# Auger electrons emitted from nitrogen ions passing through a metallic microcapillary

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**Abstract**. K Auger electrons emitted from excited N ions produced by multi electron transfer from the inner surface of a metallic microcapillary were observed in the energy region of 310-400 eV, for 60keV $N^{6+}$ incident ions. The lower energy part (310-340eV) can be attributed to Auger electrons from Li- and Be-like excited states in vacuum, which may have information about decay processes of the hollow atoms (ions), which has not been observed by previous ion-surface collision experiments. The higher energy part (340-400eV) of the spectrum may be attributed to Auger electrons from hollow atoms (ions) and from Li-like K-LM Auger electrons.

## 1. Introduction

When highly charged ions (HCIs) approach a metallic surface, multi-electrons are resonantly transferred from the surface into the excited states of ions and hollow atoms (ions) are produced [1]. We have measured x-rays [2-4] and the visible light [5] emitted from such excited ions and the charge state distributions [2, 6, 7] and scattering angle measurements [6] of ions after their stabilization in order to study hollow atom formation and its decay processes. We have used a metallic microcapillary thin foil [8] as a target to produce such excited ions, which permits us to study the primordial stage of hollow atom formation [5, 9, 10] and the final stage of the decay processes for the excited ions [2-4, 9, 10].

According to our x-ray measurements of $N^{6+}$ with a Ni microcapillary, especially coincidence measurements between x-rays and the final charge states of N ions [2], the K shell vacancy is mainly filled by non-radiative processes in the final stage of the hollow atoms (ions) decay. Also, the existence of spin-aligned long-lived excited states like (1s2s2p $^4$P) in the final stage of decay processes was predicted [2]. To study these dominant decay processes directly, we have measured the K Auger electrons emitted from excited N ions produced by the interaction between $N^{6+}$ and the inner wall of the microcapillary.

## 2. Experiments and results

Experiments were performed at the Highly Charged Ion facility in RIKEN [11]. A 60keV $N^{6+}$ ion beam extracted from a 14.5 GHz ECR ion source was magnetically analyzed and then collimated to give a 1 mm diameter spot size on the capillary target, with a roughly 0.5 deg angular divergence. Typical beam intensity was 1-30nA. We used thin microcapillary foils made of Ni and Au as a target. The microcapillary foils used in our experiments were ~1mm$^2$ in size with a thickness of ~1μm and had a multitude of straight holes of ~100 nm in diameter. Typical vacuum of the beam line and the target chamber was $1\times10^{-5}$ Pa. Electron spectra were measured by a tandem type electro-static analyzer [12] at an observation angle of zero-degree with respect to the beam direction. To estimate the background electrons produced in collisions between projectile ions and residual gases, we measured the electron spectra with and without a Ni microcapillary foil at the target position. Electron intensity with the Ni microcapillary foil is two orders of magnitude larger than that without the Ni microcapillary foil, when the electron intensities are normalized by the ion currents after the target. It is estimated that the effect of the collisions with the residual gases inside the capillary is smaller than that with the residual gases outside the capillary. This means that the background due to collisions between projectile ions and residual gases is negligible as compared with the real signals. Observed electron spectra show almost the same features for Ni and Au capillary foils. Here, we show and discuss spectra for only the Ni capillary.

A typical K-Auger spectrum is shown in figure 1. The energy resolution is about 6eV. So far, many groups have studied the collisions of $N^{6+}$ ions with a flat solid surface by measuring electron spectra, and reported K-LL Auger electrons emitted from the hollow atoms above and below surface at the energy region of 340-400eV [13-15]. An $N^{6+}$ ion approaches the flat solid surface and capture multi electrons from the solid surface into its excited states resonantly. Hollow atoms above surface (1st generation) are produced in this way [9, 16]. Some of the hollow atoms emit K Auger electrons before they collide with the solid surface, but many of them collide with the solid surface keeping their K shell vacancy. Such ions then form rather small size hollow atoms (2nd generation) below the surface [9, 16]. After the formation of 2nd generation hollow atoms, they emit K-Auger electrons below the surface. Electrons in the range of 340-400 eV have been identified as K-LL Auger electrons from hollow atoms in 1st and 2nd generations ($1s2l^{r}3l'^{(6-r)}$, $r \geq 2$) [17]. Our observed spectra around 340-400eV may be attributed to the K-LL Auger electrons from the hollow atoms as reported by them.

