

# Total Photon Cross-sections of Compounds in the Energy Range 145–1120 keV

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Total photon cross-sections have been measured in 15 compounds and in 3 selected elements at 7 different photon energies in the range of 145–1120 keV on a good geometry set-up using a NaI(Tl) detector coupled to a ND 60 multichannel analyser. The results include some data points which have not been previously reported. From the measured total cross-sections per molecule of the compound, atomic cross-sections in elements have been extracted using the mixture rule. The derived atomic cross-sections have been compared with the theoretical Hubbell–Scofield values and of Storm and Israel. In addition, the experimental total photon cross-sections of the three selected elements are compared with those derived from measurements on the compounds containing the selected elements. A good agreement is observed amongst the different values, within experimental error.

## Introduction

Accurate data on total photon attenuation coefficients are essential for the analysis of radiation physics experiments and for application in such diverse fields as medicine, engineering and crystallography. While extensive measurements are available over a wide range of photon energies on a number of elements, a careful survey of these investigations indicate that data are still lacking on a few elements (Hubbell, 1971; Hubbell *et al.*, 1986), especially those which are gaseous as also those which are unsuitable for use as absorbers in their elemental forms. Recently, some measurements on compounds (Perumallu *et al.*, 1984; Nageswara Rao *et al.*, 1984; Smiles *et al.*, 1982, 1984; Umesh *et al.*, 1981, 1982, 1984) have been reported where the mixture rule (Hubbell, 1969; Deslattes, 1969; Jackson, 1982) has been employed to deduce the cross-sections in elements in a satisfactory manner. However, such measurements appear to be limited in number. Thus, it is felt that a systematic investigation of the cross-sections in compounds over a wide range of photon energies and molecular weights may prove useful as such a study can provide information on the extent of the applicability of the mixture rule in extracting the atomic cross-sections of those elements which are otherwise unsuitable for a direct investigation. With this aim, 15 compounds of elements, where data are either meagre or absent, have been selected for the present investigation. Transmission experiments have been conducted on a good geometry set-up at seven different photon energies with the help of

a NaI(Tl) scintillation detector coupled to a ND 60 multichannel analyser, to obtain the total cross-sections.

## Experimental

The present experimental studies were carried out in a good-geometry set up (Venkateswara Rao *et al.*, 1982). Three lead block collimators with cylindrical apertures of diameters 2.2, 3.0 and 6.0 mm were placed between the source and detector both of which are provided with adequate lead shielding. The aperture of diameter 2.20 mm, placed before the source, collimates and produces a narrow, well-defined gamma-ray beam while the second and the third apertures serve to restrict the maximum angle of scattering to a value of  $2^\circ 47'$ . Radioactive sources,  $^{141}\text{Ce}$  (145 keV),  $^{203}\text{Hg}$  (279 keV),  $^{51}\text{Cr}$  (320 keV),  $^{198}\text{Au}$  (412 keV),  $^{137}\text{Cs}$  (661 keV) and  $^{46}\text{Sc}$  (889 and 1120 keV), obtained from Bhabha Atomic Research Centre, Bombay, India, in the form of radiographic capsules, were used in the present investigation. A 5.1 cm  $\times$  5.1 cm NaI(Tl) scintillator integrally coupled to a RCA 8053 photomultiplier was chosen as the detector for the present investigation. In view of its high efficiency coupled with reasonable resolution and the monoenergetic nature of the radiation from most of the isotopes used, the NaI(Tl) scintillation detector is preferred over other types of detectors in the photon energy range of the present investigation.

The chemical compounds selected for the present investigations have purities ranging from 99 to 99.9%. These materials, in the powder form, were poured into PVC tubes of i.d. 1.4 cm and of suitable

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length completely filling them, taking due care to achieve uniform thickness of the samples. Thin mylar foils were used at both ends of each sample-containing tube to keep the material intact within it. The thicknesses of the samples were tested for uniformity by exposing different portions of the samples to a well-collimated photon beam, and measuring the transmission. Only such samples were chosen which did not show any discrepancy in the transmission, outside statistical errors. The mass of each sample was determined correct to three decimal places with an electrical balance, while the i. d. of the sample container was measured accurately with a travelling microscope. From these data, the thickness of the sample in  $\text{g}/\text{cm}^2$  has been estimated. Sample thicknesses ranging from 0.5 to  $13 \text{ g}/\text{cm}^2$  were used resulting in transmission ratios between 0.4 and 0.7. The samples were mounted on a perspex sample-holder to present them normally to the incident beam. Similar dummy targets without the absorbing material were also prepared for measuring the incident intensity. From the estimated incident and transmitted photon intensities, the total cross-sections of the compounds could be computed following usual procedures (Perumallu *et al.*, 1984).

