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Electron spectra from fast projectile Si and S ions studied by zero-degree electron spectroscopy

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Abstract

Zero-degree electron spectra were measured with high resolution for 2 MeV/u Si^{q+} and S^{q+} ions on a C-foil target. The most prominent lines were attributed as Si^{10+} $1s^22p(^2P_{1/2})nl{-}1s^22s\epsilon l'$ and $1s^2p(^2P_{3/2})nl{-}1s^22s\epsilon l'$ transitions for Si^{q+} + C collisions, where the n appears from 9 to 20. For S^{q+} + C collisions, it was also found that the prominent lines came from S^{12+} $1s^22P(^2P_{1/2})nl = 1s^22s\epsilon l'$ ($n = 10$–20) and $1s^22p(^2P_{3/2})nl{-}1s^22s\epsilon l'$ (n = 9–20) transitions. The angular momentum (l) distributions of S^{12+} ions in the auto-inonizing states of n = 9 were measured and evidence of high l enhancement was found in the C-foil target. The high Rydberg Coster–Kronig transition energies were compared with the theoretical calculations. © 1998 Elsevier Science B.V.

Keywords: Coster–Kronig transition; Zero-degree electron spectra; 2 MeV/u Si^{q+} and S^{q+} ions; C-foil target

1. Introduction

Recently, we have applied the method of zero-degree electron spectroscopy to projectile Auger and Coster–Kronig (C–K) electrons reducing the kinematic broadening effects [1–4]. At zero-degree observation angle of the emitted electrons, the broadening effects cancel in first order. Thus, a high-resolution study is possible for projectile energies from several keV to several hundreds of MeV. Moreover, the zero-degree electron spectroscopy has various advantages. Low-energy lines, which are difficult to detect, may be shifted kinematically to an energy range which is readily accessible to the electron spectrometer.

A great deal of attention has been paid to measurements of secondary and Auger electrons emitted during high energy ion–atom or ion–solid collisions to obtain dynamic properties of the collision processes. It is shown that zero-degree electron spectroscopy is an excellent tool to the study dynamic properties of the collision processes inside a solid [5,6]. Concerning Coster–Kronig electrons from

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Rydberg states in high-energy projectiles, it has been shown that a weak and intense series of C–K electrons are observed as for gas and solid targets, respectively [1,2,4,7–10], although they cannot survive inside the solid, which indicates that the Rydberg states are formed upon or near the exiting surface of the solid. The models for producing such high Rydberg electrons and subsequent enhancement of high angular momentum have been proposed [4,11]. These measurements are also useful as a test for an important subject for highly charged ion–atom collisions of forming doubly excited states via correlated or uncorrelated electron excitation [2,12,13].

In the present work, we measured zero-degree electron spectra with high resolution for 2 MeV/u silicon and sulfur projectiles through a carbon foil target to investigate static and dynamic properties of the highly charged fast ions inside a solid.

2. Experimental

The experiments to measure emitted electrons in high-energy ion–foil collisions at zero degrees are performed using an electrostatic spectrometer inside a high vacuum scattering chamber. The experimental apparatus used in these measurements has been described previously [1,2] and Fig. 1 shows a typical experimental set-up for zero-degree electron spectroscopy. Projectiles of 2 MeV/u Si^{5+} and S^{5+} were provided by the tandem accelerator at the Japan Atomic Energy Research Institute of Tokai. To produce the higher charge states, the initial Si^{5+} and S^{4+} ions passed through a C post-stripper foil (~20 μg/cm^2) and then Si^{10+} and S^{12+} ions were selected by a switching magnet.

Electrons emitted form the Si and S projectile ions colliding with a thin carbon foil were energy analyzed by a tandem 45° parallel plate electrostatic analyzer at zero degrees. The first analyzer was used as a deflector to separate electrons from projectile ions as well as to suppress background electrons. The second analyzer determined the electron energy with high resolution. Electron energies observed are 0–25 eV for the Si projectile and 0–35 eV for the S projectile. The pass energy for the second analyzer was set at 50–100 eV to improve the resolution and to avoid any correction of the measured intensity for each energy channel. The laboratory frame spectra, which have a cusp shape peak at 1.08 keV and Coster–Kronig electron peaks on both wings of the cusp, are obtained by scanning the retarding potential between the first and the second analyzers by typically a 1.0 eV step. Two spectra corresponding to the low and the high-energy wings of the cusp are obtained from each spectrum by converting the laboratory frame spectrum into the projectile rest frame to result in the energy resolution of ~0.1 eV at lower region and of ~0.5 eV around 30 eV. After subtracting the background, these two spectra correlate well in energy and intensity, except for a very low-energy region, which may

