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AN EXPERIMENTAL INVESTIGATION OF THE ENERGY
OF THE CHARACTERISTIC K-RADIATION FROM
CERTAIN METALS

BY EMORY CARL UNNEWEHR

ABSTRACT

Energy of K-radiation from Cr, Cu, Rh, and Ag, for applied voltages to 45 kv.—Using a special Coolidge tube with a thin mica window, and a rotatable anti-cathode on which were mounted four metals, the intensities of the characteristic K x-rays from Cr(atomic number 24), Cu(29), Rh(45), and Ag(47), corrected for general radiation, for incomplete absorption in ionization chamber, for incomplete reflection by crystal, and for absorption by mica window, were found to be approximately linear functions of the square of the applied voltage on the tube. The ratio of the intensities of the α and β radiations was constant for each metal and decreased regularly with increasing atomic number from 7.36 for Cr to 4.65 for Ag. The ratio of the α radiation to the general radiation also decreased, but more markedly, from 25 for Cr to 11.2 for Cu and 2.7 for Ag. *Comparison with the theory* of Bergen Davis shows good agreement for Ag and Rh, but not for Cr and Cu. This is probably due to the fact that the theory neglects the fluorescent re-emission of absorbed general radiations.

Absorption coefficient of Rh for its K-radiation was found to be 222 per cm for $K\alpha$ and 178 per cm for $K\beta$.

Absorption coefficients of mica for K-radiation from Cr, Cu, Rh, and Ag were found to be 227, 89.2, 7.7 and 5.1 per cm, for the $K\alpha$ radiation and 171, 66, 5.5 and 3.6 per cm, for the $K\beta$ radiations of the respective metals.

THE experiments reported here are part of a systematic investigation of the energy of x-ray emission, which is now being carried forward in the Phoenix Physical Laboratory of Columbia University.

The particular object of the present experiments was the investigation of the K-characteristic emission from silver (atomic number 47), rhodium (45), copper (29) and chromium (24), under identical conditions for the purpose of comparison. These radiations were investigated for:

- (a) The dependence of energy of emission upon applied voltage;
- (b) The dependence of energy of emission upon the atomic number;
- (c) The relation of the energy of the K-characteristic emission to the energy at that wave-length in the continuous spectrum;

(d) The ratio of the energies of the α to the β characteristic emission.

The purpose also was further to check and test a theory of characteristic x-ray emission developed by Bergen Davis.¹ This theory was developed from purely theoretical considerations after D. L. Webster² had shown that the energy of emission of characteristic x-radiation from a target increases rapidly with the voltage. In this theory, Bergen Davis formulated an expression for the intensity of the characteristic radiation in terms of the applied voltage. The values calculated from this theory agreed very closely with experimental results obtained by B. A. Wooten.³

DESCRIPTION OF APPARATUS

A motor generator set furnished current at 125 volts and 500 cycles to a 3 kw oil immersed transformer. The alternating current at high voltage was rectified by means of two General Electric kenetrons and a large condenser. Power was supplied to the x-ray tube from this condenser.

The voltage was measured by an electrostatic voltmeter. It consists of two fixed spheres and two movable spheres hung in the same plane by a steel suspension. When the spheres were charged to the same potential, there was a repulsion between the movable and fixed spheres, thus causing a deflection of the movable spheres. Before the data were taken, the voltmeter was recalibrated by means of a spark gap between two spheres which were 12.5 cm in diameter, since for such spheres tables of the relation between the length of spark gap and voltage are available, and a calibration curve was drawn. It proved to be a smooth, consistent curve. During the time during which readings were taken, the voltage was kept constant to within about one per cent.

The spectrometer was of the usual type employed, except that the ionization chamber was quite long, being 150 cm in length. The measurements were made with a gold leaf electroscope of special design attached directly to the end of the ionization chamber. In this chamber air saturated with vapor of methyl iodide was used since it shows no critical absorption in the range of frequencies obtained in this investigation. The air and vapor were kept dry by means of phosphorous pentoxide in the usual manner. The slit in the end of the ionization chamber was closed by a mica window .001 cm thick, which permitted the passage of even the softest radiation without very great absorption. The beam

¹ Davis, Phys. Rev. **11**, 433, 1918

² Webster, Phys. Rev. **7**, 599, 1916

³ Wooten, Phys. Rev. **18**, 71, 1919

of x-rays was defined by two adjustable lead slits placed between the x-ray tube and the crystal.