The incident and the transmitted intensities were determined for a fixed preset live time in each experiment by choosing a narrow region symmetrical with respect to the centroid of the photopeak. The background spectrum was recorded with a 5" thick lead block in the absorber position for the same interval of time. For the transmission ratio range of the present investigation, the criterion  $\mu t < 1$  (Gopal and Sanjeevaiah, 1973), where  $\mu$  is the attenuation coefficient of the material, was adhered to, and thus, the influence of multiple scattering on the measured attenuation coefficients was eliminated. A sufficient number of counts was always collected under the photopeak to limit the statistical errors to  $< 1\%$ . The theoretical tabulations of form-factors (Hubbell and Øverbo, 1979) were used to apply corrections to the transmitted intensities for the coherently scattered photons included under the photopeak.

## Results and Discussion

The measured compound cross-sections from the present investigations are given in Table 1. Atomic cross-sections in the elements of interest were derived using the mixture rule and subtracting the contributions of all the other elements from the measured cross-sections of the compound. The subtraction procedure was carried out with the help of the combined Hubbell-Scofield theoretical values in a few low  $Z$ -elements. The derived values of the total atomic cross-sections for the elements of interest in the present investigation are given in Table 2. Also included in the same table are the Hubbell-Scofield cross-sections which are a combination of the theoretical values of coherent (Hubbell and Øverbo, 1979) and incoherent (Hubbell *et al.*, 1975) scattering and photoelectric processes (Scofield, 1973). In the majority of the cases investigated at present, the contribution from the elements of interest to the compound cross-section is  $> 70\%$ . However, in a few cases the contribution varies between 40 and 60%.

Sources of significant error in the present investigation are:

- (a) counting statistics;
- (b) impurities in the material;
- (c) uncertainty in the thickness of the sample;

and

- (d) error due to small-angle scattering.

The errors due to counting statistics are always limited to  $< 1\%$  in the present investigation. The errors due to impurities do not exceed 1% in the present study, as the concentration of heavy elements in the samples is negligibly small. The mass and diameter of the absorbers was measured accurately and each of the absorber samples was carefully tested for uniformity. Hence, the error arising out of the uncertainty in the thickness is negligibly small. As already mentioned, the measured values of the cross-sections were corrected for the included coherent scattering. Errors that may arise due to the short half-life of  $^{198}\text{Au}$  were minimized by incorporating

Table 1. Total photon cross-sections in compounds (barns/molecule) (error  $\sim 2\%$ )

Compound	Energy (keV)						
	145	279	320	412	661	889	1120
NaF	9.49	7.48	6.91	6.35	5.19	4.49	4.07
NaCl	14.17	10.51	10.09	9.08	7.31	6.38	5.67
$\text{H}_3\text{BO}_3$	14.49	11.77	11.14	10.21	8.34	7.11	6.49
KCl	19.74	13.85	12.80	11.75	9.51	8.23	7.33
$\text{TiO}_2$	20.76	14.57	13.86	12.30	9.98	8.60	7.73
$\text{Al}_2\text{O}_3$	23.64	18.53	17.49	15.76	12.92	11.12	10.17
NaBr	45.67	21.16	19.23	16.38	12.49	10.70	9.51
$\text{Na}_2\text{SeO}_3$	59.68	33.04	30.98	27.12	21.10	17.98	16.29
$\text{CdCl}_2 \cdot \text{H}_2\text{O}$	136.4	49.60	44.25	35.13	25.60	21.96	19.22
KI	168.1	49.21	41.46	31.54	21.28	17.60	15.23
$\text{BaF}_2$	206.4	55.23	44.72	33.67	22.43	18.18	16.09
$\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$	551.5	140.4	115.5	80.61	49.27	38.81	33.44
$\text{Eu}_2\text{O}_3$	609.8	146.5	118.7	81.29	48.77	39.22	33.85
HgO	689.2	156.4	114.4	71.88	37.76	27.49	22.61
$\text{NaBiO}_3$	802.6	177.8	138.2	88.48	46.79	35.51	29.74

Table 2. Total photon cross-sections in elements (barns/atom) (error ~3%)

