and hardness of the rays. He shows that the means secured by such methods are valueless compared with ionization measurements.

Fursteneou (25) contradicts Voltz's conclusion (24), explaining his difficulties by the peculiarities of the type of cell used.Voltz experimented with a cell which attains its maximum comparatively slowly. Although he gives no results Fursteneou says that it is possible to produce cells suitable for X-ray radiometry.

Scope of Thesis

My original intention in undertaking this work was to determine by means of an X-ray spectrometer the effect of the individual lines of the L radiation of tungsten upon the electrical conductivity of selenium crystals of the hexagonal variety (6). However, preliminary experiments indicated that change in conductivity due to these wave-lengths at such intensities afforded by the spectrometer is very small. In fact it seemed that if measurable with my apparatus it must be comparable to the deviations from the balance of the Wheatstone's bridge by which the resistances of the crystals were obtained, for with a sensitive galvanometer it is impossible to secure an absolute balance. This led to a search for some means of increasing the sensitivity of the crystals to X-rays. As has been mentioned, in the study of the light effect it has been found that the sensitivity increases with the pressure (7)(20). Following analogous reasoning an investigation was

carried on to determine whether a similar law holds when the change in conductivity is produced by Röntgen rays. Following the suggestion indicated by the results new measurements were made upon five of the strongest lines in the L radiation of tungsten(26). Excitation and recovery curves for the total radiation were necessary in order to determine the degree of sensitivity of the crystals used.

From these experiments it was only a short step to make similar observations using the gamma rays of radium in place of Röntgen rays. After finding the effect and developing a new method suitable for its study excitation, recovery, and pressure-sensitivity curves were obtained.

Throughout this work the attempt has been made to keep pressure and other factors as nearly the same as possible in the study of different crystals so that finally a preliminary comparison of the effects per unit of energy might be made.

Experimental

These experiments upon the electrical conductivity of selenium crystals may be discussed as follows:

I. The Action of Röntgen Rays.

A. Excitation and Recovery.

B. Change of Sensitivity with Pressure.

C. The Effect of Separate Wave-Lengths of the

L Radiation of Tungsten.

II. The Action of the Gamma Rays of Radium.

II. The Action of the Gamma Rays of Radium (continued)

A. Excitation and Recovery.

B. Change of Sensitivity with Pressure.

III. Energy Comparisons.

Each series of experiments will be discussed under three headings, viz.: 1. Apparatus, 2. Method, 3. Results.

I. The Action of Röntgen Rays.

A. Excitation and Recovery. 1. Apparatus. Throughout the experiments carried on with Röntgen rays the source used was a Coolidge tube (27) with a tungsten anticathode, excited as is shown diagrammatically by Plate I. Commercial alternating current of 110 volts was stepped up with a transformer (28), T, to 49.5 or 57.7 kilovolts* as desired. The heating of the filament of the tube was accomplished by means of a 10 volt battery of storage cells controlled with the rheostat, Rh. The selenium crystals** to be studied were placed between the polished platinum electrodes of a mount (Plate XL, Fig. 2) enclosed in a metal covered box (Plate II, Fig. 1, and Plate XIII, M). Wires from the electrodes were conducted thru lead tubing to a Wheatstone's bridge arranged as is illustrated by Plate II., Fig. 2. It was found necessary to use the metal covered box and lead tubing in order to shield the crystal and bridge from the high potentials actuating the Coolidge tube. In addition the parts of the bridge shown in Plate II, Fig. 2 were removed to an adjoining room. This was found sufficient to eliminate entirely the effects of the high potentials upon the resistance.


(28) Thordarson Electric Co. Chicago, Ill., Type T

*Calculated maxima-spark gap method gives 47.9 and 54.6 kv.

**See Appendix for method of production and description

***About 33 CMS. FROM THE ANTICATHODE
measuring device. The galvanometer used was one of the high resistance type designed by Leeds and Northrup. It had a period of from 10 to 15 seconds, a resistance of 482 ohms (Thompson's method), and a critical damping resistance of about 20,000 ohms. With the scale 146 cms. distant from its mirror it showed a sensitivity of \(0.713 \times 10^{-10}\) amperes per millimeter. Throughout the measurements a two volt storage battery was used with the bridge.

2. Method. The purpose of these measurements was to determine the magnitude and rate of the composite effect of the radiations** from the Coolidge tube, operating at 150 watts*, upon the electrical conductivity of crystals. Inasmuch as the action of the rays was found to produce a much slower motion (.1 to .2 the rate) of the galvanometer spot upon the scale than when the galvanometer coil was made to vibrate freely in the bridge, a method of changing the variable resistance, \(V\), (Plate II. Fig. 2) by regular steps and observing the time at which the spot crossed the 0 position on the scale was adopted (time measurements were made with an 18 jewelled Elgin watch). From these data the conductivity of the crystal under observation can be calculated after the intervals observed following the throwing on and off of the Coolidge tube. By the adjustment of the heating current (Plate I, Rh.) the attempt was made to keep the total watts consumed in the circuit constant over the time of observation (240 watts). Owing to variation of the source supplying the transformer the error here sometimes amounted to as much as \(\pm 15\) watts though usually it was not so great. Pressure

*Wattages given in this thesis represent actual input of energy to the tube secured by subtracting the iron and copper losses of the transformer and circuit from the total watts (Plate I, W and A).

