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*THE DETERMINATION OF
SOME X-RAY ATTENUATION COEFFICIENTS
IN THE RANGE 26.3 TO 2.3 keV*

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The Determination of Some X-Ray Attenuation Coefficients in the Range 26.3 to 2.3 keV

By J. L. Dalton* and J. Goldak**

The need for reliable measurement of the X-ray mass attenuation coefficients of many elements over a wide wavelength range has been pointed out by several authors^(1,2,3,4). The data presented in this note will expand the range of measured coefficients for praseodymium, gadolinium, and erbium, corroborate recent work^(3,7) on titanium, vanadium, iron, nickel, and copper, and also illustrate the reliability of Heinrich's tables⁽¹⁾.

The measurements were made on a 100 kv Norelco constant potential single-crystal X-ray spectrometer. Pure elements, oxides, or simple salts of analytical reagent quality were used to obtain K series fluorescent radiation. Two Soller collimators, one located before and one after the analyzing crystal, were used to collimate the emitted radiation. Two LiF crystals and an EDDT crystal, all of different 2d spacings, were available for the study. The spectrometer is equipped with two detectors in tandem, a gas flow proportional counter leading and a scintillation counter trailing. The scintillation counter was used with wavelengths up to approximately 2A and the flow counter for wavelengths greater than 2A. A helium path was used for measurement of wavelengths greater than 2.748A.

An externally operated four port foil holder was used to insert absorbing foils into the X-ray path. The foil holder was located between the first Soller collimator and the analyzing crystal. A coefficient of variance of 0.3 per cent was obtained for a reproducibility investigation of this device.

In most cases 384,000 and 96,000 counts were collected for incident and attenuated intensities respectively. Where attenuation was large, however, 64,000 counts were collected for the attenuated intensity. The count rate was maintained below 12,000 cps and correction for count

loss was applied. Five replications per foil and a minimum of three foils were used to obtain a single mass attenuation coefficient.

The transition metal foils were purchased from Advanced Materials Corporation and the rare earth foils were purchased from Johnson, Matthey and Mallory Ltd. The foils were examined for purity by optical emission analysis and found to be acceptable for attenuation coefficient measurement. The uniformity of thickness was assessed by measuring the coefficient in different areas of a foil. This was accomplished by masking portions of the X-ray beam.

In a study of this nature, it is desirable to maintain the ratio of the attenuated to incident intensity between 0.04 and 0.6. Absorbers of approximately ten microns thickness are required to maintain this range. The purchased foils were therefore reduced in thickness from twenty microns to approximately ten microns by pack-rolling⁽⁵⁾.

The mass attenuation coefficient was calculated by the standard absorption equation

$$\frac{\mu}{\rho} = \frac{A}{w} \ln \frac{I_0}{I} \quad (1)$$

where $\frac{\mu}{\rho}$ is the mass attenuation coefficient

A is the area of the foil

w is the weight of the foil

I_0 and I are the incident and attenuated intensities respectively.

The foil area was measured with a Gaertner tool-makers microscope and the weight with a Mettler Micro gram-atic analytical balance. The results of the study are listed in Table 1.

The relative standard deviation, calculated from the replications for a single coefficient, varied from 0.3 per cent to 2.4 per cent. It was less than one per cent for titanium and copper coefficients. For vanadium, iron and nickel, the relative standard deviation was less than one per cent for coefficients less than 200 cm²/gm, and 1.5 to 2.4 per cent for coefficients greater than 200. The relative standard deviation for the rare earths is in the range one to two per cent.

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Table 1
Mass Attenuation Coefficients

