THE ACTION OF ROENTGEN AND GAMMA RADIATIONS UPON THE ELECTRICAL CONDUCTIVITY OF SELENIUM CRYSTALS.

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SYNOPSIS OF RESULTS.

Action of Gamma and Roentgen Radiations Demonstrated.—The increase in conductivity of selenium "cells" accompanying the absorption of X-rays has been found characteristic of individual crystals of metallic selenium. A similar effect upon the crystals has been observed to be produced by the absorption of the gamma rays of radium. The fact that a crystal fatigued to gamma rays is fatigued also to X-rays is evidence that the action in the two cases is similar. The indications are that the crystals are approximately twice as sensitive to gamma rays as to X-rays of the type used (L rays of tungsten).

New Electro-mechanical Properties.—Increase of mechanical pressure upon a crystal results in an increase of its sensibility both to X-rays and gamma rays. This is exactly the same result, qualitatively, as that secured by Brown in his study of the light effect (PHYS. REV., 4, p. 85).

Action of Separate X-ray Frequencies.—Unsatisfactory results obtained in the study of the strong lines of the L radiation of tungsten are thought to be due to the low intensities afforded by the X-ray spectrometer. Another method of attack is being planned.

Comparison of the Light, X-ray, and Gamma Ray Effects upon an Isolated Crystal.—Calculations made upon the basis of the energy absorbed indicate that a selenium crystal is most sensitive to gamma rays. The ratios of the change in conductivity to absorbed energy for exposures of one minute are 33.2, 58.5, and 108.9 $\left(\frac{\text{Mhos}}{\text{Joules}}\right)$, respectively.

I. INTRODUCTION

IN view of the established relationships between light, Roentgen and gamma rays, knowledge of their effects upon the electrical properties of crystals of metallic selenium assumes new interest. It has been shown[1] that the change in conductivity exhibited by these crystals on exposure to light depends upon the time, intensity, and character of the illumination. It is also known[2] that the sensibility (absolute ΔC) varies directly with the mechanical pressure to which the crystal is subjected. Other important facts concerning the action of visible radiations are available, but it is with those mentioned that this paper is mainly concerned. The effect of Roentgen rays upon films of metallic selenium has been investigated,[3] with the discovery that the form of the ΔC-time

[1] Brown, PHYS. REV., 33, p. 1.
[2] Brown, PHYS. REV., N.S., 4, p. 85.
[3] McDowell, PHYS. REV., 30, p. 474.

curves for this type of radiation is the same as that of those found for visible radiation, although the rate of recovery is much slower in the former case. The action of radioactive materials upon selenium "cells" has been known for some time,[1] although the separate action of the gamma rays had, within the knowledge of the writer, received no attention up to the time of the investigations reported upon in the present paper. It is thought that the continuation of this work should assist in relating properly the phenomena of conduction in solids with those of absorption, radiation, and atomic structure.

The experimental studies upon the action of X-rays, described in this paper, were initiated to secure information regarding the relation between the sensibility of these crystals and the frequencies of the strong lines in the characteristic L radiation of tungsten. Their change in conductivity on illumination has received a variety of theoretical treatments, among which that based upon a resonance hypothesis[2] offers considerable promise. According to this theory the electrons of the selenium atom whose radiation frequency corresponds, or nearly corresponds, to the frequency of the exciting agent, are loosened from their atomic bonds temporarily, and, in addition to the normal number free at any instant within the crystal, as indicated by the conductivity in the dark, contribute to the total current resulting from the application of a potential. A region of maximum sensibility has been found[3] in the red, and indications of a maximum in the ultra-violet. It was thought that if a region of maximum sensibility could be found within the range of X-ray frequencies the resonance theory would be much strengthened, and important evidence concerning the structure of the selenium atom obtained. Other experiments, incidental to this purpose, which have brought out a significant relation between the X-ray, gamma ray, and light effects, as regards the dependence of sensibility (absolute ΔC), upon mechanical pressure, constitute an important part of this report.

