

Photoelectric cross-sections of light elements and compounds at low photon energies

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Abstract. Total photon mass attenuation coefficients in C, Al, S, Ti, B₂O₃, LiF, ZnO, Y₂O₃ and H₈O₂C₈ (perspex) are measured on a good geometry set-up using proportional counter, Si(Li) and Ge(Li) detecting systems in the energy region from 6.47 to 52.014 keV employing x-rays and gamma rays from radioactive sources. The deduced photoelectric cross-sections are found to agree with the theoretical values of Storm and Israel, Scofield and semiexperimental values of Veigele wherever available within a few percent. The photo-electric cross-sections in elements, S, Ti and Y at their respective K-edges obtained by extrapolation technique agree with the theoretical values of Storm and Israel and Scofield at the respective K-edges except in S. In the case of S both the theoretical values at K-edges are found to be underestimations, more in the case of Scofield evaluations.

Keywords. Photoelectric cross-section; extrapolation technique.

1. Introduction

In view of the importance of atomic photoeffect process, a variety of experimental attempts have been made. The experimental approaches (Pratt *et al* 1973) can be divided broadly into two classes: (1) direct method and (2) indirect method or subtraction technique. The direct method involves measurements basically of photoelectron intensity and incident-photon intensity. In determining photo-electron intensity, either the electron intensity or the x-ray intensity following the photoelectron is measured. In the direct method the total photon interaction cross-section can be measured by conducting a transmission experiment on a good geometry set-up and then the contribution due to other partial cross-sections can be subtracted. In the case of direct method, accuracy of the order of 3 to 5% is difficult and it is therefore more useful at high incident photon energies. However, in the indirect method, accuracy of the order of 1 to 3% is possible and is generally employed at very low energies where the photoelectric effect dominates.

Many experimental methods are available at very low energies. The set-up required is a simple good geometry set-up and a good resolution detector especially to detect the characteristic x-rays or low energy gamma rays. For these measurements, thin

NaI(Tl) crystal systems and later proportional counters were used. However, after the advent of solid state detectors there has been a renewed interest in these measurements in view of their high resolution characteristics. But in view of the existing discrepancies in the available experimental data, semi-experimental compilations have been reported by Veigele (1973). On the theoretical side after Storm and Israel (1970), Scofield (1973) reported highly accurate theoretical data (0.1%) on photoelectric process. It is therefore felt that data on these cross-sections are needed using high resolution solid state detectors in elements and compounds. In the present investigation systematic measurements are made using the indirect method in the energy range 6.47 to 52 keV in a few light elements and compounds employing argon proportional counter, Si(Li), and Ge(Li) detecting systems to compare the following three aspects: (i) the experimental photoelectric cross-sections with the most accurate theoretical data of Scofield as well as with those reported by Storm and Israel, (ii) the photoelectric cross-sections with semi-experimental data and (iii) photoelectric cross-sections at *K*-edges with the accurate theory of Scofield as well as with that of Storm and Israel.

2. Experimental

The geometrical arrangement employed in the present investigation is shown in figures 1, 2 and 3. This consists of a set of three collimators, each of which are made by sandwiching collimators of Pb, Cu and Al, always the low *Z* element facing the detector. This arrangement, known as graded collimation, is essential for low energy investigation to reduce the fluorescent level generated in the collimators to a non-interference level of 1.6 keV (*K*-x-ray energy in Al). These collimators are 5 cm in diameter with holes at the centre ranging from 2 to 8 mm. The first slit with 2 mm hole in the centre is placed before the source which is housed in a small lead cylinder. This slit collimates the incident photon beam so as to get a well-defined narrow cross-section. The second and third slits allow one to calculate the exact

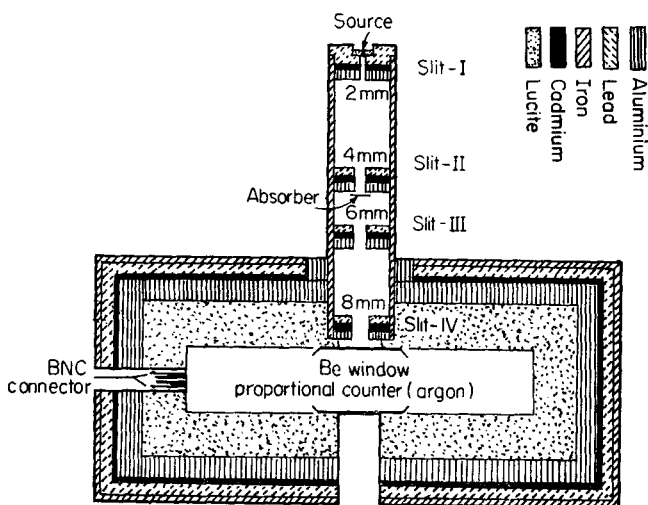


Figure 1. Good geometrical set-up of proportional counting system.

