

## Measurement of mass attenuation coefficients in some Cr, Co and Fe compounds around the absorption edge and the validity of the mixture rule

U TURGUT\*, O ŞİMŞEK and E BÜYÜKKASAP

Department of Physics Education, Education Faculty, Atatürk University, 25240, Erzurum, Turkey

\*Corresponding author. E-mail: umitturgut2000@yahoo.com

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**Abstract.** The total mass attenuation coefficients for elements Cr, Co and Fe and compounds  $\text{CrCl}_2$ ,  $\text{CrCl}_3$ ,  $\text{Cr}_2(\text{SO}_4)_3 \cdot \text{K}_2\text{SO}_4 \cdot 24\text{H}_2\text{O}$ ,  $\text{CoO}$ ,  $\text{CoCl}_2$ ,  $\text{Co}(\text{CH}_3\text{COO})_2$ ,  $\text{FePO}_4$ ,  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ,  $\text{Fe}(\text{SO}_4)_2 \cdot \text{NH}_4 \cdot 12\text{H}_2\text{O}$  were measured at different energies between 4.508 and 14.142 keV using secondary excitation method. Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr were chosen as secondary exciters. 59.5 keV  $\gamma$ -rays emitted from a  $^{241}\text{Am}$  annular source were used to excite a secondary exciter and  $\text{K}_\alpha$  (K-L<sub>3</sub>, L<sub>2</sub>) lines emitted by the secondary exciter were counted by a Si(Li) detector with a resolution of 160 eV at 5.9 keV. It was observed that mixture rule method is not a suitable method for determination of the mass attenuation coefficients of compounds, especially at an energy that is near the absorption edge. The obtained values were compared with theoretical values.

**Keywords.** Absorption edge; mixture rule; mass attenuation coefficients; X-ray absorption fine structure.

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### 1. Introduction

Reliable values of X-ray mass attenuation coefficients of compounds are required in a variety of applications, such as radiograph, tomography, dosimetry, space physics, plasma physics, etc. It is well-known that the mass attenuation coefficient,  $\mu/\rho$ , for compounds is customarily computed using the mixture rule which is given by

$$\frac{\mu}{\rho} = \sum_i w_i \left( \frac{\mu}{\rho} \right)_i \quad (1)$$

where  $w_i$  is the proportion by weight and  $(\mu/\rho)_i$  is the mass attenuation coefficient of the  $i$ th constituent element of the compound. However, the  $\mu/\rho$  value for an element in a compound may vary substantially for incident photon energies that lie

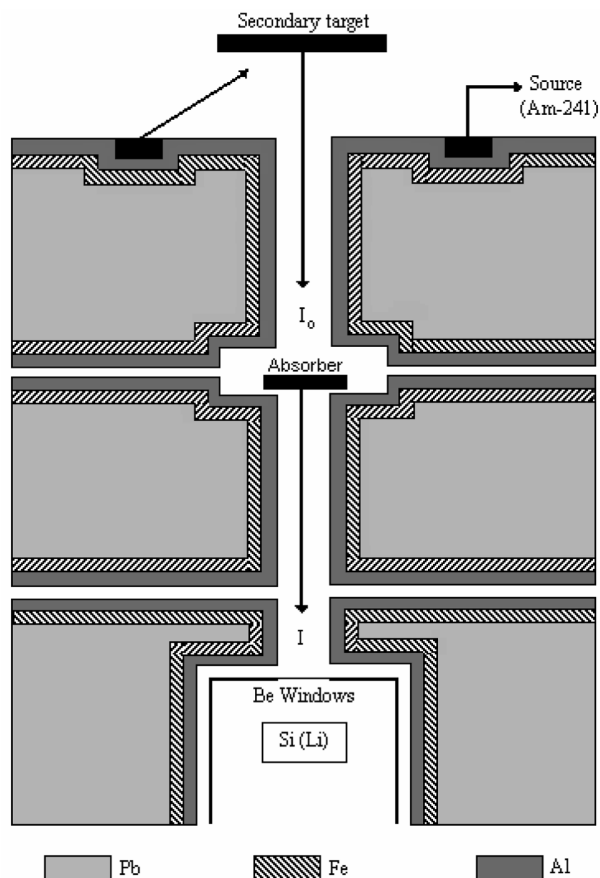
within about 1.5 keV above the element's absorption edge. This is because of the existence of fine structure above the edge (XAFS; X-ray absorption fine structure) that is known to be oscillatory in nature. The  $\mu/\rho$  values are also believed to be affected by the chemical, molecular and thermal environments. These phenomena lead to the deviation of the experimental  $\mu/\rho$  value from that of the theoretical value, since the calculation of the theoretical value has been done by considering the cross-section of an isolated atom. This deviation is termed as the breakdown or the nonvalidity of the mixture rule. Mass attenuation and energy absorption coefficients are widely used in the study of interaction of  $\gamma$ -rays with matter. Many measurements have been reported [1–4]. In recent years, there has been renewed interest in the measurement of photon interaction cross-sections at low energies, especially energies close to absorption edges of elements [5–8].

