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Cross sections for *K*-shell ionization of niobium by electron impact

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K-shell ionization cross sections of Nb by electron impact in the energy range 20–34 keV have been measured. The influence of electrons reflected from a backing on the measurement was corrected using an electron transport model. For comparison several calculations using theoretical and empirical expressions have been performed. [S1050-2947(98)02909-6]

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I. INTRODUCTION

The behavior and values of the cross section for inner-shell ionization by electron bombardment have been the subject of numerous investigations. A number of experimental and theoretical works have recently been devoted to the study of the ionization cross section of inner-shell electrons for atoms and ions by electron impact [1–3]. Values of this type are required for an electron probe microanalysis, Auger electron spectroscopy, and electron-energy-loss spectroscopy. In addition, the data have applications in the diagnosis of fusion reactors (both inertial and magnetic) where considerable energy is lost in the ignition process due to x-ray production from highly stripped ions or inner-shell excitations. Unfortunately, such experimental data, in particular at lower energies, are quite scarce and in some cases nonexistent such as for niobium [4].

If an atom is impacted by an energetic electron beam, inner-shell vacancies of the atom will be produced. These vacancies will decay either by the characteristic x-ray emission or by Auger electron emission. The cross sections of inner-shell ionization can be determined by measuring the characteristic x-ray or Auger electron intensities. A series of experimental measurements on *K*-shell ionization cross sections for elements such as Ti, Cr, Fe, Ni, Cu, and Mo has been performed by our group [5–9]. In this paper we deduced the *K*-shell ionization cross sections for Nb by counting the photons emitted by bombarded Nb atoms in the subsequent deexcitation process.

II. EXPERIMENT

An electron beam with energies from 20 to 34 keV was produced by an electron gun and a 50-kV dc power supply was used to accelerate electrons. The experimental arrangement is similar to that described in Refs. [5, 7]. The high voltage was stabilized via a resistive feedback system and the monoenergetic electron beam was focused and then steered to the target position through two graphite apertures on the 0° beam line. The spot on the target was less than 3 mm in diameter. A Si(Li) detector was inside the target chamber and about 10 cm from the center of the target, which was placed at 45° with respect to the direction of the incident beam. The detector has a 12-mm^2 active area, a 3.5-mm active depth, and an energy resolution of 180 eV (full width at half maximum) at 5.9 keV for the Mn $K\alpha$ x ray. A deep graphite Faraday cup was employed to collect the charges on and through the target. The Faraday cup was coupled to an ORTEC model 439 digital current integrator. To reduce the pulse pileup effect, the intensity of the electron beam current was adjusted to be about 1 nA. During the experiment the gas pressure was kept less than 3×10^{-3} Pa in the chamber. Generally, targets should be thin enough to minimize (i) the degradation of the beam energy and intensity, (ii) the bremsstrahlung production, and (iii) the self-absorption of the x ray. A Nb target of 132 μg/cm^2 was manufactured by means of magnetron sputtering of Nb atoms onto a 5-mg/cm^2 Al backing. The thickness of the Al and Nb foils was determined by weighing, using a balance with a precision of 10^{-5} g. The efficiency calibration of the detector system was carefully performed by using a set of standard sources of 3% uncertainty: ^{55}Mn, ^{137}Cs, ^{57}Co, ^{65}Zn, and ^{241}Am, which were placed at the same target position.

III. RESULTS AND DISCUSSION

The *K*-shell ionization cross section σ_k can be derived from the $K\alpha$ x-ray counts N_x by the formula

$$\sigma_k=\frac{4\pi N_x\cos\,\theta}{N_e d n\,\omega_k\epsilon\Omega}\,[1+(I_\beta/I_\alpha)], \tag{1}$$

where θ is the angle between the incident electron beam and the normal of the target surface, N_e the number of electrons hitting the target of thickness d (cm) and density n (atom/cm^3), ω_k the fluorescence yield (which is the number of x rays emitted per vacancy produced), ϵ the efficiency of the detector, Ω the solid angle subtended by the beam spot to the detector's effective area, and I_β/I_α the intensity ratio of $K\beta$ and $K\alpha$ x rays. The main sources of uncertainties come

TABLE I. Relevant constants for the calculation of the Nb *K*-shell ionization cross section.

