Atomic photoelectric effect near threshold edges

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Total photon attenuation coefficients near absorption edges are determined in certain suitable elements and compounds. Photoelectric cross sections for elements are deduced from these by subtracting the coherent and incoherent scattering cross sections as well as other elemental cross sections in the cases of compounds. Certain deviations are observed on comparison with the available theoretical and experimental compilations. The I_{L_α}/I_{L_l} x-ray intensity ratio measured by photon excitation near threshold is found to agree better with the theory than the other available experimental data.

I. INTRODUCTION

Atomic photoeffect studies are important to many areas of basic and applied research. For this reason, extensive theoretical work has been carried out over the years for the purpose of providing reliable estimates of those cross sections, particularly over a wide range of energies. The compilation of Storm and Israel[1] is based on relativistic calculations and is expected to be accurate within 2% over the energy region 1 keV to 100 MeV. Scofield[2] has made detailed evaluations for individual shells, and total photoelectric cross sections are reported to an estimated error of the order of 0.1%. Two compilations based on experimental data appeared in recent years by Viegele[3] and Robouch and Cicerchia,[4] respectively. However, all these data show considerable discrepancies near absorption edges. In addition the I_{L_α}/I_{L_l} x-ray intensity ratios for elements measured by photon excitation[5,6] are found to be smaller than those measured by other methods.[7–9] In particular, so far the energy of the photons used for the excitation is far above the energy of the absorption edge. Thus, the present investigations are motivated to get data on photoelectric cross sections near threshold and on the I_{L_α}/I_{L_l} intensity ratio using photons of energy very near to L edge for excitation (i.e., near threshold excitation).

II. EXPERIMENTAL METHOD AND DETAILS

Experimental measurements on photoelectric cross sections can be classified broadly into two categories:[10] (a) direct method and (b) indirect method (subtraction method). The direct method involves the determination of photoelectron or x-ray intensity produced by the irradiation of the foils with a known photon flux. The indirect method involves the measurement of a total photon attenuation coefficient by transmission experiment on a good geometry setup. The photoelectric cross section is

TABLE I. Mass attenuation coefficients in elements and compounds.

Energy (keV)	Element or compound	Nearest K-, L-, or M-edge energy (keV)	Mass attenuation coefficient (cm^2/ + gm)
6.4	Yb	8.94 (L_3)	258±7
6.4	Pb	3.85 (M_1)	419±17
11.89	Au	11.919 (L_3)	85.5±5
13.944 13.760	Pt	13.88 (L_1)	189.6±4
14.414	Pb	15.2 (L_2) 13.04 (L_3)	126±2.3
17.774	Zr	17.998 (K)	15.9±0.3
26.35	Cd	26.711 (K)	9.3±0.1
59.54	Tm	59.39 (K)	15.1±0.4
6.4	$PbCl_2$	3.85 (M_1 of Pb)	361±18
6.4	PbI_2	5.19 (L_1 of I)	461±23
14.414	$PbCl_2$	15.2 (L_2 of Pb) 13.04 (L_3 of Pb)	96±4
14.414	PbI_2	15.2 (L_2 of Pb) 13.04 (L_3 of Pb)	90.5±4

