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X-rays emitted from N ions transmitted through a thin Ni microcapillary target

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Abstract

K X-rays emitted from 2.1 keV/u N ions transmitted through a thin Ni microcapillary foil were measured in coincidence with a final charge state q_f, using a Si(Li) X-ray detector in the cases of incident charge states of $q_i = 7$ and 6. It was found that (1) the coincidence X-ray yield for $(q_i, q_f) = (7, 6)$ decreased faster than those for other (q_i, q_f) combinations, (2) the coincidence X-ray yields did not depend on the number of K-shell holes of the incident ions but on the final charge state q_f.

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Keywords: Highly charged ions; Hollow atom; Microcapillary; X-ray emission; Coincidence measurements

1. Introduction

When a slow highly charged ion (HCI) approaches a solid surface, the ion is accelerated toward the surface by its image charge, and then resonantly captures target valence electrons into its excited states above the surface. Such an atom (ion) with multiply excited electrons and inner shell vacancies is called a “hollow atom (ion)” (HA). HAs have been the key targets in studying HCI–surface interactions, and investigated through measurements of charge states and angular distributions of specularly reflected ions, and emission of X-rays, Auger electrons, etc. [1–12]. Since the HA formed above the surface moves toward the surface with a finite velocity due to the

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self-image force, the survival time of HA above the surface is limited, typically less than ~10^{-13} s. This time duration could be shorter than that required for HA to cascade down to its ground states, i.e. it is often difficult to study HAs above the surface with HCI–flat surface collision. To study the intrinsic nature of HAs, HAs are extracted in vacuum [6–12] combining the HCIs with a microcapillary target [13,14], where a part of slow HCIs capture electrons from the wall and can still escape from the target before colliding against the inner wall. For example, Ninomiya et al. measured X-rays with a Si(Li) detector in coincidence with a final charge state q_f for 2.1 keV/u N^{q_i+} ($q_i = 6$) ions incident on a Ni microcapillary target [7]. It was found that the K-hole lifetimes were ~ns even when several electrons were in L-shell. In the present paper, N^{7+} ions as well as N^{6+} ions were selected as projectiles so that the relaxation dynamics with different number of innershell vacancies can be studied.

2. Experiment

The present study was performed using a 14.5 GHz Caprice type electron cyclotron resonance ion source (ECRIS) in RIKEN, and 2.1 keV/u $^{14}N^{6+}$ and $^{15}N^{7+}$ ions extracted from the ECRIS were delivered to a vacuum chamber via a switching magnet. Since $^{14}N^{7+}$ ion could not be separated from other naked ions, $^{15}N^{7+}$ ion was used. Further details of the ion source and the beam line are described elsewhere [15]. The vacuum of the beam line and the chamber were ~10^{-6} Pa during the experiment. A microcapillary target was mounted on a linear motion manipulator. The microcapillary target was made of Ni having ~1 mm^2 in area with a thickness of ~1 μm and a multitude of straight holes of ~100 nm in diameter [13,14]. A windowless Si(Li) X-ray detector was installed at 90° with respect to the incident ion beam, as shown in Fig. 1. The shield located between the ion beam and the detector was movable along the z-axis and was used to limit the detection region of delayed X-rays, where z-axis was taken along the beam with its origin at the target position. The ions passed through the microcapillary target were charge state analyzed with an electrostatic deflector and detected by a channel electron multiplier (CEM). In order to estimate the X-ray yield, the solid angle covered by the Si(Li) X-ray detector was calculated in Fig. 2 as a function of X-ray emission point for

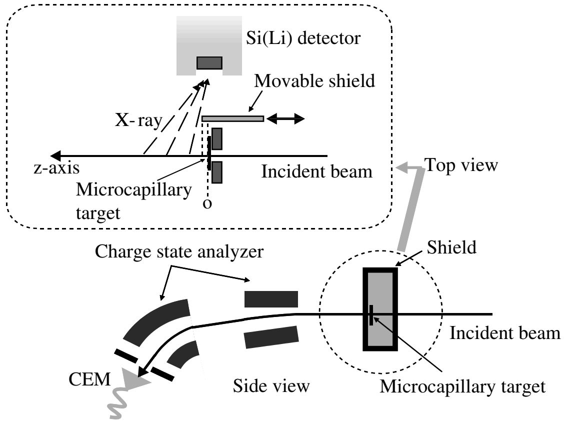

Fig. 1. Schematic drawing of the experimental setup.

