High energy operation of the Tokyo-electron beam ion trap/present status

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We are using the Tokyo electron beam ion trap (Tokyo-EBIT) to study a wide range of the physics of highly charged ions. Transition wavelengths have been investigated using visible and x-ray spectroscopy. The charge-state distributions of the extracted ions from the trap are shown for the different experimental conditions. Ionization cross sections are measured by observing the time dependence of the charge state evolution in the extracted ions. A brief introduction of the recent studies is given. [S0034-6748(00)52302-8]

I. INTRODUCTION

Based on the development of the electron beam ion source (EBIS),[1] the first electron beam ion trap (EBIT) was constructed by Levine *et al.*[2] At the present, several EBITs are operated in the world.

An EBIT is a device for producing and trapping very highly charged ions (HCIs) within the ion trap region with a small volume, which has been mainly used for spectroscopic studies to investigate the relativistic and QED effects in simple atomic systems and to obtain useful data for the research of fusion and astrophysical plasmas.[3] Recently, HCIs have been extracted to use as projectiles for various atomic collision researches such as ion-atom and surface collisions.[4]

The maximum electron beam energy and the electron beam current of the Tokyo-EBIT[5–7] is designed to be 340 keV and 300 mA with a magnetic field of 4.5 T. The present highest energy of the beam without the insulation outside the vacuum system is approximately 100 keV. A SF_6 insulation system has been constructed in order to reach the maximum parameters.

In this article, we show the typical charge-state distribution of the HCIs extracted from the source and the recent activities of the experimental research with HCIs produced with the Tokyo-EBIT.

II. CHARGE DISTRIBUTIONS OF EXTRACTED IONS

In the course of the research program with the Tokyo-EBIT, various kinds of atomic collision experiments are planned, such as measurements of electron impact ionization cross sections of HCIs and investigations of the HCI interaction with matter. In order to design these experiments, an extraction system has been constructed.

The charge-state distributions of extracted HCIs have been observed as functions of operational parameters with the Tokyo-EBIT. There are two types of extraction methods: continuous and pulsed mode. Figure 1 shows typical charge-state distributions for highly charged krypton ions with different experimental conditions. The intensity distribution of charge analyzed krypton ions is shown in Fig. 1(a) for the electron beam energy of 25 keV, and current of 100 mA. This spectrum was taken with the continuous extraction mode. The charge-state spectra with the pulsed mode are shown in Figs. 1(b) and 1(c) at the beam energy of 25 and 48 keV with the same current of 100 mA.

As shown in these figures, the charge-state distributions of extracted ions are different between the continuous and pulsed mode. The ions are trapped radially due to the space charge of the electron beam and also in the axial potential

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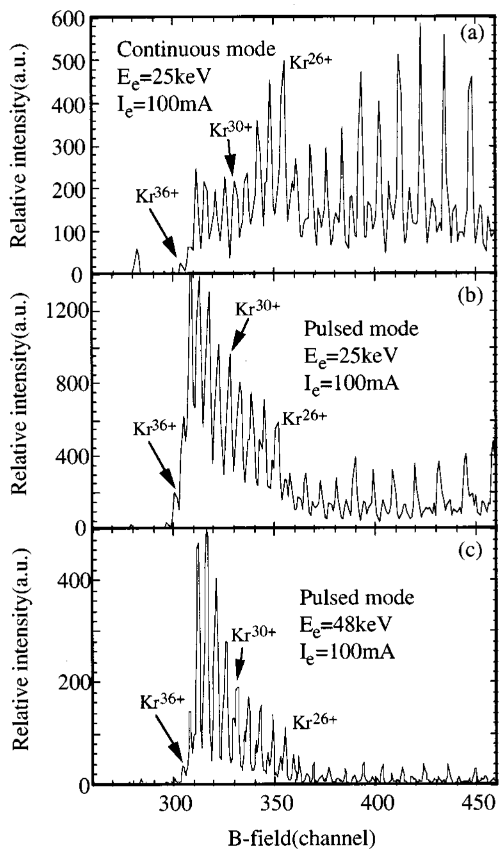

FIG. 1. Measured spectrum of charge analyzed krypton ions taken in the continuous and pulsed modes. In the pulsed mode, the width of extraction pulse is 100 ms.

applied to the drift tubes. The trapping efficiency is approximately proportional to the charge of the trapped ions. As seen from Fig. 1(a), ions with lower charge states easily evaporate out of the trap than the ions with higher charge states. In the pulsed mode, higher charged ions that are efficiently trapped are forced out of the trap by raising the potential applied to the center drift tube, resulting in a larger population of those ions in the charge-state distribution. As can be seen in Figs. 1(b) and 1(c), the population of higher charged ions becomes larger at the high energy operation of the electron beam.

