Coster-Kronig electrons from $N^{q+}$ ($q$=1-3) and $O^{q+}$ ($q$=1,2) Rydberg states produced in high-energy collisions with He

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Abstract. Coster-Kronig (C-K) electrons ejected through autoionization decay of high-Rydberg states in high-energy collisions of $N^{q+}$ ($q$ = 1-3) and $O^{q+}$ ($q$ = 1,2) with He have been measured with high resolution by using zero-degree electron spectroscopy. Autoionizing lines are observed corresponding to decays from $1s^22p(^P)nl$ Rydberg states for 21 MeV $N^{3+}$ + He, from $1s^22s2p(^P)nl$ Rydberg states for 21 MeV $N^{2+}$ + He and from $1s^22s2p(^P)nl$ Rydberg states for 14 MeV $N^+$ + He, respectively. Angular momentum distributions of these three series of C-K decaying Rydberg states for $N^{q+}$ ($q$ = 1-3) projectiles are also discussed, where the highly excited states are formed by single-electron excitation. Similarly, series of the autoionizing Rydberg states are observed for two charge states of incident O ions. The C-K spectra observed can be assigned to decays from $1s^22s2p(^P)nl$ states for 30 MeV $O^{2+}$ + He and from $1s^22s2p(^S)nl$ states for 15 MeV $O^+$ + He.

1. Introduction
Beryllium is the simplest atom with two closed shells. However, compared to helium it has only been studied marginally. Be-like ions are also interesting to the theorists and experimentalists continuously. Due to their relative simplicity, this four-electron system is an excellent test case for atomic theory as it can be treated in a rigorous manner [1-3]. It is still a labor to study a large amount of various states of Be-like ions [1,4,5]. The Coster-Kronig (C-K) transitions for Be-like N, O, Si, S and Ar ions in high-energy collisions with He-gas and C-foil targets have been widely investigated experimentally and theoretically by our group [6-12]. Furthermore, it is well known that multiply charged ions of low-Z elements such as carbon, nitrogen, and oxygen are important species existing in the terrestrial atmosphere, in the interstellar medium, as well as in the envelopes of many stars. In the present study, we have systematically studied high-resolution C-K electron spectra from high-Rydberg states.
produced in Be- to C-like N\textsuperscript{q+} projectile ions (q = 1-3) in high-energy collisions with He, where the highly excited states were formed by single-electron excitation. We also present the first measurements for C-K electron spectra from high-Rydberg states produced in high-energy collisions of O\textsuperscript{q+} (q = 1,2) with He for comparison with the collision system of N\textsuperscript{q+} (q = 1-3) + He and for extension of previous measurements for 32 MeV O\textsuperscript{q+} (q = 3,4) + He [11,13].

2. Experiment

The experiments were performed at the tandem accelerator facility at the Japan Atomic Energy Agency (JAEA) of Tokai, using the 20 MV tandem accelerator. The experimental setup has been presented before [6] so that only a brief outline is given here. The primary N\textsuperscript{q+} (q = 1-3) and O\textsuperscript{q+} (q = 1,2) ion beams were produced by using ECRIS installed at the high-energy terminal of the tandem accelerator [14], and then accelerated up to 14 MeV for N\textsuperscript{+} and 21 MeV for N\textsuperscript{q+} (q = 2,3) ions, and 15 MeV for O\textsuperscript{+} and 30 MeV for O\textsuperscript{2+} ions. The projectile beams passed through a He gas target under single collision conditions. The C-K electrons produced in the target cell were measured under an observation angle of 0° relative to the incident direction with a tandem-type 45° parallel plate electron spectrometer. The beam currents were 0.3–30 nA and were collected in the Faraday cup placed right after the spectrometer. All data were normalized to the same target pressure and ion fluence. The electron spectra presented here are transformed from the laboratory into the projectile rest frame.

3. Results and discussion

3.1. Angular momentum (l) distribution for Coster-Kronig spectra of Be-, B- and C-like N\textsuperscript{q+} (q = 1-3)

We have measured for the first time Coster-Kronig electrons ejected form high-Rydberg states produced in high-energy collisions of N\textsuperscript{q+} (q = 1-3) + He [12]. In such high-energy collisions using a He target, the ejected electron spectrum is expected to be pure and simple as the “needle ionization” is realized. There, we have calculated the C-K electron energies by using following equation,

\[ E_n = \Delta E - \frac{Q}{R} \left( n^2 - \mu^2 \right), \]

where \( E_n \) is the C-K electron energy, \( n \) is the principal quantum number, \( \Delta E \) is the energy difference between the initial and final states of the ion core configuration, taken from the compiled transition energy tables [15], \( Q \) is the effective charge of the ion core (assumed to be \( q+1 \) for this case), and \( R_l \) is the Rydberg energy (13.606 eV). It has been found that the C-K spectra for N\textsuperscript{q+} projectiles (q = 1-3) show some structures reflecting the \( l \) distributions in the low-energy side of the C-K electron energies calculated by using equation (1).

