

Experimental Study of the Absorption- Formula of the X-Rays.

Part I.

By

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1. Introduction.

The present investigation is the first step in the systematic study of the variation of the absorption coefficient of X-rays with wave-length and with the atomic number of the absorbers and also of the influence of the physical or chemical state of the absorbers on the absorption coefficient.

The generally accepted formula of the mass absorption coefficient is given, in usual notation, by

$$\frac{\mu}{\rho} = c\lambda^p \frac{Z^q}{A} + \frac{\sigma}{\rho} \dots\dots\dots (1)$$

in which the values of p and q are roughly 3 and 4 respectively, but slightly different values are proposed by different authors. For example, for q , Richtmyer¹ gives 4 for $\lambda < \lambda_k$ and 4.4 for $\lambda > \lambda_k$, while Wingårdh² gives (for the Mo K_α line) 3.77 for $\lambda < \lambda_k$ and 3.61 for $\lambda > \lambda_k$.

The measurement of this constant q is here undertaken with the molybdenum K_α line over the elements from Na to Pb.

2. The Experimental Details.

The X-ray tube used was a molybdenum target of the Coolidge

¹ Phys. Rev., **18**, 13 (1921).

² Zeits. f. Phys., **8**, 363 (1922.)

type. The filament of the tube was maintained at a constant temperature by a set of storage batteries, while the potential was supplied as high as 50 KV. by a 2 KVA high-tension transformer rectified by a kenotron. Special attention was paid to eliminating the variation of the voltage applied to the tube and the current through it, and measurements were performed almost always during the night and in the early morning. It is believed that the voltage and the current did not vary by 1 per cent during the observations.

A calcite crystal was mounted on the revolving table of the X-ray spectrometer, and fixed in the position to reflect the molybdenum K_{α} line into the ionization-chamber 22 cm. away from it. The reflected rays were confined to a narrow pencil by a system of slits, so that the image of the beam at the entrance of the ionization-chamber was 0.4 mm., while the width of the chamber slit was fixed at 1.5 mm. The absorbers were placed more than 2 cm. in front of the chamber slit.

The ionization-chamber was 40 cm. long, and 4.5 cm. in diameter. It was charged to a potential of 200 volts, the saturation voltage being 160 volts. The collecting rod was supported by amber with suitable guard rings.

The ionization current was measured by the rate of drift of a Dolezalek electrometer of the Leeds and Northrup Co. of America, which was operated at a sensitivity of approximately 600 mm. per volt.

The natural leakage of the instrument was so small that it was certainly less than one half per cent of the ionization current.

The absorbing materials were used in the form of plates in the case of Al, Cu, Zn, Sn and Ag, but in most cases water solutions of salts were used owing to the difficulty either of getting the substances in the state of elements or of making plates of uniform thickness. With solid absorbing substances the areas and masses of the screens were determined accurately and the mass absorption coefficients determined from the mass per square centimeter of the absorbing screen. The measurements were carried out at several places in the absorbers in order to avoid error arising from lack of homogeneity. For the work on solutions, cells with parallel sides were made by cutting slots in an ebonite plate, and cementing on the two sides of it celluloid films with amyl acetate. The thickness of the cell was 3.93 mm. and the concentration of the absorber was so chosen that the intensity of the transmitted beam was about from 60 to 30 per cent of the incident beam.

In the case of solutions, the intensity of the X-rays was determined in passing through the empty cell, and then in passing through the cell

filled with the solutions, and again after the cell had been dried with blotting paper.

All the substances used as absorbers were of high purity, being mostly those supplied by Kahlbaum and Merck.

3. Data and Results.

To obtain the absorption coefficients of elements from the data of salt solutions we proceeded in the following manner.

At first the mass absorption coefficient of water was determined, which was found to be 1.086.

The absorption coefficient of hydrogen was assumed to be 0.466 from the data of several authors shown in Table II. Then the value of oxygen was calculated from those of water and hydrogen by the assumption of the additive property. It was found to be 1.16. Next HCl, HNO₃ and H₂SO₄ were investigated and the absorption coefficients of Cl, So₄ and NO₃ were obtained. The data of the elements were thus found from measurements of the salt solutions which contain these radicals.

