Resonant electron processes with open-shell highly charged ion targets

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Abstract. Recent activities at the Tokyo electron beam ion trap related to observations of resonant processes in the collisions of electrons with open-shell highly charged ions are reported. Extracted ion observations and high resolution x-ray spectroscopic observations have been applied to resolve the contribution from different charge states. In particular, dielectronic recombination (DR) of a H-like ion have been observed by high resolution x-ray spectroscopy for the first time. The DR satellite spectra obtained in the present experiment are compared with theoretical spectra.

1. Introduction
Resonant ionization and recombination are both initiated through capture of a free electron by a highly charged ion (HCI) while a bound electron is excited. The resultant unstable system may decay by photon emission: Dielectronic Recombination (DR), or by emission of two electrons due to successive autoionization: Resonant Excitation/Double Autoionization (REDA).

DR: \[ A^{q+} + e^- \rightarrow A^{(q-1)+} \rightarrow A^{(q-1)+} + h\nu . \]

REDA: \[ A^{q+} + e^- \rightarrow A^{(q-1)+} \rightarrow A^{(q-1)+} \rightarrow A^{(q+1)+} + e + e . \]

There have to date been few measurements of these processes reported involving change of principal quantum number for few-electron HCIs other than the well established DR measurements for closed-shell He-like systems made by x-ray observations with an electron beam ion trap (EBIT) (see Ref. [1] and references therein). Such measurements with an EBIT are usually performed using a Ge detector whose energy resolution is not sufficient to resolve x-rays from different charge states involved in the trap, so that most measurements to date have been performed for closed shell systems for which it is rather easy to concentrate the charge state.

Alternatively, measurements for open shell systems can be made efficiently by observing extracted ions [2] whose charge state can be easily separated with an analyzing magnet. Because
the charge state distribution should change suddenly at a DR resonant energy, one can study DR processes through the measurement of the ion count ratio between adjacent ions by keeping the system at the equilibrium while slowly varying the electron beam energy [3]. We used this technique to study $KLn$ DR processes for various open shell systems (e.g. Li-, Be-, B-, C-like ions for I, Ho, Bi, and so on) [4]. Using the same technique we have also made the first observation of REDA in Li-like highly charged heavy ions [5].

Another method to separate the contribution from different charge states is to improve wavelength resolution in x-ray observation. In principle, wavelength resolution can be easily improved by using a crystal spectrometer instead of a Ge detector. However, since the efficiency of a crystal spectrometer is much smaller than that of a Ge detector, few high resolution measurements have been performed to date. In this paper, we present the first high resolution x-ray observation of DR processes for a H-like ion. In DR of H-like ions, doubly excited He-like ions with two K-vacancies are produced. These doubly excited systems can decay, sequentially emitting two photons:

$$e+1s \rightarrow (nlnl') \rightarrow (1snl') + h\nu \rightarrow 1s^2 + h\nu + h\nu'$$.

The decay of such doubly excited states is not only important for the charge balance in hot plasmas but also is interesting because such a doubly excited state can be considered as the simplest ‘hollow’ atom; it will be very useful to test relativistic theories which treat the electron-electron interaction in many-electron systems.

2. Experiments

The present experiments were performed using the Tokyo EBIT [6, 7] with a flat crystal spectrometer [8]. The experimental procedure was similar to that used in our previous study [9]. Figure 1 shows the time sequence used in the present experiment to control the electron energy and the ion trap. H-like Fe was produced by keeping the electron energy at 14 keV (refered to as the ‘cooking energy’) for 300 ms. The electron energy was then quickly dropped to 5.5 keV and scanned with a triangular waveform between 5.5 keV and 4.3 keV, which cover the KLL resonant region. The scan was done only once for 0.5 ms, and then quickly returned to the cooking energy again. The electron energy was repeatedly switched between the cooking energy (7 ms) and the probe energy ramp (0.5 ms). Finally all the trapped ions were dumped to prevent accumulation of unwanted ions, and the above procedure was repeated again. Both the wavelength of emitted x-rays and the electron energy when the x-ray was detected were
recorded. Fe was continuously injected from an effusion cell [10] and the electron current was kept at 130 mA throughout the measurement.

3. Results and Discussion

Figure 2(a) shows the x-ray spectrum obtained by integrating the x-ray counts obtained for the electron energy range which corresponds to the KLL resonance energy of the He-like ion. Since the energy is lower than the direct excitation threshold, the spectrum does not contain any lines from the He-like ion; all the lines are from doubly excited states of Li-like ions produced through DR of He-like Fe.

