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High-resolution soft X-ray spectroscopy of 2.3 keV/u N^{7+} ions through a microcapillary target

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Abstract

X-rays emitted from 2.3 keV/u $^{15}N^{7+}$ ions transmitted through a highly ordered Ni microcapillary were measured with a high-resolution soft X-ray spectrometer. The highly ordered microcapillary has recently become available employing a nano-lithographic technique. A transmission ratio and charge state distribution of ions through the microcapillary target were found to be consistent with theoretical predictions. A preliminary analysis showed that a series of X-rays from *n*p–1s transitions with *n* as high as 8 were identified, which is consistent with the classical over barrier model.

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1. Introduction

An interaction of a slow highly charged ion (HCI) with a solid has been studied intensively for the last two decades [1–10]. When a slow HCI approaches the solid surface, it resonantly captures electrons from the solid valence band into its excited states. The classical over barrier model predicts that the critical distance d_c for the resonant charge transfer to start is given by $d_c(q) \sim (2q)^{1/2}/W$, where q is the charge state of the ion and W is the work function of the target (physical quantities are given in atomic units unless otherwise stated) [11]. The principal quantum number n_c in which electrons are captured is given by $n_c \times (q) \sim q/(2W(1+(q/8)^{1/2}))^{1/2}$. Such an atom (ion) with multiple electrons in excited states and inner shell vacancies is called a "hollow atom (ion)" (HA).

The formation and relaxation dynamics of HA have been one of the central subjects, which have been studied through measurements of charge states, angular distributions of scattered ions, X-rays, Auger electrons, etc. Since the HA generated above the surface is accelerated toward the surface due to its image charge, the survival time

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of HA above the surface, is very limited, i.e. $\sim 10^{-13}$ s. The survival time is normally shorter than a characteristic lifetime of HA, and it is difficult to observe HA above the surface. The difficulty can be overcome by using a microcapillary which is a thin foil with small straight holes. In this configuration, a part of HCIs passing near the hole wall capture electrons and leave the target before colliding against the wall [12–14]. A fraction of ions which capture finite number of electrons is geometrically estimated to be $\sim 2d_c(q)/r$, where r is the inner radius of the straight hole. Ninomiya et al. measured K X-rays emitted from N^{q+} ions downstream of a Ni microcapillary target with a Si(Li) detector [15,16]. They observed that HAs so formed had extremely long K-hole lifetimes of ~ns. However, the energy resolution of Si(Li) detector (~80 eV at 500 eV) is not enough to identify the electronic configurations, which are very important to study the dynamics of the HA formation and relaxation processes. In order to identify electronic core configurations, we have developed a high-resolution soft X-ray spectrometer [17]. Morishita et al. measured visible light spectra emitted from Ar ions downstream of the Ni microcapillary target [18]. It was found that several lines were attributed to transitions emitted from ions captured one electron into an initial state of $n \sim q + 1$.

In this paper, we report on (1) the transmission ratio and charge state distribution and (2) X-rays spectra of 2.3 keV/u $^{15}N^{7+}$.

2. Experiments

The present study was performed using a 14.5 GHz Caprice type electron cyclotron resonance ion source (ECRIS) in RIKEN [19]. Ions extracted from the ECRIS were charge-state-selected by an analyzing magnet and delivered to a target chamber with the X-ray spectrometer via a magnetic quadrupole triplet lens and a switching magnet. Further details of the ion source and the beam line are given elsewhere [19]. The microcapillary target was mounted on an X–Y stage and was movable perpendicular and parallel to the ion beam.