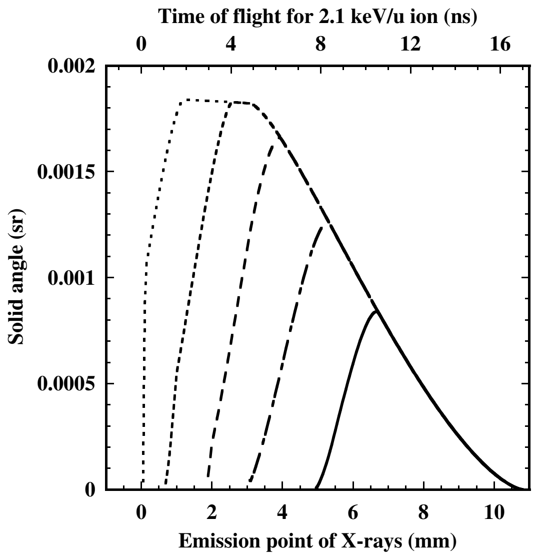

Fig. 2. Solid angle subtended by the Si(Li) X-ray detector as a function of position z for the shield positions of 0 mm (dotted line), 1 mm (short-dashed line), 2 mm (long-dashed line), 3 mm (dot-dashed line), and 4 mm (solid line). The z-axis is the along the ion beam and the origin is at the microcapillary target position. The time of flight for 2.1 keV/u ions is shown in the top.

various shield positions. The dotted line, the short-dashed line, long-dashed line, dot-dashed line and solid line show the solid angle for the shield positions at 0 mm, 1 mm, 2 mm, 3 mm and 4 mm, respectively.

3. Results and discussion

K X-rays from N ions transmitted through the microcapillary target were measured in coincidence with the final charge state q_f. The coincidence yield was obtained as the ratio of the number of the coincidence events to the number of N^{q_f+} ions. Fig. 3 shows the coincidence X-ray yields as a function of the shield position. The solid circle (●), solid diamond (♦), solid triangle (▲), open square (□), open triangle (▽) and cross (×) show energy-integrated X-ray yields for $(q_i, q_f) = (7,6)$, $(7,5)$, $(7,4)$, $(6,5)$, $(6,4)$ and $(6,3)$, respectively. The coincidence X-ray yields for $q_i = 6$ reported by Ninomiya et al. [7] were reasonably reproduced in this experiment considering that the solid angle was $\sim 10^{-3}$ sr as seen in Fig. 2. It is seen that the X-ray yield for $(q_i, q_f) = (7,5)$ is almost the same as that for $(6,5)$ and the same is true between $(7,4)$ and $(6,4)$, i.e. the coincidence X-ray yields does not depend on the number of K-shell holes of the incident ions but on the final charge state q_f. The coincidence X-ray yield for $(q_i, q_f) = (7,6)$ decreased faster than those with other (q_i, q_f)-combinations. Some common behaviors were observed also for Ar ions, where the coincidence X-ray yields for $q_f = q_i - 1$ ($q_i = 14, 13, 11$) decreased faster as compared with those for $q_f \leqslant q_i - 2$, and the coincidence X-ray yields for $q_i = 9$ did not depend on q_f [16]. It seems that the coincidence X-ray yields with $q_f = q_i - 1$ for incident ions having multiple inner shell holes have decreased faster as compared with those for $q_f \leqslant q_i - 2$.

Fig. 4 shows K X-ray energy spectra for 2 keV/u N ions measured with the Si(Li) detector and with a high-resolution grating spectrometer. The

