Pramāṇa – J. Phys., Vol. 33, No. 4, October 1989, pp. 505–511. © Printed in India.

Total attenuation cross-sections of fluorescent X-rays of Zr, Sn, Ba, Au, Pb, Th and U in elements $6 \leqslant Z \leqslant 82$

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MS received 25 February 1989; revised 6 June 1989.

Abstract. The total attenuation cross-sections in elements $6 \leqslant Z \leqslant 82$ for K_α and K_β groups of lines of elements Zr, Sn and Ba and L_l, L_α, L_β and L_γ groups of lines of the elements Au, Pb, Th and U have been measured. The experimentally measured attenuation cross-sections have been found in good agreement with the theoretical estimates.

Keywords. Total attenuation cross-sections; K-shell; L-shell; fluorescent X-rays; photoelectric absorption.

PACS No. 32·80

1. Introduction

The attenuation cross-sections of photons of energy ranging from 0·1 keV to 1 MeV in almost all elements have been extensively investigated, theoretically and experimentally and the data are now available for use in many areas of research which involve the measurement of photon intensities. The investigations of many problems in diverse fields in physics require the measurement of intensities of fluorescent X-rays. The presently available energy dispersive X-ray spectrometers are not able to resolve the individual lines of the K and L X-ray emission spectra of various elements. Usually two peaks K_α and K_β and five peaks L_l, L_α, L_η, L_β, and L_γ are observed in the K and L emission spectra of high Z elements respectively. Each peak contains a number of X-ray lines of different energies and intensities. It is, therefore, desirable to provide accurate values of the attenuation cross-sections for the group of lines under various peaks of X-ray emission spectra. We have measured the total attenuation cross-sections in elements $6 \leqslant Z \leqslant 82$ for K_α and K_β group of lines of elements Zr, Sn and Ba and L_l, L_α, L_β and L_γ groups of lines of Au, Pb, Th and U. The experimental results are interpreted in terms of attenuation cross-sections, energies and intensities of various lines in the group. This paper reports the method of measurement and the analysis of results.

2. Experimental arrangement and measurement

The total attenuation cross-sections were determined by measuring transmission of the fluorescent K or L X-rays through targets of known thickness. The experimental arrangement is shown in figure 1. Targets of Zr, Sn, Ba, Au, Pb, Th and U were