The studies herein described were made upon a single crystal selected from a lot prepared by Dr. W. E. Tisdale in the spring of 1916. They were of the hexagonal[2] variety secured by distillation in vacuo at 185° C. Investigations were in air at barometric pressure. The dimensions of the crystal chosen were roughly 3.2 × .2 × .1 mm. It was mounted between carefully polished platinum electrodes, the mechanical pressure necessary being supplied by weights. In every case the direction of the rays was parallel to the long axis of the crystal.

[1] Brown, Phys. Rev., 26, p. 273.

[2] Pfund, Phys. Rev., 28, p. 324.

[3] Sieg and Brown, Phys. Rev., N.S., 4, p. 507.

II. THE ACTION OF X-RAYS.

Preliminary measurements upon the change of conductivity produced by single lines in the L radiation of tungsten indicated that the effect, if discernible with the apparatus used, is very small. A simple experiment was then planned and carried out to ascertain whether the addition of mechanical pressure would, as is the case when the exciting agent is visible light, produce an increase of sensibility.

The crystal was mounted in a metal box which was grounded. The leads were carried through lead tubing to a Wheatstone bridge of high resistance arms, situated in an adjoining room. All of this was found necessary to eliminate the electrostatic effects which otherwise resulted from the presence of the high potential transformer actuating the Coolidge tube furnishing the X-rays. In this experiment the total radiation from the tube, operating at 48.0 kv. and 3.5 amps. heating current, was used. It was found difficult to maintain the constancy of the input with better than 10–15 per cent. accuracy. Hence the distribution of points in Fig. 1. A heavy pendulum operating contact keys controlling

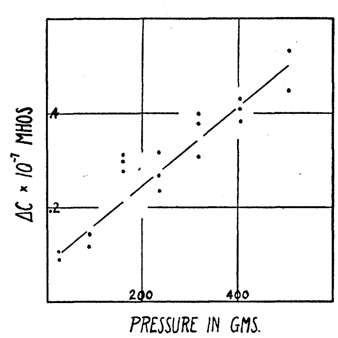

Fig. 1.

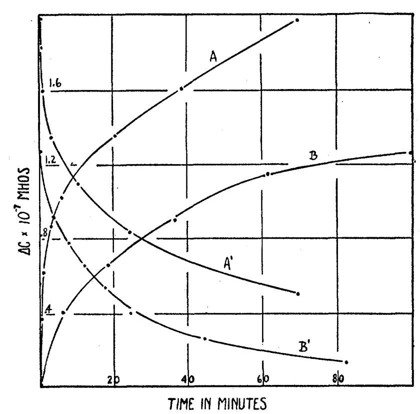

Fig. 2.

FIG. 1. The effect of change in mechanical pressure upon sensibility to X-rays.

FIG. 2. Excitation and recovery curves—X-rays. *A*, Excitation. Pressure 320 gms. Initial Conductivity 4.8×10^{-7} Mhos. *A'*, Recovery. *B*, Excitation. Pressure 320 gms. Initial Conductivity 4.6×10^{-7} Mhos. *B'*, Recovery.

the primary circuit of the transformer provided the means of keeping the time of exposure constant (one second), for different pressures. Time for recovery was allowed between observations. Brown and Clarke's method[1] was used in observing the change in conductivity. The results, plotted in Fig. 1, indicate an unmistakable increase of sensibility with pressure, similar to that found by Brown to exist when the exciting

[1] Brown and Clarke, PHYS. REV., 33, p. 53.

agent is light. Two other crystals studied in the same manner gave data which bear out this conclusion.