Atomic weight	*K*-shell fluorescence yield ω_k	*K*-shell binding energy E_k (keV)	Intensity ratio of K_β and K_α x rays I_β/I_α
82.9	0.748	18.98	25.6/152.4

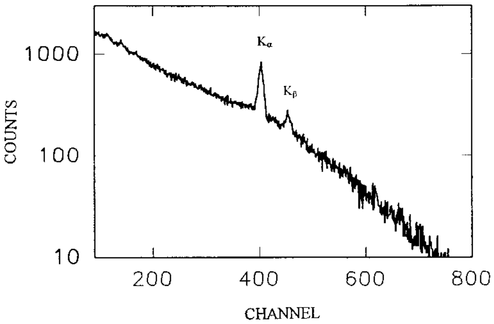

FIG. 1. Typical x-ray spectrum for Nb at an impact energy of 26 keV.

from (i) the target thickness inhomogeneity (5%), (ii) the fluorescence yield value (4.2%), (iii) the detector efficiency (3.5%), (iv) the counting statistical errors (5–11%), and (v) the beam integration (3%). The overall uncertainty of the cross section was estimated to be about 14%. In Table I some constants from Ref. [10] are given. A typical characteristic x-ray spectrum is shown in Fig. 1 and *K*-shell ionization cross section data for Nb and the corresponding errors are given in Table II and Fig. 2.

Because the preparation of a thin self-supporting target is rather difficult, we used a 5-mg/cm^2 Al backing. However, as the thickness of this backing can match the range of the incident electron, the electrons reflected from the backing film, when passing through the Nb foil, may once again ionize Nb atoms, resulting in a systematic overestimation of the measured cross sections. We have calculated the fraction of *K*-shell ionization events caused by the electrons reflected from the A1 backing and the *K*-shell ionization cross section as

$$\sigma_k(E)=\frac{4\pi N_x\cos\theta}{N_e d n\omega_k\epsilon\Omega}\,[1+(I_\beta/I_\alpha)]-\cos\theta\int_{E_k}^{E}\Phi_{\text{ref}}(E')\sigma_k(E')dE', \qquad (2)$$

where the second term is the fraction of *K*-shell ionization events caused by the electrons reflected from the backing and $\Phi_{\text{ref}}(E')$ is the energy spectrum of the electrons reflected on the backing surface, which can be obtained by using a so-called bipartition model of electron transport [11]. $\sigma_k(E')$ is the ionization cross sections induced by the electrons with energy E'. Equation (2) can be solved by iteration [6]. First, assuming $\Phi_{\text{ref}}(E')=0$, $\sigma_k(E)$ obtained from Eq. (2) is the value of the *K*-shell ionization cross section without a backing correction. The $\sigma_k(E)$ values calculated through several iterations, when becoming stable, are the corrected *K*-shell ionization cross sections for which the influence of the backing has been considered. The corrected values of the measured cross section and errors are also presented in Table II.

TABLE II. Uncorrected and corrected *K*-shell cross sections for Nb by electron impact.

Electron energy E_e (keV)	Reduced energy of electron U_k (E_e/E_k)	Cross section (barns)			
		Uncorrected	Error	Corrected	Error
20.0	1.05	10.6	1.4	10.6	1.4
22.0	1.16	20.0	2.1	19.1	2.0
24.0	1.26	26.4	2.6	24.1	2.4
26.0	1.37	35.0	3.2	31.4	2.9
28.0	1.48	47.1	5.3	42.0	4.7
30.0	1.58	60.0	6.6	53.1	5.8
32.0	1.69	67.5	8.9	58.5	7.7
34.0	1.79	76.0	10.2	65.3	8.8

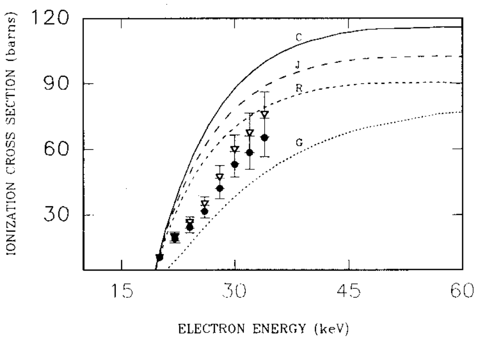

FIG. 2. *K*-shell ionization cross sections for Nb as functions of electron energy: open triangles, uncorrected data; solid circles, corrected data. *C* denotes the results of Casnati *et al.*, *J* those of Jakoby *et al.*, *R* those of Rudge and Schwartz, and *G* those of Gryzinski.

