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Autoionization of N^{q+} ($q = 1-3$) Rydberg States Produced in High-Energy Collisions with He

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Abstract:

Energy spectra of electrons ejected through autoionization decay of high-Rydberg states in high-energy collisions of N^{q+} ($q = 1-3$) with He have been measured with high resolution by using zero-degree electron spectroscopy. Several series of autoionizing lines were observed, corresponding to decays from $N^{3+} 1s^2 2p(^2P)nl$ Rydberg states produced in $N^{3+} + \text{He}$ collisions, from $N^{2+} 1s^2 2s 2p(^3P)nl$ Rydberg states produced in $N^{2+} + \text{He}$, and from $N^+ 1s^2 2s 2p(^4P)nl$ Rydberg states produced in $N^+ + \text{He}$, respectively. Angular momentum distributions for the first or second peak of three series of C-K electron transitions for N^{q+} ($q = 1-3$) projectiles are also discussed, where the highly excited states are formed by electron excitation.

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1. Introduction

High-Rydberg states in low-energy highly charged ions are produced by electron capture processes, especially double electron capture (DEC). Most of the studies have been made on He-like projectiles such as C^{4+} , N^{5+} , O^{6+} and Ne^{8+} [1,2], where the Coster-Kronig (C-K) electrons from $1s^2 2pnl$ states were observed. It is found that similar high-Rydberg states are also produced by dielectronic recombination (DR) in Li-like projectiles such as B^{2+} , C^{3+} , F^{6+} , Ne^{7+} , Si^{11+} , Cl^{14+} and Ar^{15+} [3-8], where most of DR spectra have been measured with modest resolution. For high-energy collisions with He, such highly excited states are formed mainly by single-electron excitation of metastable $1s^2 2s 2p$ state for Be-like ions such as O^{4+} [9] and S^{12+} [10]. In these cases, the excited electron was found to occupy Rydberg state of the $1s^2 2pnl$ configuration with relatively low angular momenta, while in DEC process, Rydberg electrons with high angular momenta are produced. Recently, the DR spectra for Li-like and Be-like N ions have been observed with high resolution at heavy-ion storage ring [11,12]. The DR spectrum for Li-like $N^{4+} 1s^2 2s$, which recombines into Be-like $N^{3+} 1s^2 2pnl$ ($n \geq 5$) has been measured with high resolution at the heavy-ion storage-ring by Glans et al. [11]. The experimental DR spectrum is in agreement with the calculations and also with the optical values. It is also found that states with high angular momenta are produced in DR processes. Furthermore, they have measured DR processes of Be-like C^{2+} , N^{3+} and O^{4+} ions, which recombine into B-like C^+ , N^{2+} and O^{3+} ions [12].

In the present, we have measured C-K electrons from high-Rydberg states produced in 21 MeV $N^{3+} + He$ collisions with high resolution to compare with the DEC and DR data. By extending our

projectiles from Be-like N^{3+} to B-like N^{2+} and C-like N^+ ions, for the first time, we have systematically measured autoionization spectra from high-Rydberg states of four- to six-electron N ions with high resolution, where the highly excited states were formed by electron excitation/ionization. The measured spectra are also compared to our results obtained from 32 MeV O^{q+} ($q = 3,4$) + He [9, 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 primary N^{q+} ($q = 1-3$) 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^+ , and 21 MeV for N^{2+} and N^{3+} ions. With the tandem accelerator used in this experiment, it is not possible to accelerate N^+ ions at an energy higher than 14 MeV. As the detail of the experimental set up for zero-degree electron spectroscopy has been described before [15,16], only a brief outline is given here. The projectile beams passed through a He gas target cell under single collision conditions. Electron emission spectra were obtained at zero degree with respect to the beam axis with a tandem-type 45° parallel plate electron spectrometer [17]. The beam currents were 0.3~10 nA and were collected in the Faraday cup placed right after the spectrometer. All spectra were normalized to the same gas cell target pressure and ion charge.