III. RECENT ACTIVITIES

A. X-ray and visible spectroscopy

Because ions in the neonlike sequence have closed shell structure, their abundance is high in high temperature plasmas. Therefore, the neonlike ions can be used for many kinds of applications, such as x-ray lasers and plasma diagnostics. In particular, the study of atomic structure for neonlike ions is very important for x-ray laser modeling. From the view point of atomic physics, highly charged neonlike ions are interesting elements since the excited states contain strong configuration mixings in those characters. Therefore, the systematic study for neonlike ions is also important to understand the atomic system in the relativistic region. We have made the systematic observation of x-ray transitions for various kinds of neonlike ions.[8] Neonlike ions were produced and trapped in the Tokyo-EBIT. Ions are trapped in a 3 cm long region and excited by a 60 μm diam electron beam. Consequently, an x-ray emitter from the EBIT represents a line source whose width corresponds to an entrance slit of the spectrometer.[9] The spectrometer consisted of a flat LiF(200) crystal and a position sensitive proportional counter (PSPC). The wavelength for several $n=3-2$ transitions have been determined and compared to theoretical calculations with the multiconfigurational Dirac–Fock method. The calculations reproduce the experimental values quite well. In addition to the above observation, the systematic studies for investigations of x-ray transitions in highly charged atomic systems are planned and partly begun.

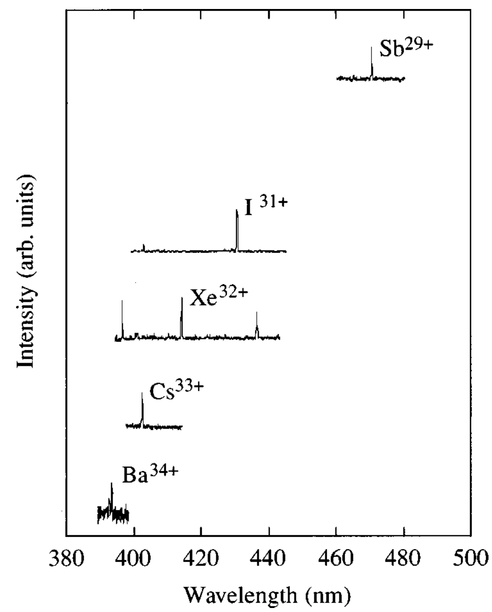

FIG. 2. The visible spectra of the highly charged Sb, I, Xe, and Ba ions.

Forbidden lines play an important role in the diagnostics of high temperature plasmas. Because of the long wavelengths of the forbidden lines, Doppler profiles can be easily measured to determine the ion temperatures of the plasmas. Feldman *et al.*[10] reported that their preliminary calculations showed an interesting behavior in wavelengths of the $M1$ transitions between ground-state fine structure levels: $(3d^4)_{J=3}$ and $(3d^4)_{J=2}$ of the titanium sequence. The wavelengths were predicted to be almost constant for HCIs with a wide range of the atomic number. In the course of the spectroscopic studies, systematic investigation has been performed using the Tokyo-EBIT to determine the wavelengths of the titaniumlike ions in the visible region. In these measurements, the EBIT was operated with the electron beam energy of about 2.2 keV and the current of 25 mA.

Figure 2 shows a set of spectra for the $M1$ transitions in the titanium-like Sb(Z=51), I(53), Xe(54), Cs(55), and Ba(56) ions. The calculations of these transitions were also made using the multiconfigurational Dirac–Fock method (GRASP92 code[11]).[12] Agreement between the present experiments and the calculations is very good.

