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Measurement of L-shell photoelectric cross sections in high Z elements at 60 keV

K L ALLAWADHI, S K ARORA and B S SOOD
Nuclear Science Laboratories, Department of Physics, Punjabi University, Patiala 147 002

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Abstract. L-shell photoelectric cross sections have been measured at 60 keV for six elements in the range $74 \leq Z \leq 92$. The measurements are found to agree with theoretical calculations.

Keywords. Photoelectric cross section; Z-elements; K-shell; L-shell.

1. Introduction

It was pointed out in an earlier paper (Allawadhi *et al* 1977) that more experimental data for L-shell photoelectric cross sections are needed to check theory against experiment at photon energies near and below K-threshold. The measurements of L-shell photoelectric cross sections in elements W, Hg, Tl, Pb, Bi and U at 60 keV have been made using a method different from the one reported earlier (Allawadhi and Sood 1975, 1976; Allawadhi *et al* 1977). The method was modified to get rid of any systematic error which might have escaped attention in the earlier measurements. 59·570 keV gamma rays from ^{241}Am instead of suitable internal/external conversion x-rays were used to avoid complications arising from the non-monochromatic character of conversion x-rays. The conversion x-rays consist of various lines having close energies but of different intensities. Even though the energies of conversion x-rays do not differ much from one another, the photoelectric cross sections being a sensitive function of energy differ considerably. The target elements were so chosen that the incident photon energy was below the K-threshold of the target element and vacancies could not be created in K-shell which would, in turn, have shifted to L-shell by the jump of electrons from L to K shell. Obviously such a selection of the target elements limits the creation of L vacancies to direct interaction of incident photons with L-shell electrons of the target elements only and avoids the use of the term $\sigma_K \cdot f_{KL} \cdot (\bar{\omega}_{KL})/\omega_L$ which was essential for the evaluation of L-shell cross sections in the previous measurements (Allawadhi *et al* 1977) and thus improves the accuracy of the present results.

2. Experimental arrangement and procedure

The experimental set up used is shown in figure 1. 59·570 keV gamma rays from ^{241}Am (Model AMC 726) disc source of strength $\sim$ 100 mC, purchased from Radiochemi-

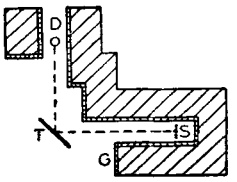

Figure 1. Experimental set up for measurement of *L*-shell photoelectric cross sections. S—Source; T—Target; D—detector; G—graded absorber of Pb, Fe and Al. The distances DT and TS are 12 and 16 cm respectively. The source S is covered with a graded filter to absorb 26 keV gamma rays and Np *L* x-rays.

cal Centre, England, were collimated to fall on targets of W, Hg, Tl, Pb, Bi and U, respectively. The source also emits (Lederer *et al* 1967) Np *L* x-rays, 26 keV gamma rays and some other high energy gamma rays in addition to 59·570 keV gamma rays. The high energy gamma rays were not of any significance in the present measurements because of their low relative intensities and small interaction cross sections. However, great care was exercised to avoid the interference from the Np *L* x-rays and 26 keV gamma rays because of their very large interaction cross sections. These were almost completely (more than 99·99%) filtered out from the incident beam with the help of graded filters.

The direct radiation from the source was prevented from reaching the counter by graded shielding consisting of Pb, Fe and Al. Source and detector were also shielded by the graded absorbers to prevent scattering from the walls and surroundings reaching the detector. The graded shielding had to be used for preferential absorption of fluorescent x-rays produced in the lead shielding. The targets in the form of circular disc of 4 cm dia with thickness varying from 12 mg/cm^2 to 27 mg/cm^2 were placed at a distance of 16 cm from the source at an angle of 45° to the incident gamma ray beam. Since metallic foils of target materials other than Pb were not available, thin self-supporting targets were made by mixing finely powdered salt with polystyrene dissolved in benzene. The mixture was poured on a glass plate, left to dry cut to size and mounted as described in an earlier paper (Singh and Sood 1972). The presence of a small amount of polystyrene in the target material produced almost negligible effect on the results of the present experiment. This was verified by comparing the performance of PbO_2 target with metal foil target containing the same amount of lead. The intensity of emitted fluorescent x-rays was measured with a proportional counter spectrometer the window of which was at about 12 cm from the target and placed at 90° with respect to the incident beam. The spectrometer consisted, of Xe (95%) and CO_2 (5%) filled proportional counter model P3-1605-261 manufactured by Reuter-Stokes, USA, ECIL-charge sensitive pre-amplifier model HA502C, ORTEC spectroscopic amplifier model 451, and ND series 1100 analyser system. To subtract any contribution due to low energy scattered photons, etc., the background counts were recorded with an equivalent aluminium target. Figure 2 shows typical spectra of *L* shell fluorescent x-rays. L_α, L_β and L_γ lines are seen. The scattering from experimental target matches fairly well with that from equivalent aluminium target. The difference between the experimental target spectrum and the equivalent aluminium target spectrum gives the contribution of *L*-shell fluorescent x-rays. The spectrum without any target in position shows a general background lower than that with Al target indicating that the effect of scattering from surroundings in the region of the fluorescent x-rays peaks is not of any significance and only the fluorescent x-rays emitted from the target, which are of interest in the present investigation, are taken into account. In the case of U target, the background arising due to the natural