Following a procedure made obvious by these results, measurements were made anew upon five of the principal lines in the L radiation of tungsten (λ's-1.47, 1.27, 1.24, 1.09, 1.06 Å). Five hundred grams pressure was applied to the crystal—as much as was deemed advisable in view of the danger of fracturing. I am indebted to Dr. Elmer Dershem for the use of one of his X-ray spectrometers in these experiments as well as for initiation into the technique of its manipulation. Up to the present time, however, attempts to secure the effects of separate lines in this manner have been unsuccessful. Experiments are being considered which may solve the intensity difficulty, for this is thought to be the main reason for the failure.

It is very readily demonstrated that the total radiation from a Coolidge tube, operating upon a moderate energy input, produces a change in conductivity. Fig. 2 gives the results of two series of observations made upon the excitation and recovery characteristics of the crystal. Two additional experiments prove that these data come from changes in the conductivity of the crystal due to the absorption of X-rays. The apparatus was the same as described for the pressure-ΔC experiment. First, with no heating current flowing in the Coolidge tube filament, but with the customary 48.0 kv. potential applied, no galvanometer deflection was observed—*i.e.*, the balance of the bridge was maintained. Second, the introduction of a sheet of lead into the path of the rays from the target to the crystal resulted in a smaller total change than that produced in the absence of the lead. In making the measurements from which the data represented in Fig. 2 were computed a null method was used. The excitation and recovery of the crystal are so very much slower than the action of the galvanometer used that it was practical to change the balancing arm of the bridge by a convenient amount, usually 100 ohms, and observe with a watch the time required for the balance to be reattained.

III. The Action of Gamma Rays.

It was found time conserving to carry on experiments with gamma rays along with the X-ray studies, and in consequence of this practice a very interesting relation was discovered to exist between the gamma ray and X-ray effects, which, however, might have been predicted. In the first experiments with the crystal whose properties are here discussed gamma rays were used. When these were finished X-ray excitation and recovery curves were secured, six hours having been allowed for recovery. The results of the latter are given by curves B and B' of Fig. 2. By comparison with the characteristics of other crystals from the same lot it was thought that the equilibrium value of the conductivity change, indicated by *B*, was too low. More time (48 hrs.) was allowed for recovery and curves *A* and *A′* secured, which show an equilibrium value comparing favorably with those secured for other crystals. Unquestionably, therefore, a crystal fatigued to gamma rays is also fatigued to X-rays, a result which is in accord with the view that these radiations are of a similar nature.

The effect of the gamma rays was obtained by lowering a thin glass vial containing a milligram of radium into proximity with the crystal through a hollow lead cylinder with walls a millimeter thick to absorb the alpha and beta rays. In these experiments the drift of the galvanometer spot was noted at ten second intervals and later translated into change in conductivity by proper calibration of the bridge. This alteration in method was found necessary in order to differentiate clearly between the effect of the gamma rays and the initial variation common in the balance of the bridge. Much more data than can be given here were taken to make sure of this point. It is thought that the action of

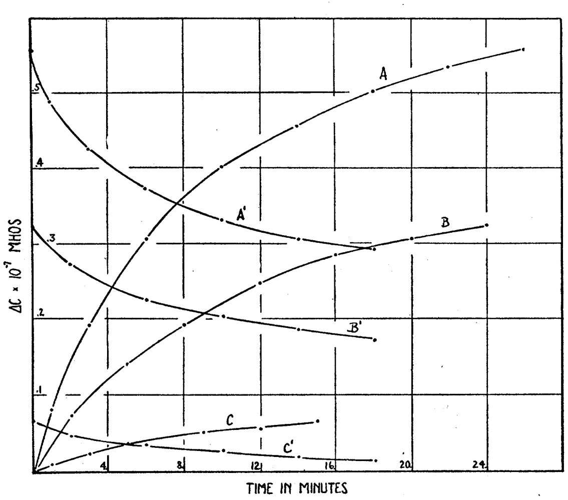

Fig. 3.