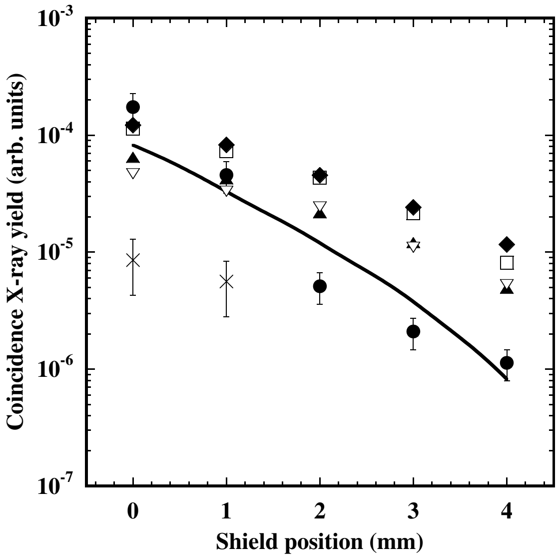

Fig. 3. The integrated coincidence X-ray yields as a function of the shield position for incident and final charge state combinations (q_i, q_f) of $(7,6)$(●), $(7,5)$(♦), $(7,4)$(▲), $(6,5)$(□), $(6,4)$(▽) and $(6,3)$(×). The solid line shows the integrated K X-ray yield obtained via cascade calculation of one electron (H-like) ion initially populated according to the report of visible light measurement [8], considering the solid angle calculation (Fig. 2).

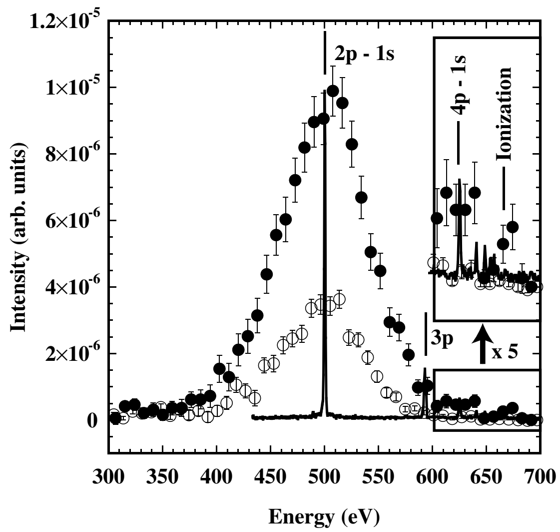

Fig. 4. Energy spectra of N K X-rays with $(q_i, q_f) = (7,6)$ for shield positions of 0 mm (●) and 1 mm (○). A spectrum of X rays measured with a high-resolution soft X-ray spectrometer at immediately downstream of the Ni microcapillary target for 2.3 keV/u N^{7+} incidence was shown by solid line for comparison [11]. The bars with transition terms show transition energies [17].

solid circle (●) and open circle (○) are for the coincidence spectra with the Si(Li) X-ray detector for $(q_i, q_f) = (7, 6)$ setting the shield at 0 mm and 1 mm, respectively. The solid line shows the spectrum measured with the high-resolution spectrometer for $q_i = 7$ [11] immediately downstream of the Ni microcapillary foil. X-rays corresponding to np–1s transitions with n as high as eight have been observed, where n is the principal quantum number. When the high-resolution spectrum was taken at 1 mm, all the peaks except for the 2p–1s transition were hardly observed, in consistency with the fact that the spectrum with the shield at 1 mm (○) plotted in the inset of Fig. 4 had no high energy tail. It is then concluded that the coincidence X-rays with $(q_i, q_f) = (7, 6)$ have been primarily attributed to 2p–1s transition.

Morishita et al. measured visible light emitted from Ar ions transmitted through the Ni microcapillary target [8] and found that (1) the initial principal quantum number distributed around $n_{COB} \sim q_i + 1$ with a width $\delta n \sim 2$, and (2) the angular momentum distributions were more or less statistical, where n_{COB} was the principal quantum number predicted by classical over barrier model for the first electron transfer [18]. Assuming that the above findings are also true for the present collision system, a cascade calculation has been performed to see how the K X-ray yields evolve. The solid line in Fig. 3 shows the result of such a calculation, where the solid angle variation with respect to the shield position and the emission position (see Fig. 2) are taken into account. It is seen that the calculation can crudely reproduce the experimental result for $(q_i, q_f) = (7, 6)$.

4. Summary

K X-rays emitted from 2.1 keV/u N ions ($q_i = 7$ and 6) transmitted through a thin Ni microcapillary target were measured in coincidence with the final charge state q_f, varying the time window for delayed X-ray emission. The coincidence yields for $q_i = 6$ reported by Ninomiya et al. were reasonably reproduced [7]. The coincidence X-ray yield for $(q_i, q_f) = (7, 6)$ decreased faster than other (q_i, q_f) combinations. The coincidence X-ray yield did not depend on the number of K-shell holes but on the final charge state q_f. The coincident X-ray for $(q_i, q_f) = (7, 6)$ was dominated by the 2p–1s transition. This 2p–1s transition had a $\sim n$s lifetime due to a cascade filling from highly-excited, high-angular momentum states.

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