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X-ray Measurements of Charge Transfer Reactions Involving Cold, Very Highly Charged Ions

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Abstract

The magnetic trapping mode of the Livermore high-energy Electron Beam Ion Trap is exploited to study charge transfer reactions between cold (few eV/amu) highly charged ions and gases. By selectively puffing neutral gases and monitoring the X-ray emission, state-selective measurements of the charge transfer reaction channels are possible. The observed K-shell X-ray spectra show prominent emission from high-n levels decaying to the n=1 ground level, which is enabled by electron capture into states with low orbital angular momentum. A comparison with modeling calculations, therefore, allows a determination of the range of principal and angular momentum quantum numbers involved in the reaction.

1. Introduction

Charge transfer reactions between neutrals and ions are important processes in a variety of laboratory and astrophysical settings. They are the dominating process during neutral beam heating in tokamaks [1,2] and in the plasma-wall or plasma-divertor transition region in most magnetic plasma confinement systems. They are the cause of X-ray emission at the intersection of solar wind and cometary comae [3]. Charge transfer reactions can strongly affect the ionization balance in plasmas. They lead to prominent line radiation, and the resulting radiation can be used as a plasma diagnostic [4]. The need for accurate measurements of charge transfer reactions is especially strong for those involving highly charged ions at very low collision energies where no experimental data exist.

Recently, a new mode of operation of the high-energy electron beam ion trap (SuperEBIT) at Livermore was introduced [5,6]. In this mode, dubbed the magnetic trapping mode, the electron beam is turned off after production of very highly charged ions in the usual mode of operation and SuperEBIT is operated like a Penning trap. In the absence of the electron beam, the ions are confined in the 3-T magnetic field generated by superconducting Helmholtz coils and the potential applied to the outer trap electrodes. Using this mode of operation, we have begun to study charge transfer reactions between very highly charged ions confined in the trap and neutral gases injected into the trap.

The temperature of the ions in the trap is about 100–800 eV, or about 1–3 eV/amu. This means that our technique allows us to study charge transfer reactions in a regime inaccessible to earlier studies. Moreover, we have a direct line of sight into the interaction region. This allows us to record the spectra produced in the reaction.

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In the following we present X-ray spectra resulting from charge transfer reactions between neutral krypton atoms and hydrogenic and bare krypton ions as well as between neutral neon atoms and hydrogenic uranium ions. The resulting spectra show prominent X-ray emission of the highly charged ions from high-n levels decaying directly to the n=1 ground level, indicating a limited spread among orbital angular momentum values associated with the capturing n levels. These results at the present low ion velocities differ significantly from accelerator-based studies involving fast ion beams where the Lyman emission from high-n levels is minimal [7].

2. Experimental arrangement and results

An electron beam ion trap uses a magnetically compressed electron beam to produce and confine highly charged ions inside a cylindrical trap. In the electron trapping mode, the ions are trapped in the space charge of the electron beam, which gives rise to a radial potential, and an axial trap formed by the potential applied to the top and bottom drift tubes, i.e. the electrodes below and above the trap region.

The present measurements are performed in the magnetic mode. This trapping mode is achieved by turning the electron beam off after it has been applied for ion production. The ions are still trapped: radially by the vertical magnetic field and axially by the potential applied to the top and bottom drift tubes.

After electron impact ionization in the electron trapping mode, the system is switched to the magnetic trapping mode, as shown schematically in the timing sequence in Fig. 1. Finally, we discontinue trapping altogether in order to empty the trap and prepare for a new cycle.

During both trapping modes, we record the X-ray emission from the trap using a high-purity Ge detector. During the electron trapping mode, the X-ray emission stems predominantly from electron-impact excitation, i.e., the interaction between the ions and the electron beam. During the magnetic trapping mode, X rays are produced by charge exchange reactions, i.e., the interaction between the ions and neutral gases. The latter are injected radially into the trap via a ballistic gas injector. We operate the injector either in a continuous mode [6] or in a pulsed mode [8].

The X-ray emission from highly charged krypton ions (Kr^{34+}, Kr^{35+}) measured during the two phases of operation (electron trapping, magnetic trapping) is shown in Fig. 2.