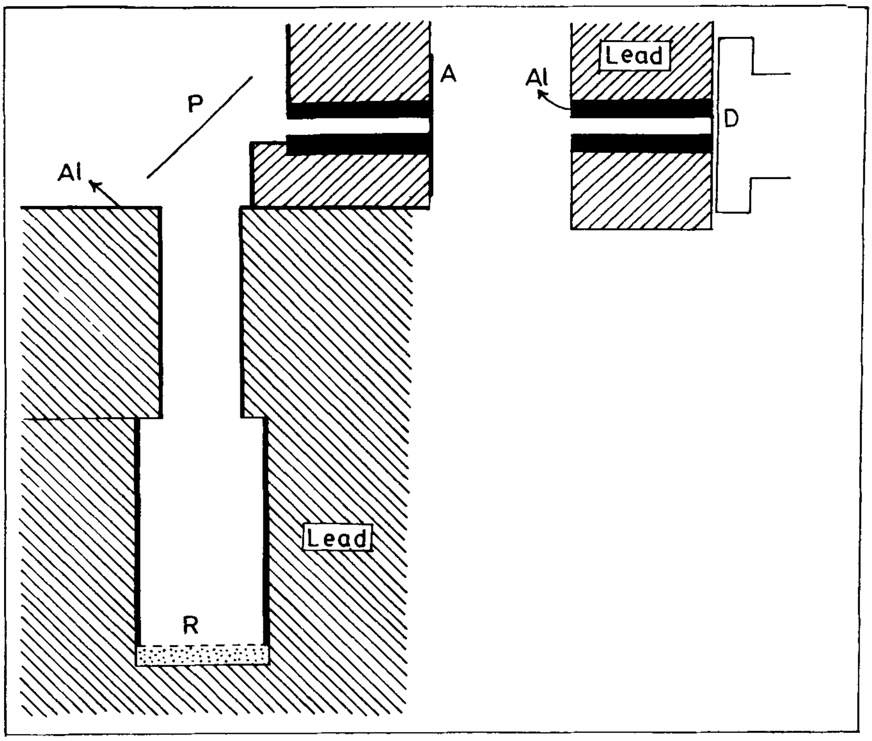

Figure 1. Experimental set-up used for the measurement of the total attenuation cross-sections for K or L X-rays. R-radioactive source (^{241}Am); T-target; A-absorber; and D-detector Si(Li).

irradiated, in turn, with 59·57 keV γ-rays from ~ 1 Curie ^{241}Am source. The Np L X-rays and 26 keV gamma rays, which are also emitted from ^{241}Am source, were almost completely ($\sim$99·99%) filtered out (Shatendra *et al* 1984) to avoid their interference in the present experiment. The emitted K or L shell fluorescent X-rays were collimated to fall on the absorbers of C, Al, Ti, Fe, Ni, Cu, Zn, Zr, Mo, Pd, Ag, In, Sn, Gd, Ta, W, Au and Pb cut from their high purity ($\sim$99·99%) foils of diameter 4 cm each. The thicknesses of the absorbers varied from 5 to 50 mg/cm^2 and were so selected that the condition $\mu t < 1$ is well satisfied. To minimize the effect of small angle scattering in the absorber, the transmitted K or L X-rays were further collimated and counted using a Si (Li) X-ray detector of active area 200 mm^2 thickness 5 mm, and 5 mil Be window having energy resolution of $\sim$300 eV at 5·9 keV.

Spectra were recorded with and without the absorber in position for different K or L X-ray groups (K_α, K_β, L_l, L_α, L_β, L_γ). Typical spectra are shown in figure 2. In addition to K or L X-rays, scattered 59·57 keV γ-rays were also present in the spectra. However, in the present experiment the counts under K or L X-ray groups only were counted. For some of the target-absorber combinations used in the present measurements (e.g. Zr target Zr absorber) the target and absorber fluorescent X-ray spectra overlap. The fluorescent X-rays produced in the absorber by the 59·57 keV γ-rays scattered from the target are also counted alongwith the target fluorescent X-rays transmitted through the absorber. The measured attenuation cross-sections, therefore, need to be corrected for the contribution of the absorber fluorescent X-rays

