Multiple Charge Transfer by Slow Multi-Charged Xe Ions

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Abstract. Electron capture processes between low energy multi-charged ions and atoms are studied by an energy loss spectroscopy technique. Energy-loss spectra of charge-state-changed projectile ions scattered in the forward direction in collisions of Xe\(^{q+}\) (up to \(q=11\)) ions with He and Ar atoms have been measured at a collisional energy of 9 keV. The results are discussed using the classical over-barrier model.

1. Introduction
Charge transfer reactions between multi-charged ions and atoms are of both theoretical and practical interest. Light emission from Xe plasmas has received considerable interest in connection with a source of 13.5 nm light for EUV lithography. However, few works have been reported on the energy levels of highly charged Xe ions, and on the charge-changing reactions in high-temperature Xe plasmas. In the case of simple systems such as naked-ions and H atom, the predictions of the classical over-barrier model (COBM) agree well with experimental results [1-3]. On the contrary, multi-electron transfer processes occur for the reactions between multi-charged ions and many-electron

![Figure 1. Schematic view of the apparatus.](image)
atom targets. Such multi-electron processes are still far from being understood in the term of a rigorous theoretical treatment.

In this paper, experimental results for the charge transfer reactions of Xe\(^{q+}\) (up to \(q=11\)) ions, where \(q\) is the charge of the projectile ion, with He and Ar at 9keV obtained by an energy loss spectroscopy technique are presented.

2. Experiment

Figure 1 shows a schematic view of the apparatus. The multi-charged ions are generated by a 10 GHz ECRIS (NANOGAN). Extracted ions are selected according to \(m/q\) values using an analyzing magnet and injected into a collision chamber. The ion beam is interacted with an effusive target gas after the ion-beam energy is monochromatized by a tandem-type energy selector. Scattered ions in the forward direction are detected by an energy analyzer. The energy selector and analyzer are the same type of 52-mm radius hemispherical electrostatic analyzer. The energy resolution \(\Delta E\) of this experiment is about \(q \times 2\) eV.

3. Results and Discussion

The energy-spectroscopic measurements have been made for multi-charged Xe\(^{q+}\) \((q = 7-11)\) ions at the energy of 9 keV. Figures 2 and 3 show the measured energy spectra for single-electron capture processes of Xe\(^{q+}\) with He and Ar, respectively. The values of the energy gain don't depend strongly on the charge state \(q\) for both cases. The energy levels of the Xe ion given by Saloman [4] are shown in the figures. These levels are those of charge-changed Xe ions assuming that the target ions are in their ground states. As is seen from Fig. 3, some structures are observed in the spectra for an Ar target.

The measured energy spectra for double-electron capture are shown in figures 4 and 5. The energy levels of the Xe\(^{(q-2)+}\) product ion are also shown in the figures. In this case, the values of energy gain depend on charge state \(q\) for both cases.

The energy gains can be estimated from the COB model. The binding energies \(E_i\) of the transfer

![Figure 2](image-url)  
**Figure 2.** Energy gain spectra of scattered ion for the one-electron capture processes, Xe\(^{q+}\) + He → Xe\(^{(q-1)+}\) + He\(^+\), at incident energy 9 keV. The arrows in the figure indicate the energy gain estimated from the COB model.

![Figure 3](image-url)  
**Figure 3.** Energy gain spectra of scattered ion for the one-electron capture processes, Xe\(^{q+}\) + Ar → Xe\(^{(q-1)+}\) + Ar\(^+\), at incident energy 9 keV. The arrows in the figure indicate the energy gain estimated from the COB model.
electron in the Xe ions are given by

\[ E_i = I_i + \frac{Z_i^*}{R} - \frac{Z_t^*}{R} \]  

(1)

Here, \( R \) is the nuclear distance satisfying the over barrier condition, \( Z_i^* \) the effective charge of projectile ion, \( Z_t^* \) the effective charge of target atom, and \( I_i \) the ionization energy of target [2]. The hydrogenic approximation for the effective charge,

\[ Z^* = n \left( \frac{I}{I_H} \right)^{1/2} \]  

(2)

will not introduce large errors. Here, \( I_H \) is the ionization potential of H atom, and \( I \) the ionization potential of the ions or atoms, \( n \) the principal quantum number. For the case of double-charge transfer, we assume independent electron model and sequential electron transfer [3]. Thus the energy gain \( Q \) is given by

\[ Q = \sum_{j=1}^{2} (E_j - I_j) \]  

(3)

where \( E_j \) denotes the binding energies for first and second electron given by equation (1), and \( I_j \) the ionization energy of those electrons in the target atom.
The arrows in figures 2-5 show the calculated energy gains. For the He target case, the agreements between experimental and theoretical values are fairly good for both single- and double-electron transfer. However, the estimated energy gains are a little smaller than the experimental one for single transfer, and a little larger than those for double transfer. For the Ar target case, the agreements are not so good for both cases. The estimated energy gain depends strongly on the target effective charge. It seems that the equation (2) overestimates the effective charge for many electron targets such as Ar. Another possible reason for this discrepancy is that it is possible for the product Ar ions to be in their excited states. The electron transfer from 3s states of Ar target gives larger binding energies and larger energy gains. However, this effect is smaller than that of the effective charge.

For the processes in which many electrons participate, the electron correlation effects should be taken into account. The COB model is somewhat oversimplified to deal with the electron correlation. The theoretical studies of electron correlation effects are required for an understanding of multi-charge transfer processes.

Figure 6 shows the ratios of double capture intensity to single one as a function of charge state $q$. The ratios change largely between $q=8$ and $q=9$. This may be attributed to 4d hole of the $\text{Xe}^{9+}$ ion. Since double capture may be followed by autoionization (transfer ionization), observed single-electron capture processes contain both single and double capture processes. The probability of transfer ionization becomes large due to the 4d hole for $q \geq 9$ ions.

The coincidence measurements between the projectile and the recoil ions using a time-of-flight mass spectrometer (TOF-MS) in the apparatus would be performed near future. Indeed, these measurements would help to differentiate the true double capture and the transfer ionization.

![Figure 6](image.png)

**Figure 6.** The ratios of double capture intensity to single capture as a function of charge state $q$. solid triangles : Ar target, solid circles :He target.

References

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