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I hereby recommend that the thesis prepared under my supervision by CHARLES H. PERRY

entitled A STATISTICAL AND EXPERIMENTAL METHOD OF DETERMINING THE RELATIVE SCATTERING COEFFICIENT OF X-RAYS

be accepted as fulfilling this part of the requirements for the degree of DOCTOR OF PHILOSOPHY

Approved by:

S. J. M. Allen

Louis J Moore

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A STATISTICAL AND EXPERIMENTAL METHOD OF DETERMINING THE RELATIVE SCATTERING COEFFICIENT OF X-RAYS

A dissertation submitted to the

Graduate School
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requirements for the degree of

DOCTOR OF PHILOSOPHY

1935

by

CHARLES H. PERRY

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OBJECT

The purpose of this investigation was to develop an experimental method for finding statistically the total mass scattering coefficient of the various elements, taking into account the absorption of the scattered radiation itself.

INTRODUCTION

When a beam of homogeneous X-rays passes through a layer of matter, energy is removed from the incident beam in two distinct ways. If the incident radiation has a frequency which is greater than that of the characteristic K radiation of the absorbing element, then electrons from all the shells of the atom will be ejected. The energy required to remove these electrons is taken from the incident beam. This type of absorption is called "true" or "fluorescent" absorption and it is designated by the symbol τ . When the incident beam passes over the electrons of the atom, these electrons are forced into vibration, the frequency of vibration being closely identified with that of the incident radiation. This type of absorption is called scattered absorption and is designated by the symbol σ . Therefore, we have the relation for the total linear absorption coefficient $\mu = \tau + \sigma$ or

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} \tag{1}$$

which expresses the coefficients in such a way that they do

not depend upon the state of the absorbing substance. If the wave-length of the incident radiation is sufficiently removed from the K and L characteristic radiation of the absorber, it is found that the total mass absorption coefficient $\frac{\mu}{\rho}$, when plotted against the cube of the wave-length, gives nearly a straight line. More correctly, the power should be "n" instead of 3. Furthermore, n is not a constant since it has been found to vary with both the wave-length and the absorbing element.[1] When this straight line is projected to the $\frac{\mu}{\rho}$ axis, the intersection falls between 0.10 and 0.20 for light elements, depending upon the substance used as the absorber. This may be interpreted approximately by saying that the "true" mass absorption coefficient $\frac{\tau}{\rho}$ over this region is proportional to λ^3 whereas the mass scattering coefficient $\frac{\sigma}{\rho}$ is independent of the wave-length λ and may be represented by the $\frac{\mu}{\rho}$ axis intercept. The relation just stated is as follows:

$$\frac{\mu}{\rho} = K \lambda^n + \frac{\sigma}{\rho} \qquad \text{or}$$

$$(2) \qquad \frac{\mu}{\rho} = c z^n \lambda^n + \frac{\sigma}{\rho}$$

where z is the atomic number of the absorber, and c is a constant. Equation 2 is due to Allen,[1] who has shown that over a wide range of wave-lengths and elements, the value

1. S.J.M. Allen, Phy. Rev. No. 1, July (1924)

of n approaches 3 but never quite reaches this value. His <u>average</u> value was found to be n = 2.92 over the entire range of wave-lengths and elements then investigated by him.

Our third statement for the mass scattering coefficient is due to J.J. Thomson.[2] Using the electromagnetic theory and the two assumptions that the electrons are small compared to the wave-length of the incident radiation, and that the wave-length is short compared to the distance between the electrons, Thomson derived the following equation, which is considered as classical.

(2-a) $$\frac{\sigma}{\rho} = .4019 \frac{Z}{A}$$

where Z and A are the atomic number and atomic weight respectively of the scattering element.

Thomson also derived equation 2, however, his exponents were n = 3 instead of n = n, a variable as has been suggested by Allen. Equation 2, is usually referred to as the cube-law for absorption.

Compton[3] has improved the cube-law equation by taking into account the relative size of the electron and the wave-length of the X-rays.

(3) $$\frac{\mu}{\rho} = \varphi K \lambda^3 + \theta \frac{\sigma}{\rho}$$

where φ and θ are both functions of the ratio of the wave

2. J.J. Thomson. Conduction of Electricity through Gases. 2nd. Edition.
3. A.H. Compton, Phy. Rev. Vol. 14, July(1919) and Sept.(1919)

length of the X-rays to the diameter of the electron. The electron considered by Compton was a deformable ring-shaped electron. Both φ and Θ lie between 0 and 1 and approach 1 as the wave-length becomes large compared to the diameter of the electron.

Barkla and his collaborators were the first to make direct measurements of the mass scattering coefficients. Barkla and Dunlop[4] observed the scattering at 90 degrees due to filtered radiation from a tungsten target, striking scatterers of different substances. In this series of experiments the true value of $\frac{\sigma}{\rho}$ could not be measured because all readings were taken at 90 degrees. At this time all scattering in excess of that accounted for by Thomson's classical equation was considered as extra-radiation not associated with the true scattering phenomenon.