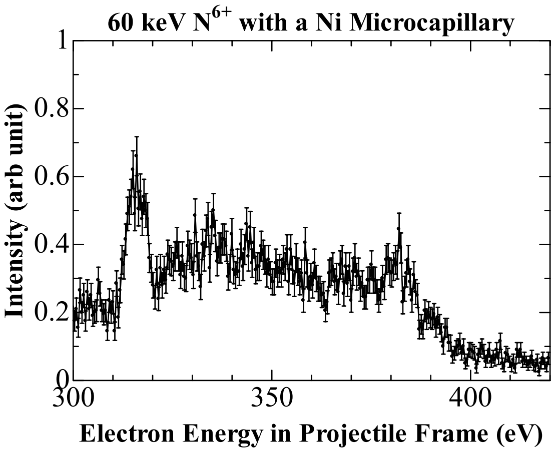


**Figure 1.** Typical Auger electron spectrum for 60 keV $N^{6+}$ with a Ni microcapillary. The higher energy part (340-400eV) of the spectrum may be attributed to the K-LL Auger electrons from hollow atoms. K-LM Auger electron signals from excited states of Li- like ions exist around 380 eV. The lower energy part (310-340eV) of the spectrum can be attributed to K-LL Auger electrons from excited states of Li- and Be-Like ions. Any background was not subtracted. Energy resolution was about 6eV.

At the lower energy region (310-340eV), no clear structure has been reported in the collisions of $N^{6+}$ ions with a flat solid surface [13-15]. However, we have observed clear structures in this energy region. Taking into account spectroscopic data [18, 19], the electron signals in this energy region can be attributed to K-LL Auger electrons from Li- and Be-like excited states. Such excited states may be produced; (1) in the decay processes of hollow atoms (ions) in vacuum and/or (2) in the decay processes of excited ions produced by a few electron transfer processes from the capillary surface. The former is a rather close collision case: the $N^{6+}$ ion approaches close enough to the inner capillary surface to capture about 6 electrons into its excited states and then goes into vacuum emitting some electrons by autoionization processes to produce Li- or Be-like excited states. The latter is a rather distant collision case: the $N^{6+}$ ion passes through the capillary with a trajectory such that it remains a large distance from the inner surface capturing a few electrons into its excited states and goes into the vacuum emitting one or two electrons. These Auger electrons have not been observed in the collisions between HCIs and flat solid surfaces, because of its intrinsic nature; electrons are continuously supplied to the ions from the solid surface.

To identify the Auger transitions, we measured an electron spectrum around 310-340eV with higher energy-resolution (1.5eV). The spectrum is shown in figure 2 along with the lower energy-resolution (6eV) spectrum. Arrows indicate the K-LL Auger electron energies for Li- and Be-like N ions [18, 19]. We observed a clear, single peak at 316eV, which can be attributed to the Auger electron from the (1s2s2p $^4$P) states within our experimental error (1.5eV).

