Measured energy dependence of K-shell photoelectric cross sections for Y, Mo, Ag, and Sn in the energy region 18–44 keV

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Our earlier measurements of K-shell photoelectric cross sections for intermediate-Z elements at 37 and 74 keV have been extended to energies in the range of $18 \leq E \leq 44$ keV. The difficulty of nonavailability of clean and strong x-ray sources encountered earlier has been overcome by using external- instead of internal-conversion x rays. The present technique gives relative rather than absolute cross-section values, but is simpler and more accurate. The experimental results show fairly good agreement with theory, and no discrepancy between theory and experiment similar to the one reported for the L shell has been found for photons in this energy region also.

INTRODUCTION

In our earlier measurements[1,2] of K, L, and higher-shell photoelectric cross section in the x-ray energy region, internal-conversion x rays from radioactive sources were used. This technique not only put serious limitations on the choice of the photon energies because of the nonavailability of clean sources of suitable strength, but also yielded cross sections with an accuracy of the order of 10%. The limit on the accuracy of the results was caused by the uncertainties associated with the internal-conversion coefficients, fluorescence yields, and absorption coefficients which were involved in the determination of the cross sections. In an effort to provide data at other energies in the range $18 \leq E \leq 44$ keV, which to the best of our knowledge[3] are not available so far, the difficulty of the nonavailability of suitable x-ray sources is overcome by using external- instead of internal-conversion x rays. The accuracy of the measurements is improved by measuring the relative cross sections so that, as will be seen later, only ratios of counting rates, absorption in target, and detection efficiencies have to be determined instead of absolute values. Evidently, measurement of ratios is simpler and more accurate as compared to the absolute values.

EXPERIMENTAL ARRANGEMENT AND METHOD OF MEASUREMENT

The experimental arrangement is shown in Fig. 1. Circular primary targets (P) of Mo, Ag, Cd, Sn, I, Ce, Sm, and Gd of 4 cm diam and thickness ranging from 15 to 65 mg/cm^2 are irradiated, in turn, by a collimated beam of γ rays of energy 84.262 keV and Yb $K\alpha, K\beta$ x rays of energy 53.542 keV, from a 2-Ci ^{170}Tm source (R) obtained from BARC, India. The external-conversion x rays in the targets are allowed to fall, in turn, on circular secondary targets (S) of Y, Mo, Ag, and Sn of 4 cm diam and thicknesses ranging from 10 to 65 mg/cm^2, and the intensities of secondary K-shell x rays in secondary targets at right angles to the primary beam are compared by measuring the counting rates under the photopeaks of the respective spectra taken with a thin, 2–3-mm-thick and 4.4-cm-diam, NaI(Tl) scintillation counter (D) coupled to a ND-1100 series multichannel analyzer. The lead shielding as well as the collimating slits were lined with graded absorbers of tin, copper, and aluminum to absorb x rays produced as a result of the interaction of photons with the lead shielding. The efficiency of the graded absorber was tested and found to be better than 99.9%.

In order to avoid scattering of photons from walls the experiment was performed in a large room and far removed from the walls and ceiling of the room. By adjusting the relative positions

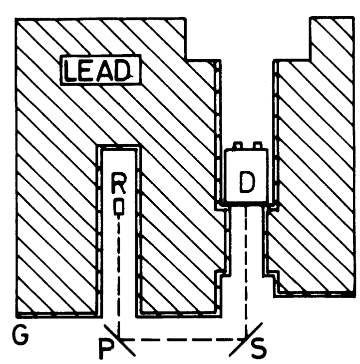

FIG. 1. Experimental setup for measurement of photoelectric cross sections: R—^{170}Tm source; P—primary target; S—secondary target; D—detector; G—graded absorber of Sn, Cu, and Al.