Hewlett[5] improved upon Barkla's method by using the K_α radiation from a molybdenum target (zirconium oxide filter) and by measuring separately the intensity of scattering at all azimuths and then integrating the intensity distribution. From this he was able to obtain a very close approximation of the mass scattering coefficient. This was quite an advance over Barkla's method, however the procedure proved too tedious.

4. Burkla and Dunlop, Phil. Mag. 31, 222 (1916)
5. Hewlett, Phy. Rev. 20, 688 (1922)

Mertz[6] made a large step in advance by partially surrounding the scatterer with an ionization chamber. His scattering substances were made in cylindrical form and held outside of the chamber in such a way that the main axis of the cylinder was perpendicular to the X-radiation and to the principal plane of the chamber. Mertz's equation followed closely that due to Hewlett[7]

(4)

where J_s is the total scattered radiation from mass m collected by the ionization chamber. φ is the dihedral angle (in radians) between the planes bounding the sector composing the main ionization chamber. I is the intensity of the incident beam. F is the correction factor which takes into account the scattered radiation which is absorbed by the scatterer.

$$F = \frac{1}{2}\left(F' + F''\right)$$

$$F' = 1 - \frac{8}{3\pi}b + \frac{3}{8}b^2 - \frac{16}{45\pi}b^3 + \cdots$$

$$F'' = 1 - \frac{4}{3\pi}\cdot\frac{b^2-a^2}{b-a} + \frac{1}{8}\cdot\frac{b^3-a^3}{b-a} - \frac{4}{45\pi}\cdot\frac{b^4-a^4}{b-a} + \cdots$$

$$a = \tau D, \quad b = \mu D = (\tau+\sigma)D$$

D = diameter of specimen[6]

6. Mertz, Phy. Rev. 28, Nov. (1926)
7. Hewlett, Phy. Rev. 20 (1922)

Mertz's correction factor varied from less than 2% for Li at a wave-length of .32 Å to 31% for Na at a wave-length of .54 Å.

Coade[8] improved upon Mertz's ionization chamber by using a dihedral angle of 28 degrees and by using the fluorescent radiation of various radiators instead of simply filtering the white radiation from a tungsten target as did Mertz. Coade likewise placed the cylindrical scatterer outside of the ionization chamber with its main axis perpendicular to the X-radiation and to the main axis of the principal plane of the chamber. The equation used by Coade follows:

$$\frac{\left(\frac{\sigma}{\rho}\right)_1}{\left(\frac{\sigma}{\rho}\right)_2} = \frac{m_2}{m_1} \cdot \frac{(I_s)_1}{(I_s)_2} \qquad (5)$$

where I_s is the observed intensity due to scattering by mass m.

Jauncey[9] has pointed out that there are at least three factors (or terms) making up the total scattering coefficient; a scattering giving an unmodified beam, a modified beam, and recoil electrons. Only the first two are experimentally measureable quantities.

8. Coade, Phy. Rev. 36, Oct. (1930)
9. Jauncey, Proc. Nat. Acad. Sci. 11, 517 (1925)

Jauncey has done much on diffuse scattering by crystals and by gases. In considering the classical equation of the scattering of X-rays by polyatomic gases, the molecules of which consist of n atoms of one kind, Jauncey[10,11] has arrived at the following equation.

$$(6) \qquad S_{classical} = 1 + \frac{(Z+1)f'^2}{Z^2} + \frac{f^2}{mz} \sum_{r=1}^{n} \sum_{s=1}^{n} \left(\frac{\sin k l_{rs}}{k l_{rs}} \right)$$

$$\text{where } k = \frac{4\pi \sin \frac{\varphi}{2}}{\lambda} \quad \text{and} \quad f'^2 = f^2 - \left(\frac{Z \sum_{r=1}^{Z} E_r^2 - f^2}{Z-1} \right)$$

f is the true atom form factor

l_{rs} is the distance between the r^{th} and s^{th} atoms of the molecules.

S is the scattering factor per electron[12]

Woo[13,14] takes into account the Compton effect and arrives at an expression which divides the scattering

10. Jauncey, Phy. Rev. 38, 194 (1931)
11. Jauncey, Phy. Rev. 39, 561 (1932)
12. Jauncey and Williams, Phy. Rev. 41, July (1932)
13. Woo, Phy. Rev. 39, 555 (1932)
14. Woo, Phy. Rev. 41, 21 (1933)

into a coherent and an incoherent term.

$$S = \frac{S_{incoherent}}{(1+\alpha \cdot vers\,\varphi)^3} + S_{coherent} \tag{7}$$

where α is the Compton quantity $\frac{h}{mc\lambda}$

$$S_{incoherent} = 1 - \frac{f'^2}{Z^2} \tag{8}$$

$$S_{coherent} = \frac{f'^2}{mZ} \sum_{r=1}^{m} \sum_{s=1}^{m} \left(\frac{\sin k l_{rs}}{k l_{rs}} \right) \tag{9}$$

Jauncey[11] objects to Woo's equation 7 on the ground that it does not reduce to the classical formula when the Compton quantity α is put equal to zero.

