X-Ray spectroscopy at a SPARC EBIT

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I report on x-ray spectroscopy of argon and krypton ions produced inside an electron beam ion trap. This work was performed within the atomic physics group at GSI. The typical experimental spectra show characteristic Kα and Kβ x-rays, as well as lines from direct excitation and radiative recombination. The goals of these experiments were to (I) optimize the detection of x-rays from Ar and Kr, and (II) measure the dependence of the x-rays on the EBIT parameters, such as electron beam energy and ion confinement time. The experiments show that the electron beam energy determines the maximum charge state that can be reached by the ions. While the confinement time determines the amount of highly charged ions in the trap.

1 Introduction

An Electron Beam Ion Trap (EBIT) is an apparatus that is used for the controlled, reliable, reproducible, and continues creation of ions from a gas[1]. The EBIT consists of an electrode structure, to which high voltages are applied, and an intense electron beam, which is guided by a strong magnetic field. It is a trap, because the ions are electromagnetically confined (in 3D) at the center [2]. In the axial direction (i.e. along the trap axis), the ions are trapped by the electric field from the biassed electrodes[1] (see figure (1)). The space charge potential of the intense electron beam, supported by the axial magnetic field, confines the ions radially. The ions are created by electron impact ionization, which is a well-known and very effective mechanism[3]. In a collision, an electron from the electron beam knocks out an electron from an atom, which is then left in an ionized state. This happens continuously during the confinement time, and can thus lead to a high charge state of the ion[4]. The degree of ionization (final charge state reached) depends on the energy E_e and intensity I_e of the electron beam, on the trap potential, and on the confinement time. Mostly, the ions are created from gas atoms/molecules that are fed into the EBIT at a very low pressure ρ, controlled by a needle valve. To create and maintain the charge states of the ions, the EBIT must be operated under Ultra-High Vacuum (UHV) conditions, which means a pressure of the order of 10^{-10} mbar. If the pressure inside the EBIT is too high, the ions will be partially neutralized by electron capture, or e.g. kicked out of the trap by collisions with atoms from the residual gas[6]. But the ions can also readily be extracted from the EBIT, by lowering the potential of one of the trap electrodes - then the EBIT becomes and EBIS (source)[1].

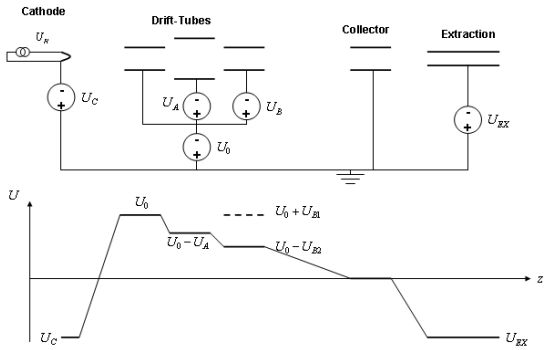

Fig. 1: *Schematic, showing the voltages applied to the EBIT*

The observed x-rays are produced by three different processes[5]:
Direct Excitation (DE) - the ion is excited by the electron impact process, and decays by x-ray emission. The corresponding reaction is

$$X^{q+} + e^- \rightarrow X^{q+*} \rightarrow X^{q+} + hv \qquad (1)$$

Radiative Recombination (RR) - the ion captures an electron from the electron beam into a strongly bound state, and the released energy is emitted as an x-ray. This is the time-reversed

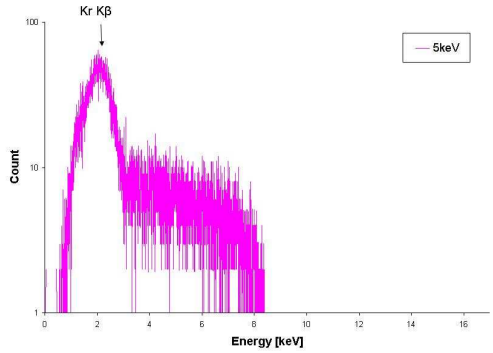

Fig. 2: *Krypton spectrum at* $E_e = 5keV$ *and* $I_e = 20mA$ *at* $\rho = 6 \times 10^{-10}$ *mbar*