Figure 3(a) shows the x-ray spectrum obtained by integrating the x-ray counts obtained for the electron energy range which corresponds to the KLL resonance energy of the H-like ion. Again, the spectrum shown in the figure does not contain lines originating from the direct excitation of H-like and He-like ions but contains only the lines originating from doubly excited He-like Fe produced through DR of H-like Fe. The manifold around 1.79 Å corresponds to the “first” photon ($2l'2l' \rightarrow 1s2l' + h\nu$), while that around 1.86 Å the “second” photon, ($1s2l' \rightarrow 1s^2 + h\nu'$). Each manifold contains several lines corresponding to the fine structure of the initial and final states.

Figure 2(b) and 3(b) show theoretical spectra obtained by convolving the theoretical resonant strengths with the experimental resolution. The theoretical resonant strengths were obtained by multi-configurational Dirac-Fock calculation. In order to obtain the second photon spectrum in Fig. 3, the branching ratio for the decay of $1s2p \quad ^3P_2$ was estimated from the radiative transition rate calculated by Lin et al. [11]. As seen in the figure, overall agreement is obtained between the theoretical and experimental spectra. However, some quantitative differences can be found in the intensity ratio.

It is noted that the experimental observation was done only at $90^\circ$ with respect to the electron beam and that the crystal spectrometer has polarization sensitivity, while the theoretical calculation does not include the polarization effects. Thus, the experimental and theoretical spectra can not be compared directly. We are planning to measure the polarization of the emitted photons using the double crystal technique [12]. The polarization measurements will also enable us to obtain the absolute resonant strength for each resonant state. The spectrum obtained at the cooking energy contains Ly-\(\alpha\) lines directly excited by the electron impact. By taking the time-averaged intensity ratio of the DR satellite lines to the Ly-\(\alpha\) lines and normalizing it to the excitation cross section of $2p$ states, the DR cross section for each line can be experimentally obtained.
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References

[1] Watanabe H, Currell F J, Kuramoto H, Li Y M, Ohtani S, O’Rourke B and Tong X M 2001 J. Phys. B 34 5095
[2] DeWitt D R, Schneider D, Clark M W, Chen M H and Church D 1991 Phys. Rev. A 44 7185
[3] Ali R, Bhalla C P, Cocke C L, Schulz M and Stockli M 1991 Phys. Rev. A 44 223
[4] Nakamura N, Tobiya H, Nohara H, Kato D, Watanabe H, Currell F J, and Ohtani S 2006 Rad. Phys. Chem. in press
[5] Nakamura N, Tobiya H, Nohara H, Kato D, Watanabe H, Currell F J and Ohtani S 2006 Phys. Rev. A 73 020705
[6] Currell F J, Asada J, Ishii K, Minoh A, Motohashi K, Nakamura N, Nishizawa K, Ohtani S, Okazaki K, Sakurai M, Shiraishi H, Tsurubuchi S and Watanabe H 1996 J. Phys. Soc. Japan 65 3186
[7] Nakamura N, Asada J, Currell F J, Fukami T, Hirayama T, Kato D, Motohashi K, Nojikawa E, Ohtani S, Okazaki K, Sakurai M, Shimizu H, Tada N, Tsurubuchi S and Watanabe H 1998 Rev. Sci. Instrum. 69 694
[8] Nakamura N 2000 Rev. Sci. Intrum. 71 4065
[9] Watanabe H, Kavanagh A P, Kuramoto H, Li Y M, Nakamura N, Ohtani S, O'Rourke B E, Sato A, Tawara H, Tong X M and Currell F J 2005 Nucl. Instrum. Methods B 235 261
[10] Yamada C, Nagata K, Nakamura N, Ohtani S, Takahashi S, Tobiya T, Tona M, Sakurai M, Kavanagh A P and Currell F J 2006 Rev. Sci. Instrum. 77 066110
[11] Lin C D, Johnson W R, and Dalgarno A 1977 Phys. Rev. A 15 154
[12] Beiersdorfer P, Vogel D A, Reed K J, Decaux V, Scofield J H, Widmann K, Hölzer G, Förster E, Wehrhan O, Savin D W and L. Schweikhard L 1996 Phys. Rev. A 53 3974