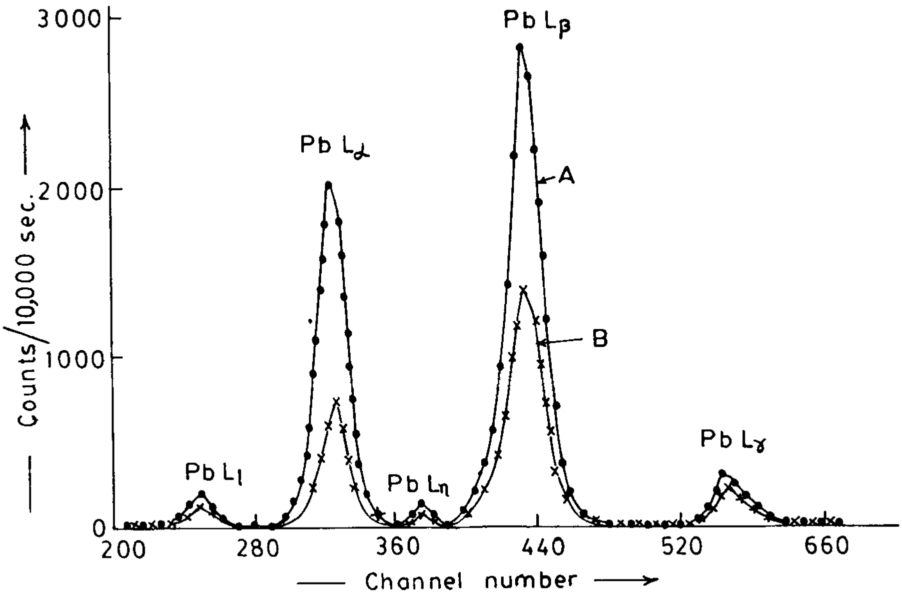

Figure 2. Spectra of Pb L X-rays recorded with Si(Li) X-ray spectrometer. A—without absorber; B—with Ti absorber.

produced by the γ-rays scattered from the target to the target fluorescent X-rays transmitted through the absorber. The contribution was estimated experimentally by replacing the experimental target with equivalent Al target (Shatendra *et al* 1984) and noting the counts under the absorber fluorescent X-ray peak which was not more than 1%.

The counts for the measurement of each X-ray group were taken in the following sequence: no absorber (I_0), absorber (I), absorber, no absorber, no absorber, absorber and so on to minimize the effect of systematic error, if any. The counting sequence was continued ranging for a time between 5000 and 20000 s to achieve a statistical accuracy of $\sim 1\%$ in all cases except L_l X-rays where the accuracy better than 3% could not be achieved due to poor counting rates. To measure the cross-sections for the different L X-ray groups of Th and U, the 59·57 keV γ-ray source was removed and counts taken in the same sequence described above and subtracted from the earlier counts with these elements to eliminate any contribution due to the natural radioactivity of these elements.

In an ideal transmission experiment, the photon once scattered in the absorber, even at very small angle, should not be detected. Keeping the counting statistics in view, in the present experiment, the angular spread of the geometry could not be decreased below 8° for K X-rays and 16° for L X-rays. Thus, in the present measurements, the X-rays scattered (incoherently and coherently) in the angular range 0–8° for K X-rays and 0–16° for L X-rays were also counted alongwith the transmitted X-rays and, therefore, warranted correction to the measured attenuation cross-section (σ_x^{exp}). The measured values of the cross-sections were converted to the true (σ_x) using the following relation:

$$\sigma_x = \sigma_x^{\mathrm{exp}} + \sigma_x^{\mathrm{Incoh}}(0^\circ - \theta^\circ) + \sigma_x^{\mathrm{coh}}(0^\circ - \theta^\circ).$$

where $\sigma_x^{\mathrm{Incoh}}$ $(0° - \theta°)$ and σ_x^{coh} $(0° - \theta°)$ are incoherent and coherent scattering cross-sections respectively integrated over angles from 0° to θ°. The values of θ are 8° and 16° for *K* and *L* X-rays respectively. The value of $\sigma_x^{\mathrm{Incoh}}$ $(0° - \theta°)$ and σ_x^{coh} $(0° - \theta°)$ were evaluated from the recent work of Hubbel *et al* (1975). It is seen that the correction applied to the experimental values σ_x^{exp} to convert them to true values (σ_x) are less than 2%.

3. Results and discussion

The values of the total attenuation cross-sections are listed in tables 1 to 7. The uncertainties in the values of the cross-sections are estimated to vary between 2 and 6%. These are due to counting statistics (~1 to 3%) as well as errors in the thickness determination (<1%) and uncertainties arising from the correction applied for the scattering contribution (<1%). The experimental values of the attenuation cross-sections for each group are compared with the theoretical cross-sections (Veigele 1973). For this purpose, the cross-sections for different components of X-ray groups were weighted with respect to the intensities of the components (Storm and Israel 1970) and are called weighted mean cross-sections. It is seen that the experimental results agree with the weighted mean cross-sections within experimental errors. For all the elements and energies under investigation in the present experiment, the weighted mean cross-sections as defined above are found to agree with those calculated at weighted mean energies (Storm and Israel 1970) within 1%. The cross-sections in some typical cases are shown in table 8.