**The heat rays given off by the anticathode are thought to have produced little effect (9). Temperature variations in the basement room where the experiments were carried on were very small (9).
Plate III

Pressure 320 gms.
Initial conductivity \(4.6 \times 10^{-7}\)

\[\Delta c \times 10^{-7}\]

Time in minutes

Plate IV

Pressure 320 gms.
Initial conductivity \(4.6 \times 10^{-7}\)
was applied to the crystals by means of the arrangement shown in Plate II, Fig. 1. Time was allowed for an approximate equilibrium of balance to be attained. Variations from this initial balance, so important in experiments to be described later*, were neglected here owing to the smallness of their magnitude in comparison with that of the effect.

3. Results. The results of four such observations upon three crystals are here given. Plates III, IV, V, and VI show curves obtained by plotting change in conductivity** against time. Both excitation and recovery seem to take place after some exponential law, very probably the composite effect of all the different frequencies of radiation generated by the tube. It is to be noted that recovery curves are smoother than excitation curves. This is likely due to the elimination of the variation in the source supplying the transformer.

Plates III and IV are especially interesting, inasmuch as they indicate that an exposure of the crystal to gamma rays fatigues it in its response to Röntgen rays. The curves of Plate III show the excitation and recovery of $T_6^{**}$ at a pressure of 320 gms. (tube wattage 150). Those of Plate IV give like data for the same crystal under the same conditions six hours following a twenty minute exposure to gamma rays****. A comparison of the changes in conductivity in the two cases reveals a 41% decrease in the latter instance after an hour's exposure. The recovery is evidently not affected. Three days later this crystal seemed to have regained its original properties. With initial conduc-

*1. C. 2.
**All values are given in amperes per volt. (Mhos)
***See Appendix for description
****II. A. 1 and 2.
$B_3$
PRESSURE 2.77 GMS.
INITIAL CONDUCTIVITY $8.41 \times 10^{-7}$

$B_4$
PRESSURE 2.77 GMS.
INITIAL CONDUCTIVITY $4.45 \times 10^{-7}$
tivity $6.27 \times 10^{-7} \Delta C$ became $2.24 \times 10^{-7}$ under the same conditions.

B. Change of Sensitivity with Pressure. 1. Apparatus. In these experiments an ordinary timing pendulum, calibrated to give exposures of one second, was inserted at $S$, (Plate I) in the primary circuit of the transformer. Other arrangements were as described previously(I. A. l.).

2. Method. Preliminary measurements indicated that the effect of rays from the tube, acting one second at 49.5 kv. and safe wattage, was not large enough so that the initial variation in the balance of the bridge could be neglected. It seems impossible to eliminate this error at present. To increase the time of exposure means a multiplication of fatigue effects. Some indications of the magnitude of the error are given by the average deviation from the mean of ten readings taken at two second intervals immediately preceding the observation which required from two to seven seconds. The attempt was again made to keep the watts consumed by the tube constant, here by observing the throw of an ammeter (Plate I A) immediately following the observation, and regulating the heating current of the tube filament as before. Later the ammeter was calibrated as to the true values of its throws in amperes so that the watts consumed by the tube could be obtained for each observation. The results given are for increase of pressure. There seems to be some difference between increase and decrease but the writer has not investigated this carefully enough to report findings at this time. The change in conductivity at each pressure is proportional to the galvanometer deflection(29)(30).

(29) Brown, Technograph 21, p.90
(30) Brown and Clark, Phys. Rev. 33, p.53

* By practice with stop watch.
3. Results. The following table gives the readings obtained for three crystals.

**Crystal T6 (Plate VII)**

<table>
<thead>
<tr>
<th>Pressure*</th>
<th>Conductivity</th>
<th>Bal. Deviation**</th>
<th>G Deflection</th>
<th>Tube Wattage</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 gms.</td>
<td>2.122 x 10^-7</td>
<td>3.4 mms.</td>
<td>30,35 mms.</td>
<td>202</td>
</tr>
<tr>
<td>89.5</td>
<td>3.020</td>
<td>3.7</td>
<td>40,49</td>
<td>202</td>
</tr>
<tr>
<td>159.5</td>
<td>3.830</td>
<td>3.3</td>
<td>106,95</td>
<td>207</td>
</tr>
<tr>
<td>234.5</td>
<td>4.525</td>
<td>0.8</td>
<td>108,98</td>
<td>198</td>
</tr>
<tr>
<td>314.5</td>
<td>5.125</td>
<td>7.7</td>
<td>129,137</td>
<td>198</td>
</tr>
<tr>
<td>403.5</td>
<td>5.775</td>
<td>3.2</td>
<td>140,148</td>
<td>186</td>
</tr>
<tr>
<td>503.7</td>
<td>7.170</td>
<td>3.0</td>
<td>154,183</td>
<td>197</td>
</tr>
</tbody>
</table>