A review of the literature shows that a number of experimental studies on mass attenuation coefficients and mixture rule were reported by Turgut *et al* [9–11]. Preşeren and Kodre [12] have studied X-ray absorption coefficient of rubidium in the K-edge region. Recently, Gesward [13] measured the total cross-sections for various elements in the energy range 4.5–20 keV. Kerur *et al* [14,15] measured the X-ray attenuation coefficients for various elements and compounds. Hubbell *et al* [16] estimated the magnitude of the discrepancy between theoretical and experimental K-edge cross-sections for the elements from Ti to Zn to be in the range from  $\pm 3\%$  to  $\pm 12\%$ . Lakshminarayana [17] found some indications for the existence of chemical effects and hence for the nonvalidity of the additivity law in some bromide compounds for photon energies that lie within 1 keV above the Br K-edge. Nagel [18] had also pointed out, while discussing the absorption edge effects in electron probe microanalysis, that the tabulated  $\mu/\rho$  values can be in error by  $\pm 50\%$  near the edge and by  $\pm 10\%$  up to 400 eV above the edge. Jackson [19] pointed out that the range of validity of the mixture rule is not established close to absorption edge.

In the present work, the effect of fine structure on  $\mu/\rho$  values by using compounds containing one element with its absorption edge close to the incident photon energy has been studied. Results obtained in this investigation show the nonvalidity of the mixture rule above the edge, within certain ranges.

## 2. Experimental set-up and measurements

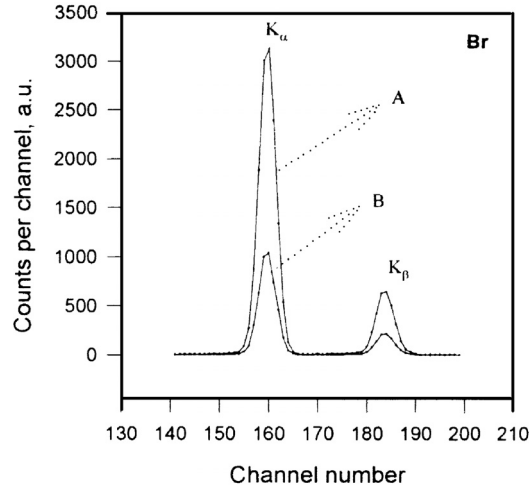
The total attenuation coefficients were determined by measuring transmission of the fluorescent K X-rays through targets of known thickness. The experimental arrangement is shown in figure 1. Target element and its compounds are selected to meet the requirements for the study of the mixture rule. Secondary targets of the elements Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr were irradiated, in turn, with 59.5 keV  $\gamma$ -rays from the  $^{241}\text{Am}$  annular source. The emitted K fluorescent X-rays were collimated by the lead collimator shielded with aluminium and iron to fall on the absorbers, each of thickness 100–200  $\mu\text{g}/\text{cm}^2$  of Cr,  $\text{CrCl}_2$ ,  $\text{CrCl}_3$ ,  $\text{Cr}_2(\text{SO}_4)_3\text{K}_2\text{SO}_4\cdot 24\text{H}_2\text{O}$ , Co, CoO,  $\text{CoCl}_2$ ,  $\text{Co}(\text{CH}_3\text{COO})_2$ , Fe,  $\text{FePO}_4$ ,  $\text{FeCl}_3\cdot 6\text{H}_2\text{O}$ ,  $\text{Fe}(\text{SO}_4)_2\text{NH}_4\cdot 12\text{H}_2\text{O}$  high-purity (99.00–99.99%) powder samples. In order to eliminate the particle size effect, all the samples were sieved through a 400 mesh sieve. The thickness of the target,  $t$ , satisfied the condition



**Figure 1.** Experimental arrangement. The distances between secondary target and absorber and between absorber and detector are 70 and 90 mm respectively and the diameter of collimator is 3 mm.