THEORY

Let us begin by using equation 5 as expressed by Coade.[8]

$$\frac{\left(\frac{\sigma}{\rho}\right)_1}{\left(\frac{\sigma}{\rho}\right)_2} = \frac{m_2}{m_1} \cdot \frac{(I_s)_1}{(I_s)_2} \tag{5}$$

where I_s is the observed scattering by mass m (both modified and unmodified scattering). Instead of having the principal axis of the cylinder at right-angles to the incident radiation, we shall have it placed parallel to the radiation and suspended completely within a spherical ionization chamber. All scattering substances shall be of the same diameter but of various lengths in order to vary the mass. All the mass is considered as being in the path of the incident radiation.

If we plot I_s against various values of m for a given element, the curve obtained will be concave downward. This shows that I_s is not directly proportional to m. By taking into account the absorption of the scattered radiation by the scatterer, this concavity, or lack of direct proportionality may be explained. For this reason equation 5 must be modified so as to account for the absorbed scattering.

First we shall derive Coade's equation 5.

(10) $$I_s^* = I_o \cdot \frac{\sigma}{\rho} \cdot m$$

where I_s^* is the total scattering intensity undiminished by absorption, I_o is the incident radiation intensity, etc. Therefore,

(11) $$\frac{\sigma}{\rho} = \frac{I_s^*}{I_o} \cdot \frac{1}{m}$$

(12) $$\frac{\left(\frac{\sigma}{\rho}\right)_1}{\left(\frac{\sigma}{\rho}\right)_2} = \frac{\left(\frac{I_s^*}{I_o}\right)_1}{\left(\frac{I_s^*}{I_o}\right)_2} \cdot \frac{m_2}{m_1}$$

Now if $(I_o)_1 = (I_o)_2$ we have

(13) $$\frac{\left(\frac{\sigma}{\rho}\right)_1}{\left(\frac{\sigma}{\rho}\right)_2} = \frac{\left(I_s^*\right)_1}{\left(I_s^*\right)_2} \cdot \frac{m_2}{m_1}$$

Comparing equation (13) with Coade's equation 5 we see that I_s^* replaces I_s where I_s^* is directly proportional to m. Two methods of determining I_s^* shall be considered.

Fig. 1

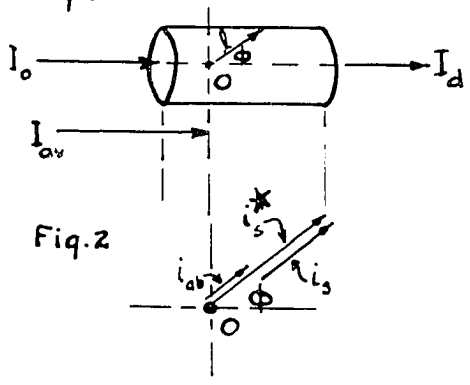
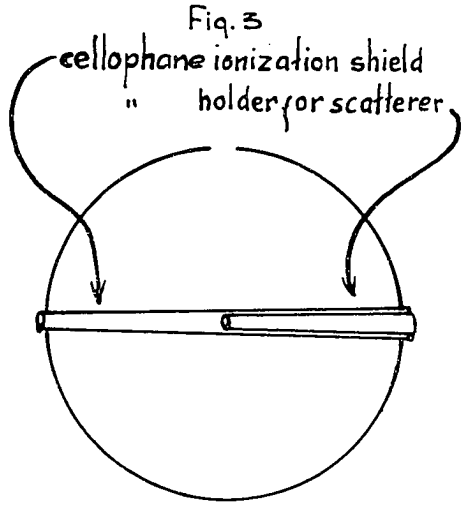


Fig. 2

Fig. 3



I

Referring to figures 1 and 2. Consider all the mass m to be concentrated at a point "O". The distance "a" being determined by making it such that one-half of the

total absorbed energy is absorbed by the scatterer while the incident radiation traverses the distance "a". This value may be determined by considering the relation of a curve plotted with $I_o e^{-\mu d}$ as ordinate and d as abscissa.

(14) $$\int_0^A dA = A = \int_0^d I_o e^{-\mu d}\, dd$$

where A is the energy under the curve and is proportional to the total energy absorbed in going the distance d. The quantity dd is the differential of the distance $d = (a+b)$.