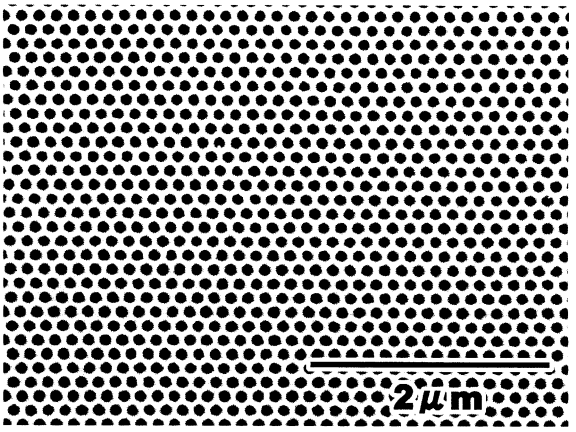

Fig. 1. An SEM image of the highly ordered Al_2O_3 microcapillary foil [20].

Recently, a new manufacturing method of the microcapillary foil has been developed using a nano-lithographic technique, which allows to prepare a highly ordered microcapillary foil. An example of such a foil of Al_2O_3 is shown in Fig. 1 [20]. In the present experiment, a highly ordered Ni microcapillary foil was used, which had ~1 mm^2 in area with a thickness of ~1.5 μm and had a multitude of straight holes of ~300 nm in diameter, and had a honeycomb structure with 500 nm interval, i.e. the geometrical opening ratio was ~30%.

The high-resolution soft X-ray spectrometer consists of an entrance slit, an Au coated concave grating and a back illuminated CCD, as shown in Fig. 2. The grating with varied groove spacing designed for a grazing-incident spectrometer was used, with which diffracted soft X-rays are focused

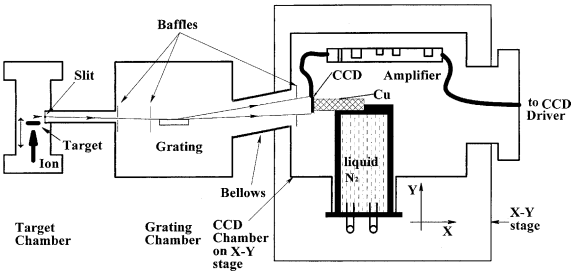

Fig. 2. A schematic drawing of the high-resolution soft X-ray spectrometer [17].

onto a plane almost perpendicular to X-rays [21]. The energy range covered by the spectrometer is from 200 to 1200 eV. The baffles were prepared to block stray lights to the CCD. The CCD was mounted in the movable vacuum chamber and operated at 150 K cooled with liquid N_2. The energy resolution and energy accuracy were 3.1 eV (FWHM) at 500 eV and 0.5 eV at 500 eV, respectively. The detailed description of the spectrometer is given in Ref. [17].

The charge state distribution was measured with an electrostatic parallel plate analyzer downstream of the target chamber.

3. Results and discussions

The transmission ratio of 230 eV/u Xe^{6+} ions through the highly ordered Ni microcapillary target was ~25%, which is consistent with the geometrical opening ratio of ~30%. Fig. 3 shows the charge state distribution $f(q_f)$ of the transmitted ions. It is seen that $f(q_f)$ shows a minimum at $q_f \sim 3$, which is similar to the result for N^{6+} [15]. Each final charge state fraction calculated by $\sim 2d_c(q)/r$ was roughly successfully reproduced the observed fractions. The charge state distribution of the simulation with consideration of Auger relaxation processes reproduced satisfactorily the U-shape tendency of the observed distribution [22]. It is noted that the transmission ratio obtained in a previous experiments with self-organized capillary was ~15% although the geometrical opening ratio was ~50% [15]. The difference between the observed transmission ratio and the geometrical one may be due to some nonuniform capillary diameter along the capillary.

Fig. 4 shows an X-ray spectrum for 2.3 keV/u $^{15}N^{7+}$ ions transmitted through the highly ordered Ni microcapillary. The eight major lines were attributed to hydrogen-like and helium-like transitions, which are summarized in Table 1 [23]. The electronic configuration of the small bump at 489.6 ± 0.5 eV was not successfully identified. According to the result of the visible light spectroscopy, the principal quantum numbers of the