**Crystal B3 (Plate VIII)**

<table>
<thead>
<tr>
<th>Pressure*</th>
<th>Conductivity</th>
<th>Bal. Deviation**</th>
<th>G Deflection</th>
<th>Tube Wattage</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>1.025</td>
<td>2.8</td>
<td>13,11</td>
<td>201</td>
</tr>
<tr>
<td>89.5</td>
<td>2.178</td>
<td>2.0</td>
<td>21,25</td>
<td>207</td>
</tr>
<tr>
<td>159.5</td>
<td>3.600</td>
<td>4.5</td>
<td>33,44</td>
<td>195</td>
</tr>
<tr>
<td>234.5</td>
<td>5.675</td>
<td>6.5</td>
<td>52,40</td>
<td>191</td>
</tr>
<tr>
<td>314.5</td>
<td>8.120</td>
<td>8.5</td>
<td>56,50</td>
<td>197</td>
</tr>
<tr>
<td>403.5</td>
<td>10.650</td>
<td>4.0</td>
<td>61,60</td>
<td>199</td>
</tr>
<tr>
<td>503.7</td>
<td>12.770</td>
<td>3.6</td>
<td>65,60,70</td>
<td>197</td>
</tr>
</tbody>
</table>

**Crystal B4 (Plate IX)**

<table>
<thead>
<tr>
<th>Pressure*</th>
<th>Conductivity</th>
<th>Bal. Deviation**</th>
<th>G Deflection</th>
<th>Tube Wattage</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>1.150</td>
<td>5.4</td>
<td>7</td>
<td>197</td>
</tr>
<tr>
<td>89.5</td>
<td>2.425</td>
<td>1.7</td>
<td>16</td>
<td>188</td>
</tr>
<tr>
<td>159.5</td>
<td>3.100</td>
<td>3.1</td>
<td>20,24</td>
<td>188</td>
</tr>
<tr>
<td>234.5</td>
<td>3.810</td>
<td>3.7</td>
<td>39,36</td>
<td>198</td>
</tr>
<tr>
<td>314.5</td>
<td>4.590</td>
<td>3.7</td>
<td>45,39</td>
<td>189</td>
</tr>
<tr>
<td>403.5</td>
<td>5.650</td>
<td>2.8</td>
<td>53,63</td>
<td>199</td>
</tr>
<tr>
<td>503.5</td>
<td>7.050</td>
<td>3.2</td>
<td>60,59</td>
<td>199</td>
</tr>
</tbody>
</table>

Plates VII, VIII, and IX give a graphical representation of the data. From the variations in the wattage and of the balance of the bridge given in the table the distribution of the points is readily accounted for. Owing to the uncertainty of the magnitudes of these variations it would be of little value to use the principle of least squares on the observations. The increase of sensitivity with pressure is, however, unmistakable. In order to arrive at qualitative conclusions concerning the relation between conductivity and

*Plus atmospheric pressure
**Average deviation from the mean of ten readings
M - Metal covered box (L.A+B)
L - Lead box
L.T. - Lead tubing
N - End of Spectrograph
I - Mount carriage
B - Brass arm
R - Brass rest
D - Plate holder
F - Filament
K - Anticathode

Be - Bearing
A - Brass surface
S - MM. slit
W - Pulley
Sp - Spindle
Sc - Scale
P - Pointer

Plate XIII
sensitivity smooth curves were drawn thru each distribution of points by eye. Plates X, XI, and XII show the values of AC obtained from these curves plotted against the initial conductivities at the pressures used. A large portion of each of these approximates a straight line. There are here, consequently, indications that the change of sensitivity to X-rays with pressure follows the same law found for light(7)(20).

C. The Effect of the Separate Wave-Lengths of the L Radiation of Tungsten. 1. Apparatus. For these measurements the Coolidge tube was used as before (Plate I) in conjunction with an X-ray spectrometer designed and constructed by Dr. E. Dershem, and very kindly loaned by him for this research. Modifications of the instrument were made in order to meet the requirements of the experiments. Plate XIII shows a photograph of the arrangement in final form. In operation the lead box, L, was provided with a lid and cover for the side opening of like material. Plate XIV gives a top-view diagram of the apparatus drawn approximately to one-third scale. A heavy black paper hood was provided for the opening, 0, so that no light could enter the box. The 1,0,0 cleavage face of a crystal of rock salt of dimensions 10 x 8 x 1mm. was used with the spectrometer.