Element		Energy (keV)						
		145	279	320	412	661	889	1120
O	Ex	3.63	2.96	2.79	2.57	2.09	1.78	1.63
	H + S	3.65	2.92	2.77	2.51	2.05	1.79	1.60
	SI	3.65	2.91	2.76	2.51	2.05	1.79	1.60
F	Ex	4.34	3.44	3.08	2.88	2.36	2.03	1.87
	H + S	4.15	3.29	3.12	2.82	2.31	2.01	1.80
	SI	4.13	3.29	3.12	2.82	2.30	2.01	1.80
Al	Ex	6.35	4.89	4.59	4.12	3.39	2.88	2.69
	H + S	6.25	4.80	4.55	4.10	3.34	2.91	2.59
	SI	6.24	4.80	4.54	4.10	3.34	2.91	2.59
Cl	Ex	9.02	6.47	6.26	5.61	4.48	3.92	3.47
	H + S	8.86	6.39	6.04	5.41	4.41	3.85	3.44
	SI	8.81	6.38	6.03	5.41	4.39	3.82	3.40
K	Ex	10.88	7.46	6.76	6.34	5.10	4.38	3.89
	H + S	10.49	7.24	6.83	6.08	4.92	4.27	3.81
	SI	10.39	7.23	6.82	6.07	4.91	4.27	3.81
Ti	Ex	13.46	8.73	8.32	7.28	5.88	5.02	4.53
	H + S	13.44	8.59	8.08	7.12	5.73	4.96	4.40
	SI	13.34	8.58	8.07	7.11	5.70	4.95	4.41
Se	Ex	38.43	16.20	15.01	12.65	9.29	7.69	7.09
	*	37.44	15.95	14.62	12.17	9.24	7.76	7.02
	H + S	37.55	16.01	14.65	12.09	9.01	7.84	6.93
	SI	36.92	15.90	14.59	12.03	9.13	7.81	6.90
Br	Ex	40.52	17.12	15.40	12.91	9.66	8.24	7.31
	H + S	40.77	16.82	15.35	12.59	9.47	8.08	7.15
	SI	40.20	16.80	15.27	12.50	9.40	8.06	7.14
Cd	Ex	114.1	33.18	28.68	21.18	14.21	12.03	10.34
	*	114.8	33.13	28.05	20.58	14.50	11.59	10.26
	H + S	111.9	32.65	28.19	20.90	14.00	11.72	10.17
	SI	110.8	32.24	27.88	20.66	13.76	11.62	10.05
I	Ex	157.6	41.97	34.63	25.46	16.36	13.33	11.58
	H + S	158.5	42.09	34.00	25.32	16.09	13.33	11.58
	SI	156.4	41.43	33.69	25.19	15.96	13.22	11.31
Ba	Ex	198.1	48.65	38.48	28.03	17.81	14.16	12.49
	H + S	193.2	48.71	39.13	27.92	17.53	14.33	12.25
	SI	192.3	48.58	38.78	27.65	17.31	14.28	12.25
Eu	Ex	299.4	68.87	55.20	36.88	21.31	16.93	14.53
	H + S	293.1	69.12	54.14	37.47	21.46	17.08	14.37
	SI	294.3	68.69	53.52	37.18	21.20	16.93	14.53
W	Ex	517.5	113.4	89.82	57.37	30.27	22.27	18.64
	H + S	522.5	114.9	87.79	56.12	30.08	22.44	18.31
	SI	520.7	113.9	86.71	55.48	29.45	22.23	18.29
Hg	Ex	685.6	153.5	111.6	69.37	35.71	25.70	21.01
	H + S	685.1	149.5	112.9	70.27	35.10	26.14	20.97
	SI	682.1	148.2	111.3	69.36	35.05	25.93	20.65
Bi	Ex	786.5	165.0	126.1	77.48	37.81	27.68	22.74
	*	784.3	170.6	128.2	77.49	39.21	27.62	22.03
	H + S	776.1	168.7	127.0	78.90	38.48	28.23	22.43
	SI	776.9	166.4	124.9	77.58	38.51	27.83	22.34

Ex, Present experimental values.  
H + S, Combined Hubbell–Scofield theoretical values (Hubbell *et al.*, 1975; Hubbell and Øverbo, 1979; Scofield, 1973).  
SI, Theoretical values due to Storm and Israel (1970).  
\*Data from direct measurements on elements.

suitable corrections to the measured intensities. Thus, an overall error of around 2% is estimated to be present in the measured values of the cross-sections. A maximum error of 3% (Smiles *et al.*, 1982) has been attributed to the combined theoretical cross-sections (Hubbell *et al.*, 1975; Hubbell and Øverbo, 1979; Scofield, 1973) of the elements H, B, C, N, O, F, Na, Cl and K. Thus, the overall error in the derived atomic cross-sections is estimated to be around 3% in all such cases where >70% of the total cross-section in the compound is contributed by

the element of interest. However, in a few cases, e.g. F, Al, Se and Cd where such contribution varies between 40 and 60%, the error is larger (~6%). Table 2 also includes the results of the direct measurements on the three selected elements, Se, Cd and Bi as well as the theoretical values of Storm and Israel (1970).  
A comparison of the values of the atomic cross-sections of Se, Cd and Bi obtained by direct measurements with those deduced from measurements on compounds using the mixture rule shows a good

agreement within experimental errors. Derived cross-sections in other elements also show a good agreement with the theoretical values within experimental errors. The data on compounds at the photon energy of 412 keV have not been reported earlier (Hubbell *et al.*, 1986).

Thus, it may be concluded on the basis of the present measurements that, in general, at photon energies far away from the absorption edges of the atoms involved, the mixture rule can be used as a convenient and reliable tool for extracting the total atomic cross-sections in elements, especially those which occur as gases and also those which are otherwise inconvenient for direct measurements.

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