In the present study, the kinetic energies of C-K electrons from initial levels, \( 1s^22p(l^p)n_l \), \( 1s^22s2p(l^p)n_l \), and \( 1s^22s^22p(l^p)n_l \) are estimated with \( l \)-dependent version of the equation (1) including the quantum defect correction as following,

\[ E_{nl} = \Delta E - \frac{Q}{R} \left( n - \mu \right)^2, \]

where \( E_{nl} \) is the C-K electron energy, \( l \) is the angular momentum, and \( \mu \) is the quantum defect [16]. Figure 1 shows C-K electron spectrum obtained for 21 MeV N\textsuperscript{3+} + He. It is noted that the C-K transitions for \( n < 5 \) are energetically forbidden. In figure 1, the representative peaks are assigned to a decay series from \( 1s^22p(l^p)n_l \) (\( n = 5,6 \)) states. For high-energy collisions with gas targets such as H\textsubscript{2} and He, single-electron excitation/ionization process is dominant [17]. So, \( 1s^22p(l^p)n_l \) configurations are produced by single-electron excitation of the \( 1s^22s2p(l^p) \) metastable state for Be-like N\textsuperscript{q+} ions, but not by double-electron excitation of the \( 1s^22s1s(l^s) \) ground state. The kinetic energies of \( 1s^22p(l^p)n_l \) and \( 1s^22p(l^p)n_l \) C-K electrons obtained using the quantum defect theory, i.e., equation (2) are indicated by the vertical bars in figure 1. The averaged energies of electrons emitted via C-K transitions \( 1s^22p5l – 1s^22s6l^d \) were calculated to be 0.236, 0.794, 1.233 and 1.298 eV for \( l = 0, 1, 2 \) and 3, respectively, by averaging the electron energies of \( 1s^22p(l_{1/2}, 2p_{1/2}) – 1s^22s(3s_{1/2}) \) for N\textsuperscript{q+} over \( J \) [15]. These values are qualitatively in agreement with the calculated ones by Glans et al. [18]. We obtained the averaged C-K electron energies for \( 1s^22p6l – 1s^22s6l^d \) to be 3.35, 3.67, 3.92 and 3.96 eV for \( l = 0, 1, 2 \) and 3,
respectively. By comparing the experimental and calculated results, we can identify the most intense peak to a low angular momentum state of the initial configuration 1s 2 2p
\(n_l\) \((n = 5, 6)\) with \(l = 1\), which obeys dipole selection rules. In the previous experiment, we have determined the C-K electron energies of the configurations 1s 2 2p6 \(l\) for 32 MeV O 4+ + He collisions and shown that the line due to the low angular momentum \(l = 1\) is the most intense [11]. On the other hand, Meyer et al. [19] have investigated the angular momentum \((l)\) distribution of the lines associated with the configurations 1s2 2p \(n_l\) \((n = 6, 7)\) for 30-105 keV O 6+ + He collisions and found that the lines due to the low angular momenta \(l = 0\) and 1 are rather weak and the maximum intensity is attributed to the high angular momentum states \(l \geq 2\). This was pointed out to be a Stark deformation of the Rydberg orbit by the Coulomb field of the receding ion in double electron capture (DEC) by low-energy highly charged ions [20].

Figure 1. Coster-Kronig electron spectrum from 1s 2 2p(3P)nl states. The vertical bars indicate energy positions calculated by equation (2).

![Figure 1. Coster-Kronig electron spectrum from 1s 2 2p(3P)nl states. The vertical bars indicate energy positions calculated by equation (2).](image1)

Figure 2. Coster-Kronig electron spectrum from 1s 2 2s 2p(3P)nl states. The vertical bars indicate energy positions calculated by equation (2).

![Figure 2. Coster-Kronig electron spectrum from 1s 2 2s 2p(3P)nl states. The vertical bars indicate energy positions calculated by equation (2).](image2)

Figure 3. Coster-Kronig electron spectrum from 1s 2 2s 2p(4P)nl states. The vertical bars indicate energy positions calculated by equation (2).