2. Method. One of the chief difficulties encountered in performing these experiments was in setting the three selenium crystals* used together so that the line desired would be incident upon them. The method finally employed was as follows. By means of the brass surface, *T₃, T₄ and T₅—for description see appendix
A* milled to the surface of the carriage, Ca, and passing thru its center, the rock salt cleavage face was mounted firmly in position with a piece of beeswax. The screws holding A to Ca were then taken out and A removed. With the heating current flowing thru the filament to illuminate the surface of the anticathode, K, the lead box was then moved into a position such that the path of the rays would make an angle of about 10 degrees** with the plane of the anticathode which was approximately⊥ to the table. This was done by sighting thru a hole in the back of the box along the cleavage face of the rock salt crystal and thru the millimeter*** slit, S, at the roughened focal spot of the electrons upon the anticathode. During the experiments this hole was occupied by the lead tubing containing the wires from the crystal mount leading to the Wheatstone's bridge(Plate II, Fig. 2). A photographic plate**** was clamped to the support, D, the box closed, and a spectrograph taken on both sides of the plate with the tube operating at 49.5kv. and 150 watts. Rotation of the rock salt crystal at about 4 degrees per hour was accomplished by means of a lever-float arrangement(31). The bearing, Be, is designed to keep the surface of the carriage, Ca, horizontal during rotation. After developing the plate fine lines were drawn with a steel point and rule graduated to .2 of a millimeter thru the centers of five strong lines(26). In like manner the central position was determined by means of symmetrical lines on the two sides of the plate. Next the spectrograph was placed in its original position by means of the brass markers, M₁, M₂. A 25 ampere lamp made

*The references are to Plates XIII and XV
**This gives a slightly greater intensity
***To increase the intensity
****Cramer's X-ray variety
with a tungsten filament about 2 mms. wide and 30 mms. long was then moved around on the opposite side of the Coolidge tube until the image of the slit, S, fell upon the central line, C. With the aid of the brass surface and pliable beeswax the cleavage face of the rock salt crystal was then replaced by a silver surface precipitated upon a piece of microscope slide of similar dimensions. By this means an image of the slit could be cast upon any desired line of the plate, N. When this was accomplished for a given line the mount, H, was lowered into a position such that X was at the same height as the mid-point of the face of the rock salt crystal, and the arm, B, rotated until the image also fell upon the electrodes in the position to be occupied by the selenium crystals. After making a check setting a fine line was drawn with a steel point upon the brass rest, R, along the left side of the arm, B, to mark the location of the line with reference to the mount. The figures 1, 2, 3, 4, and 5 indicate the positions of the arm to receive $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, and $\lambda_5$ respectively, found in this manner. The bearing, Be, of the arm, B, was made to fit the carriage spindle, Sp, very snugly, being carefully drilled thru 1.5 cms. of brass. The mount carriage, I, was milled to slide upon the arm and provided with a set screw, S3. In its final position X was 10 cms. from the center of the cleavage face of the rock salt crystal and the latter about 24 cms. from the anticathode. Next the location of the pointer, P, on the scale, Sc, was recorded for each line when the slit image was thrown first to the right and then to the left of the mount in proper position. By means of these figures it was possible to rotate the rock salt crystal thru

* See Appendix B

** When all measurements were finished these readings checked.
the required locations with the box, L, closed. When this calibration was finished the silvered surface was removed and the rock salt crystal placed in position as described previously. Three selenium crystals were placed side by side in the mount so that about 1.5 mms. of width was presented to the path of the rays. Following the suggestion of the results of previous experiments* a comparatively large pressure of 524 gms. was applied. After adjusting arm,**B, to receive a characteristic wave-length, making the proper connections with the Wheatstone's bridge, and closing the box, arrangements for the first measurements were completed. Rotation was accomplished by means of the lever-float contrivance referred to(31), attached with a fine copper wire, to the pulley, W. The practice was followed of starting the flow of water raising the float shortly before the desired position of the rock salt crystal as indicated by the pointer, P, and turning on the tube when this was attained. By changing the rate of flow of the water the rate of rotation could of course be altered. The procedure was similar in the measurement of different wave-lengths except for an increase of the potential applied to the tube which was calculated to give a greater intensity(32), especially necessary for the shorter wave-lengths.

In general the method of observing change in conductivity was as follows. As has been mentioned previously(I. A. 2) the balance of the bridge by means of which the resistances of the crystals were measured was seldom if ever absolute. However, it was found by experience that the shift took on varying degrees of steadiness after a pres-

*1. B. 3
**The weight proved sufficient to keep it in place.
(32) Webster, Phys. Rev. 7, p.599
sure had been applied from fifteen minutes to two hours time. This behavior did not always follow but could be depended upon in about two-thirds of the cases. It is noteworthy that the shifts were predominantly in the direction of increasing conductivity. Readings of the galvanometer after intervals of ten seconds were found to represent this shift approximately. The services of a student* were secured in taking these readings while the routine of setting the mount and rotating the rock salt crystal was being carried out. For each line from twenty to sixty readings were taken with the selenium crystals at rest in the lead box. When these were nearly secured the assistant called and rotation was begun. As soon as the proper position was attained the tube was excited and at the same time a signal given the man at the galvanometer to note the place in his readings. When rotation thru the required angle was accomplished for the line the supply to the transformer was cut off and a second signal given the assistant so that he might indicate the time in his data. Following this from twenty to sixty observations were again taken to ascertain whether the shift had changed.