It may be noted that in the present measurements, all the components of X-ray lines lying in a given group have energies either above the *K* edge of the absorber atoms or below it. Some discrepancies between the weighted mean cross-sections and cross-sections at weighted mean energies are expected to occur if the above conditions are not satisfied and there are discontinuities in absorption because of the presence of shell/subshell edges. Further experiments are being planned to investigate it.

Table 1. Comparison of measured values of the total attenuation cross-sections with the theoretical values (Veigele 1973).

	Total attenuation cross-sections in b/atom at Zr			
	K_α X-ray energy		K_β X-ray energy	
Elements	Present	Theoretical	Present	Theoretical
C	14·60±0·3	14·4	11·0±0·3	11·3
Al	305±10	308	215±5	219
Ti	2450±50	2480	1800±40	1774
Fe	4600±90	4638	3300±60	3333
Ni	6000±120	6057	4400±90	4379
Cu	6900±140	6924	5000±100	5009
Zn	8000±160	7951	5700±110	5745
Zr	3400±70	3328	2400±50	2437
Mo	4000±80	3989	2900±60	2922
Ag	6200±120	6292	4600±90	4610

Table 2. Comparison of the measured values of the total attenuation cross-sections with the theoretical values (Veigele 1973).

Elements	Total attenuation cross-sections in b/atom at Sn			
	K_α X-ray energy		K_β X-ray energy	
	Present	Theoretical	Present	Theoretical
Al	80±2	81	57±2	57·5
Ti	650±15	643	450±10	448
Fe	1250±25	1224	850±15	856
Ni	1600±30	1625	1150±20	1139
Cu	1850±40	1864	1300±25	1308
Zn	2100±40	2130	1500±30	1492
Zr	6000±120	6004	4300±90	4293
Mo	7200±140	7173	5200±110	5142
Pd	9900±200	9877	7100±140	7093
Ag	1800±40	1819	7600±150	7571
In	2100±40	2143	9400±190	9336
Sn	2300±50	2299	1600±30	1652
Gd	6200±120	6182	4400±90	4427
Ta	10100±200	10167	7200±150	7291
W	10900±220	10957	7800±160	7826
Au	13900±280	13923	10000±200	9986
Pb	16500±330	16603	11800±240	11850

Table 3. Comparison of the measured values of the total attenuation cross-sections with theoretical values (Veigele 1973).

Elements	Total attenuation cross-sections in b/atom at Ba			
	K_α X-ray energy		K_β X-ray energy	
	Present	Theoretical	Present	Theoretical
C	4·8±0·1	4·9	4·5±0·1	4·4
Al	45±2	43	30±1	31
Ti	330±8	323	230±6	223
Cu	950±20	944	650±15	651
Zr	3200±60	3145	2200±40	2199
Ag	5500±110	5582	4000±80	3940
Sn	6900±140	6912	4900±100	4910
Gd	3300±60	3268	2300±50	2318
Ta	5400±110	5392	3800±70	3832
W	5700±120	5763	4100±80	4075
Au	7500±150	7385	5300±110	5249
Pb	8600±170	8729	6200±120	6178

Table 4. Comparison of the measured values of the total attenuation cross-sections with the theoretical values (Veigele 1973).

	Total attenuation cross-sections in b/atom at Au					
	L_α X-ray energy		L_β X-ray energy		L_γ X-ray energy	
Elements	Present	Theoretical	Present	Theoretical	Present	Theoretical
C	50±1	50·5	32·5±0·7	32·5	20·3±0·5	20·7
Al	1275± 25	1278	795±15	788	480±10	476
Ti	9600±190	9672	6100±120	6107	3800±80	3772
Fe	17600±350	17670	11200±230	11246	7100±140	7007
Ni	22000±440	22396	14400±290	14402	9200±190	9070
Cu	25800±520	25555	16600±330	16433	10500±210	10360

Table 5. Comparison of the measured values of the total attenuation cross-sections with theoretical values (Veigele 1973).