Element	Wavelength (Å)	Mass Attenuation Coefficient (cm ² gm ⁻¹)	Element	Wavelength (Å)	Mass Attenuation Coefficient (cm ² gm ⁻¹)
Titanium	0.927	50.2	Copper	0.746	56.5
	1.041	68.6		0.876	87.4
	1.341	138.8		1.106	163.5
	1.659	248.0		1.341	284.5
	1.937	376.1		1.392	38.2
	2.103	476.9		1.937	97.3
	2.291	601.5		2.291	156.5
	2.504	88.9		2.504	200.3
	2.748	110.2		2.748	262.7
	3.359	194.2	Praseodymium	0.514	20.7
	3.742	259.6		0.787	65.7
	4.728	498.0		1.041	138.8
	5.373	678.9		1.341	270.4
Vanadium	0.710	26.1		2.085	186.0
	0.927	55.3		2.291	232.3
	1.177	107.5		2.504	284.2
	1.341	153.1	Gadolinium	0.492	23.7
	1.542	221.9		0.615	42.9
	1.937	419.7		0.748	72.6
	2.103	529.9		0.927	128.2
	2.284	74.1		1.106	205.3
	2.748	123.8		1.255	283.5
	3.359	227.3		1.436	394.2
	3.742	302.5		1.757	152.6
	4.728	558.0		2.103	249.2
Iron	0.746	43.1		2.291	308.3
	0.876	66.8		2.504	363.3
	1.177	149.7	Erbium	0.472	25.2
	1.295	193.5		0.561	40.1
	1.542	309.9		0.711	75.7
	1.659	388.0		0.877	130.4
	1.757	53.0		0.927	151.4
	2.085	86.5		1.041	207.8
	2.748	189.0		1.128	253.5
	3.359	334.2		1.255	325.8
	3.742	438.0		1.295	302.2
Nickel	0.746	53.6		1.341	247.3
	0.876	82.6		1.436	291.1
	1.106	154.5		1.500	120.3
	1.295	237.0		1.790	196.4
	1.436	320.0		2.291	369.2
	1.500	44.0			
	1.937	89.9			
	2.291	144.0			
	2.504	185.9			
	2.748	243.4			
	3.359	419.8			

The variation in the precision of the measurements can be attributed to lack of thickness uniformity in the foils. It is difficult to prepare foils with a thickness variation of less than five per cent at the ten microns level⁽⁶⁾, the thickness level which produced the largest differences amongst replications for a specific wavelength and absorber.

The results of the study were used to calculate values of the constant C and the exponent n for the equation

$$\frac{\mu}{\rho} = C\lambda^n \quad [2]$$

where λ is the wavelength, as proposed by Le-roux⁽⁶⁾. These values are listed in Table 2. The mass attenuation coefficients were analyzed for dependence on atomic number by extending equation [2] to

$$\frac{\mu}{\rho} = bZ^k\lambda^n \quad [3]$$

in a similar manner to Carter et al⁽⁷⁾. The values for the constant b and the exponents k and n are listed in Table 3.

Table 2

Values for the Constant C and the Exponent n for the expression
 $\mu/\rho = C\lambda^n$ calculated from the experimental data

Element	Z	$\lambda < \lambda_{KA}$		$\lambda_{KA} < \lambda < \lambda_{LIA}$		$\lambda_{LIA} < \lambda < \lambda_{MIA}$	
		C	n	C	n		
Titanium	22	61.71	2.746	7.382	2.696	—	—
Vanadium	23	67.84	2.760	7.566	2.782	—	—
Iron	26	95.91	2.736	11.14	2.794	—	—
Nickel	28	118.2	2.718	14.13	2.804	—	—
Copper	29	125.9	2.747	15.00	2.829	—	—
Praseodymium	59	—	—	124.0	2.678	33.97	1.531
Gadolinium	64	—	—	155.1	2.632	38.38	2.481
Erbium	68	—	—	183.7	2.626	41.81	2.640

λ_{KA} wavelength of the K absorption edge

λ_{LIA} wavelength of the Li absorption edge

λ_{LIIIA} wavelength of the LIII absorption edge

λ_{MIA} wavelength of the MI absorption edge

Table 3

Values for the Constant b and the Exponents k and n for the
 expression $\mu/\rho = bZ^k\lambda^n$ calculated from the experimental data

Z, λ Region.....	b	k	n
Z = 22 to 29.....	0.01603	2.668	2.750
$\lambda < \lambda_{KA}$			
Z = 22 to 29.....	0.0003746	3.163	2.784
$\lambda_{KA} < \lambda < \lambda_{LIA}$			
Z = 59 to 68.....	0.001216	2.827	2.644
$\lambda_{KA} < \lambda < \lambda_{LIA}$			

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