PHYSICAL REVIEW A VOLUME 11, NUMBER 6 JUNE 1975

K-shell photoelectric cross sections for intermediate Z elements at 37 and 74 keV

K. L. Allawadhi and B. S. Sood

Nuclear Science Laboratories, Department of Physics, Punjabi University, Patiala-147002, India

(Received 24 December 1974)

K-shell photoelectric cross-section measurements at 36.818 and 74.409 keV, in 15 elements in the range $33 \leq Z \leq 74$, have been made using Sood's method with minor modifications which are necessitated because of the nonavailability of clean and strong sources of low-energy photons. No discrepancy between theory and experiment similar to the one reported for the L-shell case has been found.

I. INTRODUCTION

At high energies, well above the threshold, a fairly good agreement between experimental data[1,2] and theoretical calculations[3-5] for the K-shell as well as L-shell photoelectric cross sections in various elements has been reported. But at low energies, while no experimental data are available for the K shell,[6] the experimental L-shell cross sections are found to be higher than the theoretical values[2,7-9] and the discrepancy is reported to increase with decreasing photon energy.[2,8] K-shell photoelectric cross sections in 15 elements, Z ranging from 33 to 74, have been measured at photon energies of 36.818 and 74.409 keV and the results compared with theoretical calculations, to see if any discrepancy similar to the one reported for the L-shell case exists for the K shell also. The choice of photon energy, as will be seen later, is restricted by the method chosen for the measurements.

II. METHOD OF MEASUREMENT

Sood's method[1,2] of measuring the absolute yield of K-shell fluorescent x rays when a target is irradiated with a known flux of photons, with some minor modifications which were necessitated because of the nonavailability of clean and strong sources of low-energy photons, was used, because the only other method[10,11] available for such measurements depends upon the determination of the absolute intensity of photoelectrons and thus it suffers from not only the inherent experimental complexities involved in high-resolution spectroscopic analysis of photoelectrons in the presence of Auger electrons of comparable energies but also somewhat uncertain and relatively less-known corrections for the angular distribution of photoelectrons have to be applied.

The photons of energies 36.818 and 74.409 keV were obtained from the K conversion of the 145- and 279-keV levels in ^{141}Pr and ^{203}Tl, respectively. For this purpose, about 300-mC-strong ^{141}Ce and ^{203}Hg radioactive sources were purchased from BARC India. The conversion x rays and γ rays from the sources were collimated to fall on the targets of thicknesses ranging from 13 to 42 mg/cm^2 placed at a distance of 15 cm from the mouth of the collimator slit. Self-supporting targets were prepared as reported earlier.[2] The lead shielding as well as the collimating slit were lined with graded shielding of tin, copper, and aluminum to absorb x rays produced in the lead shielding. The intensity of fluorescent K x rays produced in the target was measured by scintillation spectrometer, consisting of a NaI(Tl) crystal of thickness 2–3 mm and 4.9 cm diam. coupled with a RCA 6342 A photomultiplier tube, ND-520 amplifier, and ND-1100 series analyzer system. The detector was placed at a right angle to the incident beam at a distance of 17.5 cm from the target. The experimental arrangement is shown in Fig. 1. The background counts were recorded with an equivalent aluminum target, to take care of any contribution due to low-energy scattered photons. A sufficient number of independent runs for times ranging from 200 to 2000 sec were made with each target material so as to achieve statistical accuracy of the order of 1 to 2%. Special

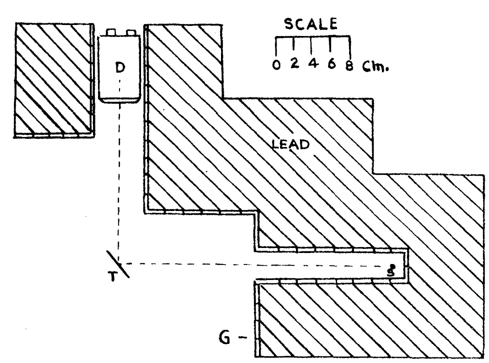

FIG. 1. Experimental setup for measurement of K-shell photoelectric cross sections. S, source; T, target; D, detector; G, graded absorber of Sn, Cu, and Al.

