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ABSORPTION OF SOFT X-RAYS IN GASES

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Abstract

A crystal spectrograph for measuring absorption coefficients of soft x-rays in gases has been constructed, and with it absorption coefficients of air, argon and oxygen have been measured for spectral lines of wave-lengths 1.537, 2.284, 4.145 and 6.973A. Absorption coefficients in the regions immediately adjacent to the K absorption limit of argon have been measured with general radiation. No departure from the ordinary absorption law greater than experimental error was found in these regions. The magnitude of the K absorption discontinuity of argon was measured by a method which is not dependent upon the extrapolation of curves to the absorption limit, and also by a method which is independent of the absolute magnitude of the absorption coefficients on either side of the absorption limit.

NOT many measurements of absorption coefficients in the range of wave-lengths from 1.5 to 10A have been made. Growther[1] has reported absorption coefficients of a few gases for the copper $K\alpha$ line. Woernle[2] has made absorption measurements for several gases over a range of wave-lengths from 2.287 to 9.868A. Jonnson[3] has done quite extensive work in measuring absorption coefficients for metals in the same wave-length region. Jonnson used a photographic method. Crowther and Woernle used ionization methods. Dershem and Schein,[4] with the aid of a ruled grating, have used the photographic method to measure absorption coefficients for the $K\alpha$ line of carbon in various gases. It was thought desirable to extend this method to the region in which crystals could be used with the view of making possible the investigation of absorption discontinuities.

Apparatus and Experimental Procedure

The apparatus was designed so as to have a very small volume and a high resolving power. The distance from the crystal to the plate holder is about 59 cm. Although expensive gases have not been used, the small volume of the spectrograph and the long path of the x-ray beam would make it possible to work with them with a minimum expense. The high resolving power of the instrument makes it possible to distinguish between adjacent wave-lengths with good accuracy and to work in regions very close to an absorption limit. Figure 1 is a schematic diagram of the spectrograph, including a top view and a side view. The copper tubes A and B, the cylinder C, and the photographic

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[1] Crowther, Phil. Mag. **10**, 329 (1930).
[2] Woernle, Ann. d. Physik **5**, 475 (1930).
[3] Jonnson, Dissertation, Uppsala, 1928.
[4] Dershem and Schein, Phys. Rev. **37**, 1238 (1931).

plate holder D form a gas tight compartment. C contains a crystal mounting attached to a divided circle. The brass plate which covers it can be removed for the purpose of adjusting the crystal. M_1 and M_2 are electromagnets which are screwed into the walls of the plate holder. They are screwed into the walls far enough to make good magnetic contact with the inside, but enough wall is left to make the plate holder gas tight. M_2 operates a mechanism, contained inside the plate holder but not shown in the diagram, which drives the slide q back and forth. Thus S_3 which is a wide slit can be opened or closed at any time. The magnet M_1 operates a mechanism which pulls the plate p past the slit S_3. Every time that M_1 is energized p moves a definite distance. The distances l_1 and l_2 are equal, so that Bragg focusing is obtained.

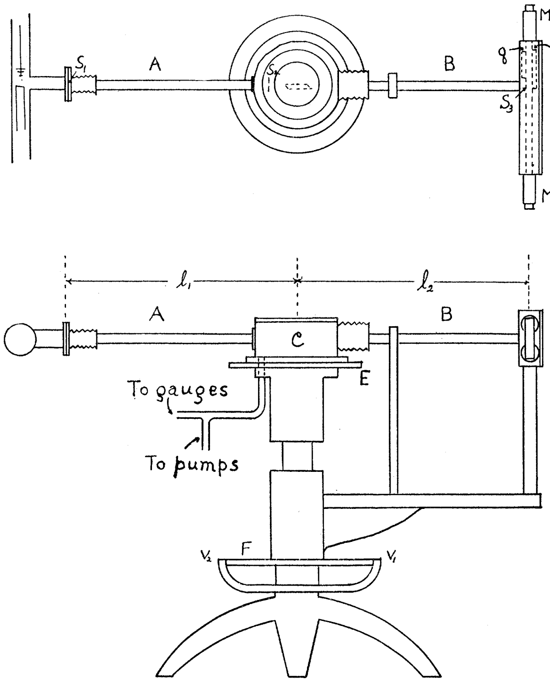

Fig. 1. Diagram of apparatus.

The tube B is fastened to the cylinder C by means of a piece of silphon tubing. The silphon tubing bends enough to permit the plate holder to be turned through an angle of eighteen degrees without rotating C. C is fastened to the plate E by means of twenty screws equally spaced around its circumference. It can thus be turned in steps of eighteen degrees, so that the plate holder can be set at any desired angle. Several faces are milled on the side of C as indicated in the diagram. Each face subtends an angle of eighteen degrees at the center of C. A wide slit is cut through each face. One end of the tube A is soldered to a small plate which can be screwed on to any one of these faces. The remaining faces are covered with interchangeable blanks. When one wishes to rotate C the tube A is simply attached to a different face.

