J. Phys. B: At. Mol. Opt. Phys. **29** (1996) 4001–4005. Printed in the UK

# Correction of the influence of the substrate upon the measurement of K-shell ionization cross sections

Zhengming Luo†, Zhu An, Fuqing He, Taihua Li, Xiangguang Long and Xiufeng Peng

Institute of Nuclear Science and Technology, Sichuan University, Chengdu, 610064, People's Republic of China

Received 10 January 1996

**Abstract.** The K-shell ionization cross sections of Ni and Cr by electron impact have been measured. In the measurements thin targets with a thick substrate were used. The influence of the reflected electrons from the substrate on the measurements has been corrected by means of a detailed calculation of electron transport. By comparison it is shown that the corrected measurement data of K-shell ionization cross section by electron impact are in good agreement with existing experimental data.

Recently, we have measured the K-shell ionization cross section of Ni and Cr by electron impact. In the experiment the thin-target technique was used [1]. The thin target is manufactured by means of a vacuum coating technique to deposit Ni and Cr atoms on a 13 mg cm$^{-2}$ mylar film backing and on a 1.3 mg cm$^{-2}$ aluminium backing, respectively. Compared with a thin target without a thick substrate, the thin target with a thick substrate can be prepared easily. However, as the thickness of these backings can match the range of incident electrons, the electrons reflected from the backing films, when passing through Ni and Cr targets, may once again ionize Ni and Cr atoms, so as to increase the x-ray detector count, resulting in errors in experimental results. If this effect is not corrected, it inevitably leads to a systematic overestimation of the measured K-shell ionization cross sections. The present paper will illustrate our estimation of the K-shell ionization events caused by the electrons reflected from the substrate and the corrected experimental results of K-shell ionization cross sections. The calculation of electron transport in the substrate has been carried out by using the bipartition model of electron transport [2].

In the experiment, the electron beam is produced by the electron gun on the experimental platform of an electron electrostatic accelerator. The monoenergetic electron beam was well collimated through two collimators. The area of the beam spot on the target was less than 3 mm in diameter. In order to avoid loss of x-rays, the detector was kept inside the vacuum chamber and approximately 10 cm from the centre of the targets. The targets were placed at 45$^\circ$ to the beam direction. The electron beam was collected in a deep Faraday cup which was connected to a current integrator. The measurements of characteristic x-rays were performed with an Si(Li) detector of 12 cm$^2$ active area and 3.5 mm active depth, the energy resolution was 180 eV at 5.9 keV for Mn $K_\alpha$ x-rays. In order to reduce the counting

† Author to whom correspondence should be addressed.

0953-4075/96/174001+05$19.50  

error caused by pulse pile-up effects the intensity of the electron beam current was adjusted to be about 1 nA. The gas pressure was kept at less than 30 Pa in the vacuum chamber. The calibrated radioactive sources $^{241}$Am, $^{57}$Co, $^{55}$Fe, $^{137}$Cs and $^{54}$Mn were used to determine the detection efficiency of the Si(Li) detector. As the thickness of the Ni (15.4 $\mu$g cm$^{-2}$) and Cr (18.4 $\mu$g cm$^{-2}$) layers basically satisfy the thin-target condition, we may assume that the majority of electrons reflected from the backing film can penetrate through the thin target without obvious energy loss. The assumption does not hold for the low-energy reflected electrons, however, as K-shell ionization cross sections of low-energy reflected electrons are extremely small, and a large error would not appear. Given that $N_x$ is the counting number of characteristic $K_\alpha$ x-rays from target atoms, $N_e$ is the number of electrons incident upon the target, $\eta$ is the detection efficiency of the detector, $\Omega$ is the solid angle subtended by the detector's effective area to the incidence point of electron beams on the target, $N_A$ is the Avogadro constant, $D$ is the target density, $A$ is the atomic weight of the target atoms, $d$ is the thickness of the target, $\theta$ is the angle between the incident electron beam and the inner normal direction of target surface, $Q_k(E)$ is the K-shell ionization cross section for electrons with energy $E$, $\omega_k$ is the fluorescent yield of the K-shell. $K_\beta$ to $K_\alpha$ x-ray intensity ratios are referred to as $I_\beta/I_\alpha$. Then the counting number of the characteristic $K_\alpha$ x-rays registered by the detector, which are produced by incident electrons in the target, is

$$N_1 = N_e\left(\frac{N_A}{A}Dd\right)Q_k\omega_k\left(\frac{\Omega}{4\pi}\eta\right)/(1+I_\beta/I_\alpha)\cos\theta. \tag{1}$$