The results obtained directly from the experiments follow in Table I, and the mass absorption coefficients got from Table I are given in the last column of Table II, the data of other authors being written in the other columns for reference.

For rough approximation, we may determine the constant q in equation (1) by drawing a $\log\left(\frac{\mu}{\rho}A\right) - \log Z$ curve, but for greater exactness, we must take the $\log\left(\frac{\mu}{\rho} - \frac{\sigma}{\rho}\right)A - \log Z$ curve. But, in the present case we are concerned with only one wave-length (0.709 Å) so we borrow the $\frac{\sigma}{\rho}$ data from preceding investigators, which are tabulated in Table III, and obtain the following formula from the inclination of two lines:

$$\left(\frac{\mu}{\rho} - \frac{\sigma}{\rho}\right)A = 0.0068. Z^{3.38} \quad (\text{from Na to Sr}),$$

$$\left(\frac{\mu}{\rho} - \frac{\sigma}{\rho}\right)A = 0.00149. Z^{3.77} \quad (\text{from Ag to Pb}).$$

Values of $\left(\frac{\mu}{\rho} - \frac{\sigma}{\rho}\right)$ calculated from the above formula compared with those observed are tabulated in Table IV.

Lastly, attention must be paid to the fact that the above formula

seems to break down remarkably for the elements below Na. The investigation in that region is left for future work.

Further investigation is going forward.