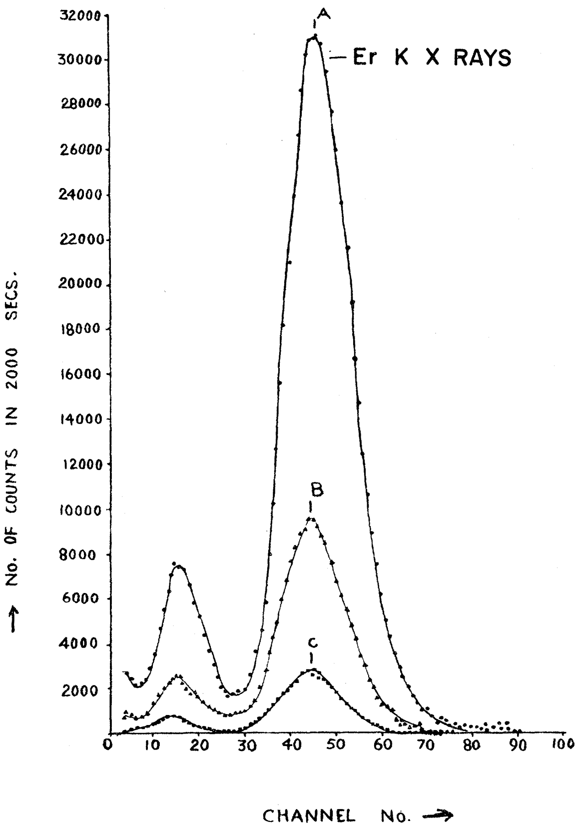

FIG. 2. Erbium K x-ray spectra recorded with thin NaI(Tl) crystal spectrometer, when the target was irradiated with ^{203}Hg source. A, target irradiated with both x rays and γ rays; B, target irradiated with x rays and γ rays after absorption in an iron absorber; C, target irradiated with γ rays only and x rays are almost completely absorbed with a graded filter.

checks were maintained to ensure the stability of the electronics by calibrating the spectrometer off and on with a standard source of ^{133}Ba.

A suitable graded filter designed and tested to absorb almost all (more than 99.99%) conversion x rays was placed in the incident beam at the mouth of the collimating slit so that only γ rays of intensity somewhat lower than before were allowed to fall on the target and the intensity of resultant K x rays emitted by the target was again measured. Some typical spectra are shown in Fig. 2. Assuming isotropic emission of x rays from the target, their intensities, as measured with the spectrometer under the photopeak, in each of the above cases are given by

$$N(\gamma+x)=S(\gamma)\frac{\omega_1}{4\pi}a(\gamma)\rho t\,\beta(\gamma)\sigma(\gamma)\,\omega_K\frac{\omega_2}{4\pi}\epsilon_K + S(x)\frac{\omega_1}{4\pi}a(x)\rho t\,\beta(x)\sigma(x)\,\omega_K\frac{\omega_2}{4\pi}\epsilon_K\,, \quad (1)$$

$$N'(\gamma)=S'(\gamma)\frac{\omega_1}{4\pi}a(\gamma)\rho t\,\beta(\gamma)\sigma(\gamma)\,\omega_K\frac{\omega_2}{4\pi}\epsilon_K\,, \quad (2)$$

where N is number of K x rays per unit time measured under the photopeak. S is the intensity of radiation, a is the correction factor for absorption of radiation in source, air column etc., and σ is the K-shell photoelectric cross section; ρ is the number of atoms per cm^3 of target material; t is the thickness of the target, β is the correction factor to take into account the absorption of incident radiations and emitted x rays in the target, and ω_K is the K-shell fluorescent yield. ω_1 and ω_2 are target-source and target-detector solid angles, and ϵ_K is the photopeak efficiency of the detector. Letters γ and x in parentheses indicate that the term corresponds to γ rays or x rays. The K-shell photoelectric cross sections at the energy of conversion x rays, $\sigma(x)$, can be expressed from (1) and (2) as

$$\sigma(x)=\frac{S(\gamma)a(\gamma)}{S(x)a(x)}\left(\frac{N(\gamma+x)}{N'(\gamma)}\frac{S'(\gamma)}{S(\gamma)}-1\right)\frac{\beta(\gamma)}{\beta(x)}\sigma(\gamma). \quad (3)$$

