X-ray Emission From Electron Capture By Highly-Charged Ions

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Abstract

Recently, electron capture by highly-charged ions has been recognized as the major source of X-ray emission from comets. It has been proposed that highly-charged ions of minor solar wind species such as C, N, O, and Ne emit X-rays following electron capture from cometary atoms and molecules such as H, CO, OH, H_2O, and CO_2. In our work we have measured accurate cross sections for single and multiple electron capture by solar wind ions in collision with various gas targets. We have also observed X-ray Lyman transitions from H and He-like ions formed in the capture process. The importance of multiple transfer, autoionization and the *l*-distribution of initial capture states will be discussed in light of our results.

INTRODUCTION

Although electron capture in ion collisions with atoms or molecules has been studied for many years, interest in these collisions continues unabated, particularly at low collision energies (<< 1 a.u.). The need for total and state-selective cross sections has been recognized through recent discoveries in astrophysics, and in the quest for controlled nuclear fusion.

Heavy solar wind ions in highly-charged states are now being acknowledged as an important source of X-rays in the solar system, through electron capture with cometary, atmospheric and interstellar gases [1-11]. Electron capture also yields visible, UV and X-ray photons from bodies as diverse as Jupiter's Aurora [12-14], the interstellar medium, HII regions, and nebulae[15,16].

In magnetically-confined fusion devices, present efforts are focussed on understanding the divertor region which is needed to provide continuous operation of an ignited plasma. Gas is injected into the divertor to cool hot impurity ions before their removal from the system. Electron capture is thus an important process in the physics of tokamaks and as a diagnostic of plasma parameters.[17,18]

Comprehensive charge-transfer data are needed for analyzing these interactions, and the light emitted from the collisions. Although simple target systems, like H, H_2 and He, have been investigated for a number of projectile ions[19,20], there is still need for further study, particularly at low energies. In more complex targets, like H_2O, CO and CO_2 important to comets, studies have only recently been initiated.

If detailed studies of the line intensities observed from fusion or astrophysical plasmas are undertaken to characterize ion or neutral densities, then electron capture needs to be well understood. While state-selective cross sections are essential, consideration of autoionizing multiple capture and anisotropic emission of photons due to magnetic sublevel population can also be important.

We have designed an experiment to measure total cross sections for single and multiple electron capture, providing absolute results which can be used by modelers and other experimentalists. Installation of an X-ray detector has also allowed us to measure emission cross sections for soft X-ray transitions.

These cross sections can be applied directly to the analysis of line strengths observed in X-ray spectroscopy of plasmas. Total cross sections have been obtained for collisions of C, N, O and Ne ions with various gases. X-ray spectra of Lyman-like transitions following one electron capture have been measured.

EXPERIMENTAL TECHNIQUE

The experimental setup has been described in more detail elsewhere[3,21], but a brief description follows. The ions of interest are produced from a *Caprice* type Electron Cyclotron Resonance ion source [22], capable of producing fully-stripped ions of C, N, O and Ne. The ions are accelerated to an energy of $7q$ keV (q is the ion charge state) and the desired ion is selected by a double-focussing 90° bending magnet. An electrostatic switcher directs the beam into the charge exchange beamline. There, the beam is collimated before entering a collision cell containing the target gas. On exiting, the ion beam current is measured in a deep Faraday cup. The pressure in the cell is determined by a temperature-stabilized capacitance manometer, while separation of different final ion charge states is achieved by a series of retarding potential apertures in front of the Faraday cup. A high-purity Ge X-ray detector is located at 90° to the ion beam direction and views the interactions through a 2 mm aperture in the cell wall. A 7.5 μm Be window separates the detector from the vacuum chamber, and blocks any photons of energies less than 500 eV.

RESULTS

Total cross sections for single and double charge exchange are shown in Figure 1 (and will be reported in detail elsewhere [21]). There, single-exchange values are compared, as a function of ion charge state, to predictions of the classical over-barrier model [23]. It can be seen that although this model gives a good estimate of the cross section, the discontinuities caused by filling of the next highest n-level are not reproduced. This suggests that one cannot assume that capture occurs into a unique n-level.

Double-exchange cross sections are also shown in Figure 1. For a CO_2 target it can be seen that these cross sections are a significant proportion of single exchange, typically 20-30%. However for He, with the exception of $q = 4$ where single exchange is very low, the double-exchange cross sections are relatively much smaller. As He has only two electrons, double exchange proceeds only by capture of two electrons which subsequently radiatively stabilize. While autoionization is often the preferred mode of decay in a multiply-excited ion, double-exchange cross sections in CO_2 are more significant as the process of multiple capture followed by emission of one or more Auger electrons is available.

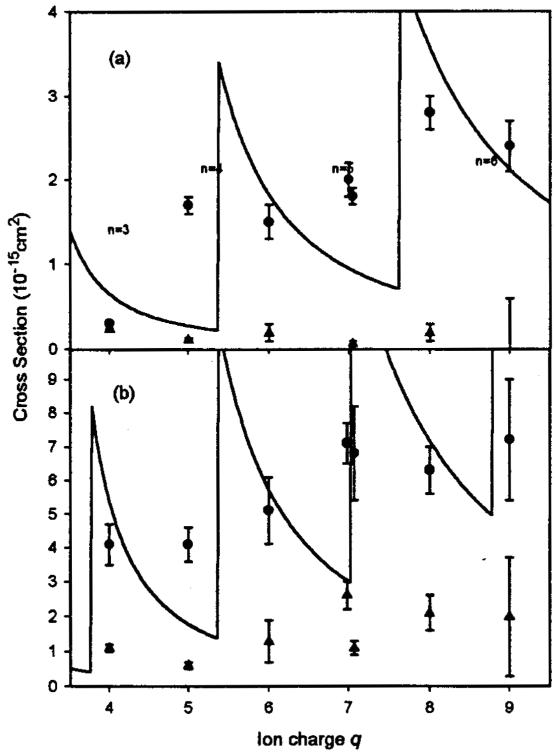

FIGURE 1. Single $\sigma_{q,q-1}$ ●, and double $\sigma_{q,q-2}$ ▲, charge-exchange cross sections as a function of ion charge state q, in collision with (a) He and (b) CO_2. Comparison is made to the predictions of the classical over-barrier model $\sigma_{q,q-1}$ (solid line).