3. Results and discussion

3.1. Coster-Kronig electron spectrum from 21 MeV $N^{3+} + He$ collisions

Fig. 1 shows a high-resolution energy spectrum of Coster-Kronig electrons ejected at zero-degree in 21 MeV $N^{3+} + He$ collisions, where the electron energy scale refers to the projectile rest frame transferred from the laboratory frame. In this figure, the representative peaks are assigned to a series of $1s^2 2p(^2P)nl - 1s^2 2s(^2S)\epsilon l'$ ($n = 5-10$) Coster-Kronig transitions. It is noted that the Coster-Kronig transitions for $n < 5$ are energetically forbidden. Vertical bars indicate line positions obtained by,

$$E_n = \Delta E - Q^2 R_y / n^2, \quad (1)$$

where E_n is the C-K electron energy, n is the principal quantum number, ΔE is the energy difference between the initial and final states of the ion core configuration, taken from the compiled transition energy tables [18,19], Q is the effective charge of the $N^{4+} 1s^2 2p(^2P)$ ion core (assumed to be +4 for this case), and R_y is the Rydberg energy (13.606 eV). In this case, ΔE is 9.9762 eV and 10.0082 eV, for $1s^2 2p(^2P_{1/2})$ and $1s^2 2p(^2P_{3/2})$ respectively.

The C-K spectra from the N^{3+} Rydberg states have been investigated in slow collisions of N^{5+} with He and H_2 , where the double electron capture (DEC) process played a major role [2]. A series of peaks below 10 eV has been measured with modest resolution and attributed to the decay of Rydberg configuration $1s^2 2pnl$ to $1s^2 2s\epsilon l'$ states. Recently, the dielectronic recombination (DR) spectrum for Li-like $N^{4+} 1s^2 2s$, which recombines into Be-like $N^{3+} 1s^2 2pnl$ ($n \geq 5$) has been measured with high resolution by Glans et al. [11]. The $1s^2 2p5l$ DR resonances in the energy range 0-1.6 eV were studied in detail showing good agreement with calculations and also with optical values. The main lines observed in the energy region of 1.2 - 1.35 eV were assigned to states with

high angular momenta ($l = 3$ and 4).

The first peak of the Rydberg series seen in Fig.1 is attributed to the configuration $1s^2 2p 5l$. It was measured to be about 0.8 eV. After the quantum defect theory, the kinetic energy of a C-K electron from an initial level, $1s^2 2p n l$, is estimated with the equation (1) including the quantum defect correction as following ,

$$E_{nl} = \Delta E - Q^2 R_y / (n - \mu_l)^2, \quad (2)$$

μ_l being the quantum defect [20], by averaging the energy difference ΔE of initial and final configurations of the ion core. The averaged energies of electrons emitted via C-K transitions $1s^2 2p 5l - 1s^2 2s \ell'$ were determined to be 0.236, 0.794, 1.233 and 1.298 eV for $l = 0, 1, 2$ and 3 , respectively, by averaging the transition energies of $1s^2 2p(^2P_{1/2}, ^2P_{3/2}) - 1s^2 2s(^2S_{1/2})$ for N^{4+} over J [18,19]. These values are qualitatively in agreement with the calculated ones by Glans et al. [11]. By comparing the experimental and theoretical data, we assign the most intense peak to a low angular momentum state of the initial configuration $1s^2 2p 5l$ with $l = 1$, which obeys dipole selection rules. In a previous experiment, we have determined the C-K electron energies of the configurations $1s^2 2p 6l$ for 32 MeV $O^{4+} + He$ collisions and shown that the line due to the low angular momentum $l = 1$ is the most intense one [9]. On the other hand, in the case of DEC, Stolterfoht et al. [21] investigated the angular momentum (l) distribution of the lines associated with the configurations $1s^2 2p 6l$ for 60 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 state $l \geq 3$. This was interpreted as due to angular momentum exchange between the two electrons involved in the double capture process [22]. For the peaks with $n > 5$ in Fig. 1, it is difficult to separate individual

lines with different angular momenta.

