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THE INDEPENDENCE OF X-RAY ABSORPTION ON TEMPERATURE

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Abstract

If the absorption coefficient of x-rays is dependent upon the temperature of the absorber it is pointed out that the effect can be made easily measurable by increasing the thickness of the absorber. Using this method in which the thickness was made very great, measurements have been made on Al, Cu, Fe, Ni, Ag, and Pb. Heterogeneous x-rays were used with voltages from 30 to 80 k.v., also the monochromatic x-ray lines $K\alpha_{1,2}$ of silver and copper were used. All measurements showed no effect of temperature on the absorption coefficients within the probable error involved in the thermal expansion coefficients.

It is also pointed out that the effect of temperature on the absorption of x-rays and γ-rays, as found by previous investigators, was probably due to an error in the determinations of the linear absorption coefficient. When their results are corrected, using the absorption coefficient of the beam transmitted by the absorber, the results are in agreement with the present experiments.

MEASUREMENTS have been reported[1,2] which indicated a change in the atomic absorption coefficient of x-rays with a change in the temperature of the absorbing screen. In the first[1] series of these measurements using the direct x-rays from a Coolidge tungsten x-ray tube and absorbing screens of Al, Cu, Fe, Ni, Ag, and Pb an increase in the atomic absorption coefficient was observed as the temperature of the absorber was increased. The increase was about 0.2 percent per 100°C up to temperatures near the melting point of the absorber. The second[2] series of measurements were made using narrow bands of x-rays of various wave-lengths absorbed in Ag and Ni. For some wave-lengths the absorption was greater than the normal absorption and for others it was less. Similar observations[3] have been made using -γ rays and absorbers of Pb, Fe, Sn, and Al. In each case it was found that the absorption coefficient increased with an increase in the temperature of the absorber. For both γ-rays and x-rays, if the change in absorption is expressed as a linear function of the temperature as $\mu' = \mu(1+\beta T)$ where μ' and μ are the linear absorption coefficients of the absorber when hot and cold respectively it is found that β is proportional to the thermal expansion coefficient of the absorber.

Existing theories of absorption of x-rays and γ-rays offer no explanation of such an effect. Thus the effect offers a critical experimental check on the theoretical correctness of absorption theories. The present experiments were

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[1] Read, Phys. Rev. **27,** 373 (1926).

[2] Read, Phys. Rev. **28,** 898 (1926).

[3] Bastings, Nature CXIX, **51** (1927), Phil. Mag. **7,** 337 (1929).

undertaken with the purpose of making more accurate observations of the change in absorption of x-rays with various wave-lengths and absorbing screens.

METHOD

The expected change in the intensity transmitted by the absorber when cold and hot due to the thermal expansion of the absorber may be calculated as follows:

Let I_0, I_c and I_h be the intensities of the direct x-ray beam, the beam transmitted by the absorber when cold, and when hot respectively.

Then $I_c/I_0 = e^{-\mu_c x}$

and

$$\frac{I_h}{I_0} = e^{-\mu_h x/(1+\alpha T)^2} \tag{1}$$

where μ_c and μ_h are the linear absorption coefficients of the absorber when cold and hot respectively, x the thickness, and αT the linear expansion of the absorber. The ratio of intensity transmitted by the absorber when cold and hot is then

$$\frac{I_h}{I_c} = e^{(\mu_c - \mu_h)x + 2\mu_h x \alpha T}. \tag{2}$$

For a heterogeneous beam μ_c and μ_h refer to the effective linear absorption coefficient of the beam transmitted by the absorber when cold and hot respectively. This of course would have to be measured by using absorbers of the same material and extrapolating to a thickness equal to the thickness x of the absorber used in Eq. (2). The percentage change in transmitted x-ray intensity is

$$\frac{I_h - I_c}{I_c} = (\mu_c - \mu_h)x + 2\mu x \alpha T \tag{3}$$

in this equation μ is really μ_h but since μ and μ_h cannot differ by more than 0.1 percent, the use of the normal absorption coefficient introduces practically no error in the value of $(I_h - I_c)/I_c$

