Correction of substrate effect in the measurement of 8–25-keV electron-impact *K*-shell ionization cross sections of Cu and Co elements

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The experimental measurement of electron-impact *K*-shell ionization cross sections of Cu and Co elements within the energy region 8–25 keV was reported. The influence of a substrate of thin targets on ionization cross sections has been corrected by a method based upon a bipartition model of electron transport [Z. M. Luo, Phys. Rev. B **32**, 812 (1985); **32**, 824 (1985)]. The measured cross sections are in good agreement with existing data and are well reproduced by the empirical formula of Green and Cosslett [Proc. Phys. Soc. London **78**, 1206 (1961)]. [S1050-2947(96)05010-X]

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I. INTRODUCTION

K-shell ionization cross sections by electron impact have been a subject of experimental and theoretical study for many years. The study is significant for understanding the interaction between electrons and atoms and play an important role in practical applications, for example, in x-ray microanalysis [1]. Unfortunately, a recent survey [2] shows that, for a wide mass range of atoms, knowledge of the *K*-shell ionization cross sections by electron impact is meager and of poor quality, especially in the lower-incident-energy region. Therefore, we plan to perform a systematic measurement of *K*-shell ionization cross sections by electron impact for those elements for which cross-section data are lacking.

In the low-incident-energy region, one of the most important criteria is that the target thickness be thin enough to fulfill the condition of a thin target [3], namely, $\Delta E \ll E$, where E and ΔE denote the incident energy of electrons and the energy loss of incident electrons passing through a thin target, respectively. This condition leads to great difficulties in preparing self-supporting thin targets. As a result, a different method is used to cope with this difficulty in this paper. Instead of using a self-supporting thin target, we use thin targets with thick backing, which are easily prepared by a vacuum coating technique. The reflected electrons from the thick backing will induce a second ionization of target atoms, which will increase the counting number of characteristic x-rays, requiring a correction on the measured cross sections. The correction method we adopted is an iterative procedure, in which reflection energy spectra of incident electrons from thick backing can be precisely calculated using a so-called bipartition model of electron transport [4]. The correction method has been applied to the analyses of experimental data of the elements Ni and Cr and preliminary success was attained [5]. In this paper we first measure, with our experimental setup, the *K*-shell ionization cross sections of copper, for which precisely measured data are available [3]. Thereafter, we apply this method to cobalt, for which cross section data are scarce [2].

II. EXPERIMENT

The *K*-shell ionization cross sections were deduced from characteristic x-ray emission. The schematic diagram of our experimental setup is similar to that given in Ref. [5]. Electron beams with an energy region 8–25 keV were supplied by a scanning electron microprobe and the beam current was adjusted in accordance with the x-ray counting rate. The characteristic x-rays emitted by targets were detected by a high-resolution ORTEC Si(Li) detector with an energy resolution of 180 eV (full width at half maximum) for Mn K_α x-rays and electron-beam charges were collected by a deep Faraday cup and recorded with an ORTEC 439 digital current integrator. Targets were placed at 10° with respect to the beam direction and the Si(Li) detector was positioned at 70° to the electron beam. The incident energies of electrons were determined by the end point of bremsstrahlung spectra [3] obtained by a data acquisition system: a multiple channel analyzer (ORTEC MCA916) based upon an IBM386 computer that has been energy calibrated. With this method, the

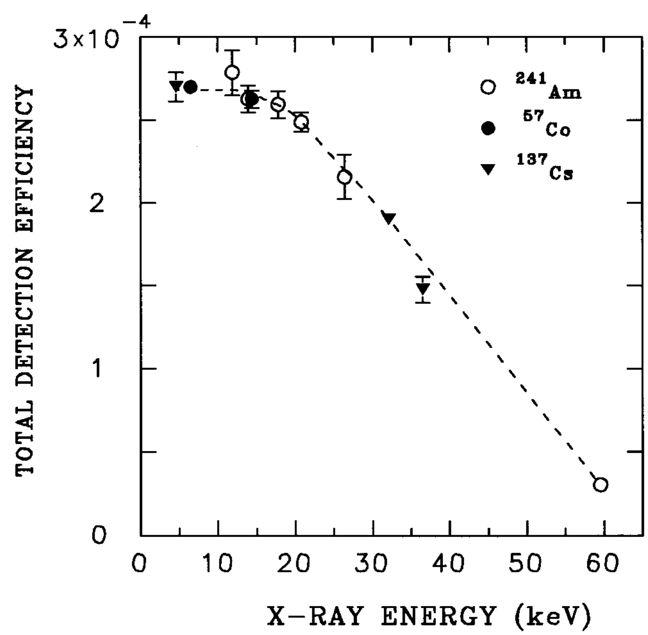

FIG. 1. Total detection efficiency of x rays as a function of x-ray energy. Standard radioisotopes have been used for calibration.

