Production and Extraction of Highly Charged Ions from the Tokyo EBIT

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In the course of an experimental study on collisional processes of highly charged ions (HCIs), we developed a procedure to produce and extract HCIs with a very high charge-state for various kinds of heavy elements at the Tokyo EBIT (Electron Beam Ion Trap). The charge-state spectra of the extracted HCIs for some elements were measured using different EBIT operation conditions.

Keywords: highly charged ion (HCI), electron beam ion trap (EBIT), ion beam

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We have been using the Tokyo EBIT (Electron Beam Ion Trap) to perform a systematic study of the physics of highly charged ions (HCIs) to gain an understanding of atomic processes in hot plasmas [1]. The main subject at the initial stage of research was the spectroscopy of HCIs in the ion trap, but we have recently undertaken an atomic collision study using the extracted HCI-beams from the trap [2].

In the course of this research program, it became important to study the atomic processes of HCIs having a high q (charge state) and high Z (atomic number) relevant to fusion and astrophysics research. Therefore, we have made intensive efforts to develop methods to produce and extract such HCIs. In this report, we introduce recent experiments conducted on HCI-extraction at the Tokyo EBIT facility.

The EBIT device basically consists of three parts: an electron gun, an ion trap with three cylindrical tubes and an electron collector. The electron beam is compressed to a radius of 30 μm by a 4 T magnetic field generated by superconducting Helmholtz coils surrounding the ion trap region. After passing through the cylindrical tubes, electrons are decelerated and collected by the collector.

Neutrals or ions are injected into the trap from a gas cell or from a pulsed ion source. An electron beam with a high current density (about 5000 A/cm^2) then ionizes them successively in the trap. The HCIs produced are trapped radially by the space charge potential (~60 V) of the electron beam and axially by the voltage (~100 V) applied to the trap tubes. The electron beam also serves to excite the HCIs which are trapped. Radiation from the excited ions can be observed through the radial windows at the center tube. The HCIs can also be extracted through the collector by controlling the applied voltage to the trap tubes and introducing them to the HCI-beam lines.

We recently tested various kinds of methods for neutral gas injection through one of the radial windows into the trap region. When the vapor pressure of specific molecules are sufficiently high at room temperature, we injected such volatile molecular compounds as CH_3I or $W(CO)_6$ from a liquid cell and ionized them. Then we produced and extracted HCIs of I (Z = 53) or W (Z = 74) [3].

Although the principle for the production of HCIs in an EBIT is rather simple, there is no clear experimental evidence for the successive ionization of trapped ions, especially in a high q region for high Z elements. Therefore, in order to obtain a general guide explaining how an EBIT can produce high q-HCIs successively in time, and how an EBIT is expected to work, we have observed the time evolution of I^{q+} ions produced with the Tokyo EBIT. Figure 1 shows the time evolution of extracted HCI-intensities for I^{q+} ions from Ne-like (43+) to H-like (52+) ions with a continuous (leaky) extraction mode, at the electron beam energy (E_e) of 58 keV and the current (I_e) of 123 mA, which is considered to correspond to the growth behavior of HCIs produced inside the trap. At the time of t = 0, the electron beam begins to interact with the injected CH_3I molecules. Ne-like I ions are produced immediately, show the peak intensity, and decrease rapidly. Next, as time goes on, O-, C- and Be-like are produced succeedingly showing relatively slow temporal behaviors in the evolution. The evolution curves for the He- and H-like ions show slow

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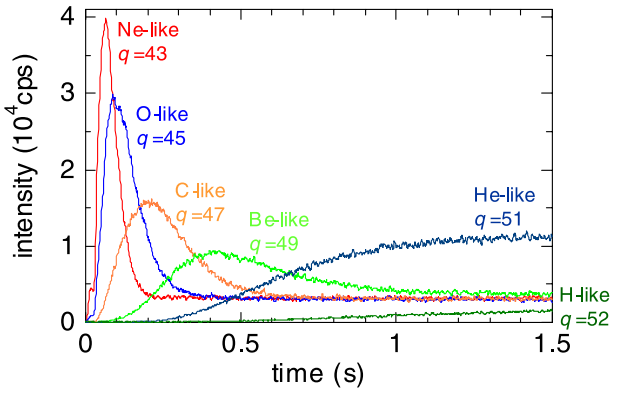

Fig. 1 Time evolution of extracted I ions (from Ne- to H-like) from the Tokyo EBIT with E_e = 58 keV and I_e = 123 mA.