For the nonrelativistic region of electron energies, most of the previous work on theoretical and experimental cross sections for ionization of inner-shell electrons has been summarized by Powell [12] and Tawara, Harrison, and de Heer [13]. Most of the theoretical predictions that are suitable for the higher-energy region are not valid around the threshold energy. For example, Bethe theory provides a simple, convenient, and physically based means for calculating the inner-shell ionization cross section, but it is expected to be valid only when the incident energy is high enough to ensure the validity of the first Born approximation ($U_{nl}\gg 1$, $U_{nl}=E_e/E_{nl}$, E_{nl} is *nl*-shell binding energy) and it cannot be expected even to be empirically useful for near-threshold incident energies ($U_{nl}<4$) [3]. While each theoretical treatment appears to have some region of validity, none has been fully successful in describing the process over a wide range of atomic numbers (or binding energies) or impact energies. In comparison, we have found that for low electron impact energy ($1<U_{nl}<4$) better agreement with the present results can be acquired by using the formulas of Rudge and Schwartz, which are based on a second Born and a Born exchange calculation for the ionization of a fictitious hydrogenic ion [14]. Their result can be expressed in the form

$$\sigma_{nl}E_{nl}^2=1.626\times10^{-14}Z_{nl}Q_{nl}(U_{nl})\ \text{cm}^2\,\text{eV}^2, \qquad (3a)$$

where $Q_{nl}(U_{nl})$ is a reduced cross section that is written for *K*-shell ionization as

$$Q_k(U_k)=\frac{\ln U_k}{U_k}\left(2.799-\frac{0.218}{U_k}+\frac{0.047}{U_k^2}\right). \qquad (3b)$$

In addition, the relatively simple and widely used expression of Gryzinski is a classical theory of inelastic collisions [15]. The theory that has appeared to be the most successful evolved on the basis of the relation for binary collisions and for the Coulomb collisions derived in a laboratory system of coordinates. For the *K*-shell ionization cross section the expression of Gryzinski can be written in the form

$$\sigma_k E_k^2 = 13.02\times 10^{-14} g_k(U_k) \quad \mathrm{cm}^2\,\mathrm{eV}^2, \tag{4a}$$

where

$$g_k(U_k) = \frac{1}{U_k}\left(\frac{U_k-1}{U_k+1}\right)^{3/2}\left\{1+\frac{2}{3}\left(1-\frac{1}{2U_k}\right)\right. \times \ln[2.7+(U_k-1)^{1/2}]\Bigg\}. \tag{4b}$$

Using formulas (4) we calculated *K*-shell ionization cross sections for Nb and the values are shown in Fig. 2. For comparison, calculations by means of the empirical expressions of Jakoby, Genz, and Richiter [16] and Casnati, Tartari, and Baraldi [17] have been made and the results can also be found in Fig. 2. From Fig. 2 we notice that the present experimental values are situated systematically under the results of Casnati *et al.* and Jakoby *et al.* and located between Rudge and Schwartz's and Gryzinski's results.

IV. CONCLUSION

In conclusion, the correction of the influence of backing on the measurements for inner-shell ionization cross sections by using the energy spectra of reflected electrons will be beneficial in obtaining reliable experimental results from the measurements using a thin target with a thick backing, considerably reducing the difficulties in preparing a thin self-supporting target. In addition, from our results it seems that the quantum-mechanical approach based on a second Born and a Born exchange interaction [14] is better suited for the lower-energy range near threshold ($1<U_k<4$) than the first Born approximation.

ACKNOWLEDGMENT

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