F is an accurately divided circle which is rigidly attached to the arm which carries the plate holder. It is fitted with two verniers v_1 and v_2. S_1 and S_2 are two slits of suitable width for collimating the x-ray beam. S_1 is covered with a thin celluloid window which separates the x-ray tube from the spectrograph. All metal joints in the spectrograph were either soldered or sealed with sulphur-free rubber. A metal x-ray tube designed by Dershem[5] was used.

The spectrograph was pumped out to a pressure of less than 10^{-5} cm of mercury and the photographic plate was exposed to the radiation for a certain interval. The plate was then moved to a new position by energizing the magnet M_1 and exposed for a longer interval. In this way four or five lines of increasing density were obtained on the plate. Sufficient gas to absorb between one half and three fourths of the x-ray energy was then admitted into the spectrograph. Several lines of different times of exposure were then obtained with the x-ray beam passing through the gas. A plate thus obtained yields sufficient data, when photometered, to determine the ratio I_0/I, where I_0 is the intensity of the x-ray beam before absorption and I its intensity after absorption.

From the absorption law $I=I_0e^{-\mu x}$ and the gas law $P_sV_s/T_s=PV/T$ one obtains the following expression for the mass absorption coefficient:

$$\frac{\mu}{\rho}=\frac{1}{\rho_s x}\,\frac{P_sT}{PT_s}\log\frac{I_0}{I} \tag{1}$$

where μ/ρ is the mass absorption coefficient, x the length of path, P the pressure of the gas, T its temperature, ρ its density and the subscript s refers to standard conditions of temperature and pressure.

I_0/I was found by photometering the plate. The instrument used was a photoelectric photometer designed by Dershem. A detailed description of this instrument will appear soon in the Review of Scientific Instruments. In this photometer a beam of light is allowed to pass through the plate, through a fine slit, and then impinge upon a photoelectric cell. The cell is connected to a string electrometer. To obtain the relative densities of a number of lines one merely finds the time necessary for the string of the electrometer to pass a certain number of divisions on its scale when the light is passing through the line and the time necessary for the string to pass the same number of divisions when the light is passing through the plate adjacent to the line. The difference between these two times, (photometer time), gives a number which represents the relative density of the line. A graph in which photometer time is plotted against exposure time is made for the lines that were obtained when the spectrograph was evacuated. From this graph and the number which represents the relative density of one of the absorption lines one can find the time of exposure which would have been necessary to produce the same density of the line if the absorbing gas had not been present. From the reciprocity law the ratio of the time of exposure when the x-ray beam is passing through the absorber to the time necessary to produce the same density when the beam is passing through a vacuum is equal to I_0/I.

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[5] Dershem, J.O.S.A. **18**, 127 (1929).

Eastman x-ray plates were used. Care was taken to obtain uniform development over the entire plate, and overdevelopment, which would have produced chemical fog, was avoided.

The gases were dried by passing them through a liquid air trap before they entered the spectrograph. The oxygen used contained less than 0.4 percent of impurities most of which was nitrogen. The argon used contained less than 0.1 percent of impurities.

RESULTS

Absorption measurements were made for air, oxygen, and argon for four spectral lines of wave-lengths 1.537, 2.284, 4.145, and 6.973A. By use of general radiation, absorption coefficients were measured in the regions immediately adjacent to the argon absorption limit for the purpose of determining whether or not there was any anomalous absorption in these regions. The wave-lengths of general radiation given in Table I are extrapolated from the argon absorption limit assuming that it occurs at 3.8657A. This value was taken from a table given in Compton's 'X-rays and Electrons'. Absorption coefficients were measured for wave-lengths within 0.002A of the absorption limit on each side of it. Table I gives the values obtained for both spectral lines and general radiation, and compares them where the wave-lengths are the same with values obtained by Crowther and Woernle.

TABLE I. *Mass absorption coefficients in air, oxygen and argon.*

Spectral line	Wave-length	Author	W or C*	Author	W or C	Author	W or C
CuK	1.537A	9.54	9.49C	11.6	11.1C	112.	
CrK	2.284	29.3	31.8W	35.5	36.4W	344.	354.W
	3.716					1320.	
	3.8637					1465.	
	3.8677					147.	
	3.946					151.	
AgL	4.145	168.	163.4W	221.	222.W	171.	174.W
WM	6.973	747.	740.W	971.	976.W	762.	748.W

* The values marked C are values published by Crowther, and those marked W are values published by Woernle.

In working with general radiation care was taken to keep the voltage low enough so that second or higher order radiation was not excited. The times of exposure varied from one to five hours. Consequently, ten to fifteen hours were required to obtain a plate.