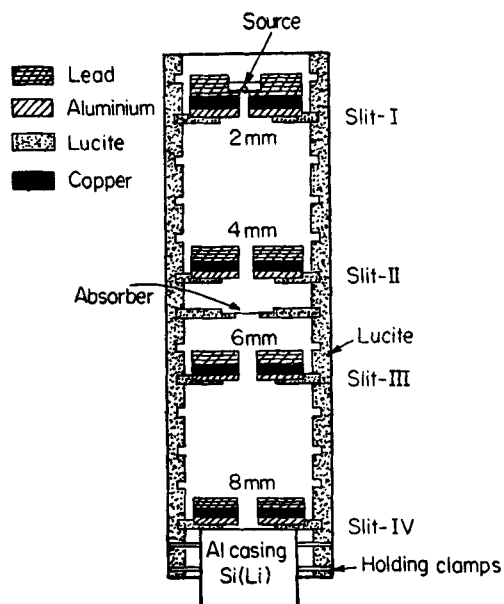


Figure 2. Geometrical set-up of Si(Li) detector.

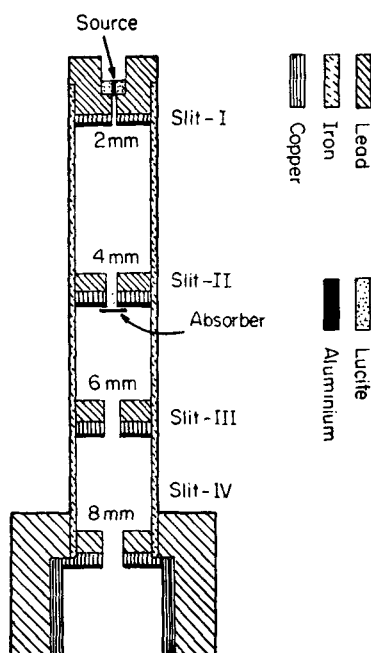


Figure 3. Geometrical set-up of Ge(Li) detector.

scattering in angle and to apply the necessary correction. The fourth slit before the detector is again a graded slit used to stop external radiation. The detectors in general are by themselves well shielded from external radiation. A brass tube (with internal diameter 5 cm, outside diameter 5.6 cm and length of 20 cm) is bisected

along the diameter and one section is used as a holder for the geometrical arrangement. This holder slides into the lead shield of the detector which has a hole of 5.6 cm.

With this geometry set-up, three detector systems, *viz* argon proportional counter, Si(Li) and Ge(Li) detector systems are used in combination with a Nuclear Data ND 512 multichannel analyser for data collection. For proportional counter and Ge(Li) detector systems, a horizontal geometrical set-up is used. For the Si(Li) detector, a vertical geometry is employed as the detector is housed in a vertical cryostat. In this arrangement the collimators are held in position by perspex sheets with holes in the centre, which slide into a perspex shelf that is clamped to the cryostat.

For elements C, Al, Ti and perspex absorbers of 10 mm dia with suitable thicknesses are used. In the case of S, B₂O₃, LiF, Al₂O₃, ZnO and Y₂O₃ amorphous powders are employed. These powders are packed in perspex holders with 8 mm inner dia and are covered with thin mylar foil on both ends. This procedure increases the foil thickness by an additional two mylar foils and hence similar dummy foils are prepared without powder to find the direct count rate without absorber while working with this set of absorbers. All the foils are weighed on an electrical balance and the area of the foils is estimated using a travelling microscope. All the substances obtained from Chempure Private Limited were 99.9% pure.