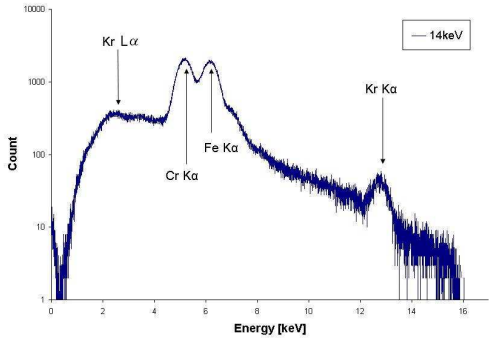

Fig. 3: *Krypton spectrum at* $E_e = 14keV$ *and* $I_e = 20mA$ *at* $\rho = 8 \times 10^{-10}$ *mbar*

photionization process. The reaction is

$$X^{q+} + e^- \rightarrow X^{(q-1)+} + hv \qquad (2)$$

Dielectronic Recombination (DR) - the ion captures an electron from the electron beam into a weakly bound state, and the released energy excites another bound electron. The ion then decays to a lower state by emission of an x-ray. This is the time-reversed Auger process, and is described by

$$X^{q+} + e^- \rightarrow X^{q+*} \rightarrow X^{(q-1)+} + hv \qquad (3)$$

These processes depend on several factors that can be controlled in an experiment. By changing the electron beam current I_e, gas pressure ρ, potential well, electron beam energy E_e and confinement time different aspects of the ionization process in the EBIT can be changed. Studying the emitted X-Rays conclusions about the charge state of the ions can be drawn[4]. The conducted experiments specifically focused on the impact of changed electron beam energy and confinement time.

2 Experimental Setup

The experiments were performed with a commercially available EBIT, which is situated in the Heckhalle of GSI. The electron beam current was about 20 mA, and the electron energy was varied between 5 keV and 14 keV, depending on the specific experiment. Argon or krypton gas was let into the EBIT at pressures between 5×10^{-10} and 2×10^{-9} mbar. The trapping potential was varied between 50-150 V. The confinement time was changed according to the requirements of the experiment, and varied between 700 and 4000 ms, after which the ions were extracted by pulsing down the voltage on one of the trap electrodes. The x-rays were detected by an Amptek XR-100CR Si-pin detector, which has a (measured) resolution of about 230 eV. The detector was set up at approx. 2 cm distance from the beryllium window of the EBIT, which was mounted at an angle of 90° with respect to the trap axis.

3 Results and Analysis

3.1 Electron Beam Energy

By changing the electron beam energy we found that certain X-Ray peaks only become visible after the electron beam energy reached a certain threshold. Figure (2) and (3) show two measurement for Krypton (Kr) injection at different electron beam energies. It is clearly noticeable that the $K\alpha$ peak of Krypton only becomes visible at E_e = 14keV. The $L\alpha$ peak, which is clearly visible at E_e = 5keV, almost completely diminishes at E_e = 14keV due to a large increase of the background radiation. This increased background radiation is due to the increased heating of the ions in the trap. The more energy the electron beam transfers to the ions the more they will gain momentum in radial direction and therefore might be able to escape the trap and collide with the trap electrodes. The EBIT electrodes consist mainly of chrome (Cr) and iron (Fe). As an ion collides with the walls direct excitation of an electron might take place and therefore photons corresponding to the energy levels of Cr $K\alpha$ and Fe $K\alpha$ can be seen in the spectra. Furthermore, background radiation