The contribution of the characteristic $K_\alpha$ x-rays produced in the target by reflected electrons from the backing film to the counting of the detector is

$$N_2 = N_e\left(\frac{N_A}{A}Dd\right)/(1+I_\beta/I_\alpha)\int_0^E \phi_{\mathrm{ref}}(E')Q_k(E')\omega_k\,\mathrm{d}E'\left(\frac{\Omega}{4\pi}\eta\right) \tag{2}$$

where $\phi_{\mathrm{ref}}$ is the energy spectrum of the reflected electrons on the surface of the backing film, so the total counting number of the detector is

$$\begin{aligned} N_x = N_1 + N_2 = N_e\left(\frac{N_A Dd\Omega\eta}{4\pi\cos\theta A}\right)/(1+I_\beta/I_\alpha) \\ \times\left[Q_k(E)\omega_k + \cos\theta\int_0^E \phi_{\mathrm{ref}}(E')Q_k(E')\omega_k\,\mathrm{d}E'\right]. \end{aligned} \tag{3}$$

Equation (3) can be rewritten as follows:

$$Q_k(E) = \frac{4\pi A\cos\theta N_x}{\eta\Omega\omega_k\,dDN_eN_A}(1+I_\beta/I_\alpha) - \cos\theta\int_0^E \phi_{\mathrm{ref}}(E')Q_k(E')\,\mathrm{d}E'. \tag{4}$$

In equation (4) the fluorescent yield is assumed to be irrelevant to the energy of the electron beam. $Q_k(E)$, the K-shell ionization cross section of target atoms, can be obtained from (4) through an iteration procedure. Assuming $\phi_{\mathrm{ref}} = 0$ initially, $Q_k(E)$ obtained from (4) is the value of the K-shell ionization cross section without a substrate correction. $Q_k$ values calculated through several iterations, when becoming stable, are the corrected K-shell ionization cross sections of Ni and Cr for which the influence of the substrate has been considered.

The energy spectrum $\phi_{\mathrm{ref}}(E)$ of the reflected electrons on the backing surface is calculated by using the bipartition model of electron transport [2]. The comparison between the calculations by the bipartition model of electron transport and extensive experimental data as well as Monte Carlo calculations shows that the bipartition model is an accurate and flexible method of calculating electron transport in solids. The energy spectra of the

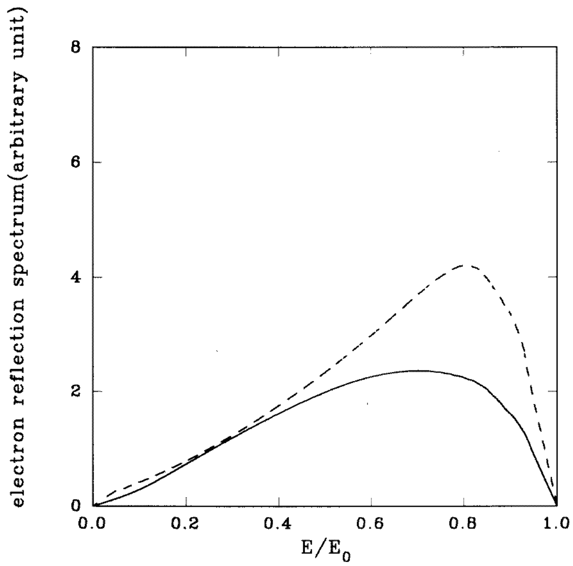


**Figure 1.** Reflection energy spectra of 20 keV electrons incident onto mylar film (full curve) and Al backing (broken curve) calculated based upon the bipartition model. The incident angle is 45°.

reflected electrons and reflection coefficients of electrons calculated by the model are in excellent agreement with the existing experimental results [2]. As an example, figure 1 shows the energy spectra of reflected electrons produced by the incident electrons with an energy of 20 keV from the mylar film and aluminium backing. Using the energy spectrum of the reflected electrons, the influence of the substrate upon the measured results can be corrected.

The errors in the experimental measurements mainly come from the following factors: (i) the errors in the current integrator are ±3%; (ii) the uncertainty of the calibrated efficiency is about ±5%; (iii) the statistical errors of the x-ray counting are about ±1–5%, depending on the energy of the electron beams; (iv) the errors in the target thickness are ±8%; (v) the errors of the fluorescence yield are ±5%. The total errors are evaluated to be ±15%. Generally, the deviation of the reflection coefficients given by the bipartition model from the experimental data is usually smaller than ±10% [2]. In addition, the energy spectra of reflected electrons given by the bipartition model also coincide with existing experimental data. Therefore we can evaluate that the relative errors included in the correction term (2), which represents the ionization contribution given by reflected electrons from the substrate, are about ±10%. The errors in the corrected term are not very important in the total errors. Because the maximum of the corrected term (equation (2)) is about 20% of the uncorrected term (equation (1)), the errors of the corrected term in the total errors can therefore be evaluated as about ±2%.

