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Nuclear Instruments and Methods in Physics Research B 205 (2003) 762–766

NIM B
Beam Interactions
with Materials & Atoms

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High-resolution soft X-ray spectroscopy of slow highly charged ions transmitted through a microcapillary target

Y. Iwai ^{a,*}, Y. Kanai ^a, Y. Nakai ^a, T. Ikeda ^a, H. Oyama ^a, K. Ando ^a,
H. Masuda ^b, K. Nishio ^b, M. Nakao ^c,
H.A. Torii ^d, K. Komaki ^d, Y. Yamazaki ^{a,d}

^a Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

^b Department of Applied Chemistry, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

^c NTT Photonics Laboratories, Atsugi, Kanagawa 243-0198, Japan

^d Institute of Physics, University of Tokyo, Meguro, Tokyo 153-8902, Japan

Abstract

To detect weak X-rays with a high-resolution spectrometer, a charge-coupled device was operated in a single X-ray photon detection mode. A procedure to effectively identify single X-ray was established. In the case of 2.3 keV/u N⁷⁺ and Ne⁹⁺ incidence, X-rays emitted from ions transmitted through a Ni microcapillary target were measured with the spectrometer using the procedure of the single event mode. The signal-to-noise ratio was improved by using the single photon counting method.

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PACS: 34.50.Bw

Keywords: Slow highly charged ion; Hollow atom; Microcapillary; X-ray emission; X-ray spectroscopy

1. Introduction

When a slow highly charged ion (HCI) approaches a solid surface, the ion is accelerated toward the surface with its image charge and then resonantly captures target valence electrons into its excited states. Such an atom (ion) with multiply

excited electrons and inner shell vacancies is called a “hollow atom (ion)” (HA). The formation and relaxation dynamics of HAs above and below the surface have been studied intensively in recent years [1–10]. Since the HA generated above the surface has a finite velocity toward the surface, it collides with the surface in a short time, which is $\sim 10^{-13}$ s at the longest. This time could be shorter than the time required for HAs to cascade down to their ground states, i.e. some specific features of such HAs are not observed in HCI-flat surface collision. To overcome the limitation, HAs are

* Corresponding author. Tel.: +81-48-467-9483; fax: +81-48-462-4644.

E-mail address: iwai@radphys4.c.u-tokyo.ac.jp (Y. Iwai).

extracted in vacuum employing a combination of HCIs and a microcapillary target [6]. The microcapillary target is a thin foil with many small straight holes perpendicular to the surface [11,12]. A part of slow HCIs, which pass near the inner wall of the hole, capture electrons from the wall and can still escape from the target before colliding against the inner wall. Using the microcapillary target, the formation and relaxation dynamics of HAs have been studied through measurements of X-rays, visible lights, and charge states [6–10].

Ninomiya et al. measured X-rays with a Si(Li) detector for 2.1 keV/u N^{6+} ions injected on a Ni microcapillary target [7]. It was found that some HAs have *K*-hole lifetimes as long as several nanoseconds. The peak energy of N *KL* X-rays observed for the capillary target was about 30 eV higher than that for a flat Al target, i.e. the number of *L*-shell electrons at the moment of X-ray emission is relatively small. However, the detailed electronic configurations, which are important to further study the formation processes of HAs, are very difficult to identify with a Si(Li) detector, because its energy resolution is not good enough (~ 80 eV at 500 eV). To identify the electronic core configuration of the ions through the capillary, X-rays were measured with a high-resolution spectrometer downstream the Ni capillary target for 2.3 keV/u N^{7+} incidence [8]. Seven major lines out of nine observed ones were attributed to *np*–1s transitions with *n* as high as eight. Morishita et al. measured visible light spectra emitted from Ar ions transmitted through the Ni microcapillary target [9]. It was found that ions capture one electron into an initial state of $n_c \sim q + 1$ with high angular momentum, where n_c and q were the principal quantum number for the first electron to be transferred and the charge of the incident ion, respectively. Combining the X-ray and the visible light spectroscopy, it was found that the initial population is peaked at $n_c \sim q + 1$ with a broad distribution of the angular momenta [8]. In order to investigate the principal quantum number distribution of initial state, it is important to observe *np*–1s transitions with a wide range of *n* including states with small population. To make spectroscopy with weak X-rays, a low noise charge-coupled device (CCD) was employed. A long accumulation time

was needed because the main source of the CCD noise was its own readout noise, which is independent of the accumulation time. On the other hand, as the accumulation time gets longer, the chance that the CCD is hit with energetic cosmic rays gets larger. In order to remove the noise by cosmic rays and improve the signal-to-noise ratio, the CCD was operated in a single photon detection mode.

