

Optimisation of the Charge State Distribution of the Ion Beam Extracted from an EBIT by Dielectronic Recombination

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The Dielectronic Recombination Resonance (DRR) processes for highly charged krypton ions have been investigated through simultaneously observing the x-ray emission and the ions extracted at the Heidelberg EBIT whilst slowly scanning the electron beam energy. It was found that at their DR resonance electron energies, the yield of the He-like krypton ions was substantially reduced, whereas that of the Li-like krypton ions was correspondingly increased. At slightly higher electron energies, similar features were observed for the Li- and Be-like krypton ions. From the observed ratios of the Li-like/He-like krypton ion currents, we have deduced the DR strength for the He-like ions, which was found to be in reasonable agreement with theoretical calculations. We have also concluded from the present

experiments that the DRR processes can be used to modify the ion charge state distributions and to concentrate the extracted ion currents into particular charge states. This is particularly important for future charge breeding experiments with short-lived radioactive isotopes.

Introduction

The charge state distribution of ions from an Electron Beam Ion Source and Trap (EBIS/T) depends on a number of the operating parameters of the ion source. Among them, the electron impact energy, electron density, confinement time and residual gas pressure are most critical. Generally, the ion charge states from ion sources are distributed over a certain range and thus, only a fraction of the total ion beam is in the specified charge state required for the further acceleration. Here we would like to propose a new technique to enhance the fraction of ions in a specific charge state through the special features of the Dielectronic Recombination (DR) processes¹ in order to concentrate almost all of the total yield in a single charge state.

It is well known that the DR process has large cross sections within very sharp resonances with a natural width of some meV up to eV depending on the specific electronic state. This means that the fine-tuning of the electron energy in the source can control the DR rate. Fractions of highly charged ions (HCI) of different charge states can be substantially modified and also increased by setting the electron beam energy to a certain DR resonance (DRR) for a selected ion charge state (q). Then, the ions in this charge state (q) are practically completely depleted and the charge state distribution of the ions is concentrated around the next lower charge state ($q-1$). This feature is especially important for utilizing the sources as charge breeders for the planned exotic nuclear beam facilities.² Better understanding of the DR processes is also required for a variety of other applications, including hot plasma diagnostics and for the spectroscopy of highly charged ions. This motivated us to perform the present experimental studies of DRR for highly charged krypton ions at the Heidelberg EBIT by simultaneously observing the x-ray emission from the trap and the extracted ions as a function of the electron energy. The present preliminary experimental results have indeed confirmed the basic principle proposed here.

Experimental setup

In the present experiment, the Heidelberg EBIT (for the detailed description see³) was operated under continuous feeding of the natural isotope-abundance krypton as a working gas. The electron beam energy was varied from 8.7 to 9.5 keV, which is needed to excite the KLL-DRR for highly charged krypton ions, particularly for He-, Li- and Be-like ions. In this process, an electron from the beam recombines into the $n=2$ (L) shell, while a bound $n=1$ electron is promoted to the $n=2$ shell, resulting in a doubly excited electronic state with a hole in the K-shell, which (for highly charged ions) relaxes to ground state by photon emission. The electron beam energy was determined by the sum of (1) the drift tube voltage fixed at +6.3 kV, (2) the electron gun cathode voltage of -1500 V, and (3) the electron gun platform voltage that was scanned from -500 to -1300 V with a scanning rate of 1.5 V per second. Such a relatively slow scan rate was chosen to ensure the quasi-adiabatic stationary response of the ion charge balance inside the trap to the varying electron beam energy. The contribution of the electron beam space charge to the electron beam energy was estimated to be below 100 eV in the range of the electron beam current that was explored (25 to 150 mA). This resulted from linear extrapolation to zero electron beam current after a number of measurements of DRR peak positions for different electron beam currents. The energy of the extracted ions, defined by the voltage of the drift tube assembly, was kept constant at 6.3 keV per charge during the experiments.