TABLE I. Parameters for the elements Cu and Co.

Element	Z	A	ω_K	E_K (keV)	$I(\beta)/I(\alpha)$	Dd (g/cm^2)
Cu	29	63.55	0.445	8.981	0.138	7.6×10^{-6}
Co	27	58.93	0.381	7.711	0.135	5.0×10^{-6}

incident energies of electrons can be measured within an uncertainty of 0.1 keV. The detection efficiency calibration of this system was conducted using standard radioactive sources, i.e., ^{241}Am, ^{137}Cs, and ^{57}Co, provided by the China Institute of Standards and Technology. The results are shown in Fig. 1. The uncertainty of the calibrated efficiency is believed to be no more than 5%.

Targets enriched to 99.9% with the thickness range 5–10 μg/cm^2 were employed in our experiments. Therefore, the values of $(\Delta E/2)/E$ are restricted to be less than 0.005. The targets, evaporated onto an aluminum foil thicker than the penetrating depth of electrons with an incident energy of 25 keV, were manufactured at the China Institute of Atomic Energy (CIAE) using a vacuum coating technique in which the thickness of targets was monitored and measured by a quartz oscillator. The uncertainty of the target thickness did not exceed 10%. The homogeneity of the targets was tested by probing the targets with the electron beam while registering the emitted x-rays. The reproducibility of the measured cross sections was also checked, and repeatedly measured cross sections were found to be consistent within an uncertainty of 1.3%.

III. RESULTS

A spectrum analysis program, computer code ALLFIT [6], was used to analyze the characteristic x-ray spectra to deduce the net x-ray peak counts. As mentioned in Sec. I, the measured cross sections should be corrected due to the thick backing. For the correction method used here, a detailed description has been given in Ref. [5]. Here we only present the final formula

$$Q_K(E)=\frac{4\pi N_X(E)}{\eta\Omega}\frac{A\cos\theta}{N_eN_ADd\omega_K}[1+I(\beta)/I(\alpha)] -\cos\theta\int_{E_K}^{E}\phi_{\rm ref}(E')Q_K(E')dE', \quad (1)$$

where ω_K is the K-shell fluorescence yield, $N_X(E)$ denotes the K_α x-ray counts, D and d are, respectively, target density and thickness, and N_e denotes the number of incident electrons. N_A and A are the Avogadro constant and atomic weight. K_β to K_α x-ray intensity ratios are referred to as $I(\beta)/I(\alpha)$. E_K represents the threshold energy of the target element. $\phi_{\rm ref}$, the reflection energy spectrum, is precisely calculated by using the bipartition model of electron transport [4] and is given in Ref. [5]. The total detection efficiency $(\eta\Omega/4\pi)$ for K_α x rays is taken from Fig. 1. The angle between the incident beam direction and the vertical direction of the target plane is denoted as θ. After performing iterations in Eq. (1), the corrected cross sections of K-shell ionization $Q_K(E)$ are given. If $\phi_{\rm ref}$ are assumed to vanish, then uncorrected cross sections are obtained. In general, the corrected cross sections, compared to the uncorrected ones, will decrease 10–30%. The parameters of the target elements

TABLE II. Uncorrected and corrected K-shell ionization cross sections for the elements Cu and Co by electron impact.

Element	E (keV)	Uncorrected (b)	Error (b)	Corrected (b)	Error (b)
Cu	9.40	21	2	20	2
	11.60	165	19	155	18
	13.64	282	32	257	29
	15.40	340	38	303	34
	17.65	427	48	375	41
	19.69	444	49	381	42
	21.74	485	52	412	44
	23.94	478	59	398	48
	25.90	482	52	397	43
Co	8.50	88	12	86	11
	10.57	338	44	314	40
	12.67	507	65	454	57
	14.78	580	78	502	68
	16.73	622	82	526	69
	18.67	685	93	575	77
	20.85	690	92	568	76
	22.80	677	91	547	74
	24.90	660	97	525	76