3. Results. The conclusions to be drawn from data secured in this manner for five lines will next be discussed. Galvanometer deflections have been plotted against time for each series of observations. A red circle containing a black dot indicates the point where the tube was turned on. One containing a black cross shows the time after which the rays ceased. The divisions of the graphs thus made may be desig-*I am indebted to Mr. W. P. Angel for competent assistance.
nated A, B, and C, respectively, proceeding from left to right. Data
to accompany the plates are given in the table following:

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Initial Cond.</th>
<th>Wave-Length (^{*})</th>
<th>Voltage</th>
<th>Watts</th>
<th>Rate of Rotation (^{**})</th>
</tr>
</thead>
<tbody>
<tr>
<td>XV</td>
<td>5.45 x 10(^{-7})</td>
<td>1.4722 x 10(^{-8})</td>
<td>49.5 kv.</td>
<td>159</td>
<td>.4° per minute</td>
</tr>
<tr>
<td>XVI</td>
<td>5.47</td>
<td>&quot;</td>
<td>185</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>XVII</td>
<td>5.60</td>
<td>&quot;</td>
<td>189</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>XVIII</td>
<td>5.58</td>
<td>&quot;</td>
<td>185</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>XIX</td>
<td>5.61</td>
<td>&quot;</td>
<td>175</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>XX</td>
<td>5.54</td>
<td>1.2784</td>
<td>57.7</td>
<td>196</td>
<td>.4</td>
</tr>
<tr>
<td>XXI</td>
<td>5.60</td>
<td>&quot;</td>
<td>49.5</td>
<td>168</td>
<td>.3</td>
</tr>
<tr>
<td>XXII</td>
<td>4.83</td>
<td>&quot;</td>
<td>185</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>XXIII</td>
<td>4.80</td>
<td>&quot;</td>
<td>57.7</td>
<td>225</td>
<td>.4</td>
</tr>
<tr>
<td>XXIV</td>
<td>4.83</td>
<td>1.2416</td>
<td>&quot;</td>
<td>178</td>
<td>.5</td>
</tr>
<tr>
<td>XXV</td>
<td>4.83</td>
<td>&quot;</td>
<td>178</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>XXVI</td>
<td>4.95</td>
<td>&quot;</td>
<td>209</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>XXVII</td>
<td>4.95</td>
<td>&quot;</td>
<td>209</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>XXVIII</td>
<td>5.10</td>
<td>&quot;</td>
<td>183</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>XXIX</td>
<td>4.83</td>
<td>1.0963</td>
<td>&quot;</td>
<td>242</td>
<td>.3</td>
</tr>
<tr>
<td>XXX</td>
<td>4.77</td>
<td>&quot;</td>
<td>235</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>XXXI</td>
<td>4.27</td>
<td>&quot;</td>
<td>178</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>XXXII</td>
<td>4.41</td>
<td>&quot;</td>
<td>209</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>XXXIII</td>
<td>4.45</td>
<td>&quot;</td>
<td>225</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>XXXIV</td>
<td>4.27</td>
<td>1.0705</td>
<td>&quot;</td>
<td>242</td>
<td>.6</td>
</tr>
<tr>
<td>XXXV</td>
<td>4.30</td>
<td>1.0648</td>
<td>&quot;</td>
<td>238</td>
<td>.6</td>
</tr>
<tr>
<td>XXXVI</td>
<td>4.33</td>
<td>1.0587</td>
<td>&quot;</td>
<td>231</td>
<td>.4</td>
</tr>
<tr>
<td>XXXVII</td>
<td>4.35</td>
<td>&quot;</td>
<td>222</td>
<td>.3</td>
<td></td>
</tr>
<tr>
<td>XXXVIII</td>
<td>4.38</td>
<td>&quot;</td>
<td>215</td>
<td>.3</td>
<td></td>
</tr>
</tbody>
</table>

The results for each wave-length will be discussed with the aid of the graphs.

\[
\lambda
\]

Plate XV. Section B indicates no change of conductivity larger than the normal variations given by sections A and C.

Plate XVI. The deflection of 12 mms. at 460 seconds assumes no significance compared with one in section C at 600 seconds of greater magnitude.

Plate XVII. During a very steady behavior of the shift no

\(^{*}\)Data kindly furnished by Dr. Dershem(26).

\(^{**}\)Approximate only
change of conductivity of the crystals is shown by section B.

Plate XVIII. The rise at 370 seconds and behavior after the
rays ceased might be explained by excitation and recovery inasmuch as
the shift assumes a comparatively steady value after 570 seconds.