If I and I_0 are the count rates with and without absorber of thickness t (g/cm²) the atomic cross-section μ_a given by expression (1)

$$\mu_a = \frac{A}{N} \left(\frac{\ln I_0/I}{t} \right), \quad (1)$$

where N and A are the Avagadro number and the atomic weight of the substance, the factor in brackets is the mass attenuation coefficient (μ/p). In the case of a compound, A/N is replaced by

$$\frac{1}{N} \sum \frac{A_i}{w_i}$$

where W_i and A_i are the respective weightages and atomic weights of the individual elements of the compound. If the transmission is varied in a suitable region least square fitting (Prema Chand *et al* 1976) can be made in obtaining the cross-section as given by expression (2)

$$\mu_a = \frac{A}{N} \left[\frac{\sum t_i \ln I_0/I_i}{\sum t_i^2} \right]. \quad (2)$$

Using the procedures already described (Radhakrishna Murty *et al* 1977; Prema Chand *et al* 1976), the mass attenuation coefficients are measured for these elements and compounds in the energy region 6.47 to 52 keV. Here again the small scattering angle (θ_{\max}) never exceeds 3° in any case. The sources employed, their energies and the substances in which these attenuation coefficients are measured are given in table 1. The measured total mass attenuation coefficients are given in table 2. The present total photon mass attenuation coefficients are estimated to be accurate

within 2%. Using this data, photoelectric cross-section relating to the following aspects are studied.

2.1 Elements and compounds: A comparison with theoretical values

The mass attenuation coefficients are converted into atomic cross-sections and from these the respective theoretical coherent and incoherent scattering cross-sections reported by Storm and Israel are subtracted. The coherent and incoherent scattering cross-sections in compounds are evaluated using the sum-rule method (Parthasaradhi 1968). In most cases this contribution is less than 15% of the total. These values are subtracted and the deduced photoelectric cross-sections in light elements and their compounds are given in table 3 along with the theoretical photoelectric cross-sections reported by Storm and Israel (1970) and Scofield (1973). The sum-rule is again used to calculate the theoretical photoelectric cross-sections in compounds. The agreement between theory and experiment is within 2%.

2.2 Elements: A comparison with semi-experimental data of Veigle (1973)

In view of the applicability of photoelectric cross-sections for basic and applied research, it is of interest to get data in all elements. However, certain elements are difficult to obtain in proper form to be used as target foils. In such cases an alternative method involving the measurement of cross-sections in compounds of such elements obtainable especially in powdered form is of interest. Assuming the sum-rule, the cross-sections of the elements can be obtained by subtracting the theoretical contribution due to other elements. Such a method is useful especially if the target is in gaseous form where a direct measurement needs an elaborate experimental arrangement. To test the validity of this method the total cross-section in Al_2O_3 and Al are determined experimentally. Then the total cross-section of Al is obtained from the first measurement by subtracting the theoretical cross-section of O. These two values are found to be 417 ± 9 and 420 ± 8 barns/atom respectively.

Table 1. Isotopes, detectors, elements and compounds used.

Radioactive source	Half-life	Energies	Detector used	Element or compound
		6.47 (Average of K_α and K_β x-rays)	Argon proportional counter	C, Al, S, Ti; B_2O_3 , Al_2O_3 , LiF, $\text{H}_2\text{O}_2\text{C}_2$ (perspex)
^{57}Co (Mössbauer source in Pd matrix)	271.65d	14.41 gamma rays	Si(Li)	C, Al, S, Ti, B_2O_3 , Al_2O_3 , ZnO, LiF, $\text{H}_2\text{O}_2\text{C}_2$
		21.12 (K_α x-ray of Pd)	Si(Li)	Al, S, Ti, B_2O_3 , Al_2O_3 , ZnO, Y_2O_3 , LiF, $\text{H}_2\text{O}_2\text{C}_2$
^{119}Sn	115.1d	24.138 (K_α x-ray)	Si(Li)	S, Ti
^{139}Ba	10.7y	30.851 (K_α x-ray)	Si(Li)	ZnO, Y_2O_3
		35.131 (K_β x-ray)	Si(Li)	ZnO, Y_2O_3
^{170}Tm	128.6d	52.014 (K_α x-ray)	Ge(Li)	Y_2O_3

Table 2. Total mass attenuation coefficients (cm²/gm) in elements and compounds.

