

# Injection of various metallic elements into an electron beam ion trap: Techniques needed for systematic investigations of isoelectronic sequences

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Several techniques for injecting various metallic elements into an electron beam ion trap are presented. They have been developed by making use of a metal vapor vacuum arc source, a wire probe, an alkali ion source, gaseous metallic compounds, and so on. These techniques are needed to systematically investigate highly charged ions along isoelectronic sequences. Merits and demerits of these methods are discussed. © 2000 American Institute of Physics. [S0034-6748(00)52202-3]

## I. INTRODUCTION

In spectroscopic studies of highly charged ions with an electron beam ion trap (EBIT),<sup>1</sup> it is frequently required to systematically investigate isoelectronic sequences. To achieve this, one needs to inject various metallic elements into an EBIT. For this purpose, a metal vapor vacuum arc (MEVVA) ion source<sup>2</sup> has been widely used. However, a MEVVA cannot be applied for all elements. Accordingly, a wire probe<sup>3</sup> is used to inject elements such as radioactive isotopes whose available amount is too small to make a cathode for a MEVVA. To inject all elements in the Periodic Table as easily, safely, and economically as possible, other techniques are needed.

In our previous study<sup>4</sup> with the Tokyo EBIT,<sup>5</sup> we investigated strong configuration mixing in the neonlike sequence for the atomic number  $Z=53-56$ . This work has been extended to lower  $Z$ . Since some of the elements of interest were difficult to inject from a MEVVA source, we used several other techniques. In addition, new techniques with a Knudsen cell and laser ablation are being developed. In this article, we present these techniques in detail and discuss their merits and demerits.

## II. INJECTION METHODS

### A. Gas phase injection

The Tokyo EBIT is equipped with a gas injector consisting of two vacuum chambers which are differentially pumped with two turbo-molecular pumps. This injector is used when the vapor pressure of interesting elements or mol-

ecules including them is sufficiently high at room temperature. As well as rare gas ions, we have thus produced Sb, Te, and I ions by introducing trimethylstibine ( $C_3H_9Sb$ ), dimethyltelluride ( $C_2H_6Te$ ), and  $I_2$  molecules with this injector. It is noted that iodine is a useful element to observe the charge-state distribution in extracted ions because it has only one stable isotope and is much cheaper than enriched Xe. Although iodine ions can also be produced by introducing HI molecules,<sup>6</sup> HI is strongly corrosive, and difficult to handle.

### B. External ion sources

A MEVVA has been widely used to inject metallic ions into an EBIT. Our MEVVA is similar to others,<sup>7</sup> so we do not describe it in detail. Briefly, it consists of a trigger electrode, a cathode, an anode, and an extractor electrode. The cathode is a tube with inner and outer diameters of 3 and 6 mm, and usually made from the metal to be ionized. The trigger, which is a rod of diameter 1.5 mm, is surrounded by the cathode with an insulator between them. The anode and the cathode are placed at the front of the trigger and the cathode in series. A trigger pulse of several kilovolts is applied between the trigger and the cathode to bring about an arc discharge between the cathode and the anode. Ions in the arc plasma are then extracted with the extractor. During the operation, the arc current is monitored to detect the discharge. If no arc discharge is detected despite application of a trigger pulse, another trigger pulse is applied. This “re-triggering” system is especially useful for elements whose melting point is high so that the arc discharge is difficult to realize. For example, Ni, Sn, Re, and Au ions have been injected with the MEVVA. It is noted that Ni was injected from the trigger electrode made of a Ni wire of 1.5 mm diameter by exchanging the wiring between the cathode and

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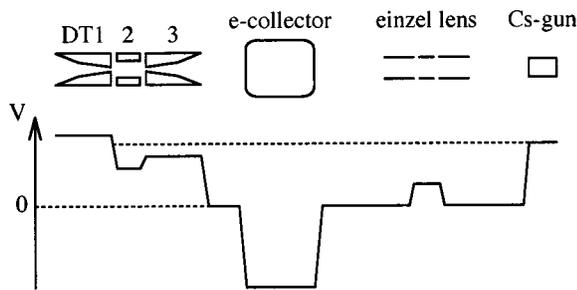


FIG. 1. Potential distribution used for the continuous injection of Cs ions emitted from the external ion source.

the trigger. Silicon, a semiconductor which when pure has an insufficient conductivity for use in a MEVVA, has been introduced into the Oxford EBIT by using a heavily doped sample of resistivity  $0.005\Omega\text{ cm}$  in the MEVVA. In this way, approximately  $2 \times 10^5$   $\text{Si}^{12+}$  ions were trapped in a 50 mA electron beam.