Plate XIX. There is no large variation in the shift except
at the point where the tube was turned off. This may indicate recovery.

$\lambda_2$

Plate XX. The sharp rise beginning at 260 seconds and the
falling off at 360 seconds is what might be expected if the rays were
producing an effect. However, the steadiness of the shift thru sections
A and C makes this conclusion questionable. Note that both wattage and
voltage were increased for this observation.

Plate XXI. Slower rotation at the lower voltage seems to re­
veal little except for a slight falling off at the end of section B
which is of doubtful importance.

Plate XXII. During slow rotation at the higher voltage the
shift evidently began to increase at about 600 seconds. This does not
seem especially significant in view of the fact that section C shows
little decrease in rate.

Plate XXIII. The lack of steadiness of shift shown by all
three portions of this graph warrants no conclusions.

$\lambda_3$

Plate XXIV. Thru section B the change in conductivity obvi­
ously goes on at an increased rate though again variations in the shift
evidenced by sections A and C prevent conclusions from being drawn with
PLATE XXX

PLATE XXXI

TIME IN SECONDS
certainty.

Plate XXV. Variations in the shift do not change appreciably.

Plate XXVI. With the wattage increased the conclusion formed from the data of Plate XXV is strengthened.

Plate XXVII. Slower rotation shows little variation from the normal shift except for a falling off at the end of section B.

Plate XXVIII. With such a rapid rate of shift as given by sections A and C the rise at 400 seconds does not assume much significance though behavior when the tube ceased operation might indicate recovery.

\[ \lambda_4 \]

Plate XXIX. The shift thru section A is too unsteady to warrant deductions being made from the rise at 260 seconds.

Plate XXX. The shift does not change appreciably.

Plate XXXI. The rate of shift thru section B is slightly increased compared with that of A and C.

Plate XXXII. There are no indications of a significant change.

Plate XXXIII. With a steady rate of shift nothing of note is observed.

\[ \lambda_5 \]

Plate XXXIV. The difference between sections A and C would indicate a decrease in conductivity on the assumption that the rays actually were effective thru section B.

Plate XXXV. The change of rate of shift beginning with sec-

*My spectrograph showed a single line in this position. Dr. Dershem has demonstrated that it is in reality three(26). See appendix p. 38
tion B compared with the rates of sections A and C give possible indica-
cations of an effect opposite that suggested by Plate XXXIV.

Plate XXXVI. Section B shows no variations not explainable
by the nature of the shift revealed by sections A and C.

Plate XXXVII. The increase in the rate of shift thru section
B when compared with the undiminished increase thru section C is not sig-
nificant.

Plate XXXVIII. No marked change of conductivity is evidenced
other than a slight decrease beginning with section C which might be in-
terpreted as recovery.

The results discussed do not warrant any certain conclusions
with regard to the effect of the five different wave lengths studied.
The best evidence of a change is that secured for $\lambda_1$(Plate XVIII). Plate
XX for $\lambda_2$ is suggestive but not conclusive. The measurements for $\lambda_3$ and
$\lambda_4$ show less effects than these if anything. Results for $\lambda_5$ are contra-
dictory if it be assumed that the rays are producing the changes evinced
by Plates XXXIV and XXXV. Variations between observations upon the same
line, however, make all such conclusions of doubtful value. One legiti-
mate deduction may be made. The intensities afforded by the spectromete-
ter of the five characteristic lines of tungsten studied do not produce
a change of conductivity readily appreciable in comparison with the ordi-
nary fluctuations of the crystals. Some idea of the sensitivity of the
combination of T$_3$, T$_4$, and T$_5$ may be had from their excitation and recov-
ery curves plotted on Plate XXXIX from data taken at 57.7 kv. and 124*
watts. Absorption differences between the wave-lengths undoubtedly ex-

*Lower than any wattage used in the measurements.
\( \Delta C \times 10^{-7} \)

\( T_1, T_4, T_5 \)

Pressure: 524 GMS.

Initial Conductivity: \( 4.55 \times 10^{-7} \)

Plate XXXIX

Time in Minutes
ist but such data much suffice at present for purposes of rough comparison. It would therefore seem that reflection from the spectrometer crystal cuts down the intensity of the rays at least a thousand times.

II. The Action of the Gamma Rays of Radium.

A. Excitation and Recovery. 1. Apparatus. The arrangement for these experiments was similar to that described for measurements of the Rontgen ray effect(I. A. 1). X (Fig. 1, Plate XL) represents the position of the selenium crystal between the platinum electrodes of the mount, M. B.G. is a brass guide for the rod transmitting pressure applied by means of weights, W, to the midpoint of the lever arm, L. L.T. is a lead tube of 1.57 mms. thickness* for lowering the radium vial** into a position 5 mms. from the location of the selenium crystal. W indicates the wires from the electrodes leading to the Wheatstone's bridge.