Element	Energy (keV)							
	6.47	14.41	21.12	24.138	30.851	35.131	52.0141	
C	8.53 ± 0.16	0.873 ± 0.017	—	—	—	—	—	—
Al	91.9 ± 1.8	8.87 ± 0.17	2.93 ± 0.05	—	—	—	—	—
S	170.6 ± 3	17.2 ± 0.3	5.64 ± 0.11	3.86 ± 0.07	—	—	—	—
Ti	354 ± 7	40.0 ± 0.8	13.42 ± 0.25	9.12 ± 0.18	—	—	—	—
B ₂ O ₃	16.6 ± 0.3	1.57 ± 0.03	0.608 ± 0.012	—	—	—	—	—
Al ₂ O ₃	58.2 ± 1.1	5.59 ± 0.10	1.88 ± 0.036	—	—	—	—	—
ZnO	—	72.5 ± 1.7	25.4 ± 0.5	—	8.92 ± 0.17	6.28 ± 0.12	—	—
Y ₂ O ₃	—	—	46.7 ± 0.9	—	16.90 ± 0.32	11.84 ± 0.22	4.1 ± 0.08	—
LiF	22.06 ± 0.43	2.07 ± 0.04	0.757 ± 0.014	—	—	—	—	—
H ₂ O ₂ C ₆	12.06 ± 0.24	1.190 ± 0.023	0.510 ± 0.01	—	—	—	—	—

Table 3. Photoelectric cross-sections (barns/atom).

Element or Compound	Energy in keV						
	6-47	14-41	21-12	24-138	30-851	35-131	52-014
C	Expt 162.4 ± 3.3	12.3 ± 0.3	—	—	—	—	—
	SI 162	12.1	—	—	—	—	—
	Sc 165.6	12.7	—	—	—	—	—
Al	Expt 4073 ± 80	377 ± 8	116.6 ± 2.6	—	—	—	—
	SI 4029	373	115.4	—	—	—	—
	Sc 4112	380	117.1	—	—	—	—
	Expt 9021 ± 180	885 ± 18	279 ± 5.8	187.0 ± 4	—	—	—
S	SI 8968	881	278.3	184.7	—	—	—
	Sc 9059	896	283.3	188.1	—	—	—
	Expt 28042 ± 550	3125 ± 60	1029 ± 20	692 ± 14	—	—	—
Ti	SI 28039	3101	1029	692	—	—	—
	Sc 28044	3130	1038	699	—	—	—
	Expt 374 ± 7	28.9 ± 0.7	8.70 ± 0.25	—	—	—	—
	SI 369	29.2	8.48	—	—	—	—
B ₂ O ₃	Sc 372	29.9	8.79	—	—	—	—
	Expt 1945 ± 38	176.2 ± 3.5	53.8 ± 1.2	—	—	—	—
Al ₂ O ₃	SI 1951	175.7	54.8	—	—	—	—
	Sc 1986	178.8	55.0	—	—	—	—
	Expt —	4836 ± 90	1675 ± 34	—	575.0 ± 12	400 ± 8	—
ZnO	SI —	4850	1695	—	574.4	396	—
	Sc —	4857	1703	—	578.3	399.3	—
	Expt 464 ± 9	38.5 ± 0.8	11.3 ± 0.3	—	—	—	—
LiF	SI 468	38.2	11.3	—	—	—	—
	Sc 470	39.3	11.6	—	—	—	—
	Expt 126.3 ± 2.5	9.91 ± 0.25	2.94 ± 0.10	—	—	—	—
H ₂ O ₃ C ₅	SI 126.8	9.78	2.85	—	—	—	—
	Sc 126.6	10.21	2.96	—	—	—	—
	Expt —	3445 ± 68	1229 ± 24	—	1229 ± 24	855 ± 16	285 ± 6
Y ₂ O ₃	SI —	—	3454	—	1242	864	286
	Sc —	—	3456	—	1243	866.5	286
	Expt —	—	—	—	—	—	—

Table 4. Photoelectric cross-sections in elements (barns/atom).