The procedure outlined above reduces the determination of photoelectric cross section to the measurements of the ratios

$$\frac{S(\gamma)a(\gamma)}{S(x)a(x)}\,,\quad \frac{N(\gamma+x)}{N'(\gamma)}\,,\quad \frac{S'(\gamma)}{S(\gamma)}\,,\ \text{and}\ \frac{\beta(\gamma)}{\beta(x)}\,,$$

which can be determined more conveniently and with better accuracy than the absolute values. The ratio $N(\gamma+x)/N'(\gamma)$ was determined by measuring the ratio of the areas under the K x-ray photopeaks when the target is irradiated with $(\gamma+x)$ and γ rays, respectively. The ratio $S(\gamma)a(\gamma)/S(x)a(x)$ was determined in a separate experiment. A small source of strength $\mathcal{S}$ was prepared on a very thin backing of polythene, and it was placed at the position of the target. The detector was placed such that it was in line with the main source and the weak source. The main source was completely shielded with a thick lead brick, and the counts $n_w(x)$ and $n_w(\gamma)$ under the conversion x-ray and γ-ray photopeaks were recorded. Assuming that there is no self-absorption in the source,

$$\alpha_K\omega_K=\frac{\mathcal{S}(x)}{\mathcal{S}(\gamma)}=\frac{n_w(x)a'(\gamma)\epsilon(\gamma)}{n_w(\gamma)a'(x)\epsilon(x)}\,, \quad (4)$$

where α_K is the K conversion coefficient and the other terms are the same as explained earlier. (Subscript w stands for the weak source.) The weak source was then removed and the main source was unshielded. The counts as measured under the x-ray and γ-ray photopeaks are given by

$$\frac{n_m(x)}{n_m(\gamma)}=\frac{S(x)a(x)a'(x)\epsilon(x)}{S(\gamma)a(\gamma)a'(\gamma)\epsilon(\gamma)}\,. \quad (5)$$

The subscript m stands for the main source and other terms have the same meaning. Combining (4) and (5),

$$\frac{S(\gamma)a(\gamma)}{S(x)a(x)} = \frac{1}{\alpha_K\omega_K}\,\frac{n_w(x)}{n_w(\gamma)}\,\frac{n_m(\gamma)}{n_m(x)}\ . \tag{6}$$

The values of $S(\gamma)a(\gamma)/S(x)a(x)$ were calculated from (6) to be 12.10 ± 0.60 and 12.90 ± 0.58, respectively, for ^{141}Ce and ^{203}Hg sources. The values of α_K equal to 0.379 ± 0.004 and 0.163 ± 0.002 were taken from a set by Van Nooijen and Hamilton.[12] These values are known to an accuracy of 1–2% and are being used for calibration purposes. The values of ω_K for Pr and Tl, equal to 0.915 ± 0.025 and 0.965 ± 0.020, were taken from the review of Bambynek *et al.*[13] $S'(\gamma)/S(\gamma)$ was measured by finding the ratio of counts per unit time recorded under γ-ray photopeak obtained with and without graded absorber under the same geometrical setup. (A typical run is shown in Fig. 3.) The ratios $\beta(\gamma)/\beta(x)$ were calculated as explained earlier[14] using the recent values of Hubbell[15] and McMaster *et al.*[16] for the absorption coefficients. Values of $\sigma(\gamma)$ at 145 and 279 keV were taken as calculated very recently by Scofield.[5] These values are in good agreement with the latest experimental values.[1]

In order to test the validity of the complete absorption of x rays in the above described method, some of the measurements were also made by another method not dependent upon the complete absorption of the conversion x rays from the irradiating beam. In this method the target was irradiated, first with x rays and γ rays as in the previous method and then with x rays and γ rays after partial absorption of their intensities in an iron absorber. A typical run is included in Fig. 2. It can be shown that if $N(\gamma+x)$ and $N^*(\gamma+x)$ are the intensities of the K fluorescent x rays of the target element, as measured by the counter, in two cases $\sigma(x)$ is given by the relation

$$\sigma(x) = \frac{S(\gamma)a(\gamma)/S(x)a(x) - [S^*(\gamma)a(\gamma)/S^*(x)a(x)][N(\gamma+x)/N^*(\gamma+x)]S^*(x)/S(x)}{[N(\gamma+x)/N^*(\gamma+x)]S^*(x)/S(x) - 1}\ \frac{\beta(\gamma)}{\beta(x)}\ \sigma(\gamma)\ , \tag{7}$$

where the various terms in (7) have the same meaning as given before. Superscript * corresponds to the terms after absorption. The ratios $S^*(\gamma)a(\gamma)/S^*(x)a(x)$ and $S^*(x)/S(x)$ were measured in a similar way as $S(\gamma)a(\gamma)/S(x)a(x)$ and $S'(\gamma)/S(\gamma)$, respectively.