2. Method. The plan followed in these experiments is almost identical with that given for the study of the separate wave-lengths of the Rontgen rays(I. C. 2). Here the change in conductivity is easily appreciable, especially for the higher pressures, but still not large enough so that variations from the initial balance may be neglected. From 30 to 70 readings of the galvanometer were taken at ten second intervals preceding the introduction of the radium vial. An assistant*** kept up the observations while this was being done, and continued taking them until the galvanometer spot seemed to be moving no faster than before the radium was lowered into position. Without stopping the readings the vial was then removed and recovery data secured. This procedure has

*To eliminate alpha and primary beta rays. The intensity of the emergent secondary beta rays is thought to be very small.
**Contained a standard milligram of pure radium bromide.
***Mr. W. P. Angel kindly helped with these observations.
NOTE: THE FIGURES REFER TO MILLIMETERS.
been followed for five pressures beginning with the largest, 420 gms.*

Varying amounts of time were allowed between observations for pressure adjustments and recovery. As before the change in conductivity is proportional** to the deflection (29)(30).

3. Results. Curve 1, Plate XLI, represents the excitation of crystal T** under the influence of the gamma rays for twenty minutes, and Curve 2 shows the recovery (pressure 420 gms.). Plate XLII indicates the variations of the bridge balance immediately preceding this interval. About two hours were allowed for pressure adjustment before taking the data at 320 gms. represented by Plate XLIII. Plate XLIV shows the preliminary variations of the balance as before. Two days intervened before the data at 216 gms. were secured (Plate XLV). Plate XLVI represents the balance variations. Four days elapsed before observations at 104 gms. were made. These are given graphically by Plates XLVII and XLVIII. The data at 24 gms. given by Plates XLIX and L were taken two hours later. Here as was found in the case of Röntgen rays excitation and recovery appear to follow exponential laws of some sort. Recovery is much slower than that from illumination (32). Comparison with recovery from the effect of Röntgen rays is difficult, using the present data, owing to differences in the magnitude of the initial change. However, it seems that the rates are not greatly different (I. A. 3).

Since making this study the writer doubts whether sufficient time for complete recovery was allowed between the observations taken at 420 and 320 gms. In view of this it is indeed singular that the sensi-

*Pressure on the crystal secured by applying double the amount upon the pan shown in Fig. 1, Plate XL. Atmospheric pressure is to be added.

**See appendix for description.


*** For small changes
PLATE XLII

PLATE XLIII

TIME IN SECONDS
tivity should be higher at the lower pressure. A second crystal subjected to the same treatment did not show this peculiarity but confirmed the obvious deduction to be made from these curves, namely that the sensitivity is greater for the higher pressures.

B. Change of Sensitivity with Pressure. 1. Apparatus was the same as that described for II. A.

2. Method. Consideration of the excitation curves given by Plates XLII, XLIII, XLV, XLVII, and XLIX, shows that for the first few minutes the change of conductivity is approximately a linear function of the time. Attempts were therefore made to get more precise data on the nature of the variation of sensitivity with pressure by giving a shorter time of exposure, thus eliminating the necessity of a long wait for recovery with all of the consequent changes in conductivity due to other causes. The time finally adopted for exposure was one minute.

3. Results. The red curves of Plates LI-LVI indicate the rate of excitation of $B_3^*$ at the respective pressures. The black lines show the shift of the bridge balance immediately preceding each measurement. About thirty minutes were allowed between observations. By subtraction of ordinates the points for the curve of Plate LVII were obtained. Likewise Plate LXIV was secured for B from Plates LVIII-LXIII. The increase of sensitivity with pressure is again unmistakable although the uncertainty of the ordinary balance variations during exposure places a qualitative value upon the results. Data from which the graphs of Plates LVII and LXIV were constructed are given in the table.

$B_3^*$, see appendix for description.
III. Energy Comparison.

Data which have been given (Plates III and XLI) are sufficient for making a preliminary* comparison of the energies of the Röntgen and gamma rays absorbed by an isolated crystal**, and the changes in conductivity produced. In making these calculations the absorption law,

\[ I = I_0 e^{-\mu d} \]

was assumed both for Röntgen (33) and for gamma (34) radiations. The absorption coefficient, \( \mu_1 (1.64) \), of selenium for soft X-rays was obtained by the interpolation of its atomic weight, 79.2, in Benoist's relation (35). \( \mu_2 (0.184) \), the coefficient of absorption for gamma rays was secured by the interpolation of the density, 4.55 (31), in Rutherford's results connecting density with the absorption of these rays (36). Absorption by paper (Plate II Fig. 1, P), and by the air were neglected, but the decrease*** in the intensity of the gamma rays in passing thru the lead tubing (Plate XL, Fig. 1) has been eliminated. The energy of the Röntgen rays was calculated from the watts input to the Coolidge tube and the value

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*These figures take no account of possible variation with intensity.