If we consider only one scattered ray we will notice that i_s^* is made up of two parts, viz.

(15) $$i_s^* = i_s + i_{ab}$$

where i_s is the observable portion and i_{ab} is the absorbed portion of the undiminished beam. Since i_s^* is assumed to originate at 0 and since scattering occurs in all directions, we may consider only one ray (i_s^*) in a direction, say, φ and proceed with it as follows.

Let i_s^* be the incident radiation in the direction φ, then neglecting the Compton effect we have

$$(16) \qquad i_s = i_s^{*} e^{-\mu l}$$

$$(17) \qquad I_s^{*} = \sum_{cylinder} i_s^{*} = \sum_{cylinder} i_s e^{\mu l}$$

where l is the distance from O to the surface of the cylinder in the direction φ . Since scattering does not occur equally in all directions we may weight equation 16 with a distribution factor I_φ which may be determined either experimentally or theoretically. We have then

$$(18) \qquad i_s = I_\varphi i_s^{*} e^{-\mu l}$$

$$(19) \qquad I_s^{*} = \sum_{cylinder} \frac{i_s}{I_\varphi} \cdot e^{\mu l}$$

It is necessary to find i_s and I_φ as a function of φ , l , and I_o in order to solve equation 19. An additional approximation could be made by considering both the modified and the unmodified beams (Compton effect). We shall now pass on to the second method of determining I_s^{*}.

2

As stated before, if we plot I_s against m we will obtain a curve as is shown below (see curve obtained from data). The straight line represents the curve which would be obtained if no scattered rays were absorbed by the scatterer.

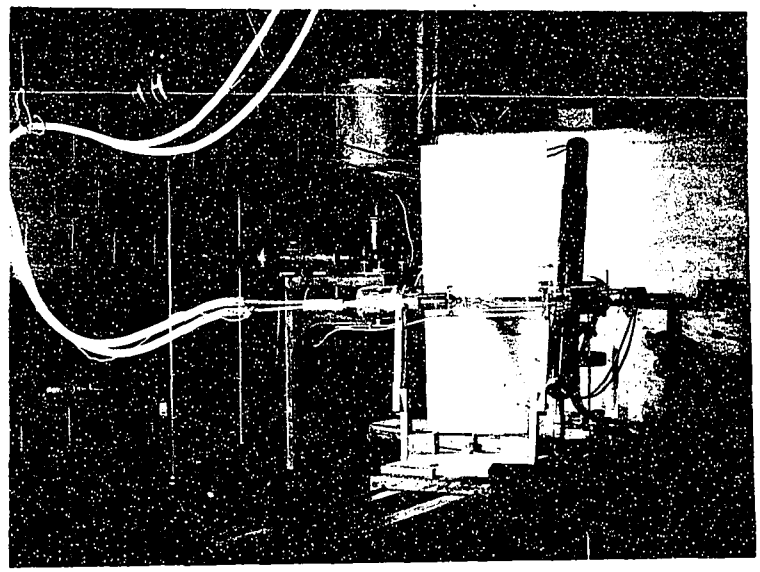
It will be noticed that as m decreases, the value of I_s^* approaches I_s. Therefore if we have m small enough we may substitute I_s^* for I_s. The difficulty is the determination of I_s for small masses. When the mass is very small the value of I_s is small and the experimental errors become difficult to handle.

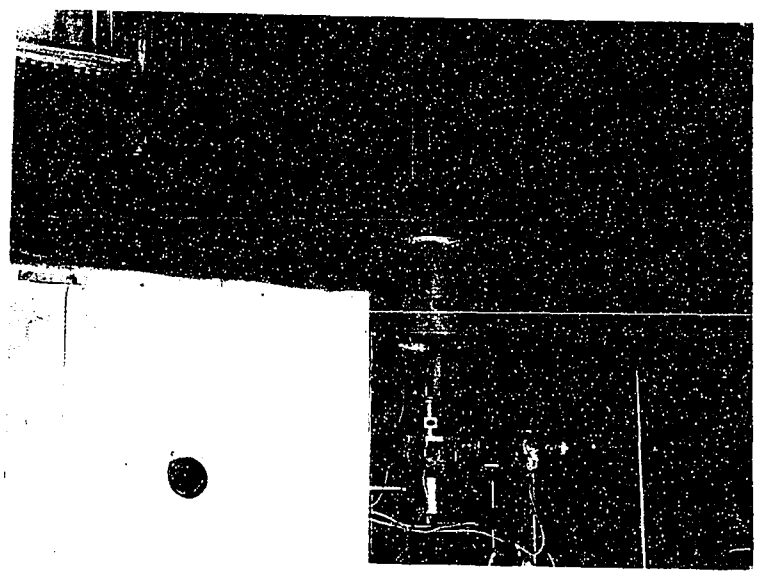
If we can conceive of "no mass" or a "differential mass" scattering, we may proceed as follows: Plot the curve OQ as accurately as is possible and as near to zero mass as is possible using experimental data. Form the derivative

