Charge changing cross sections in collisions of $^{18}\text{O}^{7+}$ with He at energies below 1 keV/u

K Ishii\textsuperscript{1}, A Itoh\textsuperscript{2} and K Okuno\textsuperscript{3}

\textsuperscript{1}Dept. of Physics, Nara Women’s University, Nara, 630-8506, Japan
\textsuperscript{2}Quantum Science and Engineering Center, Kyoto University, Kyoto, 606-8501, Japan
\textsuperscript{3}Dept. of Physics, Tokyo Metropolitan University, Minami-Ohsawa, Hachioji, 192-0397, Japan
E-mail: ishii@cc.nara-wu.ac.jp

Abstract. Single electron capture cross sections have been measured for collisions between $^{18}\text{O}^{7+}$ and He at energies from 1 eV/q to 1keV/q. Experimental cross sections are compared with those for H-like ions of $^{5}\text{C}^{5+}$ and $^{6}\text{N}^{6+}$ impacts. Cross sections for $^{5}\text{C}^{5+}$ and $^{7}\text{O}^{7+}$ are found to depend only weakly on the collision energy, while those for $^{6}\text{N}^{6+}$ vary rather strongly. By using a velocity-dependent classical over barrier model, the energy dependency is accounted for qualitatively.

1. Introduction
Electron capture cross sections of multiply charged slow ions such as $^{q}\text{C}^{q+}$, $^{q}\text{N}^{q+}$ and $^{q}\text{O}^{q+}$ are of great importance in plasma physics, astrophysics and thermonuclear fusion researches. Although a number of experimental data are available above 1 keV/u (see e.g., [1]), only a limited number of cross sections has been reported for lower incident energies. This is mainly due to experimental difficulties in producing low energy ion beams with sufficiently high intensities and narrow energy spreads. To overcome this problem, we established a mini-EBIS (Electron Beam Ion Source) apparatus combined with an Octopole Ion beam Guide, and charge-changing cross sections for various multiply charged slow ions have been measured extensively [2, 3]. It was found that single and double electron capture cross sections vary strongly depending both on the velocity and the charge state of the incident particles. The nature of this velocity dependence cannot be reproduced by a simple classical over barrier (COB) model [4, 5] in which electron capture cross sections are determined solely by the charge state of an incident ion. As described in our recent paper [3], a new formalism of the velocity dependent electron capture cross sections has been developed by adopting an induced dipole potential between collision partners, and experimental cross sections have been successfully examined with this model, referred to as modified COB model (MCOB).

In this work, we present new experimental cross section data for single electron capture by $^{7}\text{O}^{7+}$ ions in a He target at collision energies below 1 keV/u. Measured cross sections are compared with those for H-like projectile ions of $^{5}\text{C}^{5+}$ and $^{6}\text{N}^{6+}$. Velocity dependence of these cross sections is discussed with our MCOB model.
2. Experiment
The experiment was performed at the mini-EBIS atomic collision laboratory of Tokyo Metropolitan University. The experimental procedure has been described elsewhere [2].

In brief, projectile ions extracted from a mini-EBIS were focused and decelerated down to a required collision energy before entering an octopole ion beam guide which also contained a target collision cell. Primary and product ions were accelerated again and detected by an electromagnetic \( q/m \) analyzer. The energy spread of the primary ion beam was less than 1.0 eV/\( q \) at FWHM. Collision energies were determined by a potential difference between the ion source and the collision cell. The target gas pressure was low enough to ensure a single collision condition. Single electron capture cross sections \( \sigma_1 \) were obtained from initial growth curves of \( O^{7+} \) ions as a function of the target gas pressure. Double electron capture cross sections could not be measured due to low intensity of the primary ion beam. Experimental errors were about 30% at most. Present cross sections \( \sigma_1 \) are supposed to contain a contribution from double electron capture followed by autoionization.

3. Results and Discussion
Experimental data for single electron capture cross sections \( \sigma_1 \) are summarized in Table 1 and plotted by solid circles in Fig. 1, showing a good agreement with high energy data taken by Iwai et al [6]. Our previous data [3] for H-like \( N^{6+} \) and \( C^{5+} \) ions are also depicted for comparison. The velocity dependence of these cross sections is clearly different for the different projectile species. MCOB calculations for single electron capture cross sections are shown by solid lines. Since our experimental cross sections \( \sigma_1 \) include, to some extent, a TI contribution, double capture cross sections (dotted lines) are also calculated for comparison. It is seen that agreement between \( \sigma_1 \) and calculated values is attained only in a high energy region and the velocity dependence is completely different at lower energies. As one possible reason for causing these discrepancies at low energies, we suppose that the transfer ionization (TI) due to double electron capture into autoionizing states plays a dominant role at low energies, since the TI process leads to the same final charge state as single electron capture process. More detailed discussion is given below by means of a level-overlap consideration between energy window functions and actual energy levels of these ions.

