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Multiple ionization of argon accompanied by electron loss and capture of 0.22–6.35 MeV C^{q+} ions*

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In this paper a projectile ions–recoil ions coincidence technique is employed to investigate the target ionization and projectile charge state changing processes in the collision of 0.22–6.35 MeV C^{q+} ($q = 1-4$) ions with argon atoms. The partial cross section ratios of the double, triple, quadruplicate ionization to the single ionization (or the single capture) of argon associated with single electron loss (or single electron capture) by the projectile are measured and compared with the previous experimental results. In the present experiment, it is observed that the ratios of ionization cross sections R associated with single loss and single capture depend strongly on the projectile charge state and vary significantly with different reaction channels as impact energy increases. In addition, this paper gets empirical scaling laws for the ionization cross section ratios R corresponding to the projectile single loss and finds that the ratios of the double ionization to the single ionization associated with single electron capture remain constant in the present energy range.

Keywords: multiple ionization, electron loss, electron capture, ion-atom collisions
PACC: 3450, 3470, 8230F

1. Introduction

Multiple-ionization processes of atoms resulting from fast charged projectile impact have been extensively studied in the past two decades. Although single ionization induced by fast bare-ion impact is well understood quantitatively and can be satisfactorily described by using the first Born approximation,[1−3] multiple electrons processes such as multiple ionizations and charge-exchange phenomena are often difficult to describe even qualitatively, which are associated with many-body problems in ion–atom collisions. Theoretical approaches describing the many-electron Coulomb interaction are simplified by several approximations.[4,5] The shake-off model based on perturbation theory and the two-step mechanism based on the independent electron model are used to describe the double ionization process at different energy regions.[6−9] In fact, for ionization induced by partially stripped ions, the situation is very complicated: the electron-correlation effects and electron–electron interaction in multiple ionization process appear to play an important role at intermediate energies.

Considerable experimental and theoretical investigations have been made on ionization of two-electron system by fully and partially stripped projectile impact.[10−16] For many-electron targets, there are few experimental data about multiple ionization involving heavier dressed ions.[17,18] In this work, the cross section ratios of multiple ionization to single ionization (or single capture) corresponding to single electron loss and capture by the projectile are measured for 0.22–6.35 MeV C^{q+} ($q = 1-4$) ions impact on argon atoms. The aim of the present work is to investigate the multiple ionization mechanism of argon in the intermediate energy range. We compare the velocity and charge-state dependences of the ratios of the multiple ionization cross sections.

In this article, we discuss the experimental results for the following reaction channels:

(1) $C^{q+} + Ar \rightarrow C^{(q-1)+} + Ar^{1+}$, pure single capture (SC);

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(2) $C^{q+} + Ar \rightarrow C^{(q-1)+} + Ar^{2+} + e$, single ionization–single capture (SI-SC);

(3) $C^{q+} + Ar \rightarrow C^{(q-1)+} + Ar^{3+} + 2e$, double ionization–single capture (DI-SC);

(4) $C^{q+} + Ar \rightarrow C^{(q-1)+} + Ar^{4+} + 3e$, triple ionization–single capture (TI-SC);

(5) $C^{q+} + Ar \rightarrow C^{(q+1)+} + Ar^{1+} + 2e$, single ionization–single loss (SI-SL);

(6) $C^{q+} + Ar \rightarrow C^{(q+1)+} + Ar^{2+} + 3e$, double ionization–single loss (DI-SL);

(7) $C^{q+} + Ar \rightarrow C^{(q+1)+} + Ar^{3+} + 4e$, triple ionization–single loss (TI-SL);

(8) $C^{q+} + Ar \rightarrow C^{(q+1)+} + Ar^{4+} + 5e$, quadruplicate ionization–single loss (QI-SL).

Here q ($q = 1 - 4$) is the charge state of incident ions. Process (1) corresponds to pure single capture, while processes (2), (3) and (4) correspond to single, double and triple ionization of argon atoms associated with the single projectile electron capture. Processes (5)–(8) correspond to single, double, triple and quadruplicate ionization of argon atoms associated with the single projectile electron loss.

2. Experimental setup

The present experiments were performed at the 2×1.7 MV tandem accelerator in department of modern physics, Lanzhou University. The experimental apparatus used in the present experiments have been described in detail elsewhere.[19,20] In brief, the beams of 0.22–6.35 MeV C^{q+} ($q = 1 - 4$) ions were extracted and then charge state analysed by bending magnet. After well collimated with two two-dimensional apertures of 0.2×0.2 mm^2 (two metres between them) to ensure that the divergence of the beam was smaller than 0.01°, the beams passed through the collision chamber crossing with argon atoms. In order to guarantee the single collision condition, the gas pressure in the target chamber was kept at 2.66×10^{-2} Pa and the background vacuum was maintained to be better than 2.66×10^{-4} Pa. The recoil ions were accelerated out of the collision region by an electrostatic field and passed through a field free drift tube. Upon reaching the end of the flight tube, the recoil ions were further accelerated into a microchannel plate detector in a chevron configuration which was held at a potential of -3 kV and provided start signals for time-to-amplitude converter (TAC). After charge states analysed by a parallel-plate electrostatic field, scattering carbon ions were detected by a one-dimensional position-sensitive detector. The scattered projectiles from the same collision events provided delayed stop signals for TAC, ionized recoil ions were selectively identified and distinguished from background by time-of-flight analysis. A MPA-3 data acquisition system was used to record the events in the same collision.