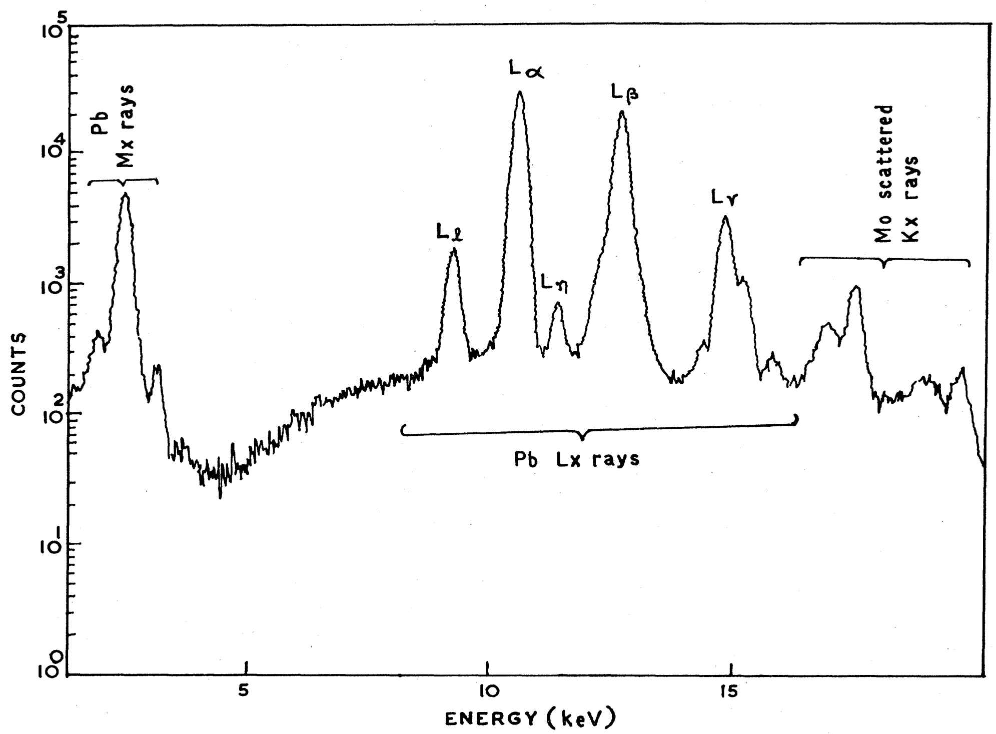

FIG. 1. L-x-ray spectrum of Pb.

then obtained by subtracting the cross sections of the competing partial processes, usually coherent and incoherent scattering contributions at low energies. The second method is generally employed for low-energy photons as most of the contribution is due to the photoelectric process. In the present investigations a Si(Li) x-ray spectrometer in combination with a good geometry setup is used. The geometry consists of a half-cylinder made of Al with machined slots to hold a set of collimators. Pb, Cu, and Al collimators with 2 and 1 mm holes are used to achieve good collimation as in the previous investigations.[11,12] ^{241}Am and ^{57}Co radioactive sources are used to provide low-energy photons to measure the cross sections to meet the special situation near threshold in certain elements and compounds as detailed in Table I. The method of experimentation is already described in many previously reported investigations.[11,12] In the case of elements thin foils are used. In the case of compounds thin vacuum-evaporated foils on Mylar backing of known thickness are used. To test and account for the foil nonuniformity, experiments are conducted at various positions of the foils and an average value is adopted. The photon energies used, the elements and compounds and their respective absorption-edge energies, along with the measured mass attenuation coefficients, are given in Table I.

L-x-ray relative intensities by photon excitation are generally measured by exciting a foil either using gamma

TABLE II. Photoelectric cross sections (in barns/atom).

Energy (keV)	Element	Experimental value	Viegele (Ref. 3)	Scofield (Ref. 2)	Robouch and Cicerchia (Ref. 4)	Storm and Israel (Ref. 1)
6.4	Yb	73 378±2200	73 886	71 154	73 928	71 040
6.4	Pb	141 704±5900	140 568	134 629	141 259	132 365
11.89	Au	26 586±1640	24 454	23 594	23 932	23 343
13.944	Pt	61 063±1830	64 097		62 217	60 271
13.855				53 109		
13.965				60 123		
14.414	Pb	42 139±990	43 681	41 463	41 773	41 182
17.774	Zr	2227±51	2236	2175	2341	2175
26.35	Cd	1565±20	1559	1538	1507	1537
59.54	Tm	4203±130	4338		3990	3885
59.444	Tm			736.5		
59.92	Tm			3834.5		