From Eq. (3) it will be seen that the greatest change in x-ray intensity will be for an absorber of maximum thickness x. Experimentally one must make x such that I_c and I_h are easily measured. For direct radiation from an x-ray tube the area of the collimating slits can be made very great and correspondingly x made larger. In the case of x-rays reflected from a crystal the area is very limited but with water cooled x-ray tubes where the x-ray intensity is very great x can still be made large. It will be noticed in Eq. 3 that a measurement of the intensity I_0 which may be 1000 times I_c or I_h is not needed. In the present experiments I_c and I_h were measured using two exactly similar pieces of metal for the absorbing screen so placed on an eccentric that either could be inserted in the path of the x-ray beam. One piece was placed in a furnace and the other kept at room temperature. After a series of measurements of I_c and I_h had been made the two absorbers were interchanged and a new set of readings taken. This procedure was adopted to make it possible to obtain I_c and I_h without a time lag and without a change in temperature of slits, sensitivity of electrometer, etc. Previous experiments[1,2,3] have indicated that

$$(\mu_c - \mu_h)x = \mu x \alpha T$$

so if one makes x large enough to make $(I_h - I_c)/I_c = 0.1$ or larger the effect of such a change in absorption would change the x-ray intensity by 5 percent or more. Such a change in intensity can be easily measured.

APPARATUS

The high voltage outfit consisted of a regular high voltage transformer (165 k.v. 500 m.a.) connected to a four kenetron full wave rectifier. The kenetrons and all filament transformers were immersed in oil in order to reduce the corona discharge. The source of a.c. was a motor generator set (15 k.w.) with the field of the generator connected to a large capacity storage battery. With this arrangement it was possible to hold the primary a.c. constant to 0.2 percent over a long period of time. Two x-ray tubes were used, one was a water-cooled copper target Coolidge tube, the other a water-cooled silver target Coolidge tube. A thin window (0.01 mm al.) was provided for the copper target tube to reduce the absorption of the characteristic copper x-rays. The x-ray tubes were operated at 20 to 40 m.a. and 25 to 80 k.v.

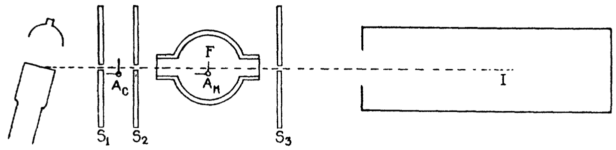

Fig. 1. Diagram of apparatus as used with heterogeneous x-rays. For the $K\alpha_{1,2}$ lines of Ag and Cu a calcite crystal was inserted between S_3 and the ionization chamber.

The ionization chamber was 7.5 cm in diameter and 30 cm long filled with argon. The electrometer (Compton type) was mounted directly above the chamber in order to reduce the electrical capacity. The sensitivity of the electrometer was about 10,000 division per volt.

The furnace was made up from a heavy wall copper tube 7 cm long with copper top and bottom (Fig. 1). The tube was insulated with asbestos on the top and sides and was heated with a gas flame from the bottom. The openings for the x-rays to pass through were made by inserting brass tubes into the side of the furnace and covering the ends of the tubes with aluminum (0.01 mm thick). The furnace was filled with hydrogen to prevent oxidation of the absorbing screens. The temperature was measured with a 600°C mercury in glass thermometer, placed so the bulb of the thermometer was very near the absorbing screen. The absorbing screen was mounted on a rod (Fig. 1) so it could be placed in or out of the path of the x-rays by rotating the supporting rod from outside the furnace. A long arm was attached to the supporting rod outside the furnace and a stop arranged so the absorber could be rotated back into exactly the same position for each measurement. A similar method was used for moving the cold absorber in and out of the x-ray beam. In the case of the thin foils it was found necessary to use a frame (made of the same material as the absorber) to hold the absorbers so they would not bend or warp when heated. This was accomplished by making two frames and placing the foil between the frames and then fastening the frames to the rotating support.

