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Charge exchange of highly charged argon ions as a function of projectile energy

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Abstract. X-ray emission of highly charged argon ions following charge exchange collisions with argon atoms has been measured as a function of projectile energy. The ions are extracted from the Electron Beam Ion Trap (EBIT) in Berlin and selected according to their mass-to-charge ratios. Experiments focussed on hydrogen-like and bare argon ions which were decelerated from 125q eV/amu to below 0.25q eV/amu prior to interaction with an argon gas target. The x-ray spectra recorded probe the cascading transitions resulting from electron capture into Rydberg states and are found to vary significantly with collision velocity. This indicates a shift in the orbital angular momentum of the capture state. Hardness ratios are observed to increase with decreasing projectile energy though at a rate which differs from the results of simulations. For comparison, measurements of the x-ray emission following charge exchange within the trap were carried out and are in agreement with the findings of the EBIT group at LLNL. Both of these *in situ* measurements, however, are in discrepancy with the results of the experiments using extracted ions.

1. Introduction

Charge exchange as a result of low energy collisions between highly charged ions and gases has become an area of increased interest due to applications in high temperature fusion plasma diagnostics [1] and the observation of x-ray emission from comets [2]. In the first case, heavy ions present as impurities in the plasma capture electrons from inherent or injected neutrals and in the second, heavy ions in the solar wind capture electrons from neutrals in the comet's bow shock region. The classical over-the-barrier model describes the process and predicts the principal quantum number n of the dominant Rydberg state into which the electron is transferred [3]. For hydrogen-like and bare argon ions interacting with argon atoms, capture into $n = 8$ is inferred. The heavy ion stabilizes predominantly by photon emission at various characteristic energies. At high collision velocities the population of angular momentum states l can be modelled statistically. However, for low energies such a description is no longer valid. This regime is of particular relevance for the interpretation of cometary emission, with solar wind velocities in the bow shock taking values of 100 km/s or below ($\leq$50 eV/amu). Assuming that the orbital angular momentum of the captured electron is given by the product of impact parameter and velocity, then the relative velocity of the collision partners is expected to control the l capture state. This in turn stipulates the radiative decay paths which the electron can take.

Thus the charge exchange emission spectrum is characteristic of the initial capture state and dependent on collision energy.

In this work highly charged argon ions were extracted from an EBIT and directed via a deceleration setup onto a gas target where the x-rays emitted following charge exchange were detected. Hereby a survey of x-ray emission over a wide range of collision energies could be conducted in a controlled manner. An *in situ* investigation involving the measurement of x-rays accompanying charge exchange from the EBIT operated as a Penning Trap were also carried out. There, trapping conditions limit the collision energy to a small but somewhat undetermined value. The transitions tracked by the x-ray emission spectra are those involved in the radiative cascade of an electron into the ground state during stabilization of the highly charged ion after a charge exchange collision, i.e. $n \geq 2 \rightarrow 1$.

2. Experimental

Highly charged argon ions were produced in the Berlin EBIT nearly at rest via successive impact ionization of injected argon gas by a monoenergetic electron beam. Radial confinement of the ions in the trap is due to the space charge of the electron beam and the 3 T magnetic field generated by a pair of Helmholtz coils. In the axial direction ions are confined by the potential well created by the voltages on three tube electrodes. The base potential of the drift tube assembly determines the interaction energy of the electron beam in the trap.