Cross sections are denoted by $\sigma_{qq'}^{0n}$, where the superscript n denotes the final charge state of the target atom, the subscript q and q' denote the initial and final projectile charge state respectively. In this work, we also determine the ratio

$$R_{n1}^{\mathrm{SC/SL}} = \frac{\sigma_{qq\pm1}^{0n}}{\sigma_{qq\pm1}^{01}} = \frac{\varepsilon_1}{\varepsilon_n} \times \frac{N_n}{N_1}$$

between the n-fold ionization and the single ionization (or the single capture) cross sections associated with single electron loss (or single electron capture) by the projectile, where N_n and N_1 are the peak areas of the coincident channel of multiple ionization, the superscript SC and SL are associated with single electron capture and single electron loss by the projectile respectively. The efficiency of detecting recoil ion is determined to be $\varepsilon_1/\varepsilon_2 = \varepsilon_1/\varepsilon_3 = \varepsilon_1/\varepsilon_4 = 0.53061$.[21] The error of the ratio of cross section comes mainly from statistic error ($5\% - 15\%$) and the uncertainty of the calibration of the detector efficiency ($< 8\%$).

3. Results and discussion

The cross section ratios for target ionization plus single electron loss and for target ionization plus single electron capture are of special interest. Post-collisional Auger-type processes have been taken into account, since they are expected to take place in the present impact energy range. According to the binary-encounter-approximation,[22] the C^{q+} ions do not have enough impact energy to ionize the K-shell electrons of argon atoms in the present energy region. Multiple-ionization therefore seems to be the dominant process in exciting and ionizing the argon atom M and L shells in the investigated collision systems. Because it is difficult to distinguish the Auger-type processes experimentally, a theoretical method is used here to take the Auger-type processes into account, the details of this method is described in Ref.[20]. The experimental data after the Auger process correction are plotted in Fig.1–Fig.8.

The reduced cross section ratios of double, triple and quadruplicate to single ionization corresponding to single electron loss in collision of C^{q+} ($q = 2 - 4$)

ions with argon atoms are shown in Figs.1–3. In Fig.1 for the cross section ratio $R_{21}^{\rm SL}$ divided by $q^{0.45}$ versus impact energy, it is obvious to find that the reduced cross section ratio is in excellent agreement with the fitted dashed line within the experimental uncertainty of about 15%. Similar trends of $R_{31}^{\rm SL}$ divided by $q^{1.45}$ and $R_{41}^{\rm SL}$ divided by $q^{2.5}$ as a function of impact energy are displayed in Fig.2 and Fig.3. The experimental cross section ratios are consistent with the fitted dashed lines within the experimental error of about 10%, respectively. From the results of the fitted dashed lines, it can be found that $R_{21}^{\rm SL} \propto q^{0.45} \times \nu^{-0.60}$, $R_{31}^{\rm SL} \propto q^{1.45} \times \nu^{-1.15}$ and $R_{41}^{\rm SL} \propto q^{2.5} \times \nu^{-1.52}$. It is obvious that the ratios $R_{21}^{\rm SL}$, $R_{31}^{\rm SL}$ and $R_{41}^{\rm SL}$ are strongly dependent on the projectile charge state, which increase with the increasing projectile charge state respectively and decrease monotonically as impact velocities increase. The $R_{21}^{\rm SL}$ is up to 0.7 for C^{2+} ions, and about 0.85 for $C^{3,4+}$ ions, even the $R_{31}^{\rm SL}$ and $R_{41}^{\rm SL}$ are much larger than 1 at low impact energy (see Fig.4). In addition, for a given projectile charge state, it is found that $R_{31}^{\rm SL} > R_{41}^{\rm SL} > R_{21}^{\rm SL}$ in relatively low energy region is shown in Fig.4, we also find that the curves of the ratios $R_{21}^{\rm SL}$ for $C^{3,4+}$ ions cross each other at high impact energy, as well as the similar result of the ratios $R_{31}^{\rm SL}$.