![Figure 3. Coster-Kronig electron spectrum from 1s 2 2s 2p(4P)nl states. The vertical bars indicate energy positions calculated by equation (2).](image3)
0, 1, 2 and 3, respectively. These energies agree qualitatively with the peak positions of 2.35, 2.75 and 3.3 eV, respectively, as seen in figure 2. Those for 1s²2s²p²l were determined to be 4.34, 4.62, 4.90 and 4.94 eV for \( l = 0, 1, 2, 3 \), respectively. In the case of N²⁺ ions, 1s²2s²pnl states, which are mainly populated in np and nd states, are formed by 2s – nl and 2p – nl transitions from the ground states of 1s²2s²p²(²P) and metastable states of 1s²2s²p²(⁴P), respectively. Spectrum in the low-energy region, where the 1s²2s²pnl \((n = 5,6)\) states contribute, shows that the peaks due to the angular momenta \( l \geq 2 \) are the most intense. This result for the \( l \) distributions is very similar to that for the high-energy collisions of O³⁺ + He [13], but different from those of dielectronic recombination (DR) processes [21].

Figure 3 shows C-K electron spectrum for 14 MeV N⁺ + He. The C-K electron energies for 1s²2s²p⁴(P)nl – 1s²2s²p²(P)el' \((n = 3-5)\) are obtained by using equation (2). In the figure, the representative peaks are assigned to decays of 1s²2s²p⁴(P)nl \((n = 3-5)\) states. It is noted that the C-K transitions for \( n < 3 \) and for \( l = 0 \) and 1 of \( n = 3 \) are energetically forbidden. Therefore, the line structure of the C-K transitions for \( n = 3 \) is rather simple and those for \( n = 4 \) and 5 show several structures between 1.5 and 5.0 eV. The averaged energies of electrons emitted via C-K transitions 1s²2s²p³l' – 1s²2s²p²l el' were determined to be 0.93 and 1.05 eV for \( l = 2 \) and 3 respectively. Those for 1s²2s²p⁴l and 1s²2s²p³l el' were determined to be 2.09, 2.85, 3.65 and 3.70 eV and 4.15, 4.50, 4.90 and 4.92 eV for \( l = 0, 1, 2 \) and 3, respectively, which are in agreement with the line structures of the Rydberg series seen in figure 3. For N⁺ ions, the spectrum for the 1s²2s²p⁵nl \((n = 4,5)\) states shows that the peaks due to the angular momenta \( l \geq 2 \) are the most intense, similar to the case for N²⁺ions.

3.2. Coster-Kronig spectra of C- and N-like O⁷⁺ \((q = 1,2)\)

Recently we have reported on Coster-Kronig electron spectra in high-energy collisions of 32 MeV O⁷⁺ \((q = 3,4)\) ions with a He gas target [11,13]. For Be-like O⁷⁺ ions, a series of 1s²2p⁴(P)nl – 1s²2s²(²S)el' \((n = 6-11)\) C-K transitions was assigned. The high-resolution spectrum for the 1s²2p6l states has shown that the peak due to the low angular momentum \( l = 1 \) is the most intense, which obeys dipole selection rules. This result for the \( l \) distribution has been found to be different from those of the DEC processes [19,22]. For B-like O⁷⁺ ions, a series of 1s²2p⁴(P)nl – 1s²2s²(²S)el' \((n = 5-11)\) C-K transitions was assigned. The sharp lines on both sides of the cusp peak have been confirmed to be due to the very low energy transition from the 1s²2s²p⁵(²P)5s state as suggested by Zouros et al. [23]. It is also found that states with the angular momenta of \( l = 0-3 \) are populated and the maximum intensity is attributed to the states with higher angular momenta \( l \geq 2 \). The C-K spectra were compared with those for the DR processes [21].