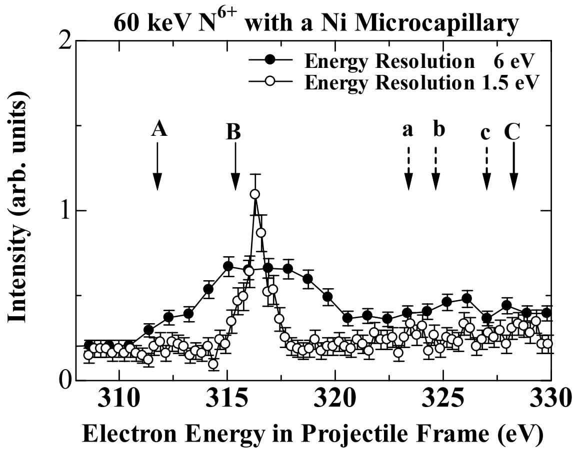


**Figure 2.** High energy-resolution spectrum for 60keV N$^{6+}$ with a Ni microcapillary. Closed circles: lower resolution (6eV) spectrum. Open circles: higher resolution (1.5eV) spectrum. Reported energy-positions for K-LL Auger Electrons are indicated by arrows. Corresponding excited states are; A: (1s2s$^2$ $^2$S), B: (1s2s2p $^4$P), C: (1s2s2p $^2$P) [18], a: (1s2s$^2$2p $^3$P), b: (1s2s2p$^2$ $^5$P), c: (1s2s$^2$2p $^1$P) [19]. Clear single peak around 316eV can be attributed to the K-LL Auger electrons from (1s2s2p $^4$P) excited states.

We also measured electron spectra while applying a voltage of -110V from the capillary to 20mm downstream. Observed energies of the electrons emitted from the N ions at the capillary region (-110V floated) should be shifted to the higher energy side by 110eV. In fact, the observed K Auger electron spectrum was shifted by 110 eV, and its intensity and shape were almost same as those without applying any voltage to the target region except that the intensity around 426eV ( = 316 + 110 eV) was decreased to less than half of the original spectrum. Lost electron intensity was left around 316eV. This means that the Auger decay emitting 316eV electrons has long-lifetime components. Considering the observed energy and the long lifetime of its decay, we can identify still more certainty the sharp peak at 316eV as the Auger electrons from the (1s2s2p $^4$P) states, which have long lifetimes: 1.7, 5.2 and 52 ns for J=1/2, 3/2 and 5/2, respectively [20]. Previous results of the coincidence measurements between x-rays and final charge states [2] predicted the existence of (1s2s2p $^4$P) states in the excited N ions passing through the Ni microcapillary. We have directly confirmed this by the present measurements.

The existence of K-LL Auger electrons from Li-like ions indicates that K-LM Auger electrons from Li-like ions also exist. Those electrons should exist around 375-390eV [18], although we can not say anything about their fractions in the observed signals around 375-390eV.

Other transitions could not be identified due to the poor statistics. Observed intensity from (1s2s2p $^4$P) states is large compared with other states in the high energy-resolution spectrum. This intense electron yield for (1s2s2p $^4$P) states may be caused not only by the production mechanism of these states but also by our experimental conditions. Taking into account the long lifetimes of (1s2s2p $^4$P) states, the ion velocity of 1mm/ns and the distance of about 70 mm from the target to the electron analyzer, the detection efficiencies of the electron analyzer should become somewhat larger for such long-lived states.

In summary, in the energy region of 310-400eV, we have observed K-LL Auger electrons from excited N ions passing through a metallic microcapillary. (1) Electrons in the energy region of 340-400eV may be attributed to the K-LL Auger electrons from hollow atoms [13-15], (2) electrons in the energy region of 310-340eV can be attributed to Auger electrons from the excited states of Li- and Be-like ions in vacuum, which may be the decay products of hollow atoms and/or a few electron excited states, (3) a clear, intense peak at 316eV can be attributed to Auger electrons from (1s2s2p $^4$P) states by considering its observed energy and long lifetime, (4) K-LM Auger electrons from Li-like ions may exist in the energy region 375-390eV, considering the existence of K-LL Auger electrons of Li-like ions.