Element	Energy in keV									
	6.47	14.41	21.12	24.138	30.851	35.131	52.014			
C	Expt	162.4 ± 3.3	12.3 ± 0.3	—	—	—	—	—	—	—
	V	161 ± 2%	12.4 ± 2%	—	—	—	—	—	—	—
O	Expt	574 ± 13	46.3 ± 1	13.5 ± 0.4	—	—	—	—	—	—
	V	569 ± 2%	46.4 ± 2%	13.7 ± 2%	—	—	—	—	—	—
F	Expt	921 ± 20	76.1 ± 1.6	22.6 ± 0.6	—	—	—	—	—	—
	V	922 ± 2%	77.4 ± 2%	23.1 ± 2%	—	—	—	—	—	—
Al	Expt	4073 ± 80	377 ± 7	116.6 ± 2.6	—	—	—	—	—	—
	V	4130 ± 2%	378 ± 2%	116.4 ± 2%	—	—	—	—	—	—
S	Expt	9021 ± 180	885 ± 18	279 ± 6	187 ± 4	—	—	—	—	—
	V	9023 ± 2%	870 ± 2%	274 ± 2%	182 ± 2%	—	—	—	—	—
Ti	Expt	28042 ± 550	3125 ± 60	1029 ± 20	691 ± 14	—	—	—	—	—
	V	28827 ± 2%	3127 ± 2%	1029 ± 2%	691 ± 2%	—	—	—	—	—
Zn	Expt	—	9625 ± 200	3335 ± 70	—	1145 ± 25	796 ± 16	—	—	—
	V	—	10024 ± 2%	3429 ± 2%	—	1152 ± 2%	787 ± 2%	—	—	—
Y	Expt	—	—	8588 ± 180	—	3066 ± 65	2155 ± 45	711 ± 15	—	—

It can be seen that these agree to within the range of errors. Hence the cross-sections in oxygen and fluorine are extracted from those of B_2O_3 and LiF by subtracting the cross-section in B and Li. Similarly the cross-sections in Zn and Y are extracted from those measured in ZnO and Y_2O_3 respectively. Thus the cross-sections obtained along with those in C, Al, S and Ti are compared with the semi-experimental values reported by Veigele (1973) in table 4 except in Y where the Veigele's data are not based on experimental evaluations. The errors in the derived values of Veigele (1973) based on the experimental values are of the order of 2% or more. It can be seen from table 4 that the present values agree with those of Veigele (1973) within the range of errors.

2.3 *K*-edge: A comparison with theoretical values

In the present investigation the lowest energy at which photoelectric cross-sections are reported in S, Ti and Y is about 4 keV or less away from the respective *K*-binding energies. Hence the data on photoelectric cross-sections are extrapolated to the respective *K*-edges using previous procedures (Sivasankara Rao *et al* 1977) and the values at the *K*-edge are compared with theoretical values in table 5. In view of the extrapolations involved an additional error of 1% is considered. It can be seen that there is good agreement within range of errors between theory and experiment except in S. Both the theoretical values are smaller than the experimental values. Of the two theoretical values, the value of Storm and Israel (1970) is in better agreement with the experimental value than with the value of Scofield (1973). However, a direct measurement of these cross-sections near the edges throws better light on the accuracy of the theoretical values near the edges.

Thus from a comprehensive study on the photoelectric effect in the energy region 6.47 to 52 keV in light elements and their compounds, the following conclusions can be drawn.

In the energy region studied both the theoretical cross-sections reported by Storm and Israel (1970) and Scofield (1973) generally agree with the present experimental values. Photoelectric cross-sections in gases, where a direct measurement needs an elaborate experimental set-up, can be obtained alternatively by measuring the cross-sections in the compounds of gases obtainable in powdered form. The present photoelectric cross-sections in elements generally agree with the semi-experimental values of Veigele (1973). The deduced photoelectric cross-sections at *K*-edges in

Table 5. Photoelectric cross-sections at *k*-edges (barns/atom).

Element	<i>K</i> -edge energy (keV)	Cross-sections at <i>K</i> -edge	SI	Sc
S	2.4731	123692 ± 3710	—	110020
	2.472	123837 ± 3705	118000	—
Ti	4.975	55288 ± 1660	—	54452
	4.966	55573 ± 1670	56200	—
Y	17.120	15054 ± 500	—	14839
	17.038	15244 ± 500	15200	—

S, Ti and Y agree with those of Storm and Israel and Scofield within the range of errors except in the case of S where the experimental value is more by 8% than Scofield and higher by 2% than the value of Storm and Israel. Of the two theories, the Scofield value predicts a much smaller value than the present experimental value. Hence, it is felt a direct measurement near the *K*-edge is desirable.

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