The x-rays were deflected from a crystal of calcite which had previously been used for x-ray reflection. No flaws in the structure of the face used had been found.

The x-ray tube was of the Coolidge type and was built in this Laboratory. The filament of the Coolidge cathode was heated by current from a small storage battery. The target consisted of a hexagonal copper cylinder, on the faces of which the other metals whose radiations were examined were mounted. These metals were placed so that the faces upon which the electrons struck were at exactly equal distances from the axis. The target was supported on a pivot which was securely anchored to the bottom of the x-ray tube. The hexagonal target could be rotated about the axis by a suitable magnet placed outside the x-ray tube. By this means, it was possible to bring any of the four metals into the same position with respect to the slit and to the Coolidge cathode.

Besides the rotating target, the x-ray tube had one other interesting feature. In the side of the x-ray tube toward the spectrometer, a hollow steel cylinder was fitted into the glass by means of a ground glass joint sealed with DeKotinsky cement. In the end of this cylinder was a narrow window about 2 mm wide and 2 cm high. This window was covered with a thin sheet of mica, 0.0014 cm thick. The small absorption in this mica window could easily be calculated.

DESCRIPTION OF METHOD

The apparatus was first carefully put in alignment. Data were then taken for wave-length intensity curves. The voltage at which the characteristic radiation first occurs was thus determined and also the positions of the α and β lines. These wave-length-intensity curves were smooth, and there was no suggestion of line radiation other than the α and β . Since this investigation is concerned only with the intensity of the characteristic radiation, no attempt was made to separate the α or the β line into its two components; the intensity of the line in all cases was taken as the maximum of the doublet. For that reason, also, the entire general radiation curve was not taken for each voltage. In order to obtain the intensity of the line radiation, the intensity of the radiation at a point on each side of the line radiation but on the general radiation curve was found; these two points were joined by a straight line, and the distance from this straight line to the peak of the characteristic radiation was taken as the intensity of the characteristic radiation. This process was carried through for each line at each voltage. Observations were made at

intervals of 3 kv up to and including 45 kv. The rate of discharge of the electroscope is a measure of the intensity of the x-rays reaching the ionization chamber, after correction for the natural leak of the instrument. To make this correction, the ionization chamber was rotated several degrees from the correct position at which the particular wave-length would be received in the chamber and the rate of discharge at this point was taken as the natural leak. This varied for different positions of the crystal and of the ionization chamber. It was subtracted from the rate of discharge for a particular wave-length and the result was divided by the electron current passing through the x-ray tube, as measured by a standard calibrated Weston milliammeter. In each case, the intensity recorded is the intensity per unit current through the x-ray tube.

The data for the various intensities for any particular metal were obtained at a single period of operation of the x-ray tube. Necessarily a number of days elapsed during the time of taking the data for all the curves of all the metals. In order to be able to compare the lines from the various metals, the voltage was kept constant; the target was rotated so that each metal in turn sent off x-rays under the same conditions; and the ionization chamber and crystal were rotated into proper positions so that the characteristic α radiation from each metal was in turn reflected into the ionization chamber. In this way data for the α radiation at one voltage from each metal were obtained under as nearly similar conditions as possible. The intensities measured at different times were then multiplied by factors, one for each run, which made the values obtained in different runs such that they could all be compared.

For the purpose of correction for the absorption of the radiation in passing through the mica window of the x-ray tube and also through the mica window of the ionization chamber, a measurement was made of the absorption of each of the characteristic radiations in mica. The absorption coefficients so obtained are given in Table I.

TABLE I

Coefficients of absorption of characteristic radiations from several targets, per cm of thickness

	α line		β line	
	in mica	in metal	in mica	in metal
Silver (47)	5.1	161	3.6	114
Rhodium (45)	7.7	221	5.5	178
Copper (29)	89.2	636	66	470
Chromium (24)	227	867	171	653

The theoretical development by Bergen Davis contains as a constant, the coefficient of absorption of the radiations in the material of the target itself. These coefficients, which are given for the α and β radiations in

Table I, are either taken from the experimental results obtained by Richtmyer (Ag), or were directly determined (Rh), or were estimated from the law of the variation of absorption with atomic number obtained by Richtmyer.

