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Convoy Electron Production and Ionization in 390 MeV/u Ar^{17+} Ion Collisions with Thin Foils

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Abstract

Interactions of relativistic clothed heavy ions with solid targets have been studied for 390 MeV/u Ar^{17+} ions traversing carbon foils of various thicknesses through measurements of the convoy electrons. The electron energy spectra at 0° were obtained by a magnetic analyzer combined with a Si surface barrier detector with a depletion layer of 5 mm. The peak widths of the convoy electrons in the laboratory frame have been found to decrease as the target thickness is increased from 25 to about 500 $\mu g/cm^2$, and broaden for thicker targets due to multiple scattering.

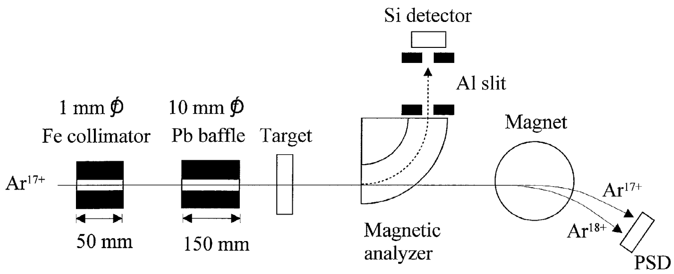

Fig. 1. Schematic diagram of the experimental setup.

1. Introduction

The energy and angular distributions of electrons ejected in energetic ion-atom and ion-solid collisions have extensively been studied so far. The energy spectrum of electrons ejected in the forward direction with their velocity matching with the projectile velocity has a cusp-shaped peak [1].

In ion-atom collisions, this cusp-shaped peak originates from ECC (Electron Capture to the Continuum) and ELC (Electron Loss to the Continuum) processes. Similar electron peaks have also been observed in ion-solid collisions and are often called convoy electrons.

The intensity and shape of the cusp peak have been investigated in detail. ECC cusps are known to be strongly skewed toward lower energy, and ECC cusp widths in energy are also known to be proportional to the projectile velocity. The energy and angular distributions of the convoy electrons have been studied in the transport theory, where the Coulomb force and multiple scattering are discussed using Monte-Carlo methods [2].

In the present experiment, we have observed the convoy electrons produced by relativistic 390 MeV/u Ar^{17+} ions traversing carbon foils. We measured the target thickness dependence of the peak width and the intensity of the convoy electrons. We also measured the charge state distributions of ions passing through the targets and determined the 1s electron ionization cross section of the hydrogen-like ions.

2. Experiment

A schematic diagram of the present experimental setup is shown in Fig. 1. A beam of 390 MeV/u hydrogen-like Ar^{17+} ions was provided at HIMAC (Heavy Ion Medical Accelerator at Chiba). The beam was collimated by a 5-cm thick Fe collimator with an inner diameter of 1 mm located at 6.5 m upstream from a target. Then the beam was transported to the carbon foil target after passing through a 15-cm thick Pb baffle with the inner diameter of 1 cm located at 35 cm upstream from the target. The Pb baffle was used to stop the fragments produced in the Fe collimator located upstream. We used carbon foils with thicknesses from 25 to 9.2×10^3 $\mu g/cm^2$.

We obtained the energy spectra of electrons ejected at 0° by a magnetic analyzer with a 10 cm deflection radius and a 90° deflection angle. Two 5-mm thick Al slits with the inner diameters of 5 mm were set at the exit of the magnetic analyzer and also just in front of an electron detector. Electrons emitted within the forward cone of about 1° were energy-selected. Then the electrons were detected with a silicon surface barrier detector (SSD) with a depletion layer of 5 mm. The use of the SSD was essential to discriminate the convoy electrons from other energetic background electrons and gamma rays. The over-all energy resolution of the present electron measuring system was about 25 keV.

We also measured the charge state distribution of ions after passing through the carbon foils. The transmitted ions were charge-separated by a magnet of 0.5 T located at 1.3 m downstream from the target, and detected with a two-dimensional position-sensitive Si detector (PSD) located at 5.6 m downstream from the targets [3].

3. Results and discussion

3.1. *Convoy electrons*

Typical measured energy spectra of electrons ejected at 0° are shown in Fig. 2. The peak widths of the convoy electrons in the laboratory frame have been found to decrease as the target thickness was increased from 25 to about 500 $\mu g/cm^2$. This

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unusual tendency has been observed for the first time. A similar experiment was performed at GANIL, where the energy spectra of electrons ejected at 0° were measured in 13.6 MeV/u Ar^{17+} ion collisions with carbon foils with thicknesses from 4.4 to 356 μg/cm^2 [4]. However, the decrease of the peak width was not observed in that experiment.