Since K-shell photoelectric cross sections are expected to be very large at the photon energies used, any contribution due to Compton scattering from K-shell electrons and secondary ionization of the photoelectrons is not of any significance and, thus, can be safely neglected.[1,2]

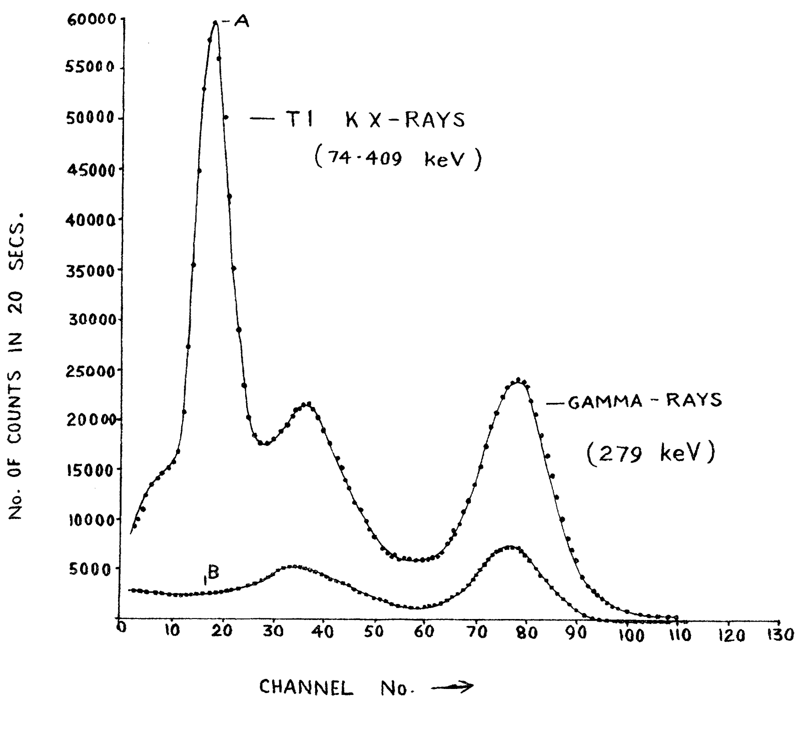

FIG. 3. ^{203}Hg (main source) spectra recorded with thin NaI(Tl) crystal spectrometer. A, without graded filter; B, with graded filter.

TABLE I. Comparison of the present measurements of K-shell photoelectric cross sections with the existing theoretical calculations.

		K-shell photoelectric cross sections			
		At 36.818 keV		At 74.409 keV	
Element	Z	Present measurements [a] (b/atom)	Existing theoretical calculations [b] (b/atom)	Present measurements [a] (b/atom)	Existing theoretical calculations [b] (b/atom)
As	33	e(1) 835 ± 66	t(1) 920		
			t(2) 880	...	...
Y	39	e(1) 1570 ± 125	t(1) 1675		
			t(2) 1650	...	...
Zr	40	e(1) 1726 ± 143	t(1) 1775		
			t(2) 1750	...	...
Mo	42	e(1) 2042 ± 167	t(1) 2175	e(1) 238 ± 19	t(1) 295
			t(2) 2125	e(2) 251 ± 26	t(2) 295
Ag	47	e(1) 2846 ± 239	t(1) 3100	e(1) 390 ± 31	t(1) 443
			t(2) 3050	e(2) 428 ± 42	t(2) 445
Cd	48	e(1) 3110 ± 258	t(1) 3375	e(1) 435 ± 35	t(1) 480
			t(2) 3350	e(2) 436 ± 43	t(2) 480
Sn	50	e(1) 3600 ± 302	t(1) 3875	e(1) 509 ± 41	t(1) 560
			t(2) 3850	...	t(2) 560
			t(3) 3875	...	t(3) 565
I	53	e(1) 4274 ± 359	t(1) 4600	e(1) 663 ± 53	t(1) 705
			t(2) 4550	e(2) 657 ± 65	t(2) 710
Ba	56			e(1) 858 ± 68	t(1) 865
				e(2) 854 ± 83	t(2) 850
La	57			e(1) 834 ± 66	t(1) 910
				e(2) 833 ± 81	t(2) 900
Ce	58			e(1) 1019 ± 80	t(1) 975
				e(2) 927 ± 94	t(2) 970
Sm	62			e(1) 1199 ± 94	t(1) 1220
				e(2) 1255 ± 122	t(2) 1220
Gd	64			e(1) 1363 ± 108	t(1) 1400
				e(2) 1402 ± 140	t(2) 1390
Er	68			e(1) 1490 ± 120	t(1) 1650
				e(2) 1521 ± 155	t(2) 1640
W	74			e(1) 2025 ± 163	t(1) 2220
				e(2) 2123 ± 217	t(2) 2240
					t(3) 2220

[a] e(1)—experimental method I; e(2)—experimental method II.
[b] t(1)—Scofield (Ref. 5); t(2)—Schmickley and Pratt (Ref. 4); t(3)—Rakavy and Ron (Ref. 3).