The ion trap was dumped every 300 sec to avoid an accumulation of heavy impurity ions by applying a HV pulse to the outer drift tube. All drift tubes of our EBIT were connected each other (total length: 35 cm), aiming to improve the accuracy of the electron beam energy determination. Therefore, the longitudinal confinement of HCI was due to the space charge of the electron beam only. This caused a reduction of the production efficiency for the highly charged ions due to the resulting short confinement time. The He- and Li-like krypton ions became a minor fraction of the total ion population inside the trap, resulting in a decreased number of extracted ions of the required charge states. On the other hand, in such

a situation the general impact on the internal trap parameters by scanning of the electron energy is simultaneously minimized.

The voltages applied to the drift tubes and electron gun platform were measured with high precision by using two combined sets of calibrated voltage dividers and Keithley-2002 multi-meters. The time response of the voltage divider circuits due to modulation of the voltage was taken into account.

A high purity Ge detector, mounted at one of the EBIT radial ports at 90° with respect to the electron beam axis, registered the characteristic x-rays emitted from the krypton ions excited through electron-ion collisions with an energy resolution of ~ 450 eV. The GOOSY data acquisition and analysis system was used to control the standard GSI MBS front-end system.⁴ It allowed simultaneous recording of the energy of the detected photons, the event time with respect to the trap dumping cycle, and the scanning voltage of the electron-gun platform power supply. In off-line analyses, 2-D plots of the x-ray energy and intensity were obtained as a function of the electron energy.

The ions were extracted from the trap in the continuous leakage mode and entered into the low-energy beam transport line. The ion optics were tuned to focus the extracted ions onto a $\varnothing 40$ -mm Roendek DLD40 position sensitive detector mounted closely behind a 90° analyzing magnet. Since the ion energy was fixed at 6.3 keV per charge during the experiments, the ion positions on the detector defined by their M/Q ratio were fixed too. Only minor changes in the beam spot position and width were observed while scanning the collector voltage, since the collector also worked as an Einzel lens. These changes were almost identical for all ions with a charge state of present interest. Therefore, all variations in the observed ratios of the extracted currents of ions with different charge states were due to the DRR processes. In the present configuration, it was possible to simultaneously detect up to three different charge states of krypton ions, e.g., from $^{84}\text{Kr}^{32+}$ to $^{84}\text{Kr}^{34+}$, though we have restricted ourselves to measuring the Li- and He-like ion currents in most cases. Note that under the present experimental conditions no H-like krypton (Kr^{35+}) ions could be produced, as the electron energy was not sufficiently high to ionize one of the K-shell electrons. The ions were detected in a count mode; the position information of each event was recorded simultaneously together with the scanning electron-gun platform

voltage. This allowed us to apply the necessary cuts to the 2-D event position maps to determine the currents of the ions with a specific charge state as a function of the electron beam energy. A pair of slits in front of the analyzing magnet was used to collimate and reduce the ion beam intensities such as to ensure that the ion count rates on the detector were kept below or close to 1 kHz, which is the limit for the proper operation of DAQ-system.

Experimental results and discussion

As described above, we have simultaneously registered the variations of the X-ray intensities and also of the extracted ion currents, while scanning the electron energy around the DRR of highly charged krypton ions. It has been found that the observed intensity of the K_{α} X-rays from krypton ions during DRR was increased by more than one order of magnitude, compared with that at the off-resonance conditions, which is exclusively due to the radiative recombination, as previously discussed.⁵ Typical variations of X-ray intensities as a function of the electron energy are presented in Fig.1 for an electron beam current of 70 mA. A group of peaks in the resonance spectrum are clearly visible, with the first three peaks (at 8.96, 9.02 and 9.12 keV) attributed to DRR of He-like krypton ions. At higher electron energies, non-separated or overlapped peaks from DRR of ions with lower charge states are observed, namely from Li-like to B-like krypton ions. Furthermore, it has been observed that these peak positions shift by varying the electron current due to the electron space charge potential, which was estimated to be around 50 eV under the trap parameters presented in Fig. 1. The electron beam energy spread was estimated to be ~ 30 eV from fitting the observed X-ray peaks consisting of a single transition with a Gaussian distribution.