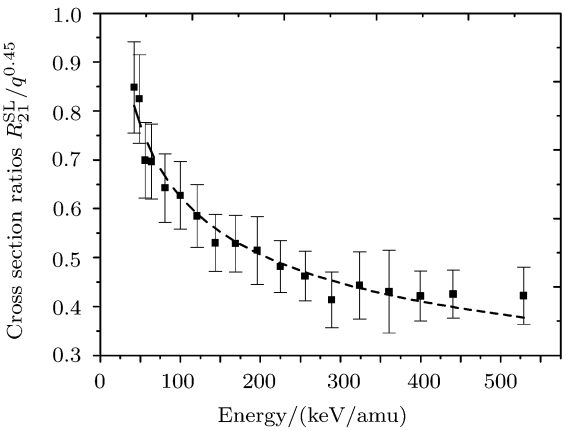


Fig.1. The reduced cross section ratio of double to single ionization associated with single electron loss for C^{q+} projectiles ($q = 2-4$). The dashed line is the least-squares fitted curve.

As we know, the physical scenario of the ionization process associated with electron loss by the projectile is due to two independent mechanisms:[23] (1) a two-step process in which the target is ionized by the screened projectile while the projectile is ionized by the screened target (loss ionization) and (2) the electron–electron interaction between the projectile and target active electrons results in the simultaneous ionization of both. As expected, loss ionization processes are dominant for high-charge-state projectiles at low velocities, electron–electron interaction dominates at high velocities and ionization cross section decreases sharply as the projectile charge state increases during the collision. As mentioned above, the first mechanism is the dominant mechanism at low velocities, so the cross section ratios of triple and quadruplicate to single ionization are larger than that of double to single ionization for multi-charged incident ions. The second mechanism is the dominant mechanism at high velocities and multiple-ionization cross section decreases sharply as the projectile charge state increases, so the ratio $R_{21}^{\rm SL}$ for C^{3+} ions at high impact energy is larger than that for C^{4+} ions, as well as the result of the ratios $R_{31}^{\rm SL}$ for $C^{3,4+}$ ions.

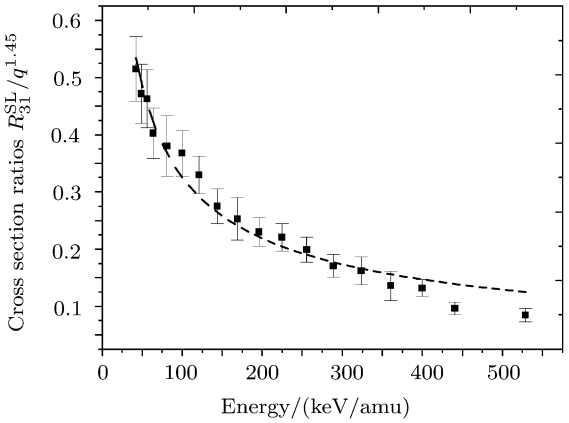


Fig.2. The reduced cross section ratio of triple to single ionization associated with single electron loss for C^{q+} projectiles ($q = 2 - 4$). The dashed line is the least-squares fitted curve.

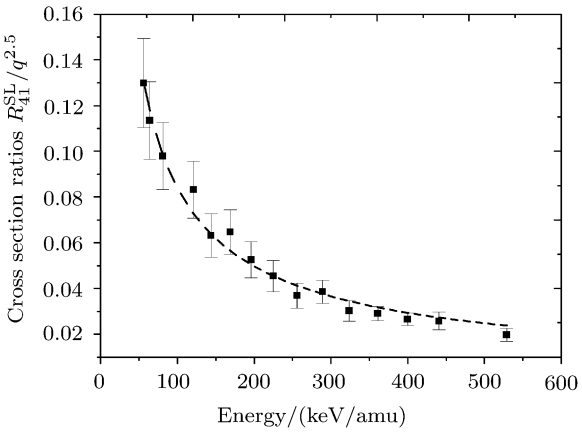


Fig.3. The reduced cross section ratio of quadruplicate to single ionization associated with single electron loss for C^{q+} projectiles ($q = 2 - 4$). The dashed line is the least-squares fitted curve.

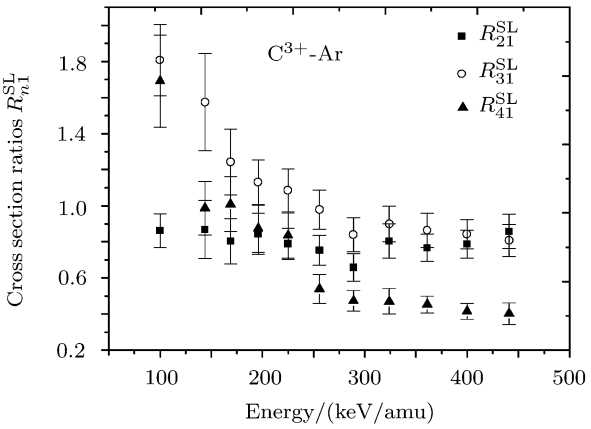


Fig.4. Ratios of n-fold ionization to single ionization cross section associated with single loss for C^{3+} projectiles incident on argon.