$\mu t < 1$ . Thus, effects of multi-scattered photons on the targets were reduced [2]. To minimize the effect of small-angle scattering in the absorber, the transmitted K X-rays were further collimated by the lead collimator shielded with aluminum and iron and counted using a Si(Li) X-ray detector (energy resolution of 160 eV at 5.9 keV) connected to a ND 66B multichannel analyzer. A typical spectrum is given in figure 2. Spectra were recorded with and without the absorber for different energies of K fluorescent lines. Average energies for  $K_{\alpha}$  (K-L<sub>2</sub>,L<sub>3</sub>) lines of secondary targets were taken from Storm and Israel [20].

The counts for the measurements of each X-ray group were taken in the following sequence: no absorber ( $I_0$ ), absorber ( $I$ ). In an ideal transmission experiment, the photon once scattered in the absorber, even at a very small angle, should not be detected. In the experimental set-up, the distances between secondary target and absorber and between absorber and detector are 70 and 90 mm respectively and the



**Figure 2.** Spectra of Br K X-rays without absorber (curve A) and with  $\text{CoCl}_2$  absorber (curve B).

diameter of collimator is 3 mm. We assumed that in the experimental arrangement we satisfied this condition.

Total mass attenuation coefficient,  $\mu/\rho$  ( $\text{cm}^2/\text{g}$ ) of elements and compounds were calculated from the following equation obtained from

$$I = I_0 \exp \left[ - \left( \frac{\mu}{\rho} \right) t \right], \quad (2)$$

$$\frac{\mu}{\rho} = -\frac{1}{t} \left( \ln \frac{I}{I_0} \right), \quad (3)$$

where  $t$  ( $\text{g}/\text{cm}^2$ ) is the thickness of target;  $I$  and  $I_0$  are areas measured under the peak for the absorber and in absence of an absorber respectively. The  $\mu/\rho$  values obtained experimentally in the present investigation and a comparison with the theoretical values obtained by Storm and Israel [20] and Hubbell and Seltzer [21], Hubbell [22] are presented in table 1. For compounds the theoretical  $\mu/\rho$  values were determined from the mixture rule by using the tables of Storm and Israel [20], Hubbell and Seltzer [21] and Hubbell [22]. The relative difference (RD) between the experimental and Hubbell and Seltzer [21] values are presented in the last column in table 1. They were calculated using the equation

$$\text{RD} = \frac{(\mu/\rho)_{\text{exp.}} - (\mu/\rho)_{\text{theory}}}{(\mu/\rho)_{\text{theory}}} \times 100\%. \quad (4)$$

Column 2 in table 1 presents  $\Delta E = E_x - E_b$ , in keV, to indicate the K-edge position of the element of interest in the respective compound from the incident photon energy [23].

### 3. Results and discussion

The present measured values of mass attenuation coefficients in some compounds at different energies were calculated using eq. (1) and are listed in table 1. The validity of the mixture rule is considered for compounds. The estimated error in the experimentally measured  $\mu/\rho$  value is  $<3\%$ . The error arises due to the uncertainties in various physical parameters, namely the errors in the evaluation of area under the  $K_{\alpha}$  X-ray peaks and target thickness. From table 1, it is clear that the experimental values for Cr, Co and Fe elements agree closely with the theoretical values. For compounds, where the K-edges lie far away from the photon energy, the experimental values agree closely with the theoretically estimated values using the mixture rule. This indicates that for compounds whose absorption edges are far away from the incident photon energy, the mixture rule is applicable. In other words, the edge structure, chemical environmental effects do not extend beyond a certain region, say more than about 1.5 keV and  $\mu/\rho$  values are not affected by these effects. Hence the mixture rule can be used to calculate  $\mu/\rho$  for compounds with such  $\Delta E$  values. However, for  $\Delta E = +0.411$  keV,  $+0.332$  keV and  $+0.360$  keV for Cr, Co and Fe compounds, the experimental value deviates by as much as  $+18.2\%$ ,  $+11.7\%$  and  $+14.6\%$ , indicating the introduction of an uncertainty in the  $\mu/\rho$  value near the absorption edge.