For the experiments with an external target the voltages of the bottom, middle and top drift tubes were set to 500, 100 and 200 V, respectively, and ions were extracted in pulse mode. In order to maximize the yield of hydrogen-like and bare argon a 1 s breeding cycle with an ionization potential of 10.1 kV was implemented. Ions were expelled from the trap by raising the middle drift tube voltage to 400 V at a rate of 3 kV/s. During this time the drift tube base potential was lowered to 5 kV to give an extraction energy more ideally suited to the beamline elements. Transport of the ion beam through the beamline is achieved with a series of electrostatic deflectors and Einzel lenses. Ar^{17+} and Ar^{18+} ions were then selected according to their mass-to-charge ratios using the crossed electric and magnetic fields of a Wien filter. Next the ions pass through a retardation assembly consisting of a series of parallel grids. With this element the collision energy of the ions impacting the gas target can be controlled and it was used to decelerate the $Ar^{17+,18+}$ ions from 5000q eV down to 10q eV. The final energy was measured using a retarding field technique [4]. Argon gas was injected into the target region using a pulsed supersonic valve with a repetition rate of 1 Hz and a pulse length of 20 μs. X-ray emission resulting from charge exchange between the highly charged ions and the argon neutrals was recorded with a Peltier-cooled solid state silicon detector. As an example, Figure 1 shows the spectrum recorded for charge exchange of 39q eV Ar^{18+} ions impacting on the argon gas target. The positions of the various transitions into the ground state are marked.

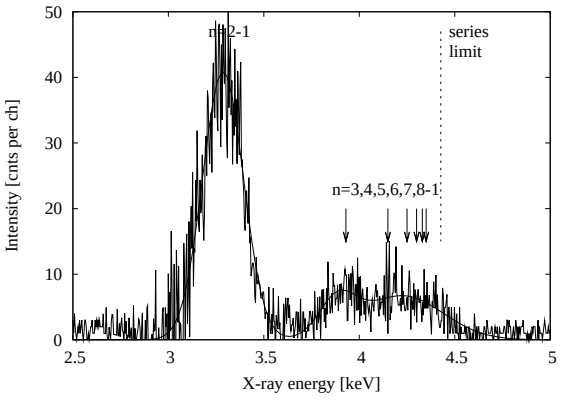

Figure 1. X-ray emission for the charge exchange of 39q eV Ar^{18+} ions with an external argon gas target. The black curve marks a fit to the experimental data.

The *in situ* measurements were carried out using the EBIT in magnetic trapping mode [5]. This involved periodically breeding the ions for 1 s and then switching the electron beam off to give 2 to 20 s during which the ions were only trapped by the magnetic field and the drift tube potentials. At the end of each cycle the trap was briefly opened to prevent the accumulation of background heavy ions. In the absence of the electron beam the only source of x-ray emission from the highly charged ions in the trap is charge exchange with residual gas, dominated by the continuous injection of argon. The x-ray spectra were recorded with a liquid nitrogen-cooled solid state germanium detector. For the Ar^{17+} charge exchange experiment the energy of the electron beam in the ionization phase was set to 4.3 keV, just below the threshold for creating Ar^{18+}. In contrast, for the Ar^{18+} experiment the amount of this ion produced was maximized by choosing a beam energy of 10.1 keV. To obtain a pure Ar^{18+} spectrum, the Ar^{17+} contribution, which is shifted slightly to lower energies, was subtracted out. An example of the charge exchange spectrum for Ar^{18+} recorded using an axial trap depth of 100 V is shown in Figure 2. The collision energy for *in situ* experiments is controlled by the barrier set by the axial potential well but is somewhat difficult to assign because the Maxwellian energy distribution is disturbed due to ion escape from the trap. Varying the trap depth between 30 and 700 V yielded no significant changes in the x-ray spectra collected.

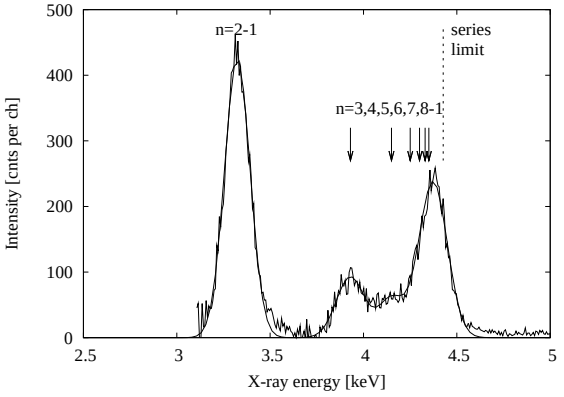

Figure 2. *In situ* x-ray emission for the charge exchange of Ar^{18+} ions with residual argon gas using a trap depth of 100 V. The black curve marks a fit to the experimental data.