The velocity distributions of the convoy electrons are represented in terms of the multipole expansion of the doubly differential cross sections in the projectile frame. High order compositions of the multipole expansion characterize the anisotropy of the convoy electron velocity distribution. A strong transverse emission (perpendicular to the projectile velocity) of the convoy electrons from the thicker targets was observed, which reflects the enhancement of the excited states of projectile ions within the bulk [5]. The transverse emission tends to narrow the longitudinal distributions (parallel to the projectile velocity), which determines the energy spectrum shape measured by the analyzer with a definite acceptance angle [6]. The target thickness dependence of the peak width observed in the present experiment can be explained qualitatively through such an enhancement of the transverse emission via excited states.

When the target thickness was increased up to more than about 500 μg/cm^2, the peak width of the convoy electrons increased and also the peak position shifted to the lower energy side, which could be understood to be due to multiple scattering.

3.2. *Ion charge distribution and ionization cross section*

We also measured the charge state distributions of ions after passing through the targets of various thicknesses. The charge state distribution as a function of the carbon target thickness is shown in Fig. 3a. At the present high collision energy, the electron capture processes are negligible compared to the ionization processes. Indeed, only Ar^{17+} and Ar^{18+} ions were observed.

We determined the ionization cross section by a least-squares fitting to the observed data (see Fig. 3 a) to be 1.3×10^{-20} cm^2. At the present collision energy, the

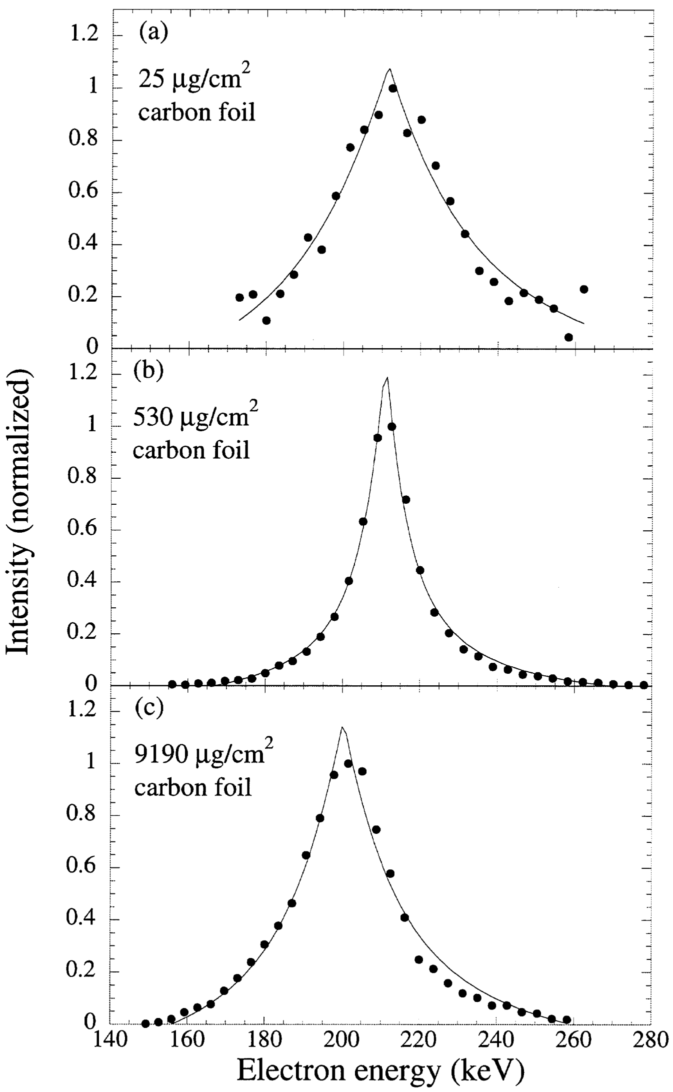

Fig. 2. Energy spectra of electrons ejected at 0° from 390 MeV/u Ar^{17+} + carbon foil collisions. (a) 25 μg/cm^2, (b) 530 μg/cm^2, and (c) 9190 μg/cm^2 carbon foil. The intensities are normalized to unity at the peak position. The solid line is drawn to guide the eyes.