METHODS OF MAKING MEASUREMENTS

Three types of radiation were used. First, the copper $K\alpha_{1,2}$ line and the silver $K\alpha_{1,2}$ line reflected from calcite; secondly, the direct rays from the copper and silver targets operated at voltages from 20 to 80 k.v. and third, the direct ray from these tubes filtered through copper and aluminum. The dispositon of the apparatus is shown in Fig. 1. The slits were made of lead in the usual manner and were protected by sheets of asbestos from the heat given off by the furnace so that no appreciable expansion took place. When the heterogeneous rays from the tube were used, the slits were 4 mm wide and 2 cm high. In the case of the x-rays reflected from calcite the slits were 1 mm wide and 2 cm high. It will also be noticed that an expansion or shift of slits cannot effect the results taken by this method of comparison. The cold absorber A was placed perpendicular to the x-ray beam. With the furnace cold the angular position of the absorber B in the furnace was adjusted until it absorbed the same amount (to within 1 percent) of x-rays as the absorber A outside the furnace. The furnace was then heated to 600°C and allowed to cool to room temperature again. A series of measurements (usually 10) were then made, alternately placing the absorber A and B in the path of the rays. The furnace was then raised to a temperature 90 to 100°C above room temperature. A series of measurements similar to those made above were then made. This process was repeated advancing the temperature in steps of 90 to 100°C for each series until a temperature of 600°C (except in the case of Pb) had been reached. The process was then reversed and the temperature lowered in similar steps and similar measurements taken until the furnace was brought back to its original temperature (room temperature).

The intensity transmitted by each absorber was never exactly the same so a small correction factor (less than 1 percent) had to be applied in order to obtain the true values of I_c and I_h. The absorption coefficient μ in Eq. (3) was measured by placing A or B in the path of the x-ray beam and then adding thin layers of the same material in the path of the x-ray beam and measuring μ for each layer. By extrapolation the value of μ was obtained for 0 thickness of added absorbers which was the value used in Eq. (3).

The values for the thermal expansion coefficients used were taken from the tables of Landolt and Börnstein, 5th edition.

RESULTS

The results for the heterogeneous x-rays are plotted in the graphs of Fig. 2, in which the values of $I_h - I_c/I_c$ are plotted against the temperature of the absorber. The solid line is calculated from Eq. (3) in which the term $(\mu_c-\mu_h)x$ has been neglected. The dotted line was calculated assuming that

$$(\mu_c - \mu_h)x = \mu x \alpha T$$

which seemed to fit with the experimental measurments of previous experiments.[1,2,3] The circle represents the experimental values obtained in the present work. It will be seen that the experimental points lie on the solid line within the error of the measurements and the error which must be present in the thermal expansion coefficients. In the case of aluminum and copper the experimental points seem to be a little higher than the solid line but there

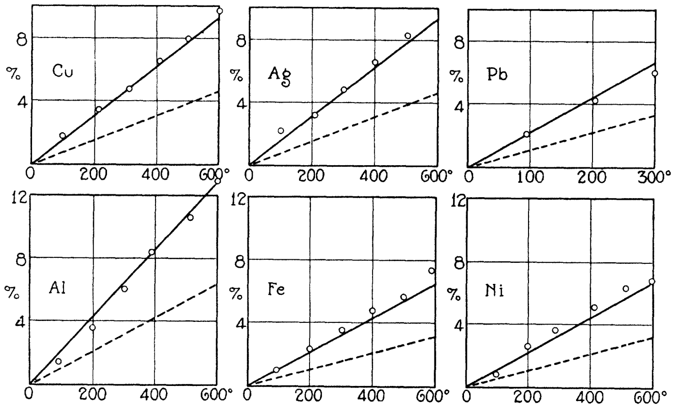

Fig. 2. The experimental points (small circles) were determined with heterogeneous x-rays from a Cu target operated at 50 kv. The solid line is drawn assuming no temperature effect on absorption of x-rays.