3.2. Coster-Kronig electron spectra from 21 MeV $N^{2+} + He$ collisions

Fig. 2 shows a high-resolution Coster-Kronig electron spectrum produced in 21 MeV $N^{2+} + He$ collisions, and the other terms are the same as Fig. 1. The autoionizing C-K spectrum for the five-electron system (in Fig. 2) is more complicated than that for the four-electron one (in Fig. 1). High-Rydberg states giving rise to autoionization decays are produced by single-electron excitation from the ground and metastable state N^{2+} ions, since the initial N^{2+} ion beam from the ECRTIS includes a considerable amount of metastable N^{2+} [$1s^2 2s 2p^2(^4P)$] component in addition to the major ground state N^{2+} [$1s^2 2s^2 2p(^2P)$] component. Two series of C-K electron energies for $1s^2 2s 2p(^3P, ^1P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ were calculated by using Eq. (1). In this figure, the representative peaks are assigned to a series of $1s^2 2s 2p(^3P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ ($n = 4-10$) Coster-Kronig transitions. It is noted that the Coster-Kronig transitions for $n < 4$ and for $l = 0$ and 1 of $n = 4$ are energetically forbidden. Therefore, the line structure of the C-K transitions for $n = 4$ is rather simple and that for $n = 5$ shows several structures between 2 and 3.5 eV. The line intensities of the series of $1s^2 2s 2p(^3P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ are high, however, it could be found that very weak transition lines for $1s^2 2s 2p(^1P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ are observed at higher energies than 8.341 eV, i.e., the series limit of $1s^2 2s 2p(^3P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ transition lines. For the $1s^2 2s 2p(^1P)nl - 1s^2 2s^2(^1S)\mathcal{E}'$ Rydberg states, the series limit is determined to be 16.204 eV [18,19].

The transition energies of $1s^2 2s 2p 5l$ C-K electrons which correspond to the second line structure of the Rydberg series seen in Fig. 2 are obtained using the quantum defect theory (Eq. (2)). The averaged energies of electrons emitted via C-K transitions $1s^2 2s 2p 5l - 1s^2 2s^2 \mathcal{E}'$ were

determined to be 2.38, 2.89, 3.34 and 3.43 eV for $l = 0, 1, 2$ and 3 , respectively, using the averaged transition energy of $1s^2 2s 2p(^3P_0, ^3P_1, ^3P_2) - 1s^2 2s^2(^1S_{1/2})$ for N^{3+} [18,19]. These energies are in good agreement with the peak positions of 2.4, 2.8 and 3.3 eV, respectively, as seen in Fig. 2.

Recently, Fogle et al. [12] presented the high-resolution DR spectrum for Be-like N^{3+} ions including the $1s^2 2s^2(^1S_0)$ ground state and the $1s^2 2s 2p(^3P_0)$ metastable state, which recombine into B-like N^{2+} ions. It is shown that the $1s^2 2s^2(^1S) - 1s^2 2s 2p(^1P)nl$ Rydberg series is intense and $1s^2 2s^2(^1S) - 1s^2 2s 2p(^3P)nl$ Rydberg series is weak for ground state ions and $1s^2 2s 2p(^3P) - 1s^2 2s 2p(^1P)nl$ Rydberg series for metastable state ions is very weak, which obeys the dipole selection rule. On the other hand, for high energy collisions, it is found that the autoionizing electrons from the high Rydberg $1s^2 2s 2p(^3P)nl$ states are most intense, which are produced via an electron excitation process of the $1s^2 2s^2 2p(^2P)$ ground state or the $1s^2 2s 2p(^4P)$ metastable-state projectile ions in collisions with He atoms. This result is very similar to the C-K electron spectra produced in 32 MeV $O^{3+} + He$ collisions [9,13].

3.3. Coster-Kronig electron spectra from 14 MeV $N^+ + He$ collisions

Fig. 3 shows a high-resolution Coster-Kronig electron spectrum produced in 14 MeV $N^+ + He$ collisions, and the other terms are the same as Figs. 1 and 2. This figure is expected to be the autoionizing electron spectrum from $N^+ 1s^2 2s 2p^2 nl$ and the other Rydberg states which were produced by electron excitation/ionization processes. However, the C-K electron spectra for six-electron C-like N^+ ions seem to be most complicated among the three different charge state of N^{q+} ($q = 1-3$) ions. We calculated four series of C-K electron energies for $1s^2 2s 2p^2(^4P, ^2D, ^2S, ^2P)nl -$