III. RESULTS AND DISCUSSION

The results obtained by both the methods are listed in Table I. Since no experimental data are available for the Z values of the target elements and photon energies used in the present measurements, the results are compared with the available theoretical calculations.[3-5] The errors shown in the experimental values are due to counting statistics and the uncertainties involved in other quantities, i.e., α_K, ω_K, $\sigma(\gamma)$ and the absorption coefficients used for the evaluation of various terms in Eqs. (3) and (7). The ratios $N(\gamma+x)/N'(\gamma)$, $N(\gamma+x)/N^*(\gamma+x)$, $S'(\gamma)/S(\gamma)$, and $S^*(x)/S(x)$ were measured to an accuracy of the order of 1–2% while the ratios $S(\gamma)a(\gamma)/S(x)a(x)$ and $S^*(\gamma)a(\gamma)/S^*(x)a(x)$ could be determined to an accuracy of the order of 4–5%. The errors involved in the evaluation of $\beta(\gamma)/\beta(x)$ and interpolation of $\sigma(\gamma)$ are of the order of 4% and 3%, respectively. The theoretical values of the cross sections at energies under consideration have been obtained by interpolating the values available for other energies and elements. It is seen that the results obtained by the two methods agree with each other within the experimental errors. The experimental results also show fairly good agreement with the predictions of the theoretical calculations.[3-5] Since the difference between the predicted values of cross sections of various calculations which are based on different potential models is small (e.g., the values of the cross section at 30 and 40 keV for $Z = 50$ as calculated by Rakavy and Ron[3] and Scofield[5] differ by 0.25% only) and the uncertainties involved in the experimentally measured cross sections are usually large (~10%), it is not possible to establish the superiority of any one calculation above an other with the help of cross-section measurements. However, it may be safely concluded that there is no discrepancy between theory and experiment, similar to the discrepancy reported for the L shell.

[1] B. S. Ghumman and B. S. Sood, Ind. J. Pure Appl. Phys. 5, 70 (1967); Ind. J. Phys. 41, 737 (1967).
[2] M. J. Singh and B. S. Sood, Nuovo Cimento B 8, 261 (1972); Curr. Sci. 40, 129 (1970).
[3] G. Rakavy and A. Ron, Phys. Lett. 19, 207 (1965); Phys. Rev. 159, 50 (1967).
[4] R. D. Schmickley and R. H. Pratt, Phys. Rev. 164, 104 (1967); Lockheed Report No. LMSC-5-10-67-11A (unpublished).
[5] J. H. Scofield, Lawrence Livermore Lab. Report No. UCRL-51326, 1973 (unpublished).
[6] R. H. Pratt, A. Ron, and H. K. Tseng, Rev. Mod. Phys. 45, 273 (1973).
[7] H. W. Boyed, W. H. Brantlay, and J. H. Hamilton, Nuovo Cimento 39, 1 (1965).
[8] M. J. Singh, Ph.D. thesis, (Punjabi Univ., Patiala, India, 1972) (unpublished).
[9] K. L. Allawadhi, M. J. Singh, and B. S. Sood, Curr. Sci. 42, 86 (1973).
[10] F. W. Titus, Phys. Rev. 69, 179 (1957).
[11] Parthasardhi *et al.*, Phys. Rev. 142, 9 (1966).
[12] B. Van Nooijen and J. H. Hamilton, in *Internal Conversion Processes*, edited by J. H. Hamilton (Academic, New York, 1966), p. 642.
[13] W. Bambynek, B. Crasemann, R. W. Fink, H. U. Freund, H. Mark, C. D. Swift, R. E. Price, and P. V. Rao, Rev. Mod. Phys. 44, 716 (1972).
[14] B. S. Sood and G. G. Shute, Proc. R. Soc. A 257, 252 (1960).
[15] J. H. Hubbell, Natl. Stand. Ref. Data Ser. No. 29 (1969).
[16] W. H. McMaster, N. K. Dal Grade, J. H. Mallett, and J. H. Hubbell, Lawrence Livermore Lab. Report No. UCRL-50174, 1969 (unpublished).