Combining HCIs and a microcapillary target, we could observe Auger electrons from Li and Be-like excited states, which may have information on the decay processes of the hollow atoms (ions). However, a detailed study is needed to identify observed weak Auger electrons and quantitatively discuss the origin of excited states emitting observed Auger electrons. We plan to measure the fraction of meta-stable states like $N^{5+}(1s2s\ ^3S)$ in the primary $N^{6+}$ beam, which contribute to the observed Auger electrons, especially Auger electrons from $(1s2s2p\ ^4P)$ states [21].

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**References**

[1] Burgdörfer J, Lerner P and Meyer F W 1991 *Phys. Rev.* A **44** 5674
[2] Ninomiya S, Yamazaki Y, Koike F, Masuda H, Azuma T, Komaki K, Kuroki K and Sekiguchi M 1997 *Phys. Rev. Lett*. **78** 4557
[3] Kanai Y, Nakai Y, Iwai Y, Ikeda T, Hoshino M, Nishio K, Masuda H and Yamazaki Y 2005 *Nucl. Instrm. Methods* B **233** 103
[4] Iwai Y, Kanai Y, Nakai Y, Ikeda T, Hoshino M, Oyama H, Ando K, Masuda H, Nishio K, Torii H A, Komoki K and Yamazaki Y 2005 *Nucl. Instrm. Methods* B **235** 468
[5] Morishita Y, Hutton R, Torii H A, Komaki K, Brage T, Ando K, Ishi K, Kanai Y, Masuda H, Sekiguchi M, Rosmej F B and Yamazaki Y 2004 *Phys. Rev.* A **70** 012902
[6] Kanai Y, Ando K, Azuma T, Hutton R, Ishi K, Ikeda T, Iwai Y, Komaki K, Kuroki K, Masuda H, Morisita Y, Nishio K, Oyama H, Sekiguchi M and Yamazaki Y 2001 *Nucl. Instrm. Methods* B **182** 174
[7] Iwai Y, Murakoshi D, Kanai Y, Oyama H, Ando K, Masuda H, Nishio K, Nakao M, Tamamura T, Komaki K and Yamazaki Y 2002 *Nucl. Instrm. Metods* B **193** 504
[8] Masuda H and Fukuda K 1995 *Science* **268** 1446
[9] Yamazaki Y 2003 Interaction of Slow Highly Charged Ions with Surfaces *The Physics of Multiply and Highly Charged Ions* vol. 2, ed F J Currell (The Netherlands: Kluwer Academic Publishers) p 47
[10] Yamazaki Y 1999 *Int. J. Mass Spectro.* **192** 437
[11] Kanai Y, Dumitriu D, Iwai Y, Kambara T, Kojima T M, Mohri A, Morishita Y, Nakai Y, Oshima N and Yamazaki Y 2001 *Phys. Scripta* T **92** 467
[12] Stolterfoht N 1987 *Physics Reports* **146** 315
[13] Meyer F W, Overbury, Havener C C, Zeijmans van Emmichoven P A and Zehner D M 1991et *Phys. Rev. Lett.* **67** 723
[14] Limburg J, Das J, Schippers S, Hoekstra R and Morgenstern R 1994 *Phys. Rev. Lett.* **73** 786
[15] Ducrée J, Mrogenda J, Rockels E, Rüther M, Heinen A, Vitt Ch, Venier M, Leuker J and Andrä H J 1998 *Phys. Rev.* A **58** R1649
[16] Stolterfoht N 2003 Interaction of Hollow Atoms with Surfaces *The Physics of Multiply and Highly Charged Ions* vol 2 ed F J Currell (The Netherlands:Kluwer Academic Publishers) p 69
[17] Limburg J, Schippers S, Hughes I, Hoelstra R and Morgenstern R 1995 Phys. Rev. A **51** 3873
[18] Mann R, Folkmann F and Beyer H F 1981 *J. Phys.* B **14** 1161
[19] Chen M H 1985 *Phys. Rev.* A **31** 1449
[20] Chan M H and Crasemann B 1989 *Phys. Rev.* A **40** 2359
[21] Mack M and Niehaus A 1987 *Nucl. Instrm. Methods* B **23** 109