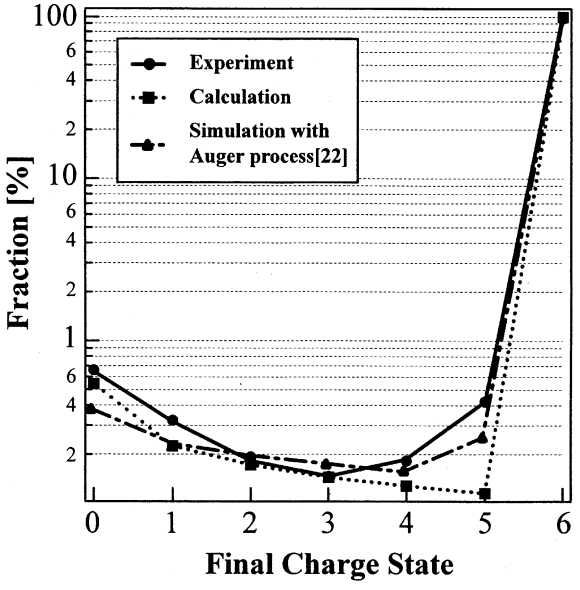

Fig. 3. The final charge state distribution of 230 eV/u Xe^{6+} ions transmitted through the highly ordered Ni microcapillary. (●): Experiment, (■): calculation with $\sim 2d_c(q)/r$, (▲): simulation [22].

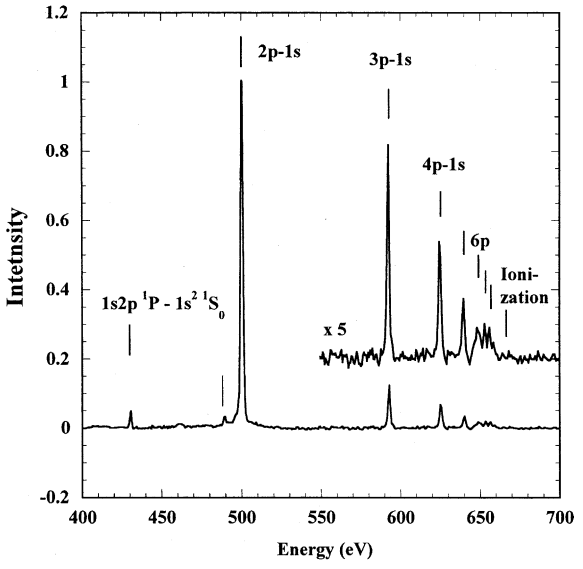

Fig. 4. *K* X-ray spectra measured, immediately downstream of the target for 2.3 keV/u $^{15}N^{7+}$ ions transmitted through a Ni microcapillary foil. The bars with transition terms show transition energies [23].

Table 1
Observed line energies and electronic configurations [23]

Experiment (eV)	Reference data (eV)	Configurations
430.8 ± 0.4	430.7	$1s2p–1s^2$
500.4 ± 0.5	500.3	2p–1s
593.0 ± 0.7	592.9	3p–1s
625.4 ± 0.7	625.4	4p–1s
640.4 ± 0.7	640.4	5p–1s
649.3 ± 0.8	648.5	6p–1s
653.9 ± 0.8	653.4	7p–1s
656.3 ± 0.8	656.6	8p–1s
cf.	658.8	9p–1s
	667.1	Ionization

initially populated states are $n \sim q + 1$, which are $\sim$8 in the present case [18]. In other words, the observed transition (8p–1s) is the transition from the initially populated states. Morishita et al. [18] observed transitions from high angular momentum states. Combining the present result and that of Ref. [18], it is concluded that the principal quantum numbers of the initial population are $n \sim q + 1$ with a broad distribution of the angular momentum.

4. Conclusion

The observed transmission ratio for the highly ordered Ni microcapillary target was in accord with the geometrical opening ratio. The charge state distribution of ions transmitted through the capillary was consistent with the prediction of the classical over barrier model.

X-rays corresponding to np–1s transitions with n as high as 8 were observed, which include direct transitions from the initially populated states. It was found that the angular momentum distribution is quite broad including p-states as well as yrast states.

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