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Measurement of L-shell photoelectric cross sections in high Z elements at 37 and 74 keV

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Abstract. L-shell photoelectric cross section measurements have been made at 36·818 and 74·409 keV for four elements in the range $81 \leqslant Z \leqslant 92$. The measurements at 74·409 keV are found to agree with theory, within experimental uncertainties, but the experimental values at 36·818 keV are found to be higher than the theoretical predictions. The possible reasons for the observed discrepancy are discussed.

Keywords. Photoelectric interaction ; fluorescent x-rays.

1. Introduction

Even though the photoelectric interaction of radiation with matter has been known since 1887 (Hertz 1887), its finer details are still not well understood. Recently there have been several renewed efforts, theoretical as well as experimental (Pratt *et al* 1973, Hubbell and Veigele 1976) towards a better understanding of the interaction because of its applications to many problems in the fields of radiation physics, solid state physics, astrophysics and nuclear physics, etc. Numerical calculations of the total atom as well as shell-wise photoelectric cross sections have been made by some workers (Rakavy and Ron 1967, Schmickley and Pratt 1967, Scofield 1973) using different potential models for various elements in the energy range from 1–1500 keV. Semi-empirical data for the total atom cross sections have been tabulated with an accuracy of 2–15%. The direct measurements of the total atom as well as shell-wise cross sections are very scarce and these too are restricted to some selected photon energies above 84 keV emitted by suitable radioisotopes, perhaps because of the non-availability of clean and strong radioisotopes of low energy photons. Lately the authors (Allawadhi and Sood, 1975, 1976) have resolved this problem by using internal and external conversion x-rays as low energy photon sources and measured the K-shell cross sections for intermediate Z elements ($39 \geqslant Z \geqslant 74$) in the energy range 18 to 74 keV. The available direct L-shell measurements are at 279, 145, 122 and 84 keV. The comparison of the existing experimental data with theoretical calculations shows that for the total atom and K-shell, there is a fairly good agreement between theory and experiment in the entire energy range in which measurements are available. The L-shell experimental values (Singh and Sood 1972) show good agreement with theory at 279 and 145 keV, but the measured values at 122 keV (Boyed *et al* 1965) and 84 keV (Singh and Sood 1970) are somewhat higher than theory and some discrepancy seems to exist. In order to check this discrepancy and provide some new data to fill the existing void, the L-shell cross sections in Tl, Pb, Bi and U have been measured at the weighted mean internal conversion x-ray energies of 36·818 and 74·409 keV and the results are reported in this paper.

2. Method of measurement

The method of using internal conversion x-rays for the measurement of K-shell photoelectric cross sections as described in an earlier communication (Allawadhi and Sood 1975) was extended to determine L-shell photoelectric cross sections for photons of energies 36·818 and 74·409 keV which were obtained from the K-conversion of 145 and 279 keV levels in ^{141}Pr and ^{203}Tl, respectively. The targets of the element under investigation were irradiated, in turn, first with both x-rays and gamma rays and then with gamma rays only. The intensity of the fluorescent L-shell x-rays emitted from the target, as a result of photoelectric interaction of the incident radiation from the source was measured with a proportional counter coupled to ND–1100 series analyser system. Measurements at 74·409 keV were also made by using the method (Allawadhi and Sood 1975) in which complete absorption of x-rays was not needed.

It can be easily seen that our earlier equations used for the determination of K-shell cross section [eqs (3) and (7); Allawadhi and Sood 1975] have to be modified for the L-shell cross section measurements as

$$\sigma_L(x) = \frac{S(\gamma)\cdot a(\gamma)}{S(x)\cdot a(x)}\left[\frac{N(\gamma+x)}{N'(\gamma)}\,\frac{S'(\gamma)}{S(r)} - 1\right]\frac{\beta(\gamma)}{\beta(x)} \cdot\left[\sigma_L(\gamma) + \frac{\bar{\omega}_{KL}}{\bar{\omega}_L}\cdot f_{KL}\cdot\sigma_K(\gamma)\right] \qquad (1)$$

(method in which x-rays are completely absorbed)

$$\sigma_L(x) = \frac{\dfrac{S(\gamma)\cdot a(\gamma)}{S(x)\cdot a(x)} - \dfrac{S^*(\gamma)\cdot a(\gamma)}{S^*(x)\cdot a(x)}\cdot\dfrac{N(\gamma+x)}{N^*(\gamma+x)}\cdot\dfrac{S^*(x)}{S(x)}}{\dfrac{N(\gamma+x)}{N^*(\gamma+x)}\cdot\dfrac{S^*(x)}{S(x)} - 1}\cdot\frac{\beta(\gamma)}{\beta(x)} \cdot\left[\sigma_L(\gamma) + \frac{\bar{\omega}_{KL}}{\bar{\omega}_L}\cdot f_{KL}\cdot\sigma_K(\gamma)\right] \qquad (2)$$

(method in which x-rays are partially absorbed)

where f_{KL} is the probability that a vacancy in the K-shell will be filled by a transition from the L-shell and $\bar{\omega}_{KL}$ and $\bar{\omega}_L$ are the average fluorescence yields for L-shell when a vacancy in the L-shell is created in the process of filling the K-shell vacancy and due to photoelectric absorption of photons in the L-shell respectively. All other terms have the same meanings as in the earlier communication (Allawadhi and Sood 1975).