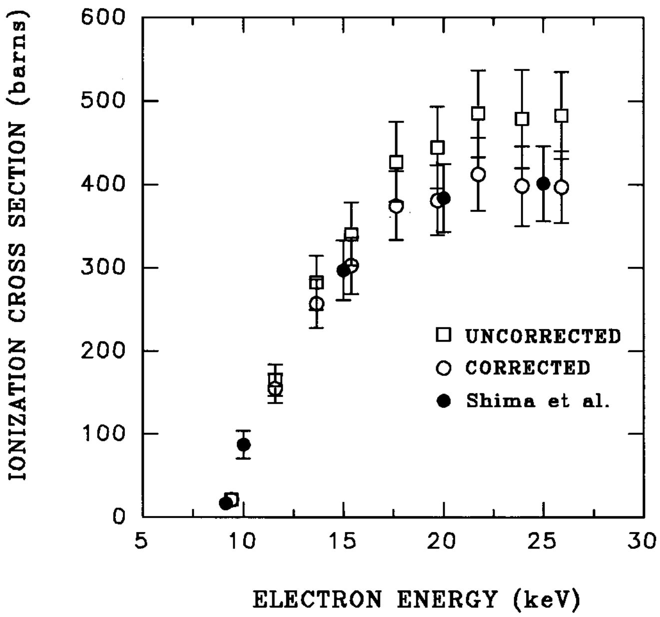

FIG. 2. Cu K-shell ionization cross sections as a function of electron energy. The present uncorrected and corrected data as well as Shima's data are plotted.

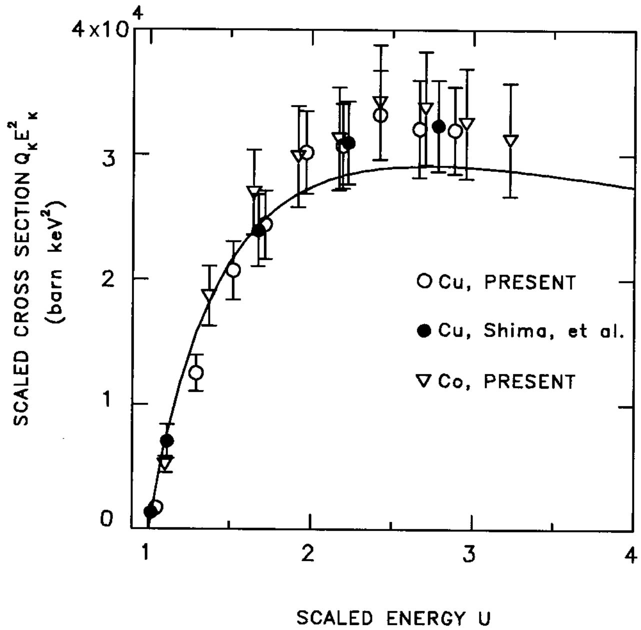

FIG. 3. Plot of the scaled cross section for the observed Cu and Co K-shell ionization as a function of scaled energy. The solid line exhibits the results of a semiempirical formula by Green and Cosslett [7].

used here are given in Table I. The present results are demonstrated in Figs. 2 and 3 and also listed in Table II. The estimated error limits added in quadrature are less than 15%. Errors mainly come from net x-ray peak counts (5%), detection efficiency (5%), fluorescence yield (6%), target thickness (10%), and inhomogeneity of the target (4%).

In Fig. 2 the present uncorrected and corrected data as well as the data of Shima *et al.* [3] for Cu are drawn. We can see that the corrected cross sections for Cu are in excellent agreement with the data of Shima *et al.*, which were precisely measured. This indicates that our data analysis method is successful. In Fig. 3 our measured cross sections (i.e., corrected cross sections) for Cu and Co as well as the data of Shima *et al.* for Cu are transformed into scaled cross sections ($Q_K E_K^2$) as a function of the scaled energy ($U = E/E_K$) and are compared with the results of a semiempirical formula of Green and Cosslett [7] as

$$Q_K E_K^2 = 7.92 \times 10^4 (\ln U)/U (\text{b keV}^2). \qquad (2)$$

Equation (2) implies that the scaled cross section as a function of the scaled energy should be independent of targets. From Fig. 3 it is noted that the scaled cross sections for Cu and Co are in good agreement and are well reproduced by Eq. (2), especially in the lower-energy region ($1 < U < 2$).

IV. CONCLUSION

In summary, we have measured the K-shell ionization cross sections of the elements Cu and Co by electron impact within the incident energy region 8–25 keV using thin targets with thick backing. The effect of thick backing on measured cross sections has been corrected. It is shown that our data analysis method works well. This will benefit measuring K-shell ionization cross sections of more elements with fewer difficulties in preparing targets, especially in the lower-energy region.

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