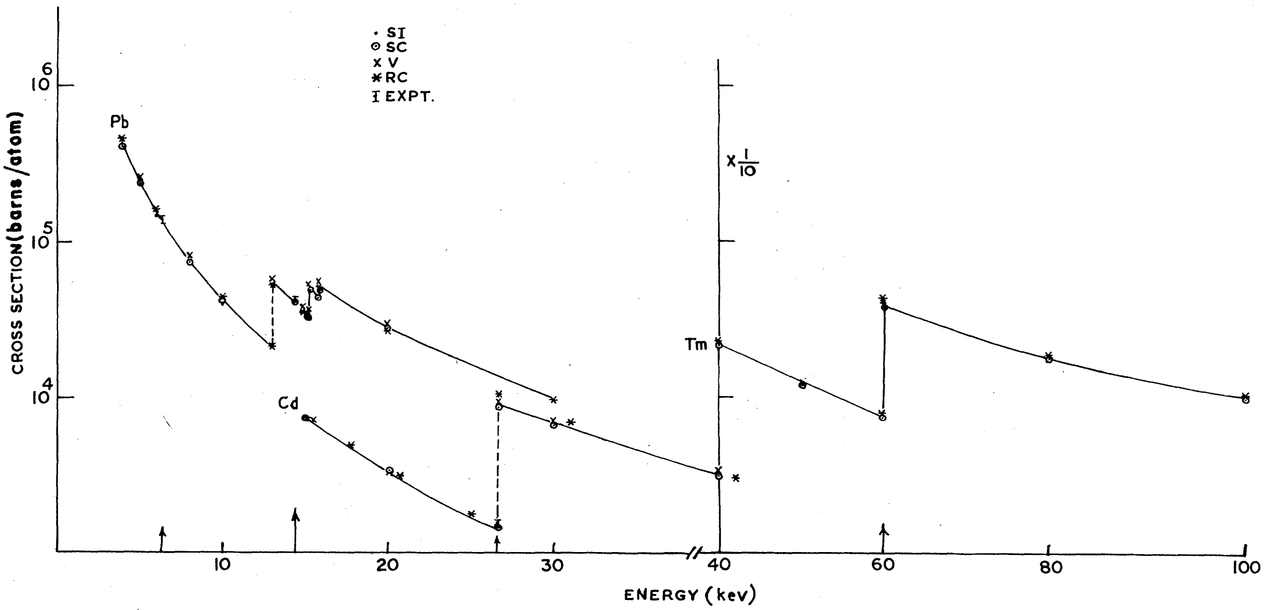

FIG. 2. Comparison of the experimental photoelectric cross sections with the available compilations (SI: Storm and Israel, Ref. 1; Sc: Scofield, Ref. 2; V: Viegele, Ref. 3; RC: Robouch and Cicerchia, Ref. 4). Arrows indicate the energies at which the cross sections are measured.

rays from a radioactive source or by using characteristic x rays from an x-ray tube with a suitable anode. But no attempt seems to have been made to measure such intensities using photons of energy very near to the absorption edge. In the present investigations Mo K x rays from an x-ray tube are used to measure the Pb L-x-ray relative intensities. Mo K-x-ray energy is 17.8 keV, whereas Pb L_1 edge energy is 15.87 keV. This situation is described as threshold excitation. Evaporated foils of about 75 μg/cm^2 of lead on a Mylar backing is excited in vacuum

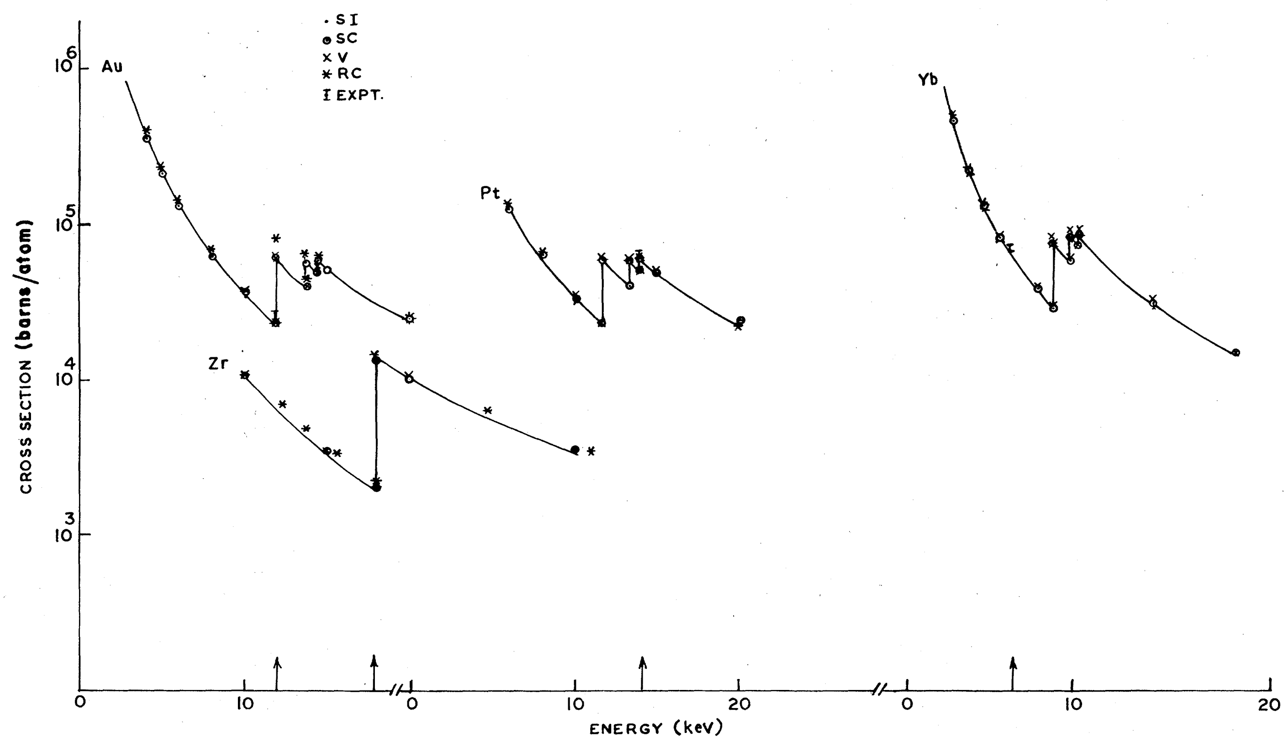

FIG. 3. Same as Fig. 2.