Excitation and recovery curves—gamma rays. *A*, Excitation. Pressure 320 gms. Initial Conductivity 5.53×10^{-7} Mhos. *A′*, Recovery. *B*, Excitation. Pressure 216 gms. Initial Conductivity 5.08×10^{-7} Mhos. *B′*, Recovery. *C*, Excitation. Pressure 24 gms. Initial Conductivity 1.25×10^{-7} Mhos. *C′*, Recovery.

the gamma rays is established beyond question. Fig. 3 gives curves secured with the same crystal as before for three different pressures. The error due to variations in the balance of the bridge is probably less than 1 per cent. for the maximum values of ΔC in curves A and B. The increase of sensibility with increase of mechanical pressure is unmistakable.

IV. A Comparison of the Light, X-ray, and Gamma Ray Effects.

It is of great importance to compare the X-ray, gamma ray, and light effects from the standpoint of absorbed energy. Although the data thus far available do not permit of direct comparison, it is possible by making certain assumptions to base a calculation upon them which leads to an interesting result. It is hoped that the additional measurements necessary for a more satisfactory comparison may be accomplished in the near future. The present calculations were made as follows.

The energy of the Roentgen rays was secured from the input to the Coolidge tube and the value for the efficiency of production at 48.0 kv. found by Rutherford.[1] The energy of the gamma rays was found from their known heating effects. An observation was made upon the change in conductivity undergone when light of .7 μ and known intensity was incident upon the crystal. Assuming the absorption law $I = I_{\cdot}e^{-\mu x}$ for Roentgen and gamma rays, and considering that all of the light entering the crystal must have been absorbed (the crystals are not transparent), we get the following results:

Radiation.	E_i = Incident Energy $\frac{\text{Ergs}}{\text{Sec.}}$.	E_a = Absorbed Energy $\frac{\text{Ergs}}{\text{Sec.}}$.	ΔC in 1 Min.
Gamma rays (Ra) . .	6.57×10^{-3}	3.74×10^{-4}	$.08 \times 10^{-7}$
X-rays (L of W). . . .	2.60×10^{-2}	1.06×10^{-2}	$.62 \times 10^{-7}$
Light (.7 μ)	1.84×10^{-3}	1.19×10^{-3}	$.15 \times 10^{-7}$

Benoist's relation between absorption and atomic weight was used in obtaining the X-ray absorption constant, $\mu = 1.64$. The assumption of Rutherfords' relation between density and absorption was necessary to secure the gamma ray absorption constant, $\mu = .184$. The distribution of X-ray, gamma ray, and light energy was considered uniform.

From these results and the intensity law,[2] $C = k\, I^{1/2}$, the change in conductivity when $E = 2.60 \times 10^{-2}$ was calculated for each type of radiation. The absorbed energy was found, also, and the ratio, $\Delta C/Ea$, formed, viz.:

Radiation.	ΔC in 1 Min.	E_a in $\frac{\text{Ergs}}{\text{Sec.}}$.	$\frac{\Delta C}{E_a}$.
Gamma rays.	$.16 \times 10^{-7}$	1.47×10^{-3}	108.9×10^{-7}
X-rays	$.62 \times 10^{-7}$	1.06×10^{-2}	58.5×10^{-7}
Light	$.56 \times 10^{-7}$	1.69×10^{-2}	33.2×10^{-7}

[1] Rutherford, Phil. Mag., 30, p. 361.

[2] Nicholson, Phys. Rev., N.S., 3, p. 1.

Although the figures resulting from these computations are in the nature of approximations it is hoped that their order of magnitude may prove suggestive of the possibilities in this line of work.

The conclusion of the greater sensibility to gamma rays seems quite certain, however. For if instead of the above square-root intensity law we assume the linear law[1] for faint illumination, the comparison is even more favorable to the gamma rays. Discussion of just what this apparent difference may mean is postponed until a more complete experimental study can be made.

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

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[1] Brown and Sieg, PHYS. REV., N.S., 2, p. 487.