Similar observations were reported by different authors [11,14,15]. In their paper Kerur *et al* [14] pointed out that when  $\Delta E$  goes from  $+1.502$  to  $+0.929$  to  $+0.332$  keV, the RD goes from  $-14\%$  to  $-8.8\%$  to  $+14.4\%$ . This shows that RD is oscillatory in nature and is evidently due to the oscillatory nature of the XAFS contribution.

We know that attenuation coefficient decreases with increasing photon energy in the region above the absorption edges. But it had been observed that, except for a simple single-atom system, absorption coefficient oscillates as the energy of photons increases in the part just above the absorption edge with higher energy generally. This complex structure in the higher energy part of the absorption edge is defined as XAFS (X-ray absorption fine structure). The reason for this event may be the interference of de Broglie waves of electrons. It is known that the appearance of an absorption edge indicates that energy of the incident photon is sufficient to remove and eject an inner shell electron in an atom. In contrast to a simple single-atom system, an atom in bulk matter is not isolated but is surrounded by other atoms. The de Broglie wave of the ejected electron can be scattered by surrounding atoms to form an inward-directed wave, which interferes with the original outward-directed wave. This interference can result in an increase or a decrease in electron intensity to produce oscillation in the absorption coefficient. Since XAFS results from the effect of adjacent atoms, it is clearly related to the atom's environments [24]. Since atom in different compounds has different environment, chemical structure plays an important role on this effect. The  $\mu/\rho$  value in the XAFS region is very sensitive to the incident photon energies. We may consider the observed deviation to be due to the effect of the XAFS and the effects of the chemical environment on the  $\mu/\rho$  value and hence conclude that the mixture rule is not applicable at this energy for these compounds. The negative deviation may be attributed to the oscillatory nature of the XAFS.

**Table 1.** Comparison of experimental and theoretical mass attenuation coefficients (in  $\text{cm}^2/\text{g}$ ) for elements Cr, Co and Fe and their various compounds at different energies.  $\Delta E = E_x - E_b$  in keV indicate the K-edge position of the element of interest in the respective compound from the incident photon energy.

Element/ compounds	$\Delta E$ (keV)	Exp.	Theor. [21]	Theor. [20]	Theor. [22]	Relative difference between exp. and theor. [21] (%)
Cr	-1.481	148.38±3	143.36	141.71	—	+3.5
	+0.411	422.40±10	439.00	449.29	—	-3.8
	+0.936	346.45±7	360.51	365.90	—	-3.9
	+1.483	309.12±6	298.09	300.18	—	+3.7
	+2.052	243.68±6	247.89	247.85	—	-1.7
	+2.642	200.72±4	205.24	204.83	—	-2.2
	+4.543	117.98±2	120.27	119.60	—	-1.9
	+5.221	98.96±2	101.40	100.85	—	-2.4
	+5.918	87.35±1	85.97	85.83	—	+1.6
	+7.386	61.42±1	62.55	62.25	—	-1.8
+8.153	52.78±1	53.70	53.45	—	-1.7	
CrCl <sub>2</sub>	-1.481	335.46±8	356.49	355.32	—	-5.9
	+0.411	272.41±6	300.34	304.17	—	-9.3
	+0.936	222.36±6	244.62	246.30	—	-9.1
	+1.483	187.28±4	200.73	200.96	—	-6.7
	+2.052	172.05±4	165.75	165.08	—	+3.8
	+2.642	130.52±4	136.67	135.99	—	-4.5
	+4.543	82.06±2	79.21	78.64	—	+3.6
	+5.221	69.10±1	66.57	66.06	—	+3.8
	+5.918	58.02±1	56.28	55.82	—	+3.1
	+7.386	41.72±1	40.71	40.35	—	+2.5
+8.153	33.84±1	34.85	34.53	—	-2.9	
CrCl <sub>3</sub>	-1.481	415.10±9	391.24	390.14	—	+6.1
	+0.411	249.47±7	277.81	280.60	—	-10.2
	+0.936	250.19±8	225.80	226.88	—	+10.8
	+1.483	200.44±5	184.91	184.84	—	+8.4
	+2.052	144.33±4	152.41	151.64	—	-5.3
	+2.642	118.75±2	125.53	124.81	—	-5.4
	+4.543	69.71±2	72.54	71.99	—	-3.9
	+5.221	59.03±2	60.92	60.41	—	-3.1
	+5.918	53.41±1	51.45	51.09	—	+3.8
	+7.386	38.35±2	37.16	36.79	—	+3.2
+8.153	33.16±1	31.79	31.46	—	+4.3	
Cr <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> K <sub>2</sub> SO <sub>4</sub> ·24H <sub>2</sub> O	-1.481	154.98±5	168.83	168.09	—	-8.2
	-0.411	122.80±6	103.89	104.41	—	+18.2
	-0.936	97.15±4	84.12	84.30	—	+15.5
	-1.483	73.50±4	68.63	68.45	—	+7.1
	+2.052	59.64±1	56.38	55.97	—	+5.8
	+2.642	44.40±1	46.40	45.94	—	-4.3
	+4.543	27.93±1	26.65	26.34	—	+4.8
+5.221	21.48±1	22.37	22.11	—	-4.0	