TABLE III. Photoelectric cross sections in Pb (barns/atom).

	6.4 keV	14.414 keV
Pb	141 704±5900	42 140±990
Pb (from $PbCl_2$)	142 918±9300[a] 140 751±9300[b]	40 786±1848[a] 40 832±1848[b]
Pb (from PbI_2)	121 555±12 200[a] 11 869±12 200[b]	40 046±3058[a] 41 999±3058[b]

[a]Derived using the Cl and I values from the experimental compilations of Robouch and Cicerchia (Ref. 4).

[b]Derived using the Cl and I values from the experimental compilations of Viegele (Ref. 3).

with Mo K x rays, as mentioned, from an x-ray tube of Mo foil anode, operated at 30 keV.[13] The spectrum is recorded with a Si(Li) spectrometer. A typical Pb L-x-ray spectrum is shown in Fig. 1. The spectra are analyzed using a least-square FACILIT program. The I_{L_α}/I_{L_l} x-ray intensity ratio is estimated after correcting for the efficiencies.[13] The correction due to self-absorption and air absorption is negligible as the experiment is conducted with a very thin Pb foil of 75 $\mu g/cm^2$ in vacuum.

III. RESULTS AND DISCUSSION

In Table II the photoelectric cross sections derived from the total cross sections reported in Table I in the case of elements are given. These are deduced by subtracting the theoretical coherent and incoherent scattering cross sections reported by Hubbell *et al.*[14] The cross section in Pt at 13.944 keV had to be corrected for the contribution from the unresolved Np L_{α_2} x-ray component in the source at 13.76 keV. This is done using the known $I_{L_{\alpha_2}}/I_{L_{\alpha_1}}$ intensity ratio[15] and the theoretical cross sections of Storm and Israel[1] at 13.76 keV. The correction is about 10%. Since Scofield used different binding energies in his calculations, the cross sections reported pertain to somewhat different edge energies than those reported by others. In Table II along with the present obtained photoelectric cross sections, the theoretical values of Storm and Israel,[1] Scofield,[2] and those derived from the experimental compilations of Viegele,[3] and Robouch and Cicerchia,[4] are given. It may be noted in this connection that a correction has been made in a few cases for the interference of x rays produced in the target with the transmitted primary photons. However, the interference is only due to the low-intensity higher-K and -L characteristic x rays and is of very small magnitude. Proper care has been taken to make such corrections, taking into account the geometrical conditions. Also, since the present measurements are near the absorption edges, the trend of the cross-section variation is not well known. Hence, only log-log interpolations are made to obtain the data of both theoretical and experimental compilations for comparison with the present measurements which are reported in Table II. In Figs. 2 and 3 the present photoelectric cross sections near edges are plotted along with those of Storm and Israel,[1] Scofield,[2] Viegele,[3] and Robouch and Cicerchia[4] for an overall view. It can be seen from Table II that the present experimental values show deviations from some of the compiled values. In Table III the photoelectric cross sections of Pb derived from those of Pb and Pb compounds are given. The cross sections for Cl and that of I are taken from the compiled experimental values of Viegele[3] and Robouch and Cicerchia.[4] It can be seen that the photoelectric cross sections of Pb are in satisfactory agreement within the range of errors except at 6.4 keV with that derived from PbI_2. A possible reason for this discrepancy is due to the possible difficulties associated with the measurement of an I cross section and, hence, the uncertainty associated with the subtracted I cross section may be large. This will have an effect since the subtracted contributions due to I is 55% of the total. Another possibility is due to the breakdown of the "sum or mixture" rule used to derive the cross section in Pb from its compound near the absorption edge, as pointed out recently.[16] However, a careful measurement of a cross section in I at 6.4 keV is directly of use in this connection.

In Table IV the I_{L_α}/I_{L_l} x-ray intensity ratio in Pb is compared with the other available experimental and theoretical values. It can be seen that the present value is in good agreement with the theoretical value[17] than any other value.

TABLE IV. Pb I_{L_α}/I_{L_l} x-ray intensity ratio.

Method	I_{L_α}/I_{L_l}
Radioactivity (Ref. 8)	20.5±10
Electron bombardment (Ref. 9)	21.5 (deduced)
α bombardment (Ref. 7)	19.4±1.3
Photon excitation	
(a) ^{241}Am (Ref. 6)	18.33±1.17
(b) W K x rays (Ref. 5)	18.20±1.7
(c) Mo anode K x rays (Present paper)	19.0±1.5
Theory (Ref. 14)	18.97

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