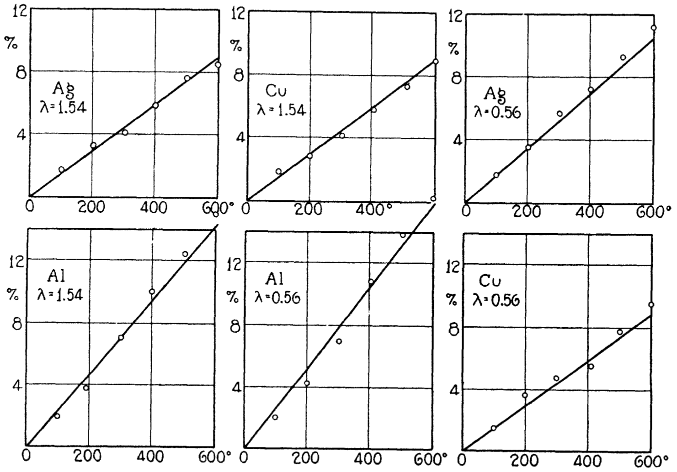

Fig. 3. Same as Fig. 2 except the monochromatic $K\alpha_{1,2}$ lines of Ag and Cu were used.

are differences in the thermal expansion coefficients given by various experimenters which would account for the difference observed here. The results using the monochromatic wave-length $K\alpha_{1,2}$ of copper and silver absorbed in silver, aluminum and copper are shown in Fig. 3. In each case the experimental points, as above, agree with the theoretical curve within the error of the measurements and the error involved in the thermal expansion coefficient.

Similar results were obtained using x-rays filtered through copper and aluminum. The x-ray measurements are believed to be more accurate than the thermal expansion coefficients are known. Thus the method may be conveniently used to measure the change in the thermal expansion coefficients with change in temperatures.

Discussion and Conclusion

The change in absorption found by Read in his first experiments[1] using a heterogeneous x-ray beam is undoubtedly due to the use of the wrong absorption coefficient μ in Eq. (3). He measured μ by removing the absorber and measuring I_0 of the direct beam. This gives a value of μ which is entirely too high. It is clear from the way in which Eq. (3) is derived that the correct μ is the μ of the transmitted beam and not that obtained by using the I_0 of Eq. (1). If this were not the case, the change in absorption with temperature would be a function of the thickness of the absorbing screen which obviously cannot be true.

The error in the second series of measurements[2] is not so apparent. In these measurements, narrow bands of wave-lengths were used so the above effect would be greatly reduced. These measurements seemed to be somewhat erratic and some undetected experimental error must have been present. Precision absorption measurements are extremely difficult to make so that an error of a fraction of 1 percent is easily made. In the measurements of Bastings[3] on the temperature coefficient of γ-ray absorption he derives an equation

$$\beta = \frac{n'\mu'd'(1 + 2\alpha T) - n\mu d}{n\mu d T} \tag{4}$$

in which n is the number of atoms per cc, μ is the linear absorption coefficient, d the thickness of the absorber, α the thermal expansion coefficient, T the temperature of the absorber, and the prime letters refer to the absorber when hot. This equation also neglects the change in effective wave-length of the heterogeneous γ-rays in passing through an absorber. Even though there were no change in absorption with temperature it can be shown that Eq. (4) would give $\beta \propto \alpha$ which is what Bastings observes. Substituting the results of Bastings in Eq. (3) using an estimated value of μ from other sources gives no temperature effect within the error of the calculation.

Thus one is lead to the conclusion that there is no effect of temperature on the absorption of x-rays or γ-rays within the error of the present determinations of the thermal expansion coefficient.