Energy gain spectroscopy of multiply charged light ions in collisions with hydrogen at 50 eV/u

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Abstract. We have measured energy gain spectra for single-electron capture collisions of He-like C, N and O ions with H2 at 50 eV/u. Energy gain spectra were examined with energy gain functions calculated from a classical over barrier model, and we obtained fairly good agreement between experimental and calculated results. We find that single electron capture occurs predominantly for C4+ and O6+ ions, while for N5+ ions double electron capture followed by transfer ionization is the dominant process in the formation of N3+ ions.

1. Introduction
Study of collision dynamics of multiply charged ions (MCI) with atoms and molecules is important in atomic physics and in various applied fields such as astrophysics and fusion plasma researches. In particular, charge-changing collisions of carbon, nitrogen and oxygen ions with H2 have been extensively studied so far because of their practical importance in thermonuclear fusion researches (see e.g., [1, 2] and references therein). It is known that a slow MCI captures target electrons into particular excited states and deexcites by photon or electron emission. Excited states of a projectile ion, into which electrons are captured, are usually predicted fairly well by a classical overbarrier model [3, 4], and experimentally the energy gain spectroscopy has often been used to identify the excited states (see e.g., [5, 6] and reference therein). Single and double electron capture collisions between a multiply charged ion Aq+ and H2 are written as

\[ A^{q+} + H_2 \rightarrow A^{(q-1)+}(nl) + (H_2)^+ + Q, \quad \sigma_{q,q-1} \]

\[ \rightarrow A^{(q-2)+}(nln'l') + (H_2)^{2+} + Q, \quad \sigma_{q,q-2}, \]

where \( \sigma_{q,q-1} \) and \( \sigma_{q,q-2} \) are the single and double capture cross sections, respectively, and \( nl(n'l') \) stands for the capture state, and \( Q \) the reaction energy of the collision. In case of double electron capture, a doubly excited state \( (nln'l') \) may be stabilized by photon or electron emission as expressed by,

\[ A^{(q-2)+}(nln'l') \rightarrow A^{(q-2)+} + h\nu, \quad \sigma_{TDC} \]

\[ \rightarrow A^{(q-1)+} + e^-, \quad \sigma_{TI}. \]
Figure 1. Single- and double-electron capture cross sections of C$^{4+}$, N$^{5+}$ and O$^{6+}$ in collisions with H$_2$. Solid and open circles are total single- and double-electron capture cross sections, respectively. Open squares are state-selective single-electron capture cross sections by Lubinski et al [10].

Hence, in the latter process, a temporarily formed A$^{(q-2)+}$ ion is observed as an A$^{(q-1)+}$ ion experimentally. Here, cross sections $\sigma_{TDC}$ and $\sigma_{TI}$ correspond to ‘true double electron capture (TDC)’ and transfer ionization (TI), respectively. For convenience, we denote $\sigma_1 = \sigma_{q,q-1} + \sigma_{TI}$ and $\sigma_2 = \sigma_{q,q-2} - \sigma_{TI}$ as experimentally measured total cross sections for single and double electron capture, respectively.

Recently, we developed a RF-induced-ion beam guide technique combined with our mini-EBIS (electron beam ion source) system [7, 8] and carried out collision experiments of MCI’s in a wide energy range from keV/u down to 0.1 eV/u. As examples [9], electron capture cross sections $\sigma_1$ and $\sigma_2$ measured for He-like C, N and O ions in collisions with H$_2$ are shown in Fig. 1, where state-selective capture cross sections $\sigma_{\Sigma nl}(n = 3, 4)$ obtained by [10] are also plotted for comparison. Figure 1 shows clearly that the values of $\sigma_1$ for C$^{4+}$ and O$^{6+}$ ions are respectively almost the same as $\sigma_{\Sigma nl}$ and $\sigma_{\Sigma hl}$, implying that single electron capture occurs predominantly into excited states of $n = 3$ and 4, respectively. Furthermore, equivalent magnitude between $\sigma_1$ and $\sigma_{\Sigma nl}$ implies that transfer ionization resulting from double electron capture is negligibly small for C$^{4+}$ and O$^{6+}$ ions. As for N$^{5+}$ ions, however, experimental values of $\sigma_1$ are significantly larger than $\sigma_{\Sigma hl}$ at incident energies below 500 eV/u, and above this energy both cross sections become identical with increasing energy. These results indicates evidently that N$^{4+}$ ions are produced predominantly via a TI process at energies below 500 eV/u and relative importance between pure single electron capture ($\sigma_{q,q-1}$) and TI ($\sigma_{TI}$) changes strongly as a function of the
Figure 2. Upper part of figures are measured energy gain spectra of C$^{4+}$, N$^{5+}$ and O$^{6+}$ in collisions with H$_2$ at 50 eV/u. Estimated energy gain spectra calculated from COB are also shown. Lower part are the energy window functions obtained from the COB model at 50 eV/u.

In order to understand these characteristics in more detail, we performed energy gain spectroscopy for He-like C, N and O ions at an incident energy of 50 eV/u. From energy spectra of outgoing projectile ions, singly excited states and doubly excited autoionizing states were estimated. Results are examined within the framework of the COB model.