To inject Cs ions, we used an alkali ion source with a commercial aluminosilicate ion emitter (Heat Wave P/N1141), because Cs is liquid at room temperature and thus unable to be used as a MEVVA cathode. A Cs ion beam with the current of several microamperes was emitted continuously<sup>8</sup> from the ion source and axially injected into the EBIT. The continuous injection is in contrast to the pulsed injection from a MEVVA. Figure 1 shows the potential distribution for the continuous injection. As shown in the figure, the voltages at the lower (DT1) and the upper drift tubes (DT3) were set slightly higher and lower than the voltage at the ion emitter, respectively. In this case, the injected singly charged ions are reflected at DT1 and escape from the trap if the ions are not ionized. However, if the ions are ionized between DT1 and DT3, they are trapped and ionized further.

The injection with an aluminosilicate ion emitter can be applied for other alkali and alkaline earth elements, such as K, Ca, Rb, and Sr. In addition, we are developing another ion source which consists of a Knudsen cell and an electron gun to ionize the elements vaporized in the cell. This ion source will be used for elements which are difficult to machine.

### C. Wire probe

Elliott and Marrs<sup>3</sup> developed a technique to inject ions from a wire probe. The technique was found to be useful for injecting small amounts of source materials. Since the laboratory at which the Tokyo EBIT is located has no equipment to control radiation, the available amount is limited for unstable elements such as Th, U, and Am. Therefore we also constructed a wire probe system to inject such elements into the EBIT. It consists of a linear motion drive, manipulators for five axes, and a probe wire with a diameter of 1 mm. The probe wire can be moved with the linear motion drive by about 500 mm. This is needed to extract and exchange the wire without breaking the vacuum of the EBIT. The manipulators are used to insert the probe without touching the cryostat and the drift tubes of the EBIT.

We have tested this wire probe system with Th. At the Livermore EBIT, Th is usually injected with a MEVVA.<sup>9</sup>

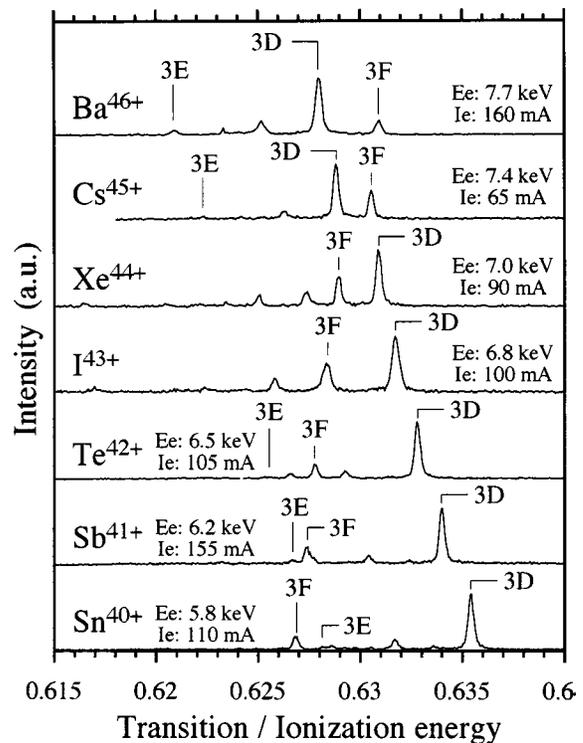


FIG. 2. High resolution x-ray spectra of the Ne-like ions with  $Z=50-56$ . The notations in the figure represent initial states;  $3D: (2p_{3/2}^{-1}3d_{5/2})_{J=1}$ ;  $3E: (2p_{3/2}^{-1}3d_{3/2})_{J=1}$ ;  $3F: (2p_{1/2}^{-1}3s)_{J=1}$ . The final state is the ground state for all lines.  $E_e$  and  $I_e$  are the electron beam energy and the current, respectively, at which each spectrum was obtained. The horizontal axis is normalized by the ionization energies (see Ref. 11) of the Ne-like ions just for display.

However, as described above, the available amount of Th is too small for us to make a MEVVA cathode. We thus injected Th using the probe wire made from thoriated tungsten, which contains 2% thoria.

### III. RESULTS AND DISCUSSION

Figure 2 shows the high resolution x-ray spectra from Ne-like ions with  $Z=50-56$ , taken with a crystal spectrometer. Through this observation, we investigated level crossings and strong configuration mixing among  $(2p_{3/2}^{-1}3d_{5/2})_{J=1}$ ,  $(2p_{3/2}^{-1}3d_{3/2})_{J=1}$ , and  $(2p_{1/2}^{-1}3s)_{J=1}$ . Various injection methods made it possible to investigate the isoelectronic sequence in detail. The EBIT has a dispenser-type of cathode, which is made from a porous tungsten matrix infiltrated with BaO. Therefore Ba and W are always evaporated from the cathode and trapped in the drift tubes. When Ba and W are not objective ions, the electric field between the gun and the trap is carefully adjusted, and the trap is dumped periodically to avoid the accumulation of these ions.