In the present study, we have systematically measured C-K electrons from high-Rydberg states produced in high-energy collisions of 30 MeV O²⁺ + He and 15 MeV O⁺ + He for comparison with the results for the collision system of N⁰⁺ \((q = 1-3)\) + He and for extending the investigation of C-K electron spectra past highly charged O⁰⁺ \((q = 3,4)\) ions. Figure 4 shows high-resolution spectrum of electrons ejected in the collision of 30 MeV O²⁺ ions with a He target. For this collision system, projectile O²⁺ ions have 6 electrons which are more than in the previous experiments for O³⁺ and O⁴⁺ ions. To our knowledge, there is no report on C-K electron spectra for such complicated collision systems. Indeed, figure 4 shows the complicated C-K electron spectrum from O²⁺ 1s²2s²p⁵nl states and other excited states which were produced by electron excitation/ionization processes during 30 MeV O²⁺ + He collision. Here, we calculate ejected electron energies arising from the possible C-K transitions using equation (1), where \( Q \) is the effective charge of the highly exited O²⁺ ion core (assumed to be +3 for this case) and the values of \( \Delta E \) are taken from the compiled transition energy tables [15]. In the figure, the representative peaks are assigned to a series of 1s²2s²p³(P)nl – 1s²2s²p²(P)el' \((n \geq 4)\) C-K transitions and vertical bars in figure 4 indicate the line positions obtained by equation (1). In this spectrum, the transitions to the \( ^3P_{1/2} \) and \( ^3P_{3/2} \) final states are not observed but some structures are recognized at each value of \( n \), to which the angular momentum \( l \) distribution should be responsible.
Figure 5 shows the measured electron spectrum resulting from the collisions of 15 MeV O\(^+\) ions on He. For this collision system, projectile O\(^+\) ions have 7 electrons which are even more than the above-mentioned collision system of 30 MeV O\(^{2+}\) with a He target. This figure shows the complicated C-K electron spectrum ejected from O\(^+\) 1s\(^2\)2s\(^2\)2p\(^3\)(S)\(n\)l states and other excited states which were produced by electron excitation/ionization processes during 15 MeV O\(^+\) + He collision. Here, we calculate ejection energies for the possible C-K transitions by using equation (1), where \(Q\) is the effective charge of the highly exited O\(^+\) ion core (assumed to be +2 for this case), adopting the values of \(\Delta E\) given by Ref. [15]. In the figure, the representative peaks are assigned to a series of 1s\(^2\)2s\(^2\)2p\(^3\)(P)\(l\)'\(n\) \(\geq 3\) C-K transitions and vertical bars indicate line positions obtained by equation (1). In this spectrum, difference among the transitions to final \(^3\)P\(_0\), \(^3\)P\(_1\) and \(^3\)P\(_2\) states is not observed but structures in the peaks for each principal quantum number \(n \geq 3\), up to the series limit of 7.48 eV \(n \rightarrow \infty\), seem to reflect the angular momentum distribution. Moreover, some structures present in the higher energy region between 8.0 and 16 eV could be assigned to a series of 1s\(^2\)2s\(^2\)2p\(^3\)(D)\(n\)l \(n \geq 3\) C-K transitions, whose series limits are 14.88 eV and 17.65 eV, respectively.

4. Summary
We have performed high-resolution measurements for Coster-Kronig electron spectra from high-Rydberg states produced in collisions of 14-21 MeV N\(^{q+}\) \((q = 1-3) + \) He. It is found that the low angular momentum states of the initial configuration 1s\(^2\)2p\(^l\)(P)\(n\)l \(n = 5,6\) with \(l = 1\) are highly populated for N\(^{3+}\) projectile ions. It shows that the high-Rydberg states are produced by 2s – np electron excitation and these transitions obey dipole selection rules, which agrees with the results for O\(^{4+}\) projectile ions [11]. On the other hand, it is found that the states with higher angular momenta are populated in the cases of 1s\(^2\)2s\(^2\)2p\(^l\)(P)\(n\)l \(n = 5,6\) for N\(^{2+}\), and 1s\(^2\)2s\(^2\)2p\(^l\)(P)\(n\)l \(n = 4,5\) for N\(^+\) ions. High-Rydberg states are possibly produced by 2s – np and 2p – nd one-electron dipole excitation for N\(^{2+}\) and N\(^+\) projectile ions in ground state and metastable state configurations with more than one 2p electron, respectively. The 2p – nd transitions could contribute to increase the population of high angular momentum states. It is also suggested that both one-electron excitation processes from the metastable and ground states and decay processes from the high-Rydberg states play an
important role in the $l$ distribution for C-K electron spectra in high-energy collisions of $N^{q+}$ ($q = 1-3$) + He. We also report on the recent efforts to extend the measurements of C-K electron spectra in high-energy collisions of $O^{q+}$ ($q = 3,4$) + He to 15-30 MeV $O^{q+}$ ($q = 1,2$) + He. The C-K spectra observed can be assigned to decays from the $1s^22s2p^2(^3P)nl$ states for $O^{2+}$ ion and the $1s^22s2p(^1S)nl$ states for $O^+$ ions, respectively. However, a comprehensive analysis for high-resolution measurements of C-K electron spectra as well as precise theoretical calculations are needed to obtain more detailed information about the production of high-Rydberg states and their decay processes in the high-energy collision regime.

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