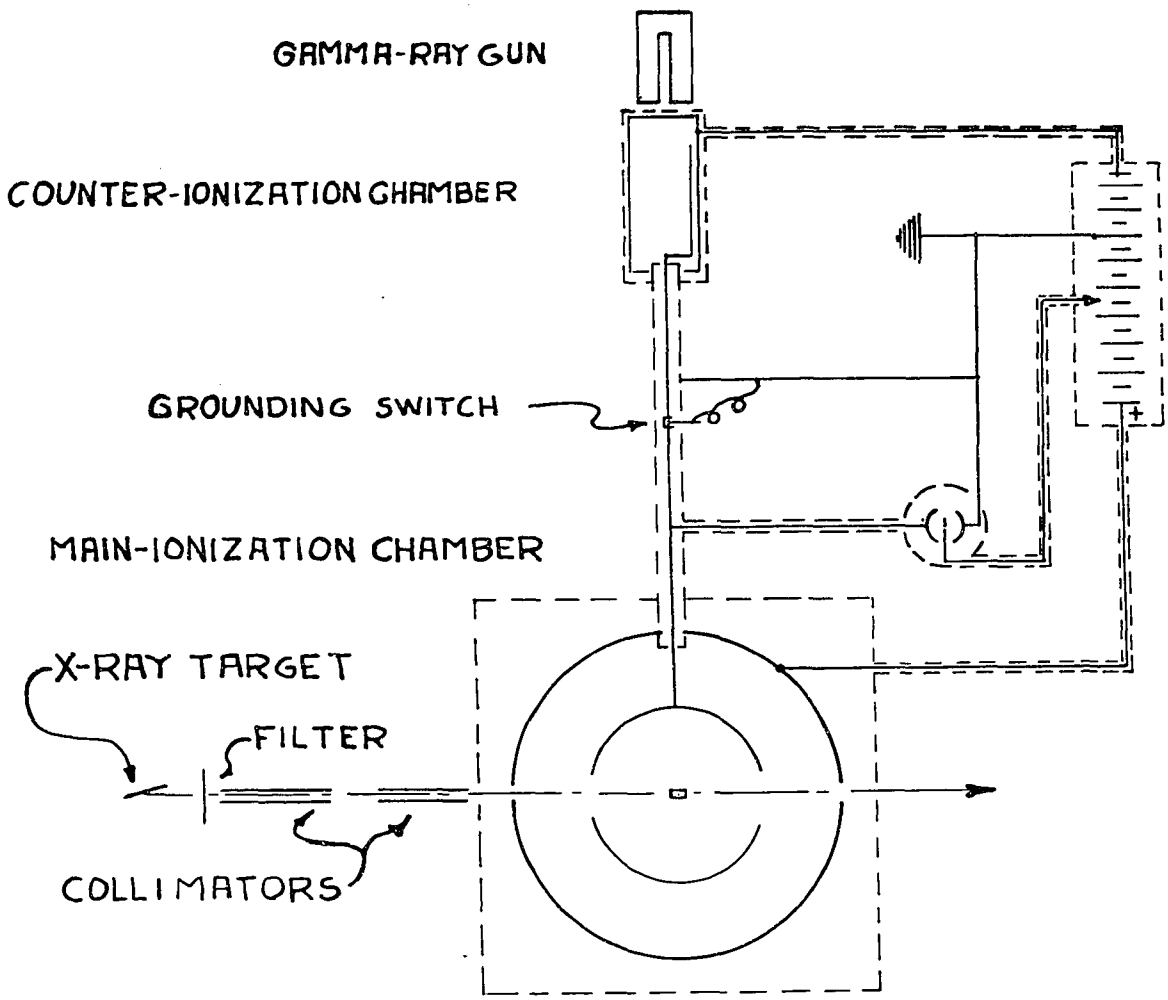
and solve for the slope using values of I_s = o and m = o. This will give the direction of the straight line OP which is tangent to the curve OQ at m = o and which represents the "total undiminished scattering curve" for the element in question.

Proceeding in the same fashion with all the elements under consideration we obtain a family of "undiminished scattering curves", from which the values of for the various elements may be compared. In this way any

value of mass may be used just as long as we use the corresponding value of I_S^* in equation 13.







APPARATUS

The General Electric Co. X-ray tube had a molybdenum water-cooled target and was rated at 25 M.A. at 45 K.V. continuous at half-wave rectification. It was powered by a transformer with control equipment manufactured by the Kelley-Koett Company.

The electrometer was of the Compton type and was of Stryker make. It was placed as close to the main ionization chamber as was practicable. The scale consisted of a graduated (perforated) closed box, 1½ meters long and illuminated from within. It was placed 3 meters away from the electrometer.