As described above, Cs ions were injected continuously. In this mode, x-ray radiation monitored with a solid state detector continued to increase for several seconds after the trap potential was applied. This observation implies that it took several seconds to fill the trap with the ions. Although we tried pulsed injection by applying the trap potential periodically, the amount of trapped ions was not sufficient for

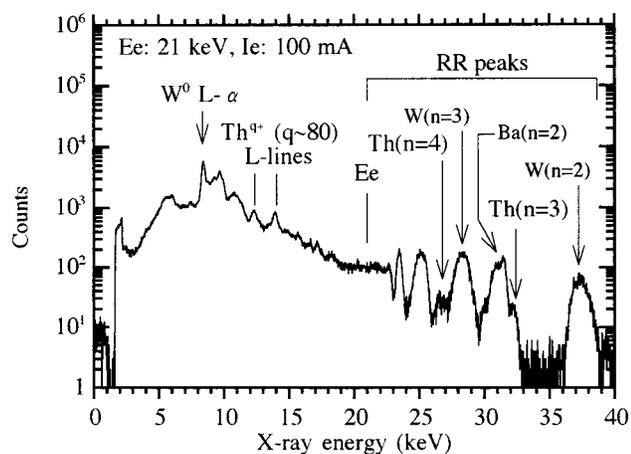


FIG. 3. X-ray spectrum obtained with a solid state Ge detector. The wire probe made from thoriated tungsten (2% thoria) was inserted into the EBIT during the observation. The probe position was about 0.5 mm from the trap center. The structures appearing at the region above the electron energy (21 keV) correspond to x rays from radiative recombination (RR) processes, e.g., Th ( $n=3$ ) corresponds to RR into the  $n=3$  levels of highly charged Th ions.

the spectroscopic study. The Cs ion source provided  $\sim 10^8$  ions/ $\mu\text{s}$ , which corresponds to several microamperes, while a MEVVA can provide  $\sim 10^{11}$  ions/pulse or  $\sim 10^{10}$  ions/ $\mu\text{s}$ .<sup>3</sup> Since the time to travel the trap region for injected ions is several  $\mu\text{s}$ , it is considered that the initial number of Cs ions was not enough for the pulsed injection. To make the pulsed injection possible, a more intense ion source will be needed. The pulsed injection, i.e., fast filling of the trap, is needed for extracting the ions with a short frequency. For the gas phase injection including metallic compounds of Sb and Te, the fast filling of the trap is found to be easily achieved.

Figure 3 shows the x-ray spectrum obtained by inserting the wire probe into the EBIT. Since the present probe was made of thoriated tungsten (2% thoria), the dominant ions were W ions with only a few Th ions in the trap soon after the trap potential was applied. However, since Th was the heaviest element in the trap, its abundance increased with time through evaporation and accumulation processes in a mixed ionic plasma. Accumulation of the spectrum shown in Fig. 3 was thus started 30 min after the trap potential was applied. From the  $L$  lines and the radiative recombination peaks in the spectrum, it is confirmed that Th ions with charge states  $q\sim 80$  have been produced. Although the

present observation showed that the probe injection is useful, magnetic materials are difficult to introduce because they may disturb the electron beam.

The wire probe can be used for other purposes. When the probe moves on toward and touches a part of the electron beam, intense bremsstrahlung x rays are emitted. Since this radiation occurs at the center of the trap, it is useful for the alignment of optical systems with x-ray crystal spectrometers. The probe was also used to focus the charged coupled device (CCD) camera in experiments to image the electron beam by Thomson scattering.<sup>10</sup>

The Tokyo EBIT is equipped with the laser systems which have been used for the Thomson scattering experiments, and are planned to be used for laser spectroscopy. By illuminating the probe with the laser, elements on the probe can be introduced into the EBIT by laser desorption. Although it is difficult for desorbed ions to reach the trap center because of the strong axial magnetic field of the EBIT, desorbed neutrals can reach the center and be ionized by the electron beam. Compared to the normal probe injection, for laser desorption the distance between the beam and the probe is not so critical. Another merit is that both pulsed and continuous injection are possible. However, the damage on a wire may be serious, i.e., the lifetime of a wire will be shorter compared to the probe injection. This technique will be tested in the near future.

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