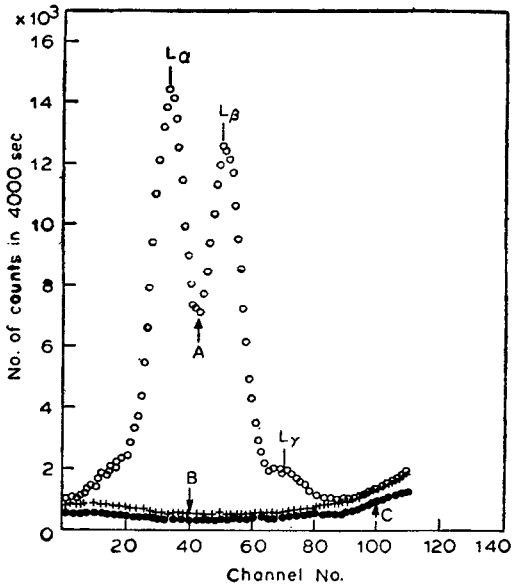

Figure 2. A- Pb *L* fluorescent x-ray spectra recorded with proportional counter spectrometer, when the target was irradiated with 60 keV gamma rays from ^{241}Am source; B- B.G. recorded with equivalent Al target; C- B.G. recorded without any target in position.

radioactivity of U was also subtracted. A sufficient number of runs for time ranging from 1000 to 4000 sec were made with each target material so as to achieve a statistical accuracy $\sim$1–2%. Special checks were maintained to ensure stability of the electronics by calibrating the spectrometer off and on with a source of ^{57}Co. Any run involving a noticeable shift was discarded.

The gamma rays incident on the target interact with the *L*-shell electrons of the target element through inelastic photoelectric and Compton interactions and elastic Rayleigh interaction. As a result of these interactions, the target emits photoelectrons, fluorescent *L* x-rays and coherently and incoherently scattered gamma rays. The scattering was isolated from the fluorescent radiation with the proportional counter. The measurement of the intensity of either the photoelectron or the fluorescent x-rays emitted from the target and the intensity of gamma rays incident on it provides a method to determine the photoelectric cross sections. The fluorescent x-rays are emitted isotropically whereas photoelectrons emitted from different subshells have different angular distribution. The measurement of the absolute intensity of photoelectrons, therefore, needs complicated, uncertain and relatively less known corrections for their angular distributions and absorption and scattering in the target. The determination of the intensity of photoelectrons especially at low energies in the presence of Auger electrons of comparable energies also offers difficulties because of the inherent experimental complexities involved in the high resolution electron spectroscopy. On the other hand, the determination of fluorescent x-ray intensities is relatively easier and simpler. It obviates almost all the difficulties encountered in the measurement of photoelectrons.

It can be easily shown that the intensity $n_L(x)$ of L fluorescent x-rays as measured with the spectrometer under the photopeak is given by

$$n_L(x) = S(\gamma) \cdot \frac{\omega_1}{4\pi} \cdot a(\gamma) \cdot \frac{N}{M} \cdot t \cdot \beta_L(\gamma) \cdot \sigma_L(\gamma) \cdot \bar{\omega}_L \cdot \frac{\omega_2}{4\pi} \cdot \epsilon(x) \qquad (1)$$

where $S(\gamma)$ is the intensity of gamma rays emitted from the source. $a(\gamma)$ is the correction factor for absorption of gamma rays in source, air column, etc. $\sigma_L(\gamma)$ is the total L-shell photoelectric cross section. N is the Avogadro's number, M is the atomic weight of the target element. t is the thickness of the target in gm/cm^2. $\beta_L(\gamma)$ is the correction factor to take into account the absorption of incident radiations and emitted x-rays in the target. $\bar{\omega}_L$ is the average L shell fluorescence yield, ω_1 and ω_2 are the target-source and target-detector solid angles and $\epsilon(x)$ is the photopeak efficiency of the detector.