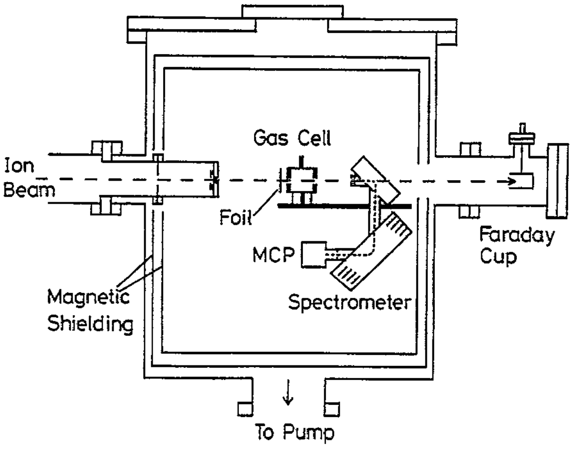

Fig. 1. Typical experimental set-up used for the method of zero-degree electron spectroscopy.

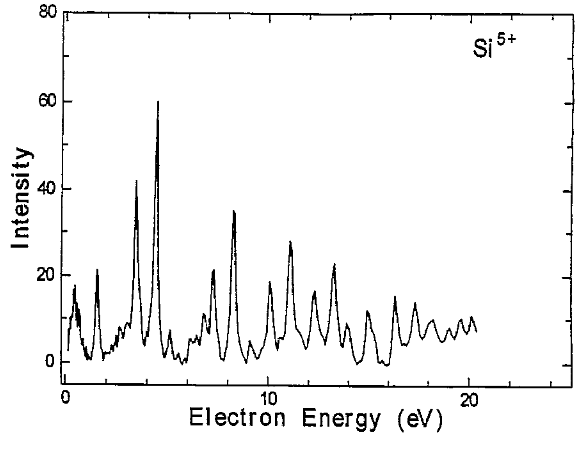

Fig. 2. Electron energy spectrum ejected at 0° in collisions of 2 MeV/u Si^{5+} on a C-foil target. The data are transformed into the projectile rest frame.

be caused by the forward–backward correlation and/or the field ionization of very Rydberg electrons, and only the spectra obtained by the low-energy wings are presented in Figs. 1–5.

3. Results and discussion

3.1. 2 MeV/u Si^{q+}+ C

Figs. 1 and 2 show electron spectra from 2 MeV/u Si^{5+} + C and Si^{10+} + C. In both spectra, the most significant peaks come from Coster–Kronig (C–K) transitions of Si^{10+} $1s^22p(^2P_{1/2})nl$–$1s^22s\epsilon l'$ or $1s^22p(^2P_{3/2})nl$–$1s_22s\epsilon l'$, respectively. Here, transitions with $n < 9$ are energetically forbidden and peaks corresponding up to $n = 20$ are clearly seen. In the figures, the marked energies are calculated by quantum defect theory [14],

$$E_n = \Delta E - Q^2 Ry/2n^2 \tag{1}$$

where ΔE is the energy difference between the initial and the final orbits of the core configuration, Q is the effective charge of the core configuration (assumed to be + 9 for the cases above), and Ry is the Rydberg energy 27.211 eV. The energy difference ΔE between the 2s and 2p states was taken from the experimental transition energy of si^{11+} $1s^22s$–$1s^2p$ compiled by Kelly [15] as 24.83 and 23.81 eV for the $^2P_{3/2}$ and $^2P_{1/2}$ states, respectively. Precisely speaking, the observed peak energies are slightly (0.05 eV at $n = 9$) smaller than the calculated values, and the difference gets smaller; i.e. observed energies come to agree well, as n grows. These shifts must be from the quantum defect for angular momentum 1 of the Rydberg electron, and the n of the Eq. (1) has to be replaced with $(n-\mu_l)$, where μ_l is a small value representing the quantum defect of the angular momentum.

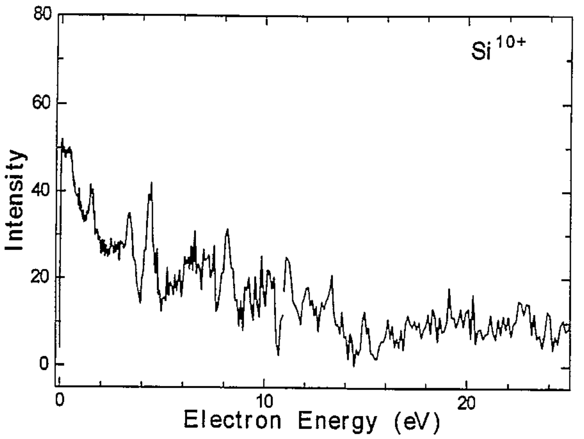

Fig. 3. Electron energy spectrum ejected at 0° in collisions of 2 MeV/u Si^{10+} on a C-foil target. The data are transformed into the projectile rest frame.