	Total attenuation cross-section in b/atom at Pb							
	L_l X-ray energy		L_α X-ray energy		L_β X-ray energy		L_γ X-ray energy	
Elements	Present	Theoretical	Present	Theoretical	Present	Theoretical	Present	Theoretical
C	57·3±3·2	59·2	40·7±1	40·3	24·8±0·6	25·3	16·3±0·4	16·0
Al	1450±70	1499	1000±20	1002	600±15	595	350±10	357
Ti	11300±560	11211	7800±160	7684	4600±90	4667	2900±60	2861
Fe	—	—	13700±270	14095	8700±170	8635	5400±110	5339
Ni	—	—	18000±360	17959	11200±220	11125	7000±140	6953
Cu	—	—	20200±410	20481	11500±250	12701	8100±160	7946
Zn	—	—	22700±450	23596	14300±290	14613	9200±180	9130

Table 6. Comparison of the measured value of the total attenuation cross-sections with the theoretical values (Veigele 1973).

	Total attenuation cross-section in b/atom at Th							
	L_l X-ray energy		L_α X-ray energy		L_β X-ray energy		L_γ X-ray energy	
Elements	Present	Theoretical	Present	Theoretical	Present	Theoretical	Present	Theoretical
C	35·2±1·8	34·9	23·9±0·6	23·4	13·5±0·3	13·8	9·6±0·2	9·5
Al	900±45	853	550±10	547	295±5	291	170±5	171
Ti	6400±320	6590	4400±90	4306	2350±50	2345	1400±40	1395
Fe	12200±490	12120	7900±160	7980	4300±80	4378	2600±60	2630
Ni	15600±780	15496	10400±205	10299	5600±120	5738	3600±90	3470
Cu	17500±880	17678	11900±240	11760	6600±130	6559	3900±100	3970
Zn	20000±1000	20358	13300±260	13527	7400±150	7531	4500±110	4550

Table 7. Comparison of the measured values of the total attenuation cross-sections with theoretical values (Veigele 1973).

	Total attenuation cross-section in b/atom at U							
	L_l X-ray energy		L_α X-ray energy		L_β X-ray energy		L_γ X-ray energy	
Elements	Present	Theoretical	Present	Theoretical	Present	Theoretical	Present	Theoretical
C	30·2 ± 1·5	31·0	20·7 ± 0·5	20·6	12·2 ± 0·2	12·2	8·6 ± 0·2	8·5
Al	750 + 30	749	470 ± 10	474	250 ± 5	245	140 ± 5	144
Ti	5800 ± 290	5817	3800 ± 80	3754	1950 ± 40	1982	1150 ± 25	1172
Fe	10800 ± 540	10721	6900 ± 140	6973	3600 ± 70	3718	2250 ± 40	2215
Ni	13900 ± 700	13746	9000 ± 180	9028	4800 ± 100	4874	2850 ± 60	2929
Cu	15600 ± 700	15686	10400 ± 210	10312	5600 ± 110	5574	3300 ± 70	3353
Zn	18200 ± 910	18058	11900 ± 240	11857	6500 ± 130	6396	3900 ± 80	3840

Table 8. Weighted mean cross-sections are compared with the cross-sections at weighted mean energy in some typical cases.

X-ray group	Element under investigation	Weighted mean cross-sections in b/atom	Cross-sections at weighted mean energy in b/atom
Zr $\bar{K}_\alpha$	Ag	6292	6292
Zr $\bar{K}_\beta$	Ag	4610	4609
Sn $\bar{K}_\alpha$	Ag	1819	1818
Sn $\bar{K}_\beta$	Ag	7571	7570
Pb $\bar{L}_\alpha$	Fe	14095	14096
Th $\bar{L}_\beta$	Fe	4378	4377
U $\bar{L}_\gamma$	Fe	2215	2209

Acknowledgement

Financial assistance from the Department of Science and Technology, Government of India and University Grants Commission, is gratefully acknowledged.

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