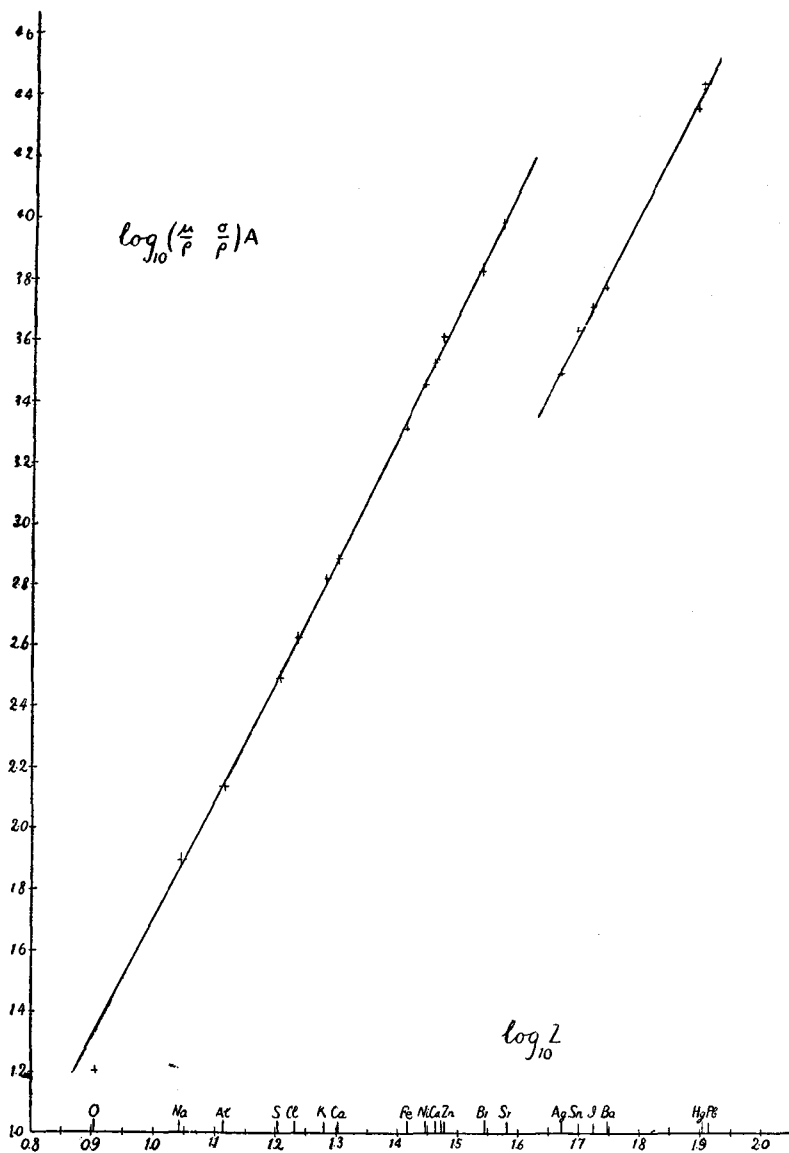


Table I.

Absorber.	Mass	Area	Intensity Ratio I_0/I	Mass Absorption Coefficient μ/ρ
Al	0.71 g	2.8035 cm ²	3.7406	5.205
Cu	0.347	8.3538	8.4746	51.43
Zn	0.170	7.1338	4.2017	60.24
Ag	0.294	6.1722	3.7736	27.88
Sn	0.192	3.4962	6.7812	34.85

Absorber.	Concentration %	Density (ρ) at Temperature (t)	Intensity Ratio I_0/I	μ/ρ
H ₂ O			1.53235	1.086
HCl	25.55	1.1273 12°C	5.3141	11.592
HNO ₃	13.50	1.078 12.7°C	1.5847	1.091
H ₂ SO ₄	28.93	1.2168 10.0°C	2.5067	3.975
NaCl	20.21	1.1519 13.5°C	3.2590	8.623
KCl	16.00	1.100 11.0°C	4.0647	14.510
CaCl ₂	15.08	1.134 11.2°C	3.9909	14.478
FeCl ₃	6.98	1.0596 13.0°C	2.7373	20.174
NiCl ₂	6.20	1.0615 12.8°C	3.1456	27.878
KBr	4.10	1.0288 15.0°C	4.0457	58.910
Sr(NO ₃) ₂	3.92	1.032 13.0°C	3.08718	44.284
KI	6.55	1.0496 13.6°C	3.74402	33.366
BaCl ₂	7.57	1.0705 15.8°C	4.04935	30.652
HgCl ₂	2.65	1.0212 17.2°C	3.63636	81.490
Pb(NO ₃) ₂	1.577	1.0122 11.7°C	2.48428	77.275

Table IV.

Z	Element.	$\left(\frac{\mu}{\rho} - \frac{\sigma}{\rho}\right)$	
		observed.	calculated.
8	O	1.0	1.37
11	Na	3.41	3.27
13	Al	5.06	5.31
16	S	9.67	10.05
17	Cl	11.76	11.30
19	K	16.70	16.06
20	Ca	18.86	19.12
26	Fe	35.72	38.01
28	Ni	46.95	48.23
29	Cu	51.22	51.01
30	Zn	60.02	56.58
35	Br	79.23	84.23
38	Sr	105.14	105.73
47	Ag	27.30	27.80
50	Sn	34.22	31.91
53	I	37.80	37.17
56	Ba	39.65	42.27
80	Hg	105.2	111.0
82	Pb	121.85	118.0

Table II. Total Mass Absorption Coefficient. ($\lambda=0.709 \text{ \AA. U.}$)