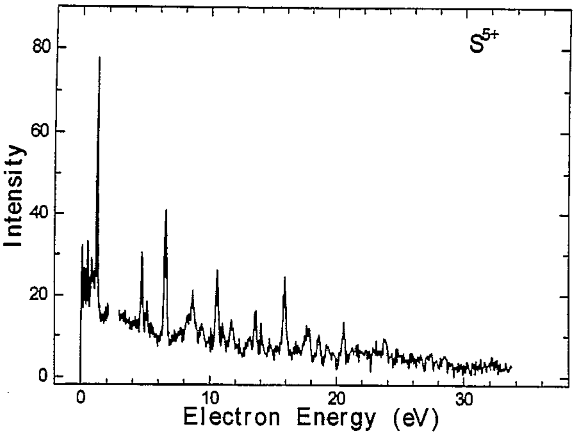

Fig. 4. Electron energy spectrum ejected at 0° in collisions of 2 MeV/u S^{5+} on a C-foil target. The data are transformed into the projectile rest frame.

Using the same formula (without the μ_l consideration), we investigated all the configurations for Si X, XI, XII, XIII, XIV transitions in Ref. [15], to obtain the possible Coster–Kronig electron energies in this energy region for Rydberg states of $Si^{q+}(q = 8–12)$,

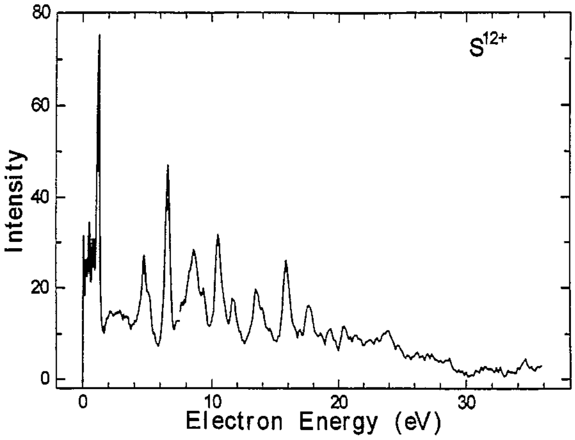

Fig. 5. Electron energy spectrum ejected at 0° in collisions of 2 MeV/u S^{12+} on a C-foil target. The data are transformed into the projectile rest frame.

respectively, and carefully checked the appearance of these lines. Some of the peaks, shoulders and quasi-peak structures seem to have candidates. This trend was also observed for Si^{10+} incident on a thin C-foil target. The angular momentum of the Rydberg electron travelling through a C foil is known to have high l value and the influence of low-l components can be negligible. In the present measurements for 2 MeV/u Si projectiles, we could not resolve the angular momentum distributions. The dependence of the initial energies and charge states of projectile ions and the thickness of the C-foil target for producing the C–K electrons with high n states will be investigated.

3.2. 2 MeV/u S^{q+}+ C

Figs. 3 and 4 show the energy spectrum of electrons emitted following 2 MeV/u S^{5+} + C and S^{12+} + C collisions. A series of peaks are attributed to electrons emitted via S^{12+} $1s^2 2p(^2P_{1/2})nl–1s^2 2s\epsilon l'$ or $1s^2 2p(^2P_{3/2})nl–1s^2 2s\epsilon l'$ Coster–Kronig transitions, respectively, and the measured electron energies agreed with the electron energies calculated by Eq. (1). The energy difference ΔE between the 2s and 2p states was taken from the experimental transition energy of S^{13+} $1s^2 2s–1s^2 2s–1s^2 2p$ tabulated by Kelly [15] as 29.68 and 27.81 eV for the $^2P_{3/2}$ and $^2P_{1/2}$ states, respectively. Transitions from the states with $n < 9$ for $^2P_{3/2}$ and $n < 10$ for $^2P_{1/2}$ are energetically forbidden.

Fig. 5 shows the low energy part of electron energy spectrum of Fig. 4. These lines are attributed to due to $1s^2 p9l(^2P_{3/2})–1s^2 2s\epsilon l'$ transitions for a solid (C foil) target. Arrows in the figures show the electron energies obtained by quantum defect theory [14],

$$E_{nl} = \Delta E - Q^2 Ry/2(n-\mu_l)^2 \qquad (2)$$

These indicate a clear difference in the angular momentum distribution, i.e. the high-l components are significantly enhanced for the solid target [1,2]. A similar difference has been observed [7] in the case of 1.5–5.0 MeV C^{2+} ions emerging from solid and gas targets and was explained as being due to multiple collisions in the solid targets [4,11]. The dependence of the angular momentum distribution on the initial energies and charge states of projectile ions and the thickness of the C-foil target is currently being investigated.

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