In these equations the additional term $\bar{\omega}_{KL}/\bar{\omega}_L\cdot f_{KL}\cdot\sigma_K(\gamma)$ appears because of the interactions of incident gamma rays with the K-shell electrons of the target element which in turn leads to some vacancies in the L-shell and hence also contribute to L-shell fluorescence radiation. The internal conversion x-rays have energies below K-threshold for all the elements used and therefore cannot create vacancies in K-shells.

3. Results and discussion

The results of the present measurements at 36·818 and 74·409 keV as obtained by the two methods explained above are compared with the theoretical calculations of Scofield (1973) which have been chosen for comparison because firstly these are the most recent values, and secondly there is an agreement among the various available calculations (Schmickley and Pratt 1967, Rakavy and Ron 1967) within 2% which is less than the experimental errors in the present measurements. Since the present measurements are for the mean cross sections of Pr and Tl K x-rays which consist of $K\alpha_1$ $K\alpha_2$, $K\beta_1$ . . ., etc. emission lines, care has to be exercised to evaluate theoretical values for comparison with the experiment. For this purpose $\bar{\sigma}_L$ ($K\alpha_1$, $K\alpha_2$, $K\beta_1$ . . .) is calculated by weighing the cross sections at $K\alpha_1$, $K\alpha_2$, $K\beta_1$ . . ., etc. energies according to their relative intensities taken from *Nuclear Data Tables* (Storm and Israel 1970) and the values are listed in column 5 of table 1. Also in column 6 of table 1 are shown the cross sections σ_L ($\bar{K\alpha}$, β)

Table 1. Comparison of the present measurements of L-shell photoelectric cross sections with theoretical calculations (Scofield 1973).

Energy in keV	Element	Z	L-shell photoelectric cross section in b/atom: Present measurements	Theoretical values (Scofield 1973): Weighted mean of the cross sections $\bar{\sigma}_L$ ($K\alpha_1$, $K\alpha_2$, $K\beta_1$ ..)	The cross section at weighted mean energy σ_L ($\bar{K\alpha}$, β)
36·818	Pb	82	e(1) 5050±480	4403	4340
	U	92	e(1) 7930±760	6855	6720
74·409	Tl	81	e(1) 780±70	614	610
			e(2) 670±75		
	Pb	82	e(1) 700±65	641	628
			e(2) 730±75		
	Bi	83	e(1) 800±70	677	670
			e(2) 750±80		
	U	92	e(1) 1200±110	1071	1050
			e(2) 1230±130		

e(1)—Method in which x-rays are completely absorbed.

e(2)—Method in which x-rays are partially absorbed.

at the weighted mean x-ray energies 36·818 and 74·409 keV. It is of interest to note that the weighted mean cross section $\bar{\sigma}_L$ ($K\alpha_1$, $K\alpha_2$, $K\beta_1$, . . .) and the cross section at weighted mean energy σ_L ($\bar{K\alpha}$, β) agree with each other within less than 2%, this is perhaps due to the fact that $K\alpha_1$ and $K\alpha_2$ lines which are very close to each other are much more intense than the other lines and difference between their energies is not very large. From the comparison of the present results with theory it is seen that though the results at 74·409 keV agree with theory within the experimental uncertainties, these are consistently higher than theory. However, the results at 36·818 keV are higher than theoretical calculations even when the experimental errors are taken into account. It may, therefore, be inferred that the observed discrepancy shows itself for photon energies near and below K-threshold. An effort to explain the reasons for this discrepancy may require to comment both on the present measurements and the theoretical calculations. The method used for the present measurements has already yielded results for the K-shell which are found to be in agreement with the theoretical calculations. The only additional quantities needed in the present measurements are $\bar{\omega}_{KL}$, $\bar{\omega}_L$ and f_{KL}. Though a large variety of data on average fluorescence yields (Bambynek *et al* 1972) are available, the experimentally determined values of Lay (1934) and Jopson *et al* (1963) were used for $\bar{\omega}_L$ and $\bar{\omega}_{KL}$ respectively because these have been measured under experimental conditions similar to the one used in the present measurements. The values of f_{KL} were taken from Rao *et al* (1972) The detailed justification for the use of these values for the determination of the cross sections is given in an earlier communication (Singh and Sood 1972). Also no such discrepancy was observed when these values of $\bar{\omega}_{KL}$ and $\bar{\omega}_L$ were used to determine L-shell cross sections at 279 and 145 keV. Thus it seems quite reasonable to assume that the present discrepancy does not arise due to the values of $\bar{\omega}_L$ and $\bar{\omega}_{KL}$ unless these are taken to be energy dependent which is not very plausible in view of the fact that average L-shell yields depend very little on the initial vacancy distribution (Bambynek *et al* 1972). On the other hand the available theoretical calculations have been made using different atomic models. The calculated cross sections obtained agree with one another within 2%. These calculated values also agree with the experimentally measured values for K-shell down to 18 keV and for L-shell down to 145 keV. But one thing common in these calculations is that the effects of correlation and exchange of electrons, which are believed to play an important role at low energies close to absorption edges and higher shells (Pratt *et al* 1973), have been neglected in all the calculations. Thus it may be concluded that more accurate theoretical calculations which take into account electron correlation and exchange effects and more experimental data are needed to resolve the observed discrepancy.

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