2. Experimental setup

The present study was performed using a 14.5 GHz Caprice type electron cyclotron resonance ion source (ECRIS) at RIKEN. Ions extracted from the ECRIS were charge-states-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 [13]. The vacuum of the beam line and the target chamber were $\sim 10^{-9}$ Torr during the experiment.

A microcapillary target was mounted on an X–Y stage movable perpendicular and parallel to the ion beam. The microcapillary target was made of Ni having ~ 1 mm² in area with a thickness of ~ 1 μ m and a multitude of straight holes of ~ 100 nm in diameter [12].

We developed a high-resolution soft X-ray spectrometer, which employs a combination of a gold-coated concave grating and a back illuminated CCD. The X-ray energy range covered by the spectrometer is from 200 to 1200 eV. The detailed description of the spectrometer is given in [14].

The X-rays were detected by the CCD (Marconi CCD42-10) with a size of 27.6×6.9 mm² having 2048×512 pixels of 13.5×13.5 μ m². The CCD was mounted in a vacuum chamber and cooled down to 150 K with liquid N₂. The specifications of the CCD are summarized in Table 1. When an X-ray photon hits one of the pixels of the CCD, it generates electron–hole pairs, the number of which is proportional to X-ray energy. The charge cloud is conveyed along the CCD array by a CCD drive unit and is converted to an analog signal by a

Table 1
Specifications of the CCD

Pixel size	13.5 μm \times 13.5 μm
Pixel format	2048 \times 512
Image area	27.6 mm \times 6.9 mm
Readout noise (at 233 K)	2 e ⁻ (r.m.s.)
Output amplifier sensitivity	4.5 $\mu\text{V}/\text{e}^-$

charge sensitive amplifier. The analog signal was sent to an A/D converter in atmosphere. The A/D converter unit was attached to the flange of the CCD chamber. The digitized signal was recorded by PC and analyzed as two-dimensional data formatted into 2048 \times 512.

3. Results and discussions

X-rays emitted from ions transmitted through the Ni microcapillary were measured with the spectrometer immediately downstream of the target for 2.3 keV/u N^{7+} and Ne^{9+} ions injections.

In order to make X-ray photon counting with the CCD, the number of X-rays on each pixel should be one or less. The charge cloud in the CCD may spread over four pixels (2×2) at the maximum. The two-dimensional data recorded by the PC were analyzed in the following procedure, which is named a single event mode analysis. When the total charge on adjoining four (2×2) pixels was over an “event threshold”, the pixels were recognized to be an event area. The pixel having the maximum charge in the area was defined as the “event pixel”. The total charge was named “event energy” which is proportional to the incident X-ray energy. When the event energy was consistent with the photon energy corresponding to the event position on the CCD, it was recognized as one X-ray having the right energy hitting the event pixel. Fig. 1 shows the event energy histogram. The thin solid and dashed lines show the event energy distribution for 2p–1s (500.3 eV) transition of N ions and for 1s2p $^1\text{P}-1s^2\ ^1\text{S}_0$ (922.1 eV) and 1s2p $^3\text{P}-1s^2\ ^1\text{S}_0$ (914.9 eV) transitions of Ne ions, respectively. The thick solid and dashed lines show Gaussian fitting of the distributions of N and Ne ions, respectively. Both event thresholds

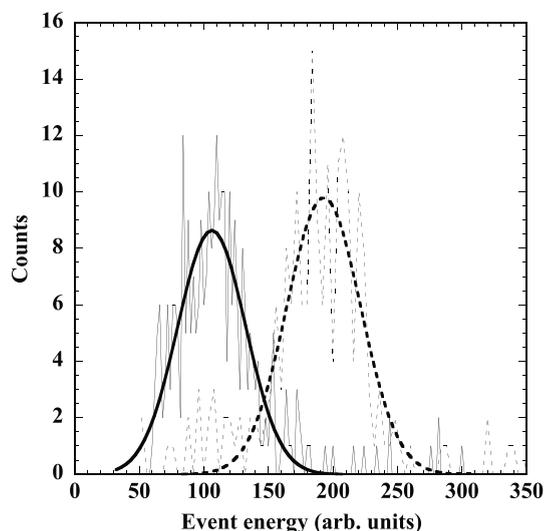


Fig. 1. The distribution of the event energy that is proportional to the energy of the incident X-ray. The thin solid and dashed lines show those for H-like N ion 2p–1s (500.3 eV) transition X-rays and He-like Ne ion 1s2p $^1\text{P}-1s^2\ ^1\text{S}_0$ (922.1 eV) and 1s2p $^3\text{P}-1s^2\ ^1\text{S}_0$ (914.9 eV) transitions, respectively [15]. The event thresholds for both lines were 50. The thick solid and dashed lines show Gaussian fitting curves for N and Ne ions, respectively.

were 50. It is seen that, the distributions of the event energy for N and Ne ions have peaks at around 110 and 200, respectively. FWHM of the peaks were about 70.