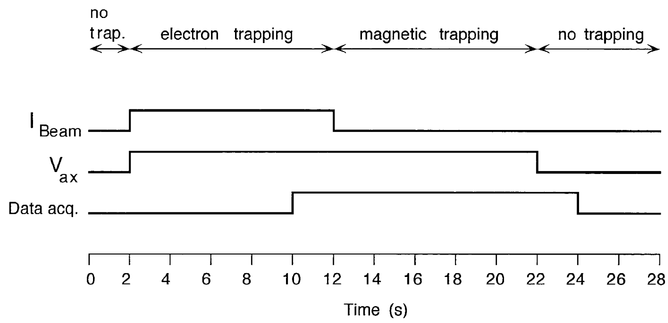

Fig. 1. Timing sequence. $I_{\rm Beam}$ denotes the beam current through the trap. V_{ax} denotes the trapping potential applied to the outer trap electrodes. Spectral data were acquired during the time indicated by the lower trace.

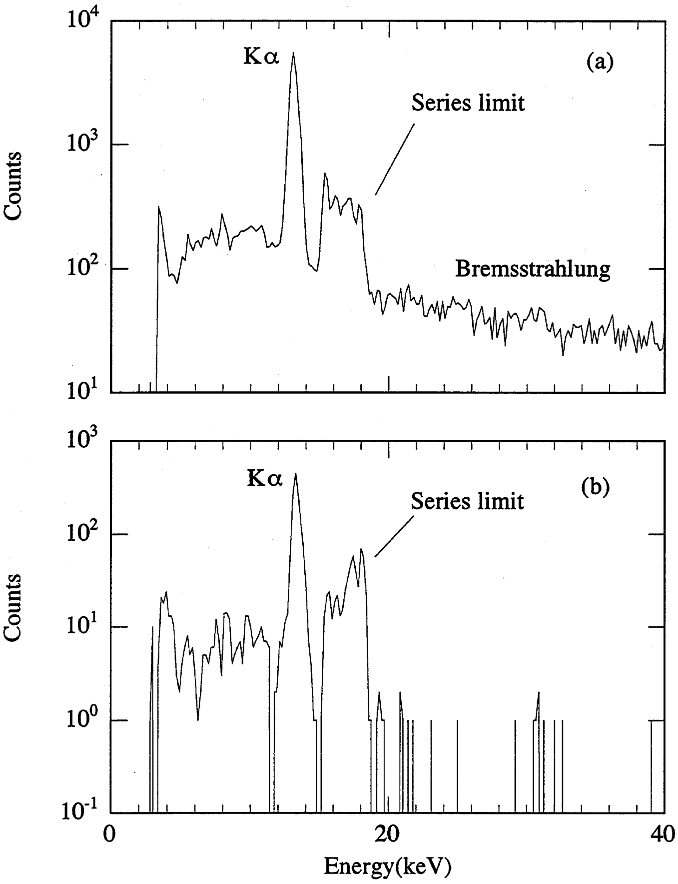

Fig. 2. X-ray spectra recorded during the (a) electron, (b) magnetic trapping mode. A continuous flow of atomic krypton was ballistically injected into the trap during the measurements.

While there is strong Bremsstrahlung emission in the electron trapping mode, it is absent during the magnetic mode, indicating the absence of the electron beam. The magnetic trapping mode spectrum, however, clearly shows emission from krypton. Because there is no electron beam this X-ray emission can only be produced by charge exchange reactions with neutral gases streaming into the trap region. The emission seen at energies below the K-shell emission of krypton is from L-shell emission of barium, which is a contaminant in the trap. An X-ray emission spectrum from U^{90+} obtained by application of neutral neon during the magnetic trapping duration is shown in Fig. 3.

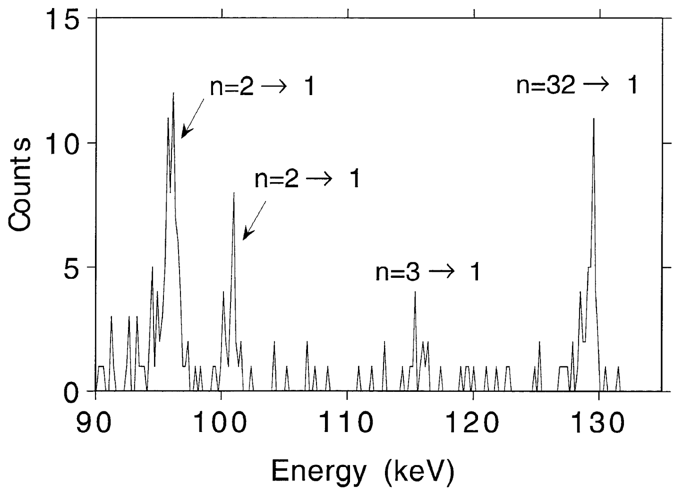

Fig. 3. K-shell X-ray spectrum of uranium recorded during the magnetic trapping mode. The spectrum shows the K-shell X-ray emission caused by charge exchange reactions between atomic neon and hydrogenic U^{91+}. Neon was puffed into the trap in a short pulse.