X-ray spectra for collisions of bare and H-like O and Ne ions in He are shown in Figure 2. These spectra are uncorrected for transmission of the detector's Be window. The observed peaks represent transitions to the ground state of the q-1 ion from np levels and have been fitted by Gaussian profiles representing the energy resolution of the detector. It can be seen that when the transmission of the Be window is taken into account, the lowest-energy transition Ly α ($2p$ – $1s$) is the dominant one, having been populated entirely by cascades from higher levels. Collisions of Ne^{10+} demonstrate the existence of a Ne^{8+} transition generated from radiative stabilization of double capture (the small low energy peak in Figure 2).

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For O^{7+} and Ne^{9+}, capture of a single electron can occur into triplet or singlet levels of the He-like ion. However, transitions to the ground state (ones energetic enough to be transmitted by the Be window) can only be observed from short-lived singlet levels, with the exception of the intercombination transition $1s2p\ ^3P_1 - 1s^2\ ^1S_0$. Decays of the long-lived, metastable triplet states $1s2s\ ^3S_1$ and $1s2p\ ^3P_{0,2}$ proceed outside the viewing angle of the detector.

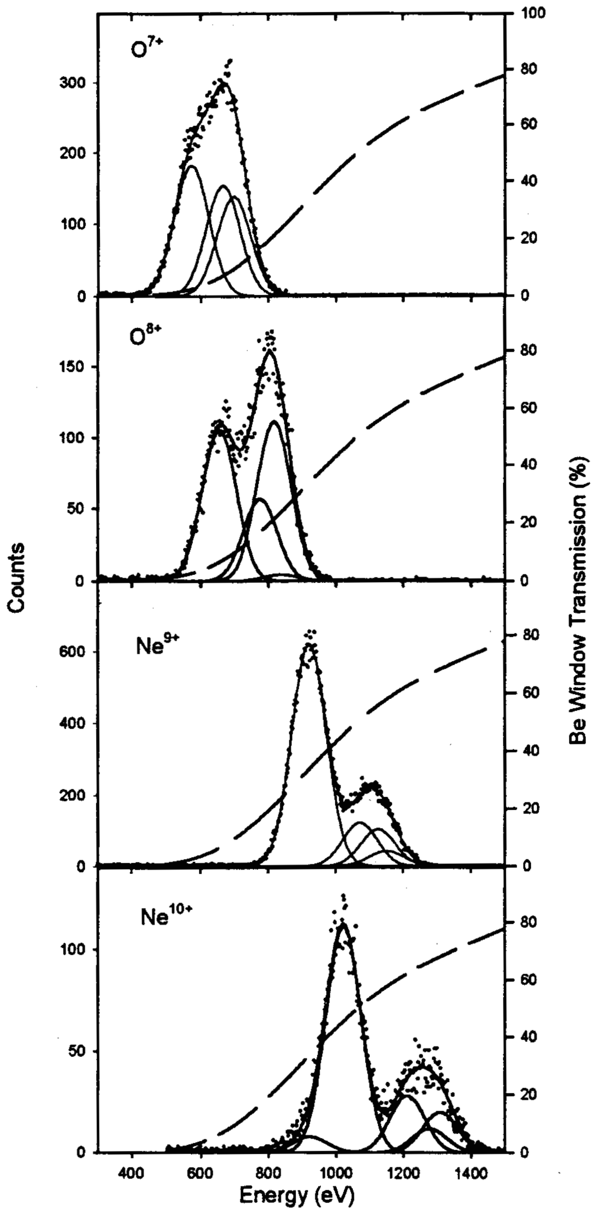

FIGURE 2. X-ray emission spectra obtained for collisions in He, fitted to the known transition energies of the product ions by a Gaussian profile. Data are uncorrected for transmission of the Be window (given as the long dashed line).

From analysis of the branching ratios for H-like ions produced from single capture by O^{8+} and Ne^{10+}, it is clear that capture into states with higher values of l tends to result in population of the $2p$ level, thus strengthening the Ly α emission intensity. However, our results indicate that the relative intensity of the Ly α lines is not as large as that expected from the assumption that the l levels are statistically populated.

Using an analysis similar to that used by Vernhert et al. [24], the average value of the initial angular momentum state $\langle l \rangle$ for collisions of Ne^{10+} in He is 2.1, compared to the statistical average of 2.8 for capture into n=5. This result agrees with the predictions of Burgdörfer et al. [25] who extended the over-barrier model to include a centrifugal barrier term.

CONCLUSION

Measurements of total cross sections for single and double charge exchange in collisions of charge states of C, N, O and Ne in He and CO_2 are reported at a collision energy of $7q$ keV. The limitations of the classical over-barrier model in accurately determining cross sections, and the significant contribution of double exchange in collisions involving many-electron targets have been highlighted. X-ray emissions from these collisions have been observed. The dominant transition is $2p - 1s$, the strength of which is determined from the distribution within initial capture states nl. Analysis has shown that a statistical distribution within l-states would give stronger Ly α transitions than are observed. This suggests that the collision velocity is too low to give the captured electron enough angular momentum to statistically populate f and g states.

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