The MCOB model was developed to obtain velocity dependent cross sections. The collision

| Collision energy (eV/\( q \)) | Cross section (10\(^{-16}\)cm\(^2\)) |
|-------------------------------|----------------------------------------|
| 0.5                           | 22.6                                   |
| 1.0                           | 20.2                                   |
| 2.0                           | 22.6                                   |
| 5.0                           | 24.1                                   |
| 10                            | 26.8                                   |
| 20                            | 27.9                                   |
| 50                            | 26.0                                   |
| 100                           | 22.2                                   |
| 200                           | 19.4                                   |
| 500                           | 14.8                                   |
| 1000                          | 17.0                                   |

Table 1. Single electron capture cross sections for \(^{18}O^{7+}\) + He.
Figure 1. Single-electron capture cross sections for $^{18}\text{O}^{7+}$ + He in comparison with $^{14}\text{N}^{6+}$ and $^{12}\text{C}^{5+}$ + He [3]. Solid and broken lines are single- and double-electron capture cross sections calculated by the modified classical over barrier model.

dynamics of the potential barrier formed by collision partners is taken into consideration [3]. Furthermore, the model uses the electron transition probabilities calculated from energy window functions determined by using energy levels of excited states of both projectile and target ions [7]. The energy window function is expressed by a Gaussian distribution peaking at the perturbed binding energy of the electron-capturing state of the projectile ion. The width of the distribution is determined from the uncertainty of potential barrier height formed during a collision and is approximately proportional to the incident ion velocity. The target electrons are numbered separately according to the ionization potential $I_i$ of each electron. Namely, in case of He, the first electron with $I_1 = 24.58$ eV is called ‘outer’ electron and the second one ($I_2 = 54.4$ eV) is called ‘inner’ electron hereafter.

Figure 2 shows such energy window functions calculated at 100 eV/u for $^{18}\text{O}^{7+}$, $^{14}\text{N}^{6+}$ and $^{12}\text{C}^{5+}$ collisions with He. Solid and dotted lines correspond respectively to energy windows of single and double electron capture collisions and will be denoted by $F_1$ and $F_2$, respectively. The energy window $F_1$ is composed of two peaks arising from the outer (left peak) and the inner (right peak) electron of He. Note that the binding energy of the active electron is assumed in the COB model to be perturbed by coulomb attraction forces from both projectile and ‘charged’ target particles (see Eqs. (2)–(7) in Ref. [3]). Comparison between $F_1$ and actual energy levels reveals that the left peaks (outer electron) of $F_1$ overlap with energy levels of $^{18}\text{O}^{6+}(1s3l)$ and $^{12}\text{C}^{4+}(1s3l)$, and the right peaks (inner electron) with $^{18}\text{O}^{6+}(1s3l)$ and $^{14}\text{N}^{5+}(1s3l)$ within their distribution widths. On the contrary, there is no such overlap between $F_1$ and $^{12}\text{C}^{6+}(1s3l)$. As the distribution width becomes smaller with decreasing velocity, capture cross sections $\sigma_1$ are predicted to decrease at low energies. Rapid decrease of both calculated and experimental values of $\sigma_1$ for $^{16}\text{O}^{6+}$ reflects fairly well this characteristic.

As for double electron capture $F_2$, MCOB calculation was made for a Li-like configuration.
The total ‘perturbed’ binding energies of two electrons captured from He are calculated to be 128eV, 121eV and 113eV for O$^7+$, N$^6+$ and C$^5+$, respectively. These values are the sum of peak energies of the inner (∼80eV) and the outer (∼40eV) electrons as shown in Fig. 2. The energy windows $F_2$ obtained in this way are compared in Fig. 2 with doubly exited energy levels of (1snln')$^-$ [7].

It is seen that $F_2$ overlaps with O$^7+(1s3l'3l')$ slightly, N$^6+(1s3l'3l')$ largely and C$^5+(1s2l'3l')$ slightly. Together with the consideration about inner electron capture in $F_1$, it can be stated safely that the double electron capture leads to the formation of doubly excited states rather strongly for O$^7+$ and C$^5+$ impacts but only weakly for N$^6+$ impact. As most of such doubly excited Li-like states of light MCIs decay to He-like ions via autoionization (TI), apparent single electron capture cross sections are increased eventually. Flat behaviors of $\sigma_1$ observed for O$^7+$ and C$^5+$ impacts may be accounted for by this level-overlap consideration for single- and double-electron capture processes.

In conclusion, single electron capture by slow H-like O$^7+$ ions from He was investigated in comparison with other H-like C$^5+$ and N$^6+$ ions. Cross sections are found to exhibit rather flat behavior for C$^5+$ and O$^7+$, while for N$^6+$ they decrease rapidly with decreasing projectile velocity. Results of these velocity dependent characteristics were examined by level overlap consideration on the basis of the classical over barrier model. It is concluded that the level overlap consideration can reproduce qualitative energy dependences of electron capture cross sections of slow MCIs and more accurate energy levels of autoionizing doubly excited states should be taken into consideration to estimate cross sections accurately at very low incident energies.

**Acknowledgments**

This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

**References**

[1] Janev R K, Phaneuf R A and Hunter H 1988 *Atomic Data and Nucl. Data Tables* 40 249
[2] Okuno K 1986 *J. Phys. Soc. Japan* 55 1504
[3] Ishii K, Okuno K and Itoh A 2004 *Phys. Rev. A* 70 042716 and references therein
[4] Ryufuku H, Sasaki K and Watanabe T 1980 *Phys. Rev. A* 21 745
[5] Niehaus A 1986 *J. Phys. B: At. Mol. Opt. Phys.* 19 2925
[6] Iwai T et al 1982 *Phys. Rev. A* 26 105
[7] WWW homepage of the NIST Atomic Spectra Database (http://physics.nist.gov/)