From eq. (1) the L-shell photoelectric cross section can be expressed as

$$\sigma_L(\gamma) = \frac{n_L(x)}{\left[S(\gamma) \cdot \frac{\omega_1}{4\pi} \cdot a(\gamma) \cdot \frac{\omega_2}{4\pi} \cdot \epsilon(x)\right] \cdot \frac{N}{M} \cdot t \cdot \beta_L(\gamma) \cdot \bar{\omega}_L}. \qquad (2)$$

In order to evaluate $\sigma_L(\gamma)$ from eq. (2), $n_L(x)$ was measured from the total number of counts per unit time under the L-fluorescent x-ray photopeak. The terms $(N/M) \cdot t$ and $\beta_L(\gamma)$ were calculated from the physical parameters of the target and the absorption coefficients of the gamma rays and x-rays, respectively (Allawadhi and Sood 1975; Singh and Sood 1972). As explained earlier (Allawadhi *et al* 1977), the experimentally determined values of Lay (1934) were used for $\bar{\omega}_L$. The physical quantity viz.

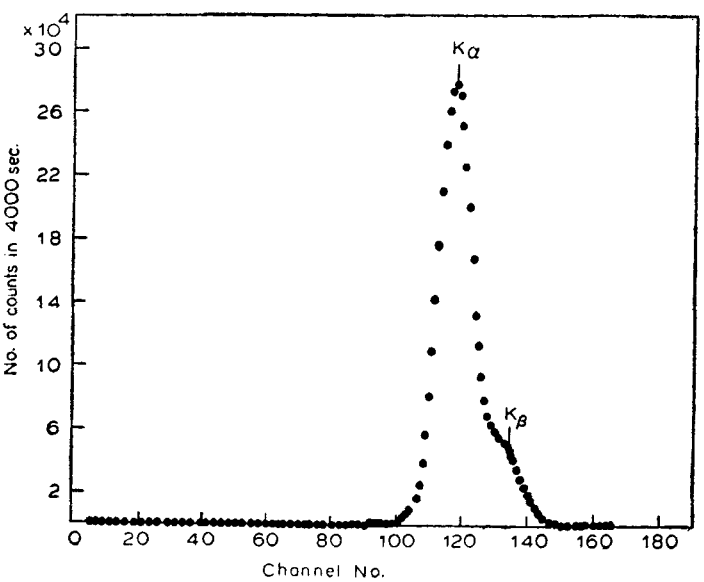

Figure 3. Mo K x-ray spectra recorded with proportional counter spectrometer when the target was irradiated with 60 keV gamma rays from ^{241}Am source (B.G. counts recorded with equivalent Al target have been subtracted out)

$[s(\gamma) \cdot (\omega_1/4\pi) \cdot a(\gamma) \cdot (\omega_2/4\pi) \cdot \epsilon(x)]$ was determined experimentally for different energies ranging from 6 keV to 18 keV in terms of K-shell photoelectric cross sections $\sigma_K(\gamma)$ (Scofield 1973) and K-shell fluorescence yields ω_K (Bambynek *et al* 1972); the values of both these quantities are known to an accuracy of 2-3%. From the measured data the values of this physical quantity at the required L-shell fluorescent x-ray energies were interpolated. For this purpose targets of Fe, Ni, Cu, Se, Zr and Mo having the same dimensions as in the main experiment were irradiated with the source and in the same experimental set up, and the intensity of K-shell fluorescent x-rays emitted in each case were recorded with the same detector as used for the L x-rays. The results of a typical run are shown in figure 3. It can be easily seen that the physical quantity under reference

$$\left[s(\gamma) \cdot \frac{\omega_1}{4\pi} \cdot a(\gamma) \cdot \frac{\omega_2}{4\pi} \cdot \epsilon(x)\right] = \frac{n_K(x)}{\frac{N}{M} \cdot t \cdot \beta_K(\gamma) \cdot \omega_K \cdot \sigma_K(\gamma)} \tag{3}$$

where $n_K(x)$, N/M, t and $\beta_K(\gamma)$ has the same meaning as explained in eq. (1) but correspond to K-shell and were evaluated as explained above. The results are shown in figure 4 which gives the value of the physical quantity at different K-shell fluorescent x-ray energies. The values of the term corresponding to various L-shell x-ray energies were read from figure 4.

Since L-shell photoelectric cross sections are expected to be very large for the photon energy used, any contribution due to Compton scattering and secondary ionization of the photo and Compton electrons is not of any significance and, therefore, can be safely neglected (Singh and Sood 1972). Any dependence of the present results on the target thickness was checked by taking measurements with eight targets of lead with thickness varying from 15 to 100 mg/cm^2 and the results are shown in figure 5, in which number of counts per unit effective thickness i.e. $n_L(x)/(\beta_L(\gamma) \cdot t)$ are plotted