3. Results

The data from the various extraction and *in situ* measurements can be summarized by calculating hardness ratios, defined here as the ratio of x-rays from $n \geq 3 \rightarrow 1$ to $n = 2 \rightarrow 1$ transitions, and plotting the values against collision energy. The result is shown in Figure 3. Solid triangles represent experiments with Ar^{17+} ions and solid circles represent those with Ar^{18+} ions. A larger hardness ratio indicates electron capture into a lower angular momentum state. This is because high energy decay directly into the ground state is more accessible to electrons captured into lower l states, due to the $\Delta l = 1$ selection rule for dipole transitions. Electrons captured into higher l states, on the other hand, favour decay via the Yrast chain in $\Delta n = -1$ and $\Delta l = -1$ steps, which results in the emission of a series of lower energy photons. From the data points for the extraction experiments (solid shapes connected by lines) it can be seen that hardness ratio increases with decreasing collision velocity. This indicates that electrons are transferred into progressively lower l states, as described, and as would also be expected from considerations of angular momentum conservation. A grey dashed line in the figure represents a calculation using the classical trajectory Monte Carlo (CTMC) method and a radiative decay matrix for electron capture by Ar^{18+} from hydrogen [6]. The publication states that the results for charge exchange with different targets do not differ significantly. At collision energies above 100 eV/amu the experimentally determined hardness ratios do not decrease as strongly as predicted by the

calculations, which level out at the statistical value. The statistical limit for Ar^{18+} is also represented by a grey dashed line [6]. Data points marked in grey at 4000 eV/amu are from extraction experiments of $Ar^{17+,18+}$/Ar charge exchange performed at the NIST EBIT [7]. The hardness ratios are in agreement with our findings.

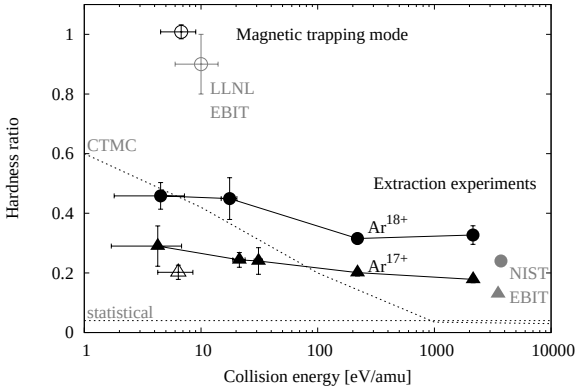

Figure 3. Hardness ratios calculated from the x-ray emission spectra as a function of collision energy. Results for capture into Ar^{17+} and Ar^{18+} are plotted with triangles and circles, respectively. Solid shapes represent extraction measurements and hollow shapes represent those taken *in situ*. Measurements from other groups are marked in grey [6, 7]. The results of CTMC and statistical calculations from [6] are represented by dashed grey lines.

For the magnetic trapping data in Figure 3 the hardness ratios for the $Ar^{17+,18+}$ 100 V trap measurement are marked, using hollow triangles and circles, respectively. For comparison, a data point for Ar^{18+}/Ar charge exchange in a magnetic trapping experiment conducted at the LLNL EBIT is also plotted [6]. This result agrees with our own measurement for Ar^{18+} to within the error bars, demonstrating that the investigations at both EBITs were carried out under similar conditions. The hardness ratio for electron capture by Ar^{17+} in magnetic trapping mode is in the range of the values calculated for the corresponding extraction experiments. However, this is not necessarily indicative as simulations of the emission spectra for capture into different l states show that for Ar^{17+} capture the relative peak intensities do not in fact vary very strongly. This contrasts with spectra simulated for Ar^{18+} and indeed, the *in situ* hardness ratios for this projectile are much larger than any of those measured in the extraction experiments or predicted by the CTMC calculations. This suggests a significant difference in the population mechanism and/or the stabilization process for high-n capture states in the EBIT environment versus the controlled conditions of an external gas target experiment.

References

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