of the radiation source, primary and secondary targets, collimating slits, and counter, a signal-to-background ratio of better than 1 : 1 is obtained in most of the cases. Primary and secondary targets are so chosen that the K absorption edge of secondary target is lower than K x-ray energy but higher than the L x-ray energy of the primary target. The intensities of primary x rays falling on the secondary target are measured with 5.1-cm-thick, 4.4-cm-diam NaI scintillation spectrometer placed at the position of the secondary target. Self-supporting primary and secondary targets of materials under investigation were prepared by the method described earlier.[4] For a set of two primary targets P and $P_{\rm ref}$ whose K fluorescence emission lines weighted mean energy values ($\langle K\alpha, K\beta\rangle$) are E and $E_{\rm ref}$ and a given secondary target S, the ratio $\sigma(E)/\sigma(E_{\rm ref})$ of the K-shell photoelectric cross sections in S at E and $E_{\rm ref}$, respectively, is given by

$$\frac{\sigma(E)}{\sigma(E_{\rm ref})}=\frac{N_s(P)}{N_s(P_{\rm ref})}\,\frac{\beta(E_{\rm ref})}{\beta(E)}\,\frac{N(P_{\rm ref})}{N(P)}\,\frac{\epsilon(E)}{\epsilon(\overline{E}_{\rm ref})}, \qquad (1)$$

where $N_s(P)/N_s(P_{\rm ref})$ is the ratio of the counting rates under the photopeaks of the spectra of the secondary x rays when the secondary target is irradiated with primary x rays from P and $P_{\rm ref}$, respectively. $\beta(E_{\rm ref})/\beta(E)$ is the ratio of corrections which have to be applied to take into account the absorption of incident primary and emitted secondary x rays in the secondary target at energies $E_{\rm ref}$ and E, respectively. $N(P_{\rm ref})/N(P)$ is the ratio of the counting rates under the photopeaks of primary x-ray spectra taken with the counter placed at the position of the secondary target, when primary targets $P_{\rm ref}$ and P are irradiated with radiations from source R. $\epsilon(E)/\epsilon(E_{\rm ref})$ is the ratio of the effective efficiencies of the counter placed at the position of the secondary target for the detection of primary x rays of energies E and $E_{\rm ref}$ under the photopeaks. As was pointed out earlier, the measurement of the ratio of cross sections at two energies E and $E_{\rm ref}$ is thus reduced to the determination of the ratios $N_s(P)/N_s(P_{\rm ref})$ and $N(P_{\rm ref})/N(P)$ from the areas under the photopeaks of the secondary and primary spectra, respectively, and calculations of the ratios $\beta(E_{\rm ref})/\beta(E)$ and $\epsilon(E)/\epsilon(E_{\rm ref})$ from the known absorption coefficients.

A sufficient number of runs for times ranging from 1000 to 4000 sec were made for each combination of primary and secondary targets, so as to achieve statistical accuracy of the order of 1–2%. Typical primary and secondary spectra are shown in Figs. 2 and 3, respectively, along with their respective background spectra taken with an equivalent aluminum primary target. The actual minus background spectrum in Fig. 2 gives K-shell primary x rays falling on the secondary target, whereas in Fig. 3 it gives the intensity of K-shell secondary x rays which are produced only by the interaction of K-shell primary x rays with K-shell electrons in the secondary target. The scattering from the experimental primary targets and equivalent aluminum targets are found to be the same. The contribution of scattering of primary K-shell x rays from the secondary target in the region of the photopeak of the secondary K