Mass attenuation coefficients for Cr, Co and Fe compounds

Table 1. Continued...

Element/ compounds	$\Delta E$ (keV)	Exp.	Theor. [21]	Theor. [20]	Theor. [22]	Relative difference between exp. and theor. [21] (%)
Co	+5.981	18.21±1	18.88	18.66	—	-3.6
	+7.386	14.08±1	13.63	13.47	—	+3.3
	+8.153	12.25±1	11.66	11.52	—	+5.1
	-3.201	206.68±4	203.03	202.43	—	+1.8
	-2.760	154.84±3	158.66	157.57	—	-2.4
	-2.298	120.33±3	124.31	122.98	—	-3.2
	-1.814	101.58±3	98.33	96.84	—	+3.3
	+0.332	303.93±6	320.60	324.69	—	-5.2
	+0.922	256.50±5	267.75	269.49	—	-4.2
	+2.823	162.72±5	158.14	159.21	—	+2.9
	+3.501	138.88±3	135.49	134.71	—	+2.5
	+4.198	119.16±3	115.24	114.60	—	+3.4
	+5.666	82.83±2	84.35	83.93	—	-1.8
+6.433	74.59±2	72.63	72.28	—	+2.7	
CoO	-3.201	177.12±5	173.47	172.97	—	+2.1
	-2.760	140.36±3	135.22	134.35	—	+3.8
	-2.298	100.86±3	105.75	104.69	—	-4.6
	-1.814	87.96±3	83.53	82.12	—	+5.3
	+0.332	235.86±6	254.43	257.59	—	-7.3
	+0.922	196.49±5	212.42	213.74	—	-7.5
	+2.823	131.15±3	125.38	126.19	—	+4.6
	+3.501	102.68±3	107.41	106.75	—	-4.4
	+4.198	94.91±2	91.34	90.81	—	+3.9
	+5.666	68.93±2	66.85	66.49	—	+3.1
	+6.433	59.68±1	57.55	57.26	—	+3.7
CoCl <sub>2</sub>	-3.201	359.49±9	371.76	371.03	—	-3.3
	-2.760	280.02±6	290.47	289.43	—	-3.6
	-2.298	237.09±6	228.19	227.16	—	+3.9
	-1.814	188.63±3	180.85	179.92	—	+4.3
	+0.332	184.19±4	203.30	204.54	—	-9.4
	+0.922	183.69±4	168.84	169.15	—	+8.8
	+2.823	104.00±3	98.67	98.89	—	+5.4
	+3.501	87.22±1	83.98	83.36	—	+3.8
	+4.198	68.14±1	71.21	70.67	—	-4.3
	+5.666	53.58±2	51.82	51.40	—	+3.4
	+6.433	46.27±1	44.49	44.13	—	+4.0
Co(CH <sub>3</sub> COO) <sub>2</sub>	-3.201	101.76±3	98.28	98.01	—	+3.5
	-2.760	80.35±2	76.02	75.60	—	+5.7
	-2.298	61.48±2	59.12	58.62	—	+4.0
	-1.814	49.17±2	46.43	45.55	—	+5.9
	+0.332	125.25±5	112.13	113.33	—	+11.7
	+0.922	103.42±6	93.51	93.94	—	+10.6
	+2.823	59.12±4	55.04	55.34	—	+7.4
	+3.501	49.69±2	47.15	46.81	—	+5.4
	+4.198	37.95±2	40.09	39.81	—	-5.3
	+5.666	30.91±2	29.32	29.14	—	+5.4
	+6.433	26.39±2	25.24	25.09	—	+4.6