$1s^22s^22p(^2P)\mathcal{E}'$ by using Eq. (1). However, it could be found that very weak transition lines for $1s^22s2p(^2D, ^2S, ^2P)nl - 1s^22s^22p(^2P)\mathcal{E}'$ are observed at higher energies than 7.10 eV just after the series limit of $1s^22s2p(^4P)nl - 1s^22s^22p(^2P)\mathcal{E}'$ transition lines, though it could not be determined which series is dominant for this collision condition. The series limits of the $1s^22s2p(^2D, ^2S, ^2P)nl - 1s^22s^22p(^2P)\mathcal{E}'$ C-K transitions are 12.53 eV, 16.24 eV and 18.10 eV, respectively [18,19]. In the figure, a series of C-K electron energies obtained for $1s^22s2p(^4P)nl - 1s^22s^22p(^2P)\mathcal{E}'$ ($n \geq 3$) is indicated by bars. The values of C-K electron energies are calculated by assuming the effective charge of the $N^{2+} 1s^22s2p(^4P)$ ion core, Q to be +2, and ΔE to be that for $1s^22s2p(^4P_{3/2})$ which is 7.0977 eV because the values for $1s^22s2p(^4P_{1/2,5/2})$ which are 7.0903 and 7.1077 eV are close to the value for $1s^22s2p(^4P_{3/2})$ and it is difficult to separate each other in the present experiments. In the low electron-energy region of $n = 3$ and 4, i.e. below the electron energy of 4.0 eV, several structures are found on the spectrum, which suggests angular momentum distributions for the $1s^22s2p(^4P)3l$ and $4l$ states. It is noted that the Coster-Kronig 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 that for $n = 4$ shows several structures between 1.5 and 3.5 eV. The transition energies of $1s^22s2p(^4P)3l$ C-K electrons which correspond to the first line structure of the Rydberg series seen in Fig. 3 are obtained using the quantum defect theory, Eq. (2). The averaged energies of electrons emitted via C-K transitions $1s^22s2p^23l - 1s^22s^22p\mathcal{E}'$ were determined to be 0.925 and 1.05 eV for $l = 2$ and 3, respectively. The transition energies of $1s^22s2p(^4P)4l$ C-K electrons are also calculated using Eq. (2). The averaged energies of electrons emitted via C-K transitions $1s^22s2p(^4P)4l - 1s^22s^22p(^2P)\mathcal{E}'$ were determined to be 2.08, 2.84, 3.65 and 3.69 eV for $l = 0, 1, 2$ and 3, respectively,

which are in agreement with the second line structure of the Rydberg series seen in Fig. 3. From Figs. 2 and 3, it seems that the states with larger angular momentum are populated in the cases of $5l$ for N^{2+} and $4l$ for N^+ ions, respectively. For N^{2+} and N^+ ions in ground state or metastable state configuration with more than two 2p electrons, high-Rydberg states are possibly produced by $2s - nl$ or $2p - nl$ electron excitation, which enables them to increase population of high angular momentum.

Summary

For N^{q+} ($q = 1-3$) ion, autoionizing electron spectra of C-K transitions from high-Rydberg states are measured with high-resolution. The major transitions are assigned to a series of $1s^2 2p(^2P)nl - 1s^2 2s(^2S)\epsilon l'$ ($n \geq 5$) for N^{3+} , $1s^2 2s 2p(^3P)nl - 1s^2 2s^2(^1S)\epsilon l'$ ($n \geq 4$) for N^{2+} and $1s^2 2s 2p(^4P)nl - 1s^2 2s^2 2p(^2P)\epsilon l'$ ($n \geq 3$) for N^+ projectile ions, respectively. These three series of high Rydberg C-K electron spectra are observed for the first time. Angular momentum distribution for the first peak of three series of C-K electron transitions for N^{q+} ($q = 1-3$) ions is also discussed qualitatively, where the highly excited states are formed by electron excitation. Furthermore, measurements with higher resolution and with better statistics of autoionizing electron spectra of C-K transitions from high-Rydberg states is necessary.

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Figure Captions

Fig. 1. High-resolution Coster-Kronig electron spectrum ejected at 0° in collisions of 21 MeV N^{3+} on

He. Electron energy scale refers to the projectile rest frame.

Fig. 2. High-resolution Coster-Kronig electron spectrum ejected at 0° in collisions of 21 MeV N^{2+} on

He. Electron energy scale refers to the projectile rest frame.

Fig. 3. High-resolution Coster-Kronig electron spectrum ejected at 0° in collisions of 14 MeV N^+ on

He. Electron energy scale refers to the projectile rest frame.