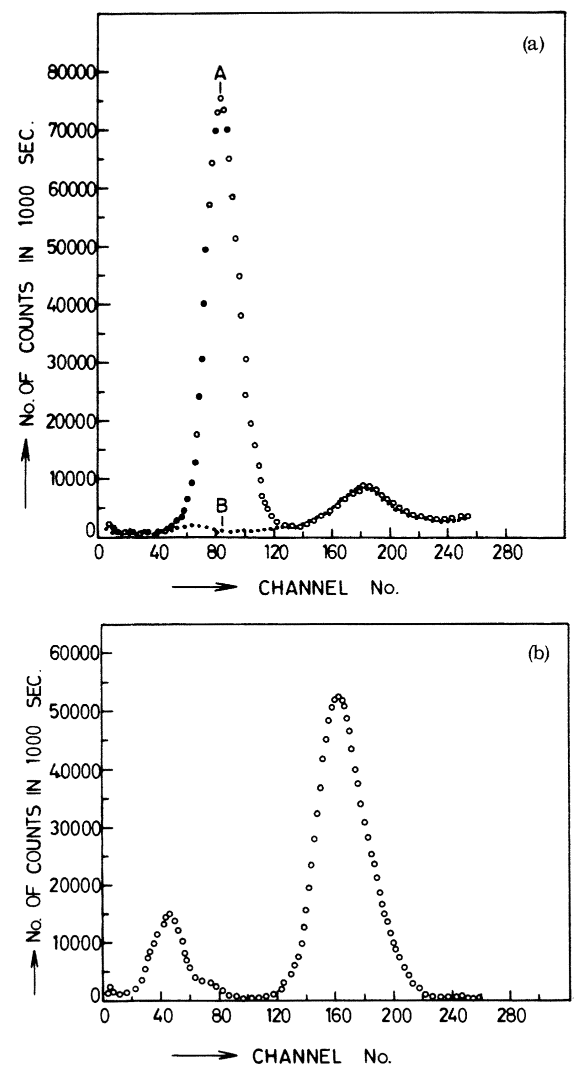

FIG. 2. Primary spectra recorded with thick NaI(Tl) scintillation spectrometer placed at the position of secondary target. (a) A—Ag target irradiated with ^{170}Tm; B—equivalent Al target irradiated with ^{170}Tm; the first intense peak is due to Ag K x rays and the second peak is due to scattered radiations. (b) Gd target irradiated with ^{170}Tm (background counts recorded with equivalent Al target have been subtracted out).

x-ray spectrum is estimated to be less than 1%. This is because the scattering cross sections are of the order of 2–3% of the photoelectric cross sections in the energy region of interest [i.e., at 30 keV the coherent plus incoherent scattering cross sections for Sn ($Z=50$) are only 2% of photoelectric cross section] and the K x rays are emitted isotropically while the scattered photons are forward peaked. The Compton scattering from K-shell electrons of the secondary target and the secondary ionization by the photo- and Compton electrons may also contribute to the photopeak of the secondary spectrum. But all these contributions are negligibly small as compared to the contribution of photoelectric interaction and have, therefore, been neglected.[1,4] The corrections for the absorption in the targets were calculated as explained earlier.[1,5] The effective efficiency for the counting of primary x rays which are falling on the counter placed at the position of the secondary target under the photopeak is the product of the fraction of the incident primary x rays that is transmitted through the window of the detector to reach the crystal and the fraction of x rays interacting in the crystal so as to lose their full energy in it, in order to get counted under the photopeak. Transmission through 0.032-in. Al window and 67-mg/cm^2 Al_2O_3 is calculated by using the recent values of absorption coefficients given by Hubbell[6] and found to agree within less than 1% with the data[7] supplied by the manufacturers of the crystals, M/s Harshaw Chemical Co. The probability of interaction of x rays with full loss of energy in the crystal used in the present experiment is estimated to be unity for all x-ray energies except for the escape of some iodine K x rays in the case of Ce, Sm, and Gd x rays. The values for Sm and Gd are determined to be 0.82 and 0.84, respectively, from the analysis of their respective spectra. [See Fig. 2(b).] These values agree within 2% with the values recently calculated by Fioratti and Piermattei[8] but using the most recent value of iodine fluorescence yield.[9] For Ce a calculated value of 0.78 is used since it was not possible to scan the escape peak completely.

RESULTS AND DISCUSSION

The experimental values of the ratio of cross sections $\sigma(E)/\sigma(E_{ref})$ are compared with theoretical values interpolated from values given by Scofield[10] in Table I and Fig. 4. E and E_{ref} are weighted mean values of the $K\alpha_1$, $K\alpha_2$, $K\beta_1$, etc. fluorescence emission lines of the target elements. The errors shown in the experimental values are of the order of 4–5% and are due to counting statistics and to the uncertainties involved in absorption coefficients used for the determination of $\beta(E_{ref})/$