The targets, silver, chromium and rhodium were in the shape of rectangular pieces whose sides varied from 1 to 2 cm in length and whose thickness varied from 1 to 3 mm. The rhodium target was obtained through the kindness of Dr. C. S. Brainin of the Baker Platinum Company. He also furnished the thin sheet of rhodium used in finding the absorption coefficient. This sample of rhodium was exceptionally pure. The targets were held in place by small machine screws.

CALCULATIONS, CURVES AND RESULTS

Corrections. In order to arrive at the actual relative intensities of the radiations as emitted from the target inside the x-ray tube, it was necessary to make the following corrections to the observed data:

- (a) For partial absorption in the ionization chamber;
- (b) For absorption in the mica window of the ionization chamber and in the mica window of the x-ray tube;
- (c) For reflection from the calcite crystal;
- (d) For absorption in air path from the crystal to ionization chamber and from the x-ray tube to the crystal.

It has been found by direct observation that the absorption in a column of air saturated with methyl iodide is equal to that of a column of air alone six times its length. Since the length of the ionization chamber of this spectrometer was 150 cm, the equivalent relative absorption and hence ionization was that of an air column 900 cm long. A considerable percentage of the radiation even of shortest wave-length was absorbed in the chamber; hence the corrections were small and a possible error in this method would introduce only a small error in final results.

The mica windows of the ionization chamber and the x-ray tube were respectively 0.001 cm and 0.0014 cm thick. The absorption was calculated and corrected for in the usual manner, using the values of the absorption coefficients given in Table I.

Crystals do not reflect all wave-lengths equally well. Bergen Davis and W. H. Stempel⁴ made a careful experimental study of the reflection of x-rays from calcite. One of the crystals which they examined was the one used in this investigation. From their curves it was possible to get directly the reflection for several of the characteristic wave-lengths used. Their experiments did not extend over the entire range of wave-lengths,

⁴ Davis and Stempel, *Phys. Rev.* **17**, 608, 1921

but they found that Darwin's⁵ equation agreed very closely with their experimental curve, so this equation was used to extrapolate for values of the reflection beyond the range obtained experimentally. In this way the intensities of radiation for all wave-lengths were corrected for reflection by the crystal.

After all corrections had been made, the resulting intensity was the intensity of radiation leaving the target. These values were plotted

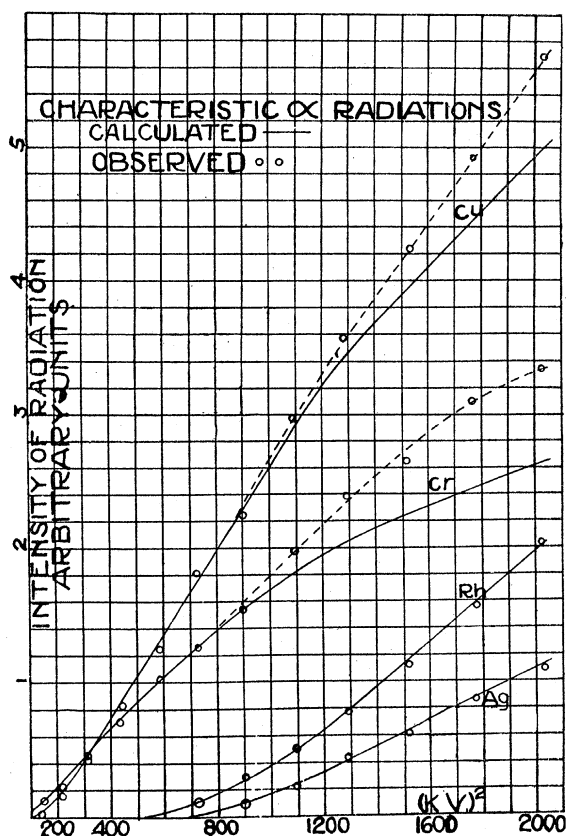


Fig. 1. Intensity of characteristic $K\alpha$ radiations.

against voltage squared. The resulting curves for metals of higher atomic number were similar in character to those obtained by B. A. Wooten³ for molybdenum and palladium.

Fig. 1 shows the intensity-voltage curves for the α radiation from all the targets plotted to the same scale. Fig. 2 shows the same for the β

⁵ Darwin, *Phil. Mag.*, Feb. and April, 1914

radiation. These curves show that while the characteristic radiation in general increases as the atomic number of the element which is giving off the radiation, decreases, there is an exception to this. The positions of copper and chromium should be reversed.