The main ionization chamber was a copper sphere, 63.5 cm. diam. and was mounted in a lead enclosure of sufficient thickness to keep out scattered radiation. The ionization grounding switch consisted of a brass cup soldered onto the output wire between the chamber and electrometer. The cup was filled with mercury into which could be dropped a brass needle. This needle was connected to the ground. Both the needle and the inside of the cup were treated with sodium amalgram so that contact-potential differences would not appear. The needle was controlled by a thread which could be operated from a convenient place.

The cooling water for the X-ray target passed

through a series of glass tubes before entering and after leaving the anode. The leak was less than 1 M.A. at 40 K.V.

METHOD OF OBSERVATION

Only the spherical ionization chamber will be considered here. The main object was to completely surround the scattering substance with the ionization chamber. This was accomplished by two methods.

1. The scatterer was suspended by fine quartz fibers through an opening at the top of the chamber. In this way the whole surface of the scatterer was in the electrostatic field. The ions formed by the incident beam were also subjected to this field.

2. The scatterer was held by means of a conical cellophane holder which was in turn held by a conical cellophane ionization shield which prevented the ions of the gas (air) in the path of the incident beam from being drawn onto the electrode. The cellophane was thin enough to permit the scattered radiation (from both air and scatterer) to pass through it without appreciable absorption. In both cases the scatterer was held in the center of the sphere so that the scattered radiation would have the same distance to travel in the chamber before striking its wall.

To neutralize the natural leak of the main chamber and the effect due to the scattered radiation of the air in the path (63.5 cm.) of the incident beam, a counter-ionization chamber was used. The latter was made adjustable by means of a gamma-ray gun.

X-rays from a molybdenum target, filtered by zirconium oxide and collimated by a series of 1.25 cm. inside diameter heavy lead columns, were directed horizontally through the center of the main chamber. The incident beam made its exit without striking the wall of the chamber. This exit was carefully shielded external to the chamber. The incident beam was approximately 1.25 cm. in diameter, and the scattering cylinders were .810 cm. in diameter, thus giving a fair margin of surety that all the mass of the scattering element was in the incident beam.

EXPERIMENTAL DIFFICULTIES AND MEASUREMENT TECHNIQUE

Considerable difficulty was experienced with the conducting quartz fiber of the electrometer. Invariably, when the fiber was coated with silver (by means of sputtering), the coating would become nonconducting in a short period of time. This was overcome by sputtering a newly made fiber with platinum.

The "B" batteries which were used to saturate both chambers caused considerable difficulty. For some reason or other two or three of them would become defective in such a way that voltage fluctuations would occur. This was overcome by frequently checking the voltage across each battery.

Scattered radiation was kept out of the chambers by placing additional lead shields in the necessary places.

The X-ray tube was designed for crystal analysis and therefore it was meant to be used in connection with a narrow slit. For this reason in the manufacture of the tube, the shield surrounding the cathode filament was placed very close to the anode. This prevented the possibility of turning the tube around to a large enough angle to supply parallel radiation having a width of 1.25 cm. Although a sodium-chloride crystal having a 4 inch face was purchased for the investigation, it could not be used for reasons just cited.

I suggest if this work is carried on, that an X-ray tube be used which has its anode at an angle of, say, 45 degrees with the main axis of the tube. Also that the filament be of the flat spiral (pancake) type. Further that the cathode shield be so constructed that the focal spot on the molybdenum target will have an area, in the plane perpendicular to the main axis of the tube, at least as large as is the collamating system. A point or line focus should not be used. If this type of tube is used, it will be possible to use a crystal and thus obtain parallel homogeneous radiation of uniform density.

The ionization chamber grounding switch described above worked exceedingly well. At no time was there a "kick" when the switch was opened regardless of how high the electrometer sensitivity was. I recommend this type switch very highly for all cases where an ionization chamber is employed.

The sensitivity of the electrometer was varied during the entire investigation from 15,000 to 30,000 mm per volt. However, for the last series of readings (the only readings contained in this thesis) the sensitivity was kept constant at about 15,000 mm per volt. Tests were made frequently to check the linearity of the electrometer.

The X-radiation used was not as homogeneous as was previously planned for. As mentioned before, it was

intended that the K_α line of molybdenum be used at the exclusion of all other wave-lengths. With this in mind the apparatus was so built and so controlled that excellent results could be obtained with this comparatively weak radiation. Since the X-ray tube construction did not permit of the use of a crystal, the investigation had to proceed with the use of filtered direct radiation which contained a large proportion of the K_α radiation of molybdenum.

Fluctuations in the supply voltage during the day time caused fluctuations in the tube potential. The final readings were taken at night to eliminate this difficulty.