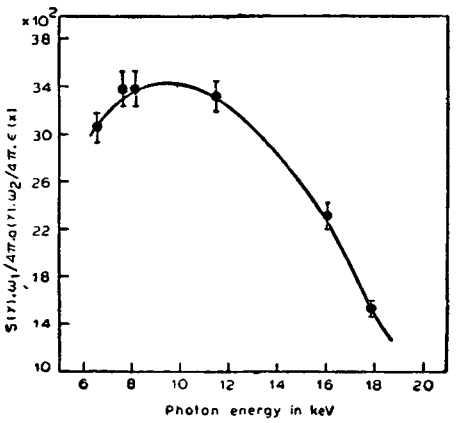

Figure 4. Plot of $\left[S(\gamma) \cdot \frac{\omega_1}{4\pi} \cdot a(\gamma) \cdot \frac{\omega_2}{4\pi} \cdot \epsilon(x)\right]$ vs photon energy. The effective efficiency under the experimental set up depends upon (i) the transmission of the radiation through the air column between target and counter and the counter window and (ii) absorption in the gas filled in the counter. The decrease below 8 keV and above 12 keV is because of decrease in (i) and (ii) respectively.

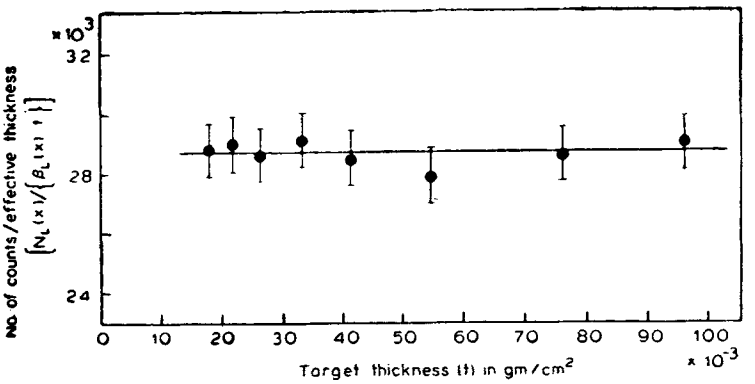

Figure 5. Plot of number of fluorescent x-rays $[n_L(x)]$ per unit effective thickness $[\beta_L(\gamma) \cdot t]$ when eight different targets of Pb were irradiated with 60 keV gamma rays from ^{241}Am source, vs target thickness (t).

against target thickness t. The results for different targets agree with one another within experimental uncertainties showing that the correction applied for the absorption of incident gamma rays and emitted x-rays in the target is correct and thus the final results do not depend upon thickness of the target used in the present measurements.

3. Results and discussion

The results of the L-shell photoelectric cross sections at 59·570 keV in elements W, Hg, Tl, Pb, Bi and U as determined from eq. (2) are listed in table 1. The errors quoted

Table 1. Comparison of the present measurements of L-shell photoelectric cross sections at 59·570 keV with available theoretical calculations

Element	L-shell photoelectric cross sections at 59.570 keV	
	Present measurements (b/atom)	Theoretical values (b/atom)
W	780 ± 80	(1) 769 (2) 765 (3) 768
Hg	1095 ± 110	(1) 1071
Tl	1130 ± 115	(1) 1129
Pb	1220 ± 130	(1) 1189 (2) 1183
Bi	1280 ± 130	(1) 1251
U	2030 ± 210	(1) 1930 (2) 1916 (3) 1935

(1) Scofield 1973; Pratt *et al* 1973.
(2) Schmickley and Pratt, 1967.
(3) Rakavy and Ron, 1967.

in the final results are ~10% and are due to counting statistics and uncertainties involved in the other quantities used for the determination of the cross sections. $n_L(x)$ was measured within 1–2%. The uncertainty involved in the evaluation of $\beta_L(\gamma)$ is ~3–4%. The physical quantity is estimated to be accurate to within 5%. The error taken in the value of $\bar{\omega}_L$ is 8%.

The L-shell cross section in Pb was again measured, after eight months by a different worker, in another independent experiment in terms of the K-shell cross sections of Br and Se to be 1180 ± 125 and 1170 ± 120 respectively as compared to the above reported value of 1220 ± 130 b/atom. The weighted mean energies of K-shell x-rays of Br and Se are 12·087 and 11·372 keV respectively as compared to the weighted mean energy 12·217 keV of L-shell x-rays of Pb. A good agreement of these values with earlier one shows that the results reported in the present communication, do not involve any serious systematic and personal errors.

The results are compared with theoretical calculations (Scofield 1973; Pratt *et al* 1973; Schmickley and Pratt 1967; Rakavy and Ron 1967) only as no other experimental values are yet available in the literature to the best of our knowledge. A good agreement of experiment with theory shows that the electron correlation and exchange effects which have been neglected in the theoretical calculations do not play any significant role in the photo-absorption of 60 keV photons in elements with atomic number greater than 74. However, the discrepancy between experiment and theory at 37 keV reported earlier (Allawadhi *et al* 1977) still remains to be explored further.

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