	Cr	Cu	Rh	Ag
α radiation	2.05	3.1	1.65	0.9
β radiation	0.27	0.5	0.3	0.2

In this investigation several points on the general radiation curve for each voltage were obtained. It was, therefore, possible to compare the intensity of the characteristic radiation with that of the general radiation. In order that the comparison might be of value, this relation was taken at that voltage for each element at which the position of the α line

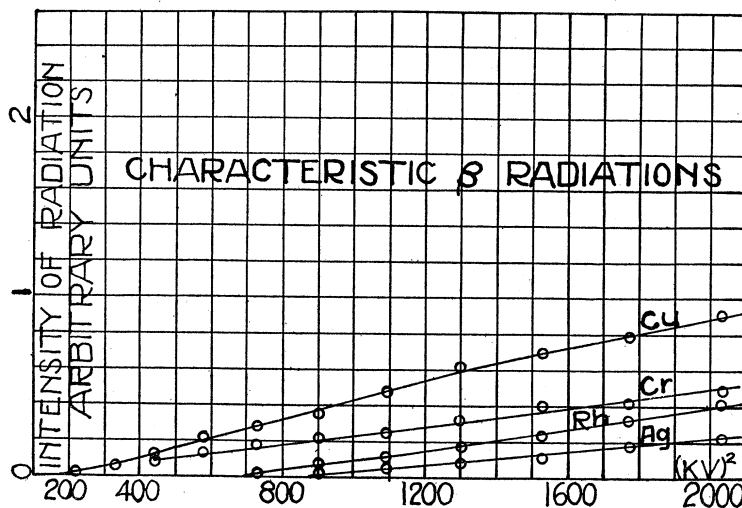


Fig. 2. Intensity of characteristic K β radiations.

was on the peak of the general radiation curve. The relation is shown in Fig. 3. The ratio between characteristic and general radiations is small for elements of higher atomic numbers and increases rapidly as the atomic number decreases. The discrepancy in the order of copper and chromium of Figs. 1 and 2 has disappeared in Fig. 3.

These results are in agreement with those obtained by C. S. Brainin.⁶ Thus, Figs. 3 and 4 of Brainin's paper show that the total radiation from copper increases decidedly at the voltage at which the characteristic radiation appears, while that from silver decreases at the voltage at which its characteristic is produced. The general radiation obtained from chromium was very small.

⁶ Brainin, Phys. Rev. 10, 461, 1917

COMPARISON WITH THEORY

In the forementioned paper by Bergen Davis,¹ Eq. (5) gives the intensity of the characteristic radiation as a function of the applied voltage. Professor Davis has recently put this equation in a different form, essentially as follows:

$$I = [E_a h n_a B N / b] \left[(1/K^2) (1 - e^{-K^2(V^2 - V_0^2)}) - (2V_0/K) e^{-K^2 V^2} \int_{KV_0}^{KV} x^2 dx \right]$$

in which for brevity K is put for $\sqrt{c\mu/b}$ and the letters refer to the same quantities as in Eq. (5) of that paper. An important property of the

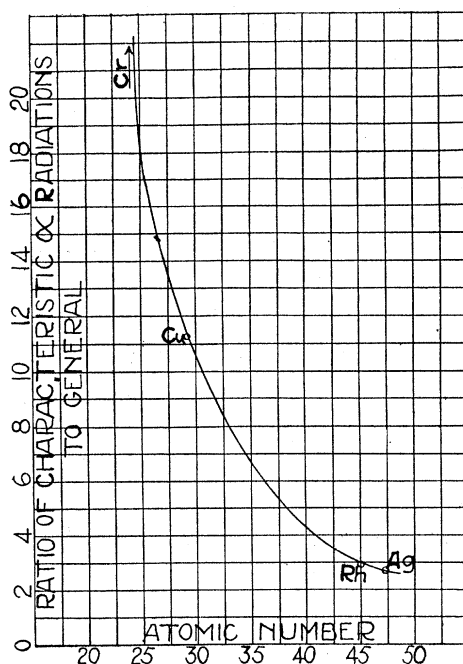


Fig. 3. Ratio of $K\alpha$ radiations to general as a function of atomic number.

above equation is that it contains no arbitrary constants. The constants b , c , and μ (hence K) are obtained from data already published or obtained in this investigation. The constant b is the constant a of Whiddington's⁷ equation,

$$v_x^4 = v^4 - ax$$

when referred to voltages instead of velocities. Actual measurements were made by Whiddington only on aluminum and gold. His results show that $a/\rho^{0.6}$ equals a constant approximately, where ρ is the density. This relation was used in calculating b for the elements of the present