**Table 1.** *Continued...*

Element/ compounds	$\Delta E$ (keV)	Exp.	Theor. [21]	Theor. [20]	Theor. [22]	Relative difference between exp. and theor. [21] (%)
Fe	-2.604	189.81±3	185.36	181.45	178.28	+2.4
	-2.163	139.87±3	143.76	140.77	138.39	-2.7
	-1.701	116.53±3	112.59	110.28	108.55	+3.5
	+0.360	379.48±9	361.75	364.18	361.48	+4.9
	+0.929	288.27±5	301.54	301.02	298.49	-4.4
	+1.519	242.60±5	250.62	250.19	248.14	-3.2
	+3.420	150.69±3	148.32	148.02	146.93	+1.6
	+4.098	122.94±3	125.32	125.01	124.15	-1.9
	+4.795	104.25±2	106.48	106.17	105.49	-2.1
	+6.263	76.78±1	77.79	77.49	77.08	-1.3
+7.030	65.78±1	66.92	66.63	66.31	-1.7	
FePO <sub>4</sub>	-2.604	165.92±3	173.92	172.12	169.75	-4.6
	-2.163	129.31±2	134.41	132.46	131.23	-3.8
	-1.701	109.39±2	104.78	103.26	102.34	+4.4
	+0.360	143.37±4	158.95	159.50	158.46	-9.8
	+0.929	144.43±2	131.90	131.40	130.46	+9.5
	+1.519	103.38±2	109.28	108.85	108.11	-5.4
	+3.420	60.18±2	64.16	63.87	63.50	-6.2
	+4.098	51.62±1	54.11	53.85	53.56	-4.6
	+4.795	44.15±1	45.89	45.65	45.43	-3.8
	+6.263	34.78±1	33.41	32.78	33.07	+4.1
+7.030	27.58±1	28.69	28.51	28.41	-3.9	
FeCl <sub>3</sub> ·6H <sub>2</sub> O	-2.604	273.74±7	262.96	261.78	258.41	+4.1
	-2.163	194.04±4	204.68	203.63	201.18	-5.2
	-1.701	168.50±3	160.47	159.67	157.77	+5.0
	+0.360	113.14±7	130.65	130.62	129.83	-13.4
	+0.929	94.04±4	107.84	107.20	106.54	-12.8
	+1.519	95.08±3	89.03	88.51	88.01	+6.8
	+3.420	54.77±1	51.77	51.44	51.20	+5.8
	+4.098	41.33±1	43.55	43.24	43.07	-5.1
	+4.795	38.65±1	36.84	36.55	36.44	+4.9
	+6.263	28.35±1	26.70	26.45	26.41	+6.2
+7.030	21.80±1	22.88	22.65	22.63	-4.7	
Fe(SO <sub>4</sub> ) <sub>2</sub> NH <sub>4</sub> ·12H <sub>2</sub> O	-2.604	133.35±3	126.64	125.68	124.35	+5.3
	-2.163	91.64±3	97.59	96.77	95.82	-6.1
	-1.701	79.79±2	75.85	75.25	74.45	+5.2
	+0.360	76.21±2	66.50	66.43	66.08	+14.6
	+0.929	61.79±1	54.83	54.42	54.17	+12.7
	+1.519	49.43±1	45.23	44.87	44.68	+9.3
	+3.420	24.53±1	26.27	26.04	25.96	-6.6
	+4.098	23.76±1	22.11	21.90	21.85	+7.5
	+4.795	19.81±1	18.71	18.53	18.49	+5.9
	+6.263	12.69±1	13.57	13.43	13.41	-6.4
+7.030	12.16±1	11.63	11.51	11.49	+4.6	