**T6, see appendix for description.

***7.5% 

(33) Kaye, "X-Rays", p.100-(35) p.102
for the efficiency of production at 48.0 kv. found by Rutherford(37).
The energy of the gamma rays was secured from their heating effects(38).
The amount of energy incident upon the crystal was in each case calculated by assuming the area presented a portion of the surface of a sphere of radius equal to the distance of the crystal from the source. For convenience the results are given in tabulated form.

<table>
<thead>
<tr>
<th>G Deflection*</th>
<th>Incident Energy</th>
<th>Absorbed Energy E r g s / s e c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Röntgen Rays</td>
<td>277 mms.</td>
<td>2.6 x 10^-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.06 x 10^-2</td>
</tr>
<tr>
<td>Gamma Rays</td>
<td>179</td>
<td>6.5 x 10^-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.7 x 10^-4</td>
</tr>
</tbody>
</table>

According to these figures the absorption of gamma ray energy of less than a tenth the amount of X-ray energy produces almost two-thirds the change in conductivity. Granted the assumptions made in obtaining these results the conclusion to be drawn is that the crystal is more sensitive to gamma rays than to Röntgen rays. With a liberal allowance for errors introduced thru these assumptions the conclusion is that the effects of Röntgen and gamma radiations in producing change in the conductivity of the selenium crystal are of about the same order of magnitude. While this is not offered as direct proof it is submitted as another fact consistent with the view that Röntgen and gamma radiations are of a similar nature.

*Time of exposure was one minute. 
(37)Phil. Mag. 30, p.361 .59 x 10^-3
(38)One gram of radium in equilibrium with its products gives off gamma ray energy at the rate of 6.5 gm. cal. per hour which is equivalent to 7.6 x 10^7 ergs per second. See Rutherford,"Radioactivity", p.581.

**Together with Similarities Previously Pointed Out(I and E).
Summary

1. The total radiation of Röntgen rays from a Coolidge tube operating at 49.5 kv. and 150 watts, increased the conductivities of three selenium crystals at pressures of 320, 277, and 277 grams, 35%, 18%, and 34%, respectively. The time required for a maximum change to be reached was over two hours. Recovery followed at about the same rate. Both kinds of curves seem to be of an exponential variety, such as have been found for light (32).

2. Three crystals studied show an increase of sensitivity (absolute $\Delta C$) with pressure when the time of exposure was kept constant and the watts input to the Coolidge tube approximately constant. Treatment of these data gives strong indications of a straight line relation between sensitivity and initial conductivity similar to that found for light (7) (20).

3. A crystal exposed to gamma rays for twenty minutes showed fatigue six hours later when an attempt was made to measure the effect of Röntgen rays upon it.

4. Measurements upon five of the principle lines in the L radiation of tungsten indicate that intensities afforded by spectrometer methods have little if any effect upon crystals. The order of the ratio of the intensity of the total radiation to the intensity of any line studied is at least $10^3$.

5. As much as a 9% increase in the conductivity of an isolated crystal has been observed with a twenty minute exposure to the gamma rays of radium (one milligram). Again both excitation and recov-
ery take place after some exponential law at a rate not greatly different from that found for Röntgen rays.

6. The sensitivity to gamma rays of three crystals increased with pressure as indicated by the results of two different methods of procedure.

7. A comparison of the incident and absorbed energies shows that the two effects are of about the same order of magnitude, the sensibility to gamma rays being in all probability a little greater.

8. Similarities between the effects of Röntgen and gamma THRE radiances upon the electrical conductivities of selenium crystals of the hexagonal variety afford facts consistent with the view that Röntgen and gamma radiations are of a similar nature.

**

In conclusion I wish to express my appreciation to the staff of the Department of Physics of the State University of Iowa for their interest in these problems. Especially do I wish to thank Dr. F.C. Brown for his suggestions and encouragement throughout the progress of the work.
Appendix A

The crystals upon which these studies were made are from two lots produced in much the same way by the sublimation of vitreous selenium at 185°C in an evacuated glass vessel for several weeks. In both cases they were opened into air. Samples from lot I, prepared in the fall of 1916, were very kindly furnished by Dr. F. C. Brown. Specimens from this lot are designated B₁, B₂, etc. I am indebted to Dr. W. E. Tisdale for samples from the second lot. These have been given the symbols T₁, T₂, etc. They were made in the spring of 1916. All crystals have been kept in alcohol washed bottles since the beginning of the experiments. Approximate dimensions for the crystals studied in connection with this thesis are as follows:

B₃ 3.0 x 0.2 x 0.2 millimeters
B₄ 3.6 x 0.4 x 0.4 "
T₃ 2.6 x 0.5 x 0.2 "
T₄ 2.2 x 0.6 x 0.2 "
T₅ 1.8 x 0.5 x 0.2 "
T₆ 3.2 x 0.2 x 0.1 "

**
Appendix B

My thanks are due Dr. E. Dershon for his excellent reproduction from one of his spectrographs of the I Radiation of Tungsten.