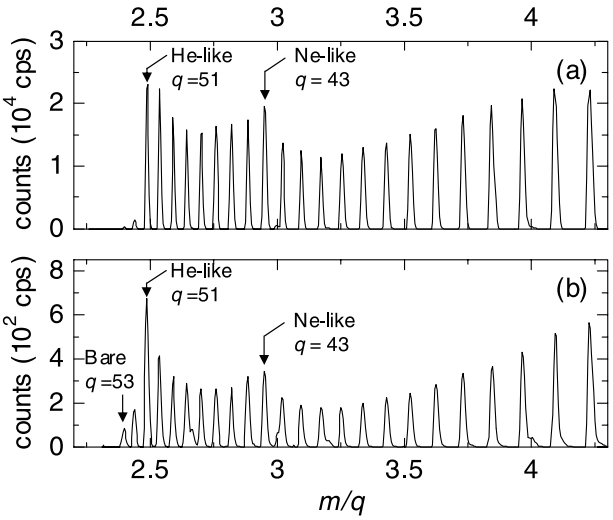

Fig. 2 Charge-state spectra of extracted I ions produced by the EBIT with different operations (a) E_e = 48 keV, I_e = 132 mA and (b) E_e = 91 keV, I_e = 184 mA.

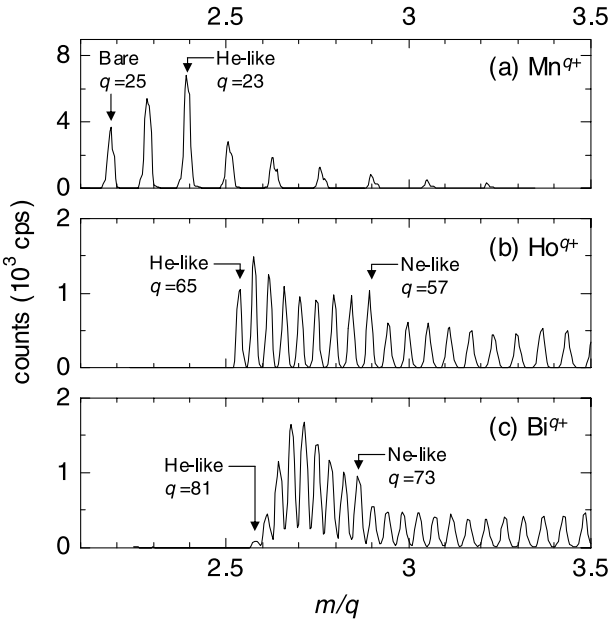

Fig. 3 Typical example of extracted metallic ions: (a) Mn^{q+} (Z = 25), (b) Ho^{q+} (Z = 67) and (c) Bi^{q+} (Z = 83). These elements were injected into the EBIT by the K-cell. The operation conditions of the EBIT were (a) E_e = 58 keV, I_e = 125 mA, (b) E_e = 63 keV, I_e = 128 mA and (c) E_e = 63 keV, I_e = 132 mA.

growth rates and do not have the peaks. The present characteristics of the time evolution are strongly dependent on EBIT operation parameters such as E_e, I_e and the injected amount of gas molecules, which show qualitative agreement with the calculated evolution curves [4].

We show next in Fig. 2 the charge-state distribution of continuously extracted I^{q+}, measured with a sector-type analyzing magnet. The extraction voltage in the present study is 3 kV. Iodine is a convenient element which has a single natural isotope with the atomic mass (m) of 129, which makes the m/q spectra clear. In this figure, the two m/q spectra of the extracted I^{q+} ions are shown for different E_e, (a) 48 keV and (b) 91 keV. The absolute intensity of these spectra cannot be compared with each other because of the different experimental conditions mainly due to the extraction efficiency; the present efficiency at E_e = 91 keV is much lower than that at E_e = 48 keV. There is a significant difference in the relative abundance of HCIs, that is, in the operation with E_e = 91 keV very highly charged ions such as bare, H- and He-like I appear clearly and dominantly in the extracted m/q spectrum, which is different from the distribution with E_e = 48 keV.

For another injection method, we have recently tested a Knudsen effusion cell (K-cell) [5]. Most of the metallic elements can be injected as a nozzle gas into the trap, since the present K-cell can be heated up to about 1300 °C. Figure 3 shows typical examples of the extracted m/q spectra for Mn (Z = 25), Ho (Z = 67) and Bi (Z = 83), which are injected as metal vapor from the K-cell. In the present observation, the EBIT operation conditions to produce HCIs are approximately similar to each other. As seen in Fig. 3, bare to He-like ions are predominantly produced in the trap and extracted for Mn which is a relatively low Z element, while, for high Z elements such as Ho and Bi, dominant species in the extracted ions are from Ne-like to He-like ions, which is reasonable in consideration of the present E_e and I_e.

In summary, it was confirmed that the Tokyo EBIT could produce high q HCIs of any element in the periodic table in principle through the present development for the injection methods into the ion trap.

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