While the electron energy was scanned, it is also found that the extracted currents of highly charged krypton ions were changed. In particular, those of He-like krypton ions decreased significantly by a factor of 2 – 4; decrease of the extracted currents of the He-like ions at DRR resulted in the corresponding increase in Li-like ions. Similar behavior was observed when the electron energy was tuned to excite the

DRR for the Li-like ions. Curve (2) of Fig.1 represents the ratios between the extracted $^{84}\text{Kr}^{33+}$ and $^{84}\text{Kr}^{34+}$ ion intensities as a function of the electron energy.

Under the assumption that a stationary ion balance is established inside the trap region, the ratio between the extracted currents of the Li- and He-like krypton ions is directly proportional to the DRR cross-section for the He-like ions. Indeed, if the electron energy is set far off-DR resonance, then the ion density of the He-like ions n_{He} is connected to the ion density of Li-like ions n_{Li} as follows:

$$n_{\text{Li}} \sigma_{\text{Li}}^i \frac{j_e}{e} = \frac{n_{\text{He}}}{\tau_{\text{He}}^{\text{total}}} \quad (1)$$

where $\tau_{\text{He}}^{\text{total}}$ represents the total average ion lifetime of He-like ions, including all influences due to 1) radiative recombination, 2) the charge-changing in collisions with residual gases, 3) ionization to higher charge states and 4) the ion losses from the trap. Under the present experimental conditions, the contribution of process 3) is negligible. In Eq. (1), j_e is the electron current density, e is the elementary electron charge and σ_{Li}^i is the electron impact ionization cross-section of Li-like ions.

On DRR, the new term appears in the equation of the charge balance due to the change of ion charge:

$$n'_{\text{Li}} \sigma_{\text{Li}}^i \frac{j_e}{e} = n'_{\text{He}} \sigma_{\text{He}}^{\text{DRR}} \frac{j_e}{e} + \frac{n'_{\text{He}}}{\tau_{\text{He}}^{\text{total}}} \quad (2)$$

The prime terms correspond to those numbers under DR-resonance condition. Note, here we assume that the ion lifetime is not changed at the resonance. Then, one can find that the ratio between the He- and Li-like ion densities in and out of the resonance depends on the ratio between the DRR cross section for He-like ions and the ionization cross-section for Li-like ions. Furthermore, the extracted currents (I) of He- and Li-like ions are directly connected to the ion density (n) inside the ion trap through the corresponding coefficients α :

$$\frac{\sigma_{\text{He}}^{\text{DRR}}}{\sigma_{\text{Li}}^i} = \frac{n'_{\text{Li}}}{n'_{\text{He}}} - \frac{n_{\text{Li}}}{n_{\text{He}}} = \frac{\alpha_{\text{Li}}}{\alpha_{\text{He}}} \left(\frac{I'_{\text{Li}}}{I'_{\text{He}}} - \frac{I_{\text{Li}}}{I_{\text{He}}} \right) \quad (3)$$

Here, the coefficients α depend on the efficiencies of the extraction and transmission through the ion optics system as well as on the longitudinal confinement times of ions in the trap, which depend on the trapping potential, the ion charge state and the ion temperature. Generally speaking, these are difficult to be known, but we may assume that they do not change significantly and, as will be demonstrated later, are indeed constant during the electron energy scanning procedure. Then, the variation in the extracted ion currents while scanning the electron beam energy directly reflects the dependence of the DRR cross-sections on the electron energy and thus, can be used for the detailed study of DR processes. A similar method has already been used to investigate the DRR processes in Ar^{16+} ions,⁶ where the extracted ion current after each dump was measured while the electron energy was changed, with the possible loss of the energy resolution in determining the DR strengths.