It was found that when the counter-ionization chamber was adjusted so that there was a very small natural leak, instead of no leak whatsoever, the electrometer readings were more stable for very small readings. This information proved to be very helpful because the final readings taken were obtained by using very small masses.

The main ionization chamber was so constructed that total absorption could be measured as well as total scattering. This was utilized in getting information to test out the first case considered under "theory" above.

Great difficulty was experienced in preparing the cylindrical scatterers which were made from the powdered or the amorphous form of the element. It was

practically impossible to compress (as for example) boron to a final length of, say, 1.5 cm. so that the density would be uniform throughout its length. For this reason the first theory, mentioned above, was abondoned. By using the second theory it was possible to use a series of thin discs when it was required to have a long cylinder. An hydrolic press utilizing 10,000 pounds per square inch was used to compress the discs.

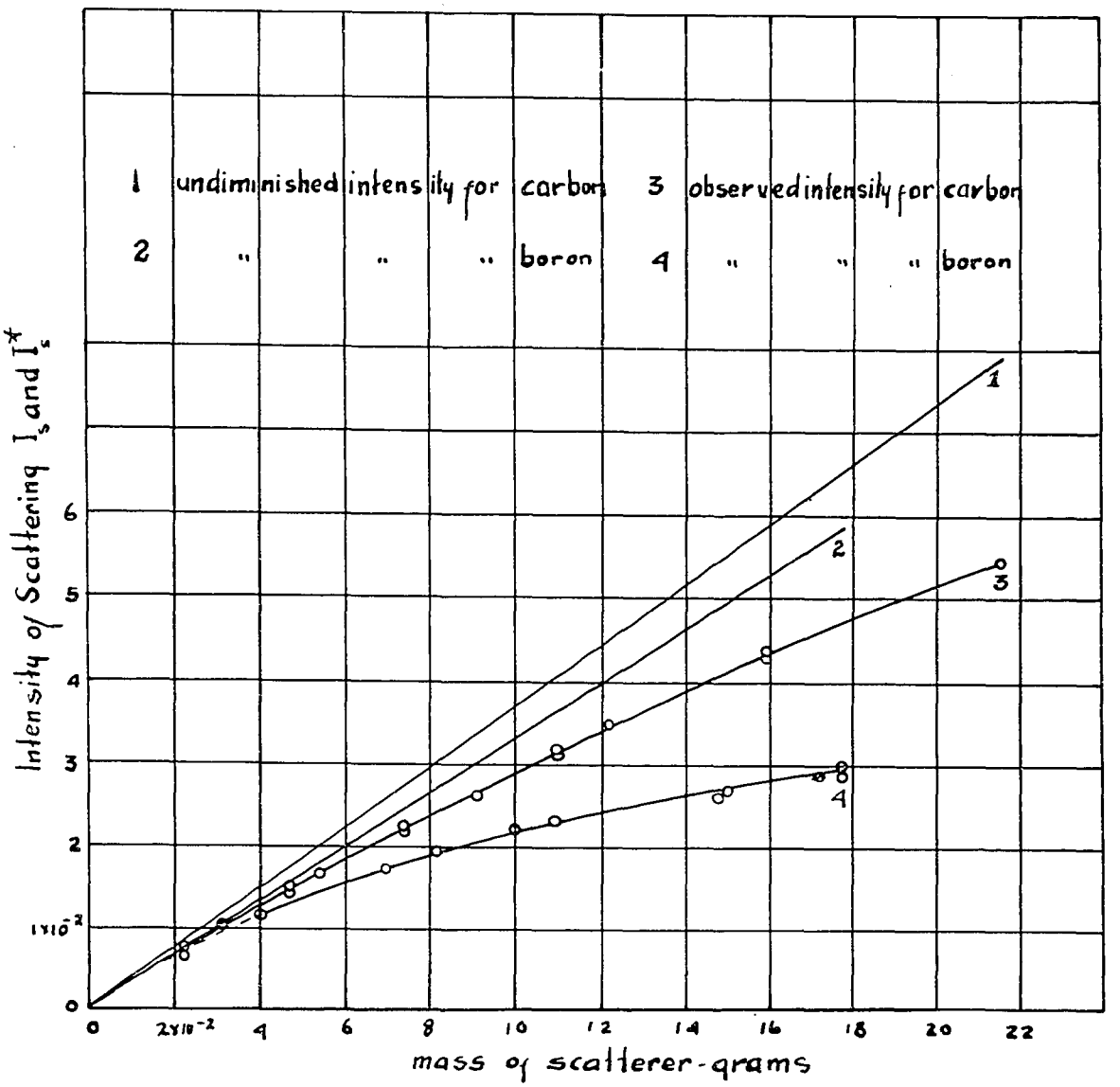
It was hoped that berylium could be compared with boron and with carbon for the final experiment. With this in mind a small lump was purchased. It was found that it would be impossible to use it in this particular form because of its porosity. Enquiry was made at the Department of Metallurgy to ascertain whether or not the sample could be molded to suit our purpose in the vacuum-electric furnace. This could be accomplished if a special mold or crucible were purchased. Since it would require two months to obtain such a special crucible, the element was eliminated from the schedule. For this reason only the relative scattering of carbon and boron will be reported on in order to illustrate the second theory described above.