⁷ Whiddington, *Pro. Roy. Soc.* **86**, 1912

investigation. The constant c is the ratio of the length of path of the rays in emerging from the target, to the depth of penetration of the electron producing them, and was equal to 2.07. The constant μ is the coefficient of absorption given in Table 1. Using these constants, the variable part of the equation was calculated to give the shape of the curve. The observed and calculated curves were then made to agree at one point. The extent of the agreement is shown by Fig. 2. The calculated values are shown by the solid line, while the points plotted are the observed values. There is good agreement between calculated and observed curves for elements of higher atomic number, but the agreement is not so good for elements of lower atomic number. It was suggested that the increased

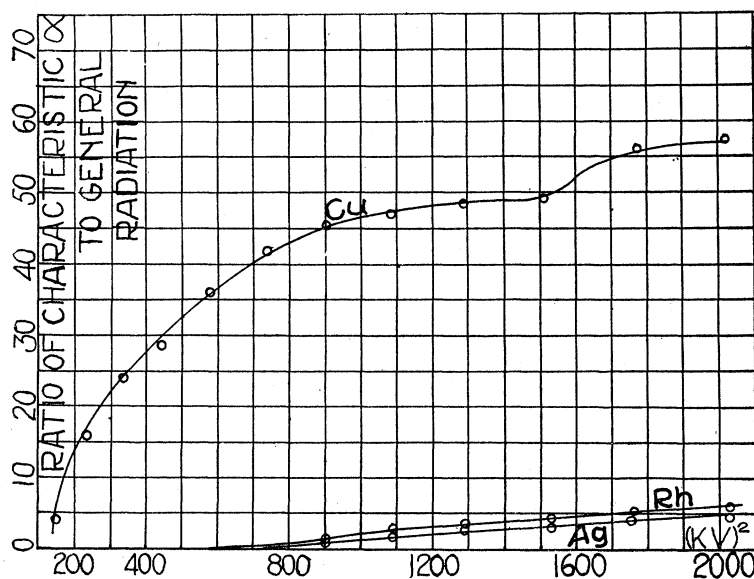


Fig. 4. Ratio of $K\alpha$ radiations to general as a function of voltage squared.

radiation from the elements of lower atomic number might be due to the higher order of spectra of shorter wave-length. This is probably not the case, for the general radiation would then have contained the same increase from the higher order of spectra of shorter wave-lengths. On the other hand these curves suggest that these metals are fluorescent and that the increased radiation is due to that cause.

The theory fails to take into account the fluorescent production of characteristic radiation by the absorption of the general radiation. Yet this absorption and fluorescent re-emission of characteristic radiation is probably of considerable importance in case of the elements of lower atomic numbers.

Too much importance should not be attached to the extent of the above agreement with theory for the following reasons:

- (a) The uncertainty as to the accuracy of the corrections to the observations to give the true form of energy of emission from the target;
- (b) The uncertainty as to the law of decrease of electronic velocities in penetrating the target, and also the uncertainty as to the value of the constant b , in case Whiddington's law is correct.

In the equation, the constant $E_\alpha hn_\alpha$ may be interpreted as expressing the particular characteristic radiation from the atom itself. Since the constant BN/b is the same for any one element, the ratio $E_\alpha hn_\alpha / E_\beta hn_\beta$ expresses the theoretical ratio of intensities of the α and β radiations as emitted from the atom. The observed ratio I_α / I_β , the corrected ratio, and the ratio of atomic emissions are given in Table II.

TABLE II

Target	Observed ratio	Corrected ratio	Atomic emission ratio
Silver (47)	6.00	4.65	4.83
Rhodium (45)	5.68	4.75	5.96
Copper (29)	4.7	6.53	7.33
Chromium (24)	3.2	7.36	12.35

In Fig. 4 the curves showing the relation between the ratio of the characteristic α radiation to the general and the voltage squared are drawn. The curve for chromium is not shown because the values for the general radiations were very small. The relation is a straight line function for silver and rhodium but copper shows quite a variation. Apparently no general law of variation for the slopes of these curves exists.

In conclusion, I wish to express my sincere thanks to Prof. Bergen Davis, who suggested the work, and whose interest and enthusiasm have been a source of inspiration to me in this and in other work. I am grateful also to Dr. C. S. Brainin for the help in securing the rhodium sample.

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