It should be noted that Fig.1 provides channel-specific information, which can be obtained from the observed variation of the extracted ion currents as a function of the electron energy. The first two peaks clearly correspond to those observed in the electron energy dependence of X-ray intensity (curve 1 in Fig. 1). The observed third peak at ~ 9.14 keV (which is connected to the e, k and l satellite lines) and fourth peak at ~ 9.2 keV (j, a and m satellite lines) are expected to be coupled with populating the $1s2p^2D_{3/2,5/2}$ levels in the doubly excited Li-like krypton ions. They overlap with the DR resonances of the Li-like ions in the X-ray plot because of the resolving power of the X-ray detector. Indeed the observed variation of the ion currents over the DRR region was found to be in good agreement with the theoretically predicted curve.^{5,7}

It also should be pointed out that in the X-ray plots (curve 1 in Fig. 1), the X-ray intensity of the third peak is not increased but more or less saturated at 9.14 keV due to depletion ($\sim 70\%$) from the original He-like ion populations inside the trap during the slow electron energy scanning used in the present experiments. This can be understood since the DR strength for this particular process is much larger than those for the other (first and second) peaks.⁵

After fitting the curves with Gaussian distributions and subtracting the ratio of ion currents at far off-resonance conditions, the total DRR strength integrated over the KLL resonance group can be obtained,

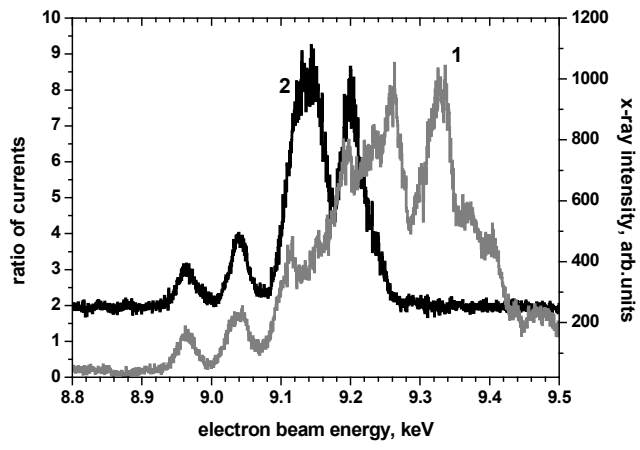
based upon Eq. (3). Adopting the direct ionization cross-section of Li-like krypton ions at ~ 9 keV electron impact energy calculated using the ATOM code⁸ to a value of $8.7 \times 10^{-22} \text{ cm}^2$, the DR strength for Kr^{34+} ions integrated over the observed resonance areas, $\sigma_{\text{He}}^{\text{DR}} * \delta E$, was found to be $\alpha_{\text{Li}}/\alpha_{\text{He}} (6.0 \pm 1.0) \times 10^{-19} \text{ cm}^2 \text{ eV}$, which is in a reasonably good agreement with the theoretically predicted value of $5.42 \times 10^{-19} \text{ cm}^2 \text{ eV}$.⁵

Then, we got $\alpha_{\text{Li}}/\alpha_{\text{He}} = 0.90 \pm 0.15$, indicating that the longitudinal confinement times in the trap did not depend significantly on the ion charge for the Li- and He-like krypton ions and indeed were quite the same under our experimental conditions, as assumed in the present analysis above.

Figure captions

Fig.1 Intensity of the krypton K_{α} characteristic x-rays (curve 1, right scale) and ratio between the extracted $^{84}\text{Kr}^{33+}$ and $^{84}\text{Kr}^{34+}$ ion currents (curve 2, left scale) as a function of the electron energy.

The electron beam current is 70 mA.



J.R. Crespo et al., Fig.1

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