The solid line in Fig. 2 shows an example of the energy spectrum analyzed according to the procedure of the single event mode for 2.3 keV/u N^{7+} incidence on the Ni microcapillary target. As a reference, the dashed line plots an example of a raw spectrum, i.e. a direct output of the A/D converter. These spectra were accumulated under the same experimental conditions and subtracted with background noise. It is seen that the signal-to-noise ratio is improved to some extent when the procedure of the single event mode is applied. In order to pin down the noise source in the event mode, the event energy distribution was accumulated from the CCD area where no diffracted X-rays are expected to arrive. It was found that the event energy distribution so prepared had almost the same distribution as the “right” diffracted X-rays arriving the right position for both N and Ne K X-rays. It is evident that stray X-rays are

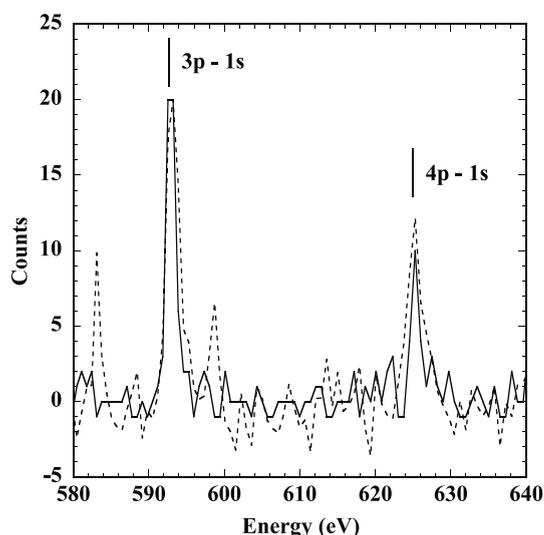


Fig. 2. *K* X-ray spectra measured with the spectrometer, immediately downstream of the target for 2.3 keV/u N^{7+} transmission through a Ni microcapillary foil. The solid line shows the spectrum analyzed using the procedure of the single event mode. The dashed line is the direct output of the A/D converter. These spectra were accumulated under the same experimental conditions and subtracted with background noise. The bars with transition terms show transition energies [15].

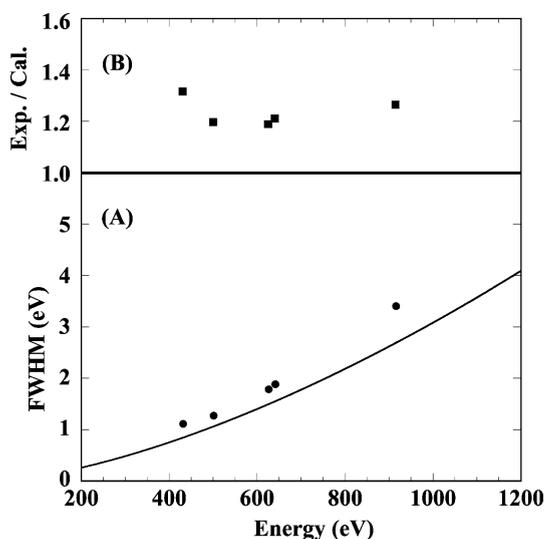


Fig. 3. Energy resolution (FWHM) of the spectrometer as a function of X-ray energy. The solid circles (●) in (A) are experimental ones. The solid line shows the calculated values taking into account the geometric arrangement of the optical elements [14]. The solid squares (■) in (B) show the ratio of energy resolution between the experimental results and the calculation.

hitting the CCD. A modification is in progress to reduce the stray X-rays.

To evaluate the energy resolution of the spectrometer, X-ray spectra were measured for N^{7+} and Ne^{9+} incident ions. Each X-ray peak was fitted by a Gaussian function. The solid circles in Fig. 3(A) show the FWHM so determined. The solid line shows the expected resolution of the spectrometer for the entrance slit of 25 μm wide, which corresponds to two pixels of the CCD. The solid squares in Fig. 3(B) show the ratio of energy resolution between the experimental results and the calculation. FWHM of each X-ray peak transition was found to be 20% wider than the calculation. The digitization error due to the pixel size is supposed to be the reason of the difference.

4. Conclusion

An analysis method for the two-dimensional data of the CCD was discussed and the procedure of the single event mode was established. X-rays of N 2p–1s (500 eV) as well as Ne 1s2p–1s² (922.1 and 914.9 eV) transitions were measured with the high-resolution spectrometer employing a single event mode. The signal-to-noise ratio was improved by using the procedure. Further improvements of the signal-to-noise ratio of the spectrometer is in progress.

Acknowledgements

We gratefully acknowledge the support from Dr. M. Takekawa and Dr. N. Oshima for data analysis. The research is supported by the special postdoctoral researchers program in RIKEN.

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