In table 1, the uncorrected and corrected experimental results are listed for K-shell electron ionization cross sections of Ni and Cr. Figure 2 shows the uncorrected and corrected K-shell ionization cross sections of electrons of Ni and Cr. Also, the existing experimental results for Ni are shown in figure 2, from which it may be seen that the uncorrected data of K-shell electron ionization cross sections can be up to 20% higher than the experimental results of targets with a thin substrate, while, having undergone substrate correction, the

**Table 1.** The uncorrected and the corrected K-shell ionization cross sections for Ni and Cr by electron impact.

| | $E$ (keV) | Uncorrected (barns) | Error (barns) | Corrected (barns) | Error (barns) |
|---|---|---|---|---|---|
| Ni | 9.0 | 80 | 8 | 80 | 8 |
| | 10.0 | 108 | 12 | 105 | 12 |
| | 12.0 | 360 | 44 | 350 | 45 |
| | 16.0 | 511 | 51 | 480 | 54 |
| | 20.0 | 562 | 55 | 512 | 60 |
| | 25.0 | 615 | 68 | 547 | 75 |
| | 30.0 | 617 | 64 | 537 | 72 |
| | 34.0 | 604 | 64 | 517 | 73 |
| Cr | 6.0 | 32 | 4 | 32 | 4 |
| | 6.25 | 92 | 11 | 91 | 11 |
| | 6.50 | 171 | 18 | 168 | 18 |
| | 7.0 | 210 | 21 | 199 | 22 |
| | 8.0 | 462 | 45 | 425 | 49 |
| | 10.0 | 771 | 70 | 666 | 80 |
| | 12.0 | 1028 | 90 | 854 | 107 |
| | 14.0 | 1200 | 102 | 969 | 125 |
| | 16.0 | 1265 | 105 | 994 | 132 |
| | 20.0 | 1350 | 111 | 1020 | 144 |
| | 23.0 | 1310 | 98 | 964 | 133 |
| | 25.0 | 1255 | 90 | 907 | 125 |

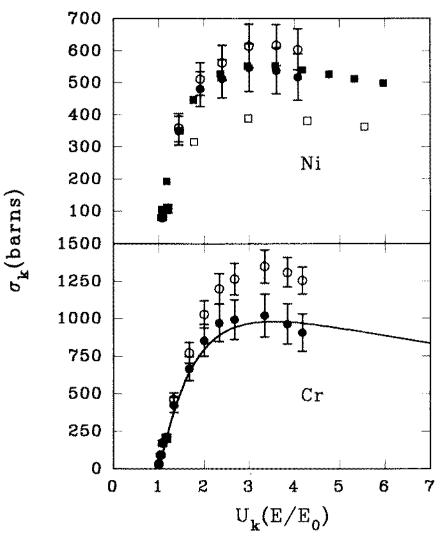


**Figure 2.** Uncorrected (open circle) and corrected (full circle) Ni and Cr K-shell ionization cross sections by electron impact. Experimental data of [4, 5] for Ni are also shown by full squares and open squares, respectively. Results of Drawin's empirical formula, with parameters $f_1 = 1.20$ and $f_2 = 1.20$, are shown for Cr (full curve).

corrected cross sections coincide very well with the existing experimental results of targets without a substrate [3–6]. This verifies that the substrate correction method developed in the paper is effective. For the Cr element, there are no data at present in the low-energy region [6]. We compare our measured data with the results of Drawin's empirical formula with parameters $f_1$ and $f_2$ which have reasonable values of 1.20 and 1.20, respectively [7]. These parameters $f_1$ and $f_2$ in Drawin's empirical formula are adjustable. It can be seen that they are in good agreement. Evidently, the correction of the influence of the substrate on the measurements of inner-shell electron ionization cross sections by using energy spectra of reflected electrons will be helpful in obtaining reliable experimental results of inner-shell ionization cross sections from the measurements using targets with a thick substrate, thereby remarkably reducing the difficulties in preparing targets, so improving the measurements of inner-shell electron ionization cross sections of more species of atoms.

## References

[1] Powell C J 1976 *Rev. Mod. Phys.* **48** 33; 1985 *Electron Impact Ionization* (Berlin: Springer) ch 6
[2] Luo Zhengming 1985 *Phys. Rev.* B **32** 812, 824
[3] Smick A E and Kirkpatrick P 1945 *Phys. Rev.* **67** 153
[4] Jessenberger J and Hink W 1975 *Z. Phys.* A **275** 331
[5] Pockman L T, Webster D L, Kirkpatrick P and Harworth K 1947 *Phys. Rev.* **71** 330
[6] Long X *et al* 1990 *At. Data Nucl. Data Tables* **45** 353
[7] Drawin H 1961 *Z. Phys.* **164** 513