Presently, we are preparing an echelle visible spectrometer with large spectral range and high resolution. This might

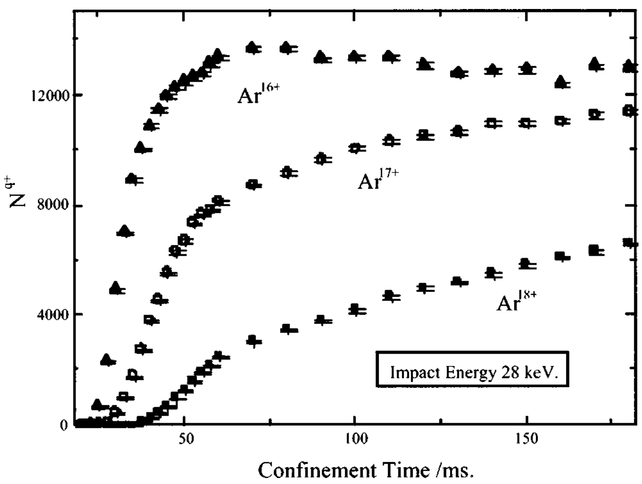

FIG. 3. Onsets for the appearance of Ar^{16+}–Ar^{18+}

be useful for measurements such as hyperfine structure transitions for hydrogenlike ions.

B. Ionization cross section measurement

Electron impact ionization is an important process in the physics of highly charged ions. Experimental determination of these cross sections has applied relevance, for example in plasma physics, as well as being a useful test of the various theoretical calculations.

The ions within the EBIT were expelled after a controlled confinement time by removing the axial trapping potential. The ions traveled towards the ion extraction line and were then charge analyzed by passing them through a magnet. A range of confinement times (~20–180 ms) were investigated. By slowly scanning the field applied to the analyzing magnet, the charge distribution of ions within the trap was determined for each confinement time. From these distributions the time evolution of the argon charge states of interest within the trap were found, as shown in Fig. 3.

In general, the time evolution of the charge distribution within the trap may be described by quite a complex set of coupled rate equations which include the most important processes that occur in the trap. However, at times shortly after the appearance of ions of a particular charge state q, the rate of increase of the number of ions of this charge state depends only on the number of ions of the charge state $q-1$ and the rate of ionization from this lower charge state.[13] These ionization rates are in turn proportional to the ionization cross section.

This study covered the range of impact energies <10 to >40 keV. Provided that the electron beam radius and overlap of the ion clouds with the electron beam remain constant, the analysis of the data should yield relative cross sections for lithium-like (Ar^{15+}), helium-like (Ar^{16+}), and hydrogen-like (Ar^{17+}) argon. This analysis is currently in progress. This experiment should therefore significantly extend the current experimental measurements which appear to have been limited to one energy.

To determine the absolute ionization cross sections, we are planning to measure the electron beam profiles by using some techniques such as an x-ray pinhole camera, Thomson scattering of the light, and other possible methods.

C. Other experiments

In the Tokyo-EBIT, other experiments are being planned and performed. Observation of the Thomson scattering of a laser from the electron beam can give us useful information about the beam characteristics such as the density and the velocity. In particular, to determine the absolute cross sections for electron impact ionization the measurements of the electron density are needed. Laser spectroscopy can open up the new research field in the physics of highly charged ions. The following experiments are planned: (i) Thomson scattering measurement; (ii) laser induced fluorescence (LIF) spectroscopy; (iii) particle injection by laser ablation. The Thomson scattering experiment has been performed at the Tokyo-EBIT.[14] In these experiments, the beam radius and the velocity were estimated from the spectrum of scattered light.

We are also planning to develop ion-surface collision experiments. To do those, the ion extraction line the collision chamber and some diagnostic tools such as a scanning tunneling microscope have been prepared.

IV. CONCLUSION

We have performed a number of different studies using the Tokyo-EBIT with the electron beam energies from several keV to near hundred keV. To operate the high energy electron beam up to 300 keV, an insulation system with 2 atmospheres of SF_6 gas has been recently completed. The production and trapping of very high charge state ions are expected with this source in the near future. Important technical developments are being done such as cooling ions in the trap and laser spectroscopy.

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