The magnitude, δ, of the K absorption discontinuity of argon, where δ is defined as the ratio of μ/ρ on the short wave-length side, (the scattering coefficient in this region is small enough to be neglected), to μ/ρ on the long wave-length side of the absorption limit, can be determined by simply dividing μ/ρ for $\lambda = 3.8637$ by μ/ρ for $\lambda = 3.8677$. This gives the value $\delta = 9.96$.

It was also found to be possible to evaluate δ by a method which is independent of the absolute magnitude of μ/ρ on either side of the absorption limit. If on the same plate one measures I_0/I on each side of the absorption limit he obtains from the definition of δ and Eq. (1)

$$\delta = \frac{\log (I_0/I)_K}{\log (I_0/I)_L}$$

where K refers to the short and L to the long wave-length side of the absorption limit. This can easily be done if a band of general radiation is reflected from the crystal so that the absorption limit falls approximately in the middle of it. The average value of δ found by this method is 10.

Figure 2 is a reproduction of one of the plates. The first two images were obtained when the x-ray beam was passing through a vacuum, and the third shows the K absorption limit of argon.

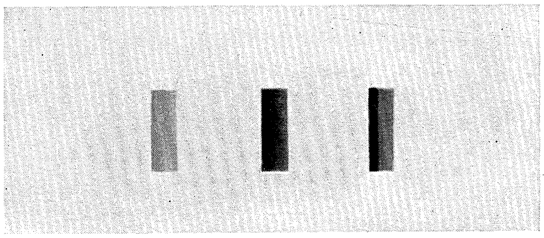

Fig. 2.

Discussion of Errors and Results

The quantities which were measured and used to determine absorption coefficients are the temperature of the gas, its pressure, and the ratio I_0/I. The temperature could easily be measured with an accuracy which would make negligible any error which it might cause. The McLeod gauges were so designed and calibrated that the measurements of the pressure were less than one half percent in error. Most of the error is thus due to measuring I_0/I. The more important factors which contribute to the error in its measurements, such as variation in intensity of the x-ray beam, irregularities in the emulsion on the photographic plate, irregularities in development, etc., introduce only random errors and should be minimized by repeated measurements. Small consistent errors might be introduced by lack of homogeneity of the x-rays and inaccuracy of the reciprocity law. But, under the conditions of the experiment such errors are probably negligible. Each plate gives several values of I_0/I and each absorption coefficient given in the table is the average of three or more plates. The probable error in most cases is less than two percent.

It is found that equations of the type $\mu/\rho = C\lambda^x$ can be made to fit the data within experimental error. C and x are constant for a given substance over a range that does not contain an absorption discontinuity. If log λ is plotted against log μ/ρ, the following equations are found from the slopes and the intercepts of the respective lines:

$$\mu/\rho = 33.9\lambda^{2.79} \text{ for argon } \lambda < \lambda_K \tag{2}$$

$$\mu/\rho = 3.39\lambda^{2.79} \text{ for argon } \lambda_k < \lambda < \lambda_L \tag{3}$$

$$\mu/\rho = 3.39\lambda^{2.91} \text{ for oxygen.} \tag{4}$$

From Fig. 3 one can see that there is no anomalous absorption greater than experimental error in the regions near the argon absorption limit. Eqs. (2) and (3) are valid at least to within 0.002A of the absorption limit.

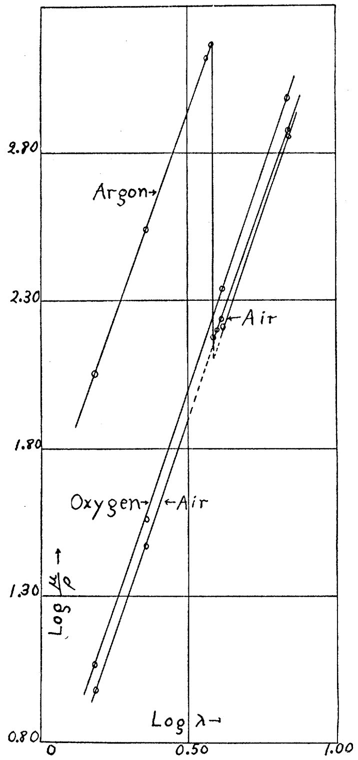

Fig. 3.

It is a pleasure to acknowledge the valuable suggestions received from various members of the staff of the department of physics of the University of Chicago. I am especially indebted to Professor A. H. Compton and Dr. Elmer Dershem who suggested the problem and cooperated in directing the work.

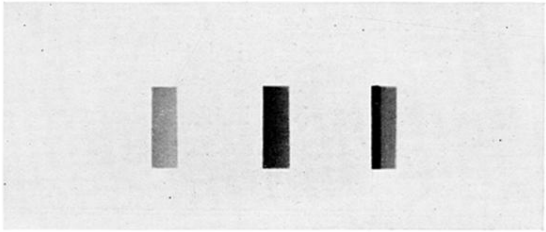

Fig. 2.