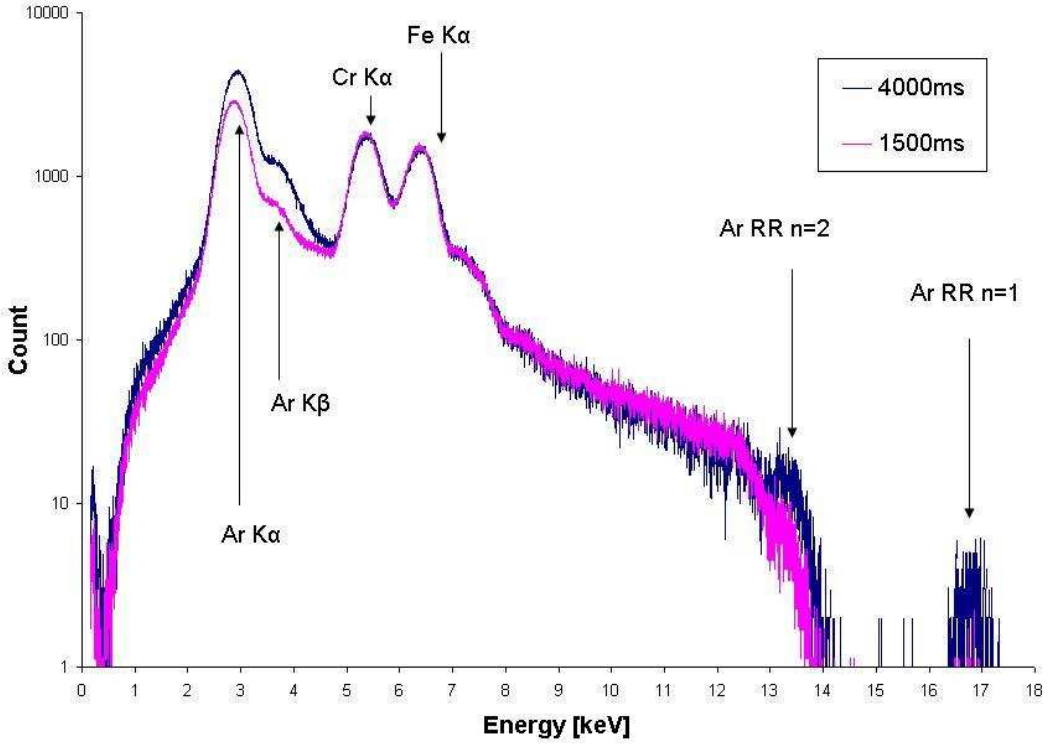

Fig. 4: *Argon injection at $E_e = 12keV$ and $I_e = 20mA$ at $\rho = 8 \times 10^{-10}$ mbar with 4000ms and 1500ms confinement times*

increases so that the Kr $L\alpha$ peak is hardly visible at $E_e = 14$keV. The Kr $K\alpha$ peak, however, only appears at $E_e = 14$keV, because energy required for an excitation to the next level is 12.6 keV. At $E_e = 5$keV this excitation cannot take place and therefore the Krypton ions can not be fully ionized. In general the electron beam energy determines which charge states can be reached by the apparatus. Thereby the electrons in the beam need to have a kinetic energy that is high enough for a bound electron to jump to the next quantum energy level[6]. The largest gap between two adjacent energy levels is, for every atom, found between the $n = 1$ to $n = 2$ levels (K and L shell). If therefore the electron beam hits the ions with an energy that is less than any of the gaps between the energy levels, the atom can not be excited. For ionization, the energy needs to be high enough for the electron to leave the atom/ion.

3.2 Confinement time

Different confinement times have especially an impact on the radiative recombination (RR) lines, as can be seen in figure (4). The graph shows that RR into $n = 1$ and $n = 2$ levels is much more likely to occur at a confinement time of 4000 ms, than at 1500 ms. Furthermore, a better signal to noise ratio is achieved for the argon peaks. This can be explained by figure (5). The longer the ions are trapped, the higher the average charge state will be. Therefore, after a long confinement time, predominantly higher charge states will exist in the trap, which makes a DE of an electron from the $n = 1$ to $n = 2$ levels more likely[7]. This will lead to an increased occurrence of the Kα and Kβ transitions. A similar reason accounts for the increase in RR lines at long confinement times. For RR lines to appear, the ion must have at least one vacancy in a certain shell. To see the $n = 2$ RR lines of argon, the charge state must at least be $q = 9+$. For the $n = 1$ RR lines of argon, even a charge state of $q = 17+$ is required. These charge states only appear after long confinement times. However, even then the RR process is very rare, as the electrons approach the ions very rapidly and are therefore only rarely captured by an ion.

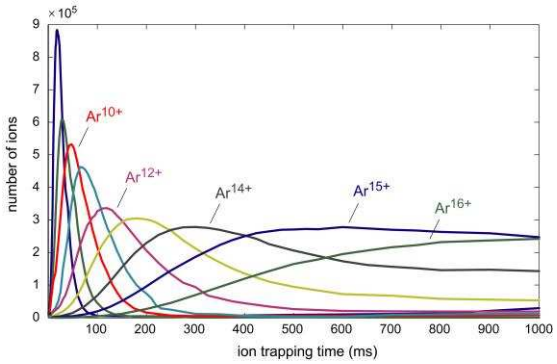

Fig. 5: *Charge states after different confinement times [8]*

4 Conclusion

The SPARC EBIT was successfully used to ionize argon and krypton ions, under stable and reproducible operating conditions. The x-rays, produced by excitation and capture processes inside the EBIT, were measured with a compact Si-pin x-ray detector (outside the EBIT). The detection of the x-rays was optimized, and the influence of the electron beam energy and the confinement time on the ionization process was systematically studied. It was found that the electron beam energy defines the maximum charge state that can be reached, and that the confinement time is related to the amount of ions produced in a specific (high) charge state. Higher electron beam energies and longer confinement times lead to higher average charge states of the ions, as expected.

Acknowledgments

I especially want to thank my tutor at GSI, Dr. Danyal Winters, for giving me the opportunity to look into and work at the EBIT, for answering all my questions, and for helping me to conduct the experiments. I also like to thank Sabrina Geyer and Dr. Gleb Vorobyev for explaining the functionality of the EBIT to me, and for assisting me with the experiments. Finally, I want to thank Prof. Jörn Knoll and Heide Rinnert for giving me the opportunity to take part in this unique programme, and for putting together an informative and enjoyable lecture programme.

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