3. Discussion

K-shell X-ray emission can only be produced if the trapped ions have a K-shell vacancy. Since there is no excitation mechanism present in the magnetic trapping mode, all trapped ions are in their ground state and, thus, K-shell X-ray emission depends on the presence and recombination of bare or hydrogenic ions. The process is:

$$A^{q+} + B^0 \to A^{(q-1)+*} + B^+, \quad (1)$$

$$A^{(q-1)+*} \to A^{(q-1)+} + h\nu. \quad (2)$$

Note that the K-shell X-ray emission recorded in the magnetic mode looks different from that in the electron mode. The main difference is an enhanced emission near the series limit. Moreover, emission asscociated with transitions emanating from the n=3 shell is reduced. Innershell excitation of Li-like or Be-like ions that contributes to the spectrum recorded during the electron trapping mode is completely absent in the magnetic mode.

The fact that charge exchange is responsible for the X-ray emission produced in the magnetic trapping mode can be checked by changing the gas pressure that controls the influx of neutral gases into the trap. In Ref. [6] it was shown that the ion storage time during the magnetic mode decreased as the neutral gas pressure was increased. Charge exchange was, therefore, determined to be the dominant ion loss mechanism during the magnetic trapping mode.

We note that the high-n K-shell lines are slightly shifted from the series limit. This is expected from energy conservation, which for charge exchange with hydrogen predicts capture into levels with n=16, 17 for krypton and n=31, 32, 33 for uranium.

The fact that the K-shell emission from the high-n levels is so pronounced is the result of the low center of mass energy of the collision. The ion temperature in EBIT is below 1 keV. This means that the energy of the ions is only a few eV/amu. This is much less than in typical ion-beam neutral collision studies performed on accelerators. Unlike in high-energy

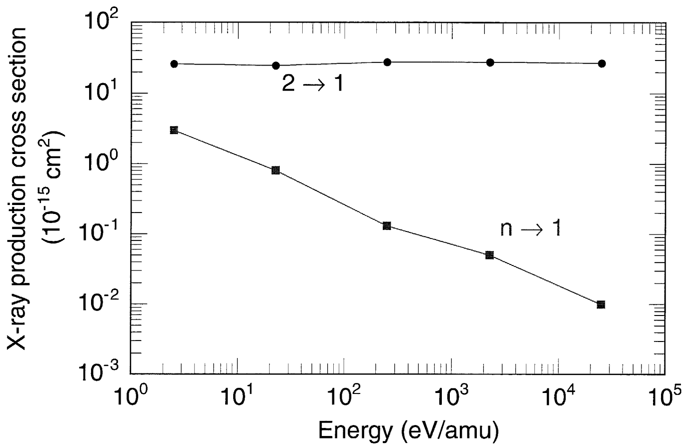

Fig. 4. Calculated X-ray production cross sections of bare xenon ions interacting with atomic hydrogen as a function of the interaction energy. The intensity of X rays from high-*n* levels strongly depends on the value of the interaction energy.

collisions where capture populates high angular-momentum states statistically, capture in low-energy reactions proceeds to low angular-momentum states ($\ell \leq 2$) [9]. As a result, the captured electron has a much higher probability to radiatively decay directly to the 1s ground state.

The results from Monte-Carlo calculations [10,11] of Xe^{54+} interacting with neutral hydrogen are shown in Fig. 4. The calculations show that the X-ray emission from high-n levels directly to the 1s ground level increases strongly as the ion temperature is lowered. The emission from the n=2 level, by contrast, is nearly constant. As a result, the emission from $n \to 1$ transitions is enhanced relative to the $2 \to 1$ emission. Because the ground level has an angular momentum of $\ell = 0$, this is equivalent to saying that capture into an $\ell = 1$ (p) orbital is favored at lower collision energies. The predicted enhancement is in agreement with our measurements. In fact, our studies find an enhancement of the $n \to 1$ emission relative to the $2 \to 1$ emission that exceeds that predicted by the calculations.

4. Conclusion

The present measurements demonstrate that systematic studies of charge transfer processes involving cold, very highly charged ions can be performed when operating an electron beam ion trap in the magnetic mode. Recording the K-shell X-ray emission following electron capture allows the determination of the n quantum number of the captured electron from the energy of the X-ray transition produced in the direct decay to the 1s ground level. Moreover, the ratio of $n \to 1$ and $2 \to 1$ decay enables estimates of the angular momentum quantum number. Such measurements can, therefore, provide stringent tests of theory. Further studies are planned to fully exploit these new capabilities.

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