It is observed that the experimental value deviates for  $\text{CrCl}_2$  as much as  $-9.3\%$ , for  $\text{Cr}_2(\text{SO}_4)_3 \cdot \text{K}_2\text{SO}_4 \cdot 24\text{H}_2\text{O}$  by as much as  $+18.2\%$ , for  $\text{CoO}$   $-7.3\%$ , for  $\text{Co}(\text{CH}_3\text{COO})_2$   $+11.7\%$ , for  $\text{FePO}_4$   $-9.8\%$ , for  $\text{Fe}(\text{SO}_4)_2 \cdot \text{NH}_4 \cdot 12\text{H}_2\text{O}$  compounds  $+14.6\%$ . This shows that when the number of atoms in a compound increases there are significant differences between experimental and theoretical values.

## References

- [1] O Icelli, S Erzeneoglu and B Gurbulak, *J. Quant. Spectrosc. Radiat. Transfer* **90**, 399 (2005)
- [2] A Khanna, S S Bhatti, K J Singh and K S Thind, *Nucl. Instrum. Methods* **114**, 217 (1996)
- [3] M Ertuğrul, *J. Rad. Nucl. Chemistry* **219**, 111 (1997)
- [4] Orhan İcelli and Salih Erzeneoğlu, *J. Quant. Spectrosc. Radiat. Transfer* **88**, 519 (2004)
- [5] M T Telı and M Chaudhari, *Radiat. Phys. Chem.* **47**, 531 (1996)
- [6] B Roy, B K Chatterjee, S C Roy, N Bhattacharya and N Choudhury, *Appl. Radiat. Isot.* **48**, 785 (1997)
- [7] B R Kerur, S R Thontadarya and B Hanumaiah, *X-ray Spectrom.* **22**, 156 (1993)
- [8] K Singh, R Kaur, Vandana and V Kumar, *Radiat. Phys. Chem.* **47**, 535 (1996)
- [9] U Turgut, O Şimşek, E Büyükkasap and M Ertuğrul, *Spectrochim. Acta* **B57**, 261 (2002)
- [10] Ü Turgut, Ö Şimşek, E Büyükkasap and M Ertuğrul, *Analytica Chimica Acta* **515**, 349 (2004)
- [11] U Turgut, E Büyükkasap, O Şimşek and M Ertuğrul, *J. Quant. Spectrosc. Radiat. Transfer* **92**, 143 (2005)
- [12] R Preşeren and A Kodre, *Radiat. Phys. Chem.* **55**, 363 (1999)
- [13] L Gesward, *J. Phys. B: At. Mol. Opt. Phys.* **22**, 1963 (1989)
- [14] B R Kerur, S R Thontadarya and B Hanumaiah, *Appl. Radiat. Isot.* **45**, 159 (1994)
- [15] B R Kerur, S R Thontadarya and B Hanumaiah, *X-Ray Spect.* **22**, 13 (1993)
- [16] J H Hubbell, W H McMaster, N Kerr Del Grande and J H Mallett, *Int. Tables for X-ray Crystallogr.* **4**, 47 (1974)
- [17] V Lakshminarayana, A T L Tan, I S Giles and A Rajaratnam, *Nuovo Cimento* **91**, 331 (1986)
- [18] D Nagel, In *Quantitative electron probe microanalysis* edited by K F J Heinrich, NBS Special Publication, National Bureau of Standards, Gaithersburg, MD, **298**, 189 (1968)
- [19] D F Jackson, *Nucl. Instrum. Methods* **A193**, 387 (1982)
- [20] E Storm and I Israel, *Nucl. Data* **A7**, 565 (1970)
- [21] J H Hubbell and S M Seltzer, Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements  $Z = 1$  to 92 and 48 additional substances of dosimetric interest, 1995 NISTIR-5632
- [22] J H Hubbell, *Int. J. Appl. Radiat. Isot.* **33**, 1269 (1982)
- [23] J B Kortright, *Characteristic X-ray energies*, X-Ray Data Booklet, Section 2-3, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, 1986, p. 2-2
- [24] F Yang and J H Hamilton, *Modern atomic and nuclear physics* (McGraw-Hill Companies Inc., New York, 1996) p. 265