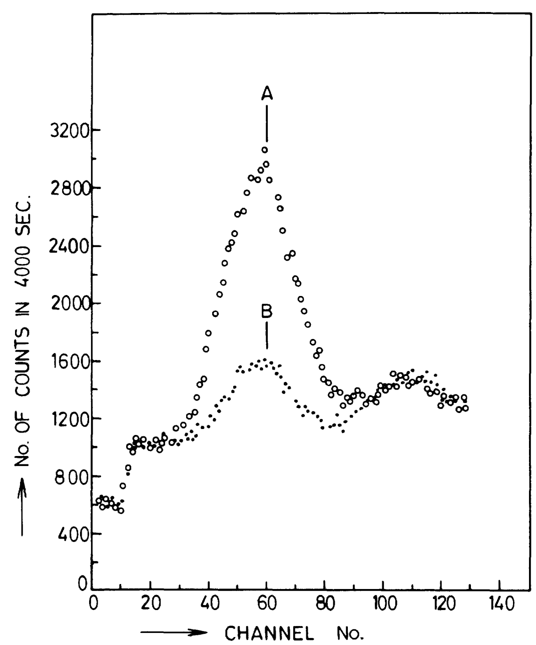

FIG. 3. Secondary spectra recorded with thin NaI(Tl) scintillation spectrometer. A—Gd primary and Sn secondary; equivalent Al primary and Sn secondary.

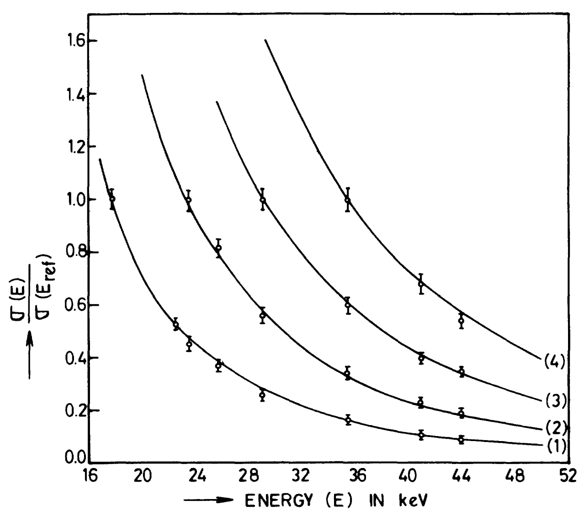

FIG. 4. Experimental values of the ratio of K-shell photoelectric cross sections at energies E and E_{ref} are compared with the theoretical values of Scofield. E and E_{ref} are weighted mean values of K emission lines of the target elements. E_{ref} is taken to be 17.781, 23.618, 29.208, and 35.478 keV for Y, Mo, Ag, and Sn, respectively. (1) Y; (2) Mo; (3) Ag; (4) Sn. Dots indicate experimental data and the solid curves indicate the theoretical values.

TABLE I. Present measurements of the relative K-shell photoelectric cross sections $\sigma(E)/\sigma(E_{ref})$ of Y, Mo, Ag, and Sn are compared with theoretical calculations of Scofield. E and E_{ref} are weighted mean values of K fluorescence emission lines $\langle\langle K\alpha, K\beta\rangle\rangle$ of the target elements. The E_{ref}'s for Y, Mo, Ag, and Sn are 17.781, 23.618, 29.208 and 35.478 keV, respectively.

X-ray energy (E) (keV)	Experimental	Theoretical	Experimental	Theoretical
	Y		Mo	
17.781	1.000 ± 0.033	1.000	...	...
22.581	0.530 ± 0.019	0.545	...	...
23.618	0.450 ± 0.016	0.473	1.000 ± 0.032	1.000
25.770	0.374 ± 0.013	0.382	0.828 ± 0.029	0.778
29.208	0.262 ± 0.010	0.277	0.561 ± 0.020	0.556
35.478	0.170 ± 0.007	0.173	0.344 ± 0.014	0.333
41.006	0.116 ± 0.005	0.116	0.234 ± 0.010	0.222
43.949	0.092 ± 0.004	0.095	0.186 ± 0.008	0.181
	Ag		Sn	
17.781	...	...	...	...
22.581	...	...	...	...
23.618	...	...	...	...
25.770	...	...	...	...
29.208	1.000 ± 0.035	1.000	...	...
35.478	0.599 ± 0.024	0.610	1.000 ± 0.038	1.000
41.006	0.403 ± 0.017	0.407	0.678 ± 0.029	0.678
43.949	0.361 ± 0.015	0.339	0.537 ± 0.023	0.563

$\beta(E)$ and $\epsilon(E)/\epsilon(E_{ref})$. There is a fairly good agreement between experiment and theoretical calculations and no discrepancy between theory and experiment similar to the one reported for the L shell has been observed even in this energy region.

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