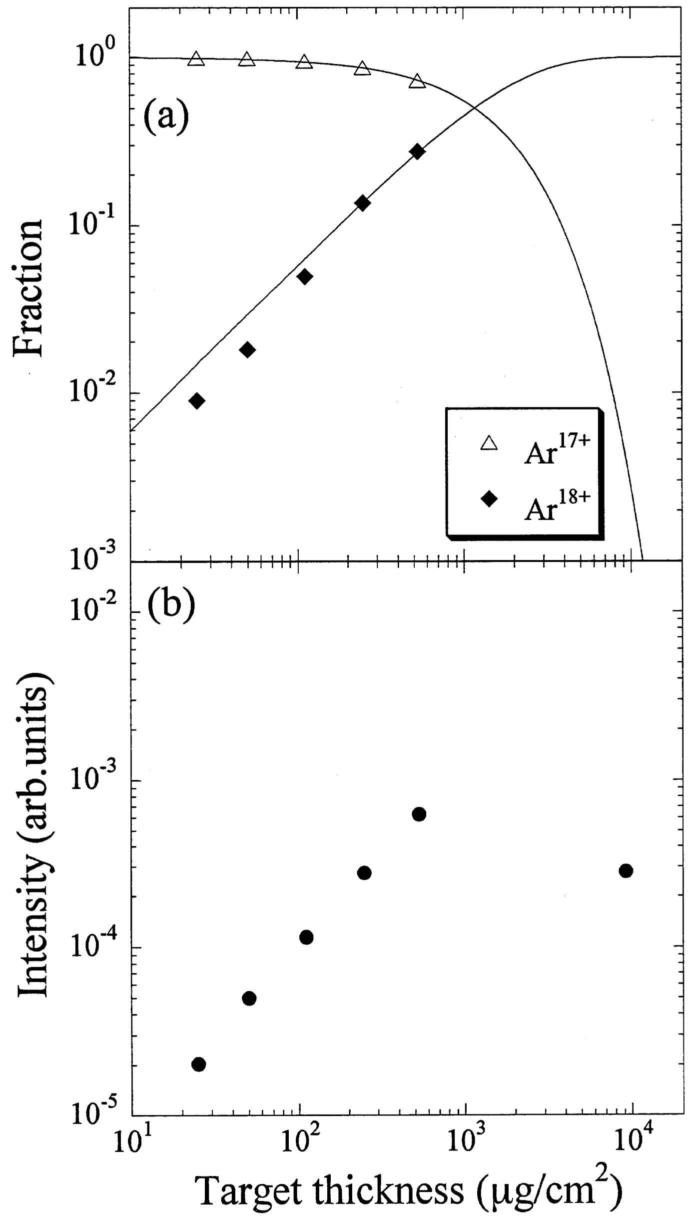

Fig. 3. (a) The charge state fractions of ions transmitted through the carbon foils as a function of carbon foil thickness. The solid lines show the fitting to the experimental data. (b) The intensity of the convoy electrons as a function of carbon foil thickness.

1s-electron ionization cross section of hydrogen-like ions per neutral target atom can be given as $Z^2\sigma_p + Z\sigma_e$, where Z is the target atomic number, σ_p and σ_e are the ionization cross sections by proton and electron impacts, respectively. Theoretical σ_e by electrons with an energy of 210 keV, which is equivalent to the present projectile velocity, is obtained as 2.7×10^{-22} cm^2 [7]. To obtain this value, we took into account the difference of binding energy between the neutral atom and the hydrogen-like ion. σ_p is considered to be equal to σ_e at the present energy. Accordingly, the total ionization cross section is estimated to be 1.1×10^{-20} cm^2. Here the screening effect is neglected. In the plane-wave Born approximation with the screening and antiscreening effects, the cross section is calculated to be 1.0×10^{-20} cm^2 [8]. A reasonable agreement is obtained between the experiment and calculations.

The total intensity of the convoy electrons as a function of the target thickness is shown in Fig. 3b. As shown in Fig. 3, the fraction of Ar^{18+} ions and the intensity of the convoy electrons were proportional to the target thickness. This indicates that ELC is the major mechanism of convoy electron emission in the present condition. In the thickness region larger than about 500 μg/cm^2, the intensity of convoy electrons decreased because of multiple scattering.

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