Element.	(1) Hull, Rice	(2) Hewlett.	(3) Richtmyer	(4) Taylor	(5) Wingårdh	(6) Wingårdh	Olson, Dershem and Storch. (7)	Richtmyer, Warburton. (8)	(9) Allen	Stoner & Martin. (10)	(11) Richtmyer	(12) Allen	Tshino, Kawata.
(H ₂ O)				1.089		1.0	1.086 (A)						1.086
H		0.65 (A)		0.28			0.467 (A)						(0.466)
N					1.072	1.1							0.90
O		1.11 (A)		1.15	1.000	1.0	1.157 (A)						1.16
Na					3.392	3.4							3.56
Al	5.42 (B)	5.03 (A)	5.21 (A)	5.15	5.276	5.27			5.35	5.176		5.29	5.21
S					8.827	8.8			9.9				9.82
Cl					11.70	11.9							11.91
K					16.21	16.1							16.87
Ca					20.17	19.7							19.03
Fe		36.7 (A)			36.93	37.4		39.4 (B)				38.4	35.92
Ni					48.19	48.0		51.9 (B)				47.0	47.16
Cu	53.6 (B)		51.3 (A)		46.33	46.2		54.7 (B)	53.7	49.8		52.0	51.43
Zn					55.22	55.2			60.0			59.	60.24
Br					67.22	67.2							79.48
Sr					94.28	94.3							105.4
Ag			31.1 (B)		30.79	30.8			28.5	26.0	26.0 (B)	26.8	27.88
Sn					35.04	35.1				31.7	33.1 (B)	32.5	34.85
I					39.76	39.4							38.45
Ba					41.36	41.3							40.33
Hg													106.1
Pb	153.4 (B)		181. (B)		101.7	102.			140.		170.3 (B)	140.	122.8

(A) Interpolated value from the author's data.

(B) Extrapolated value from the author's data.

(1) Phys. Rev. **8**, 1916.(2) Phys. Rev. **17**, 1921.(3) Phys. Rev. **18**, 1921.(4) Phys. Rev. **20**, 1922.(5) Zeits. f. Phys. **8**, 1922

(6) Diss. Lund. 1923.

(7) Phys. Rev. **21**, 1923.(8) Phys. Rev. **22**, 1923.(9) Phys. Rev. **24**, 1924.(10) Proc. Roy. Soc. London, **107**, 1925.(11) Phys. Rev. **27**, 1926.(12) Phys. Rev. **28**, 1926.

Table III. Mass Scattering Coefficient.

Author.	(1) Hull & Rice	(2) Hewlett.	(3) Richtmyer	(4) Hewlett.	(5) Wingardh	Olson, Dershem, Storch. (6)	Richtmyer, (7) Warburton.	(8) Richtmyer.	Allen. (9)	Mean	Assumed.
Wave-lengths Used.	0.147A.	0.105	(A) On short, (B) on long wave-length side of K limit	0.721	0.156	0.2455	0.12	On the long wave-length side of K limit.	(Mean of the data with 0.08, 0.12 and 0.21.)		
Element.	-0.392	-1.054		+0.455	-0.254	-0.9773	-0.30				
1	H			0.463		0.37				0.381	
3	Li									0.157	
6	C			0.220		0.18			0.147	0.181	
7	N									0.168	
8	O					0.16				0.163	0.163
11	Na										0.154
13	Al	0.12		0.16 (A)		0.13			0.143	0.145	0.145
16	S								0.151	0.151	0.150
17	Cl										0.156
19	K										0.166
20	Ca										0.170
26	Fe			0.18			0.18		0.175	0.178	0.198
27	Co				0.27		0.18			0.225	0.204
28	Ni						0.20			0.20	0.208
29	Cu	0.12		0.5 (A)		0.29	0.20		0.192	0.26	0.214
30	Zn								0.195	0.195	0.218
35	Br										0.243
38	Sr										0.257
42	Mo			1.0 (B)				1.0		1.0	
47	Ag			0.6		0.47		1.0	0.43	0.63	0.58
50	Sn							1.0	0.42	0.71	0.63
53	I										0.65
56	Ba								0.61	0.61	0.68
72	W							0.8	0.88	0.84	
79	Au							0.85	1.1	0.98	
80	Hg										0.93
82	Pb							0.7	1.1	0.9	0.95

(1) Phys. Rev. 8, 1916.

(2) Phys. Rev. 17, 1921.

(3) Phys. Rev. 18, 1921.

(4) Phys. Rev. 20, 1922.

(5) Diss. Lund, 1923.

(6) Phys. Rev. 21, 1923.

(7) Phys. Rev. 22, 1923.

(8) Phys. Rev. 27, 1926.

(9) Phys. Rev. 27, 1926.