SAMPLES OF SCATTERING SUBSTANCES

Samples of nearly all the stable elements were obtained from the Department of Metallurgy. The percentage of purity in some instances was very high. In the case of aluminum the purity was 99.998%. The carbon used in the final observation was made for spectroscopic use and was therefore very pure. The boron was of "K" quality, being prepared in Germany. The powdered compounds used in the earlier investigation were either supplied by the Physics Department or by the Chemistry Department.

DATA AND COMPUTATIONS FOR CARBON AND BORON

Sample	Mass	I_s	Sample	Mass	I_s
C_1	.0231	.00618	B_1	.0700	.01782
C_2	.0465	.01539	B_5	.1000	.02235
C_3	.0742	.02266	B_6	.1474	.02576
C_4	.1085	.03183	B_7	.1715	.02896
C_5	.1595	.04232	B_8	.1494	.02657
C_6	.2168	.05413	B_{10}	.1776	.03019
C_7	.0320	.0110	B_{10}	.1776	.02852
C_8	.0542	.0170	B_{7+10}	.3491	.03497
C_9	.0910	.0260	B_2	.0401	.0120
C_{10}	.1222	.0348	B_3	.0820	.0200
C_1	.0231	.00844	B_4	.1090	.0231
C_2	.0465	.01394			
C_3	.0742	.02203			
C_4	.1085	.03103			
C_5	.1595	.04287			



In order to get the "undiminished curves" from the experimental scattering curves, we determine the equations of the curves for carbon and for boron. The derivative is then obtained from which the slope is calculated for values of $I_s = m = o$.

Our equations for the experimental curves are as follows:

Carbon $I_s^2 + 40.45\ I_s + 16.1m^2 - 121.1m - 10\ I_s m = o.$

From which the slope for $I_o = m = o$ becomes $\frac{40.45}{121.1}$

Boron $I_s^2 + 35.139\ I_s + 26.33m^2 - 94.7m - 16.84\ I_s m = o.$

From which the slope for $I_o = m = o$ becomes $\frac{35.139}{94.7}$

After drawing the tangents to the carbon and boron experimental curves at the point where $I_s = m = o$, we may proceed to find the values of $(I_s^*)_C$ and $(I_s^*)_B$ which are the "undiminished scattering intensities" corresponding to the particular masses. It will be noted that any value for the mass may be used just as long as the corresponding value of I_s^* is used.

Our scattering ratio becomes

$$\frac{\left(\frac{\sigma}{\rho}\right)_c}{\left(\frac{\sigma}{\rho}\right)_B} = \frac{m_B}{m_c} \cdot \frac{\left(I_s^*\right)_c}{\left(I_s^*\right)_B} = \frac{.1}{.1} \cdot \frac{.0370}{.0335} = 1.104$$

CONCLUSION

The value of the ratio of the total mass scattering coefficients for carbon and for boron indicates that carbon scatters 1.104 times as much as does boron for a wave length of approximately .71 Å.

If we use Thomson's classical equation for scattering and form a similar ratio for carbon and boron we obtain

$$\frac{\left(\frac{4.019Z}{A}\right)_C}{\left(\frac{4.019Z}{A}\right)_B} = \frac{\frac{4.019\times 6}{12}}{\frac{4.019\times 5}{10.82}} = 1.082$$

It will be noted that the above experimental value is slightly larger than that due to the classical theory.

By preparing all the metals (or elements) in the form of cylinders of uniform diameter and of various lengths, a family of experimental curves could be plotted from which the respective "undiminished intensity curves" (straight lines) could be drawn. Using the procedure as outlined above, the relative values of $\frac{\sigma}{\rho}$ could be obtained of all these metals.

Further, if the absolute value $\frac{\sigma}{\rho}$ is known for any one of these metals or elements, the values of all the others may be obtained from the ratios thus formed. As for example, the Klien-Nashina formula could be used in connection with carbon, since it produces no so-called excess scattering, in order to arrive at a theoretical value for $\frac{\sigma}{\rho}$ which may be considered as absolute.

Having thus obtained the individual values of $\frac{\sigma}{\rho}$, these values may be placed in the equation for the total mass absorption.

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho}$$

Using Allen's[15] published values for $\frac{\mu}{\rho}$ we may obtain the true or fluorescent mass absorption of the elements. Also, the so-called "cube law" for absorption may be corrected for each wave-length and element used.

15. Allen, Chemical Rubber, 18th. Edition

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