2. Experiment
The experiment was performed using a Mini-EBIS atomic collision facility of Nara Women’s University. The Mini-EBIS is basically the same as established in Tokyo Metropolitan University [11]. A MCI beam extracted from the Mini-EBIS was crossed with an effusive target gas of H$_2$. It should be noted that no-extraction fields in collision region is possible to identify an energy of ions after collisions at low energies. Energy-to-charge ratios of outgoing projectile ions were measured by an electrostatic parallel plate analyzer with a 2D-position sensitive detector (PSD). Measurements were made with an ion pass energy of 200 eV/q and an energy resolution of about 1/100 was attained. All signals of PSD in a single collision event were directly recorded by a PC though digitizers.

3. Results and Discussion
Energy gain spectra obtained for single electron capture collisions of C$^{4+}$, N$^{5+}$ and O$^{6+}$ in H$_2$ are shown in the upper part of figure 2. It is noted that, for N$^{5+}$ and O$^{6+}$ incidences, the energy width of projectile ions was increased to make measurements in good statistics, and it leads to boarder peak profiles compared to the C$^{4+}$ incidence as seen in the figure.

The lower part of the figure shows energy window functions obtained from the COB model. In this model, electron capture channels from H$_2$ are designated by strings (1, 0), (0, 1) and (1, 1), where the former two strings correspond to single electron capture and the last one to double electron capture. Two electrons of H$_2$ are treated separately according to their different ionization potentials; $I_1 = 16$ eV and $I_2 = 35$ eV. The string (1, 0) implies that the outer
electron is captured and the inner electron escapes from capture, and so forth. The energy window function is a Gaussian distribution with a peak located at a perturbed binding energy of the capturing state of the projectile ion, and the width of the distribution is determined from the uncertainty of the potential barrier height. For more details, readers should refer to [4].

By comparing energy window functions of outer and inner electrons (solid lines) with actual energy levels [12] of C$^{3+}$, N$^{4+}$ and O$^{5+}$, it is found that the dominant channels for single electron capture are C$^{3+}$ ($n = 3$), N$^{4+}$ ($n = 4$) and O$^{5+}$ ($n = 4$), being consistent with the results of Lubinski et al. shown in figure 1. Similarly, as for double electron capture (dotted lines), the dominant channels may be C$^{2+}$ (2$^l 3l$), N$^{3+}$ (3$^l 4l$) and O$^{5+}$ (3$^l 4l$), respectively.

Using these energy window functions and binding energies of both projectile and target particles, we calculated energy gain functions to reproduce the experimental spectra. We assumed that the energy gain function is also a Gaussian distribution with a peak calculated by binding energy of both projectile and target. The magnitude of the function is evaluated by the degree of level-overlap between an energy window and actual energy levels, and the width of the function is determined from an energy width of primary ion beam. Calculated results are compared in the upper part of the figure. One can see that our calculated spectra are in good agreement with experimental results. The results of calculated energy gain functions indicate that a predominant channel is (1, 0) for C$^{4+}$ and O$^{6+}$, while it is (1, 1) for N$^{5+}$ incidences. Namely, single electron capture is the predominant process for C$^{4+}$ and O$^{6+}$, while double electron capture into autoionizing states is predominant in the collision system of N$^{5+}$ + H$_2$.

In conclusion, relative importance between single electron capture and double capture leading to transfer ionization was investigated by energy gain spectroscopy. It was found that energy gain spectra can be basically reproduced from energy window functions calculated from the COB model. To understand more precisely, high resolution measurements of energy gain spectra and coincidence measurements of fragment ions from target molecules are needed in the future.

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References

[1] Tawara H, Kato T and Nakai Y 1985 At. Data Nucl. Data Tables 32 235
[2] Janev R K, Phaneuf R A and Hunter H T 1988 At. Data Nucl. Data Tables 40 249
[3] Ryufuku H, Sasaki K and Watanabe T 1980 Phys. Rev. A 21 745
[4] Niehaus A 1986 J. Phys. B: At. Mol. Phys. 19 2925
[5] Ohtani S, Kaneko Y, Kimura M, Kobayashi N, Iwai T, Matsumoto A, Okuno K, Takagi S, Tawara H and Tsurubuchi S 1982 J. Phys. B: At. Mol. Phys. 15 L533
[6] Barat M and Roncin P 1992 J. Phys. B: At. Mol. Opt. Phys. 25 2205
[7] Okuno K 1986 J. Phys. Soc. Japan 55 1504.
[8] Ishii K, Itoh A and Okuno K 2004 Phys. Rev. A 70 042716
[9] Ishii K, Itoh A and Okuno K unpublished
[10] Lubinski G, Juhász Z, Morgenstern R and Hoekstra R 2000 J. Phys. B: At. Mol. Opt. Phys. 33 5275
[11] Kaneyasu T, Azuma T and Okuno K 2005 J. Phys. B: At. Mol. Phys. 38 1342
[12] WWW homepage of the NIST Atomic Spectra Database (http://physics.nist.gov/)