It is shown in Fig.5 that the cross section ratios of pure single electron capture to pure single ionization decrease rapidly as the increase of the impinging energy below 100 keV/amu, and decrease down to 0.3 when the energy is larger than 100 keV/amu. Compared with the ionization channels associated with no projectile charge change and single electron loss, the capture channel has smaller probability in the present energy region. However, transfer ionization probability is comparable to that of single capture as shown in Fig.6. It can be found that the ratio $R_{11}^{SC} > R_{21}^{SC} > R_{31}^{SC}$, and the ratios R_{n1}^{SC} $(n = 1, 2, 3)$ have maxima around 300 keV/amu for C^{3+} ions on argon atoms, which are different from the ratios R_{n1}^{SL} $(n = 2, 3, 4)$ as shown in Fig.4.

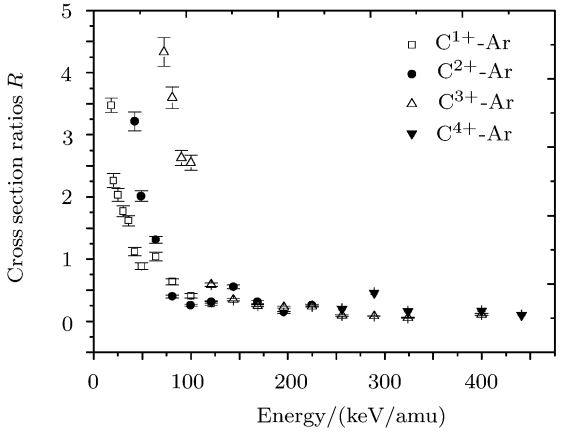


Fig.5. Argon cross section ratios of pure single capture to pure single ionization for C^{q+} $(q = 1 - 4)$ projectiles.

The data of this work are plotted in Fig.7 together with other experimental results on argon atoms. In Fig.7, the ratios R_{21}^{SC} increase not only as the energy increases but also as the charge state of the projectile increases for C^{q+} ions, which is in good agreement with the work of DuBois.[24,25] Moreover the corresponding energies of the peaks of the ratio R_{21}^{SC} for C^{q+} $(q = 1 - 4)$ shift to high impact energies with the increasing of the charge states of the projectile. As shown above, the ratio R_{n1}^{SC} $(n = 1, 3)$ depends also strongly on the charge state of the projectile and shows quite special feature different from that of the pure ionization.[15] The direct ionization cross section ratio is independent of the charge state of the projectile, only dependent on the nuclear charge of the projectile.

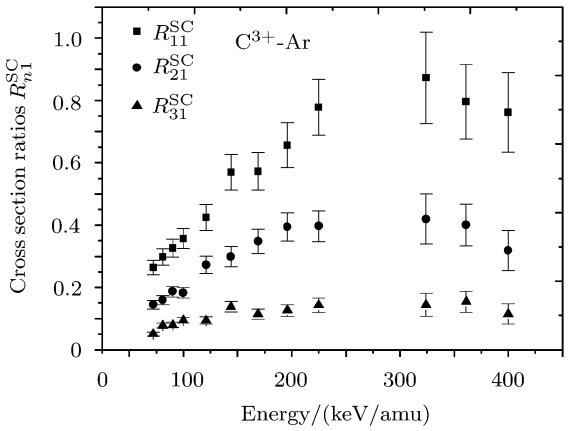


Fig.6. Ratios of n-fold ionization to single capture cross section associated with single capture for C^{3+} projectiles incident on argon.

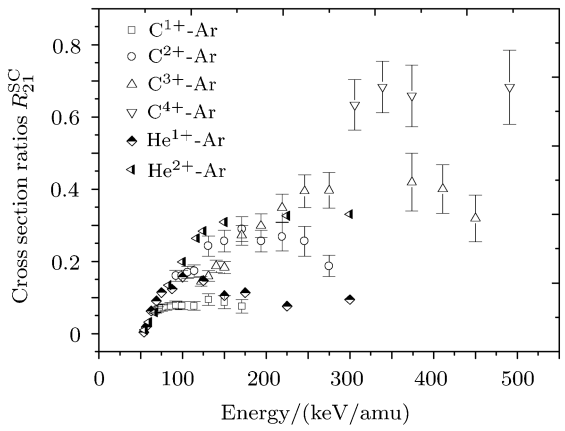


Fig.7. Ratios of double ionization to single capture cross section associated with single electron capture by several projectiles incident on argon. $C^{1,2,3,4+}$-Ar (this work); He^{1+} -Ar;[24] He^{2+}-Ar.[25]

As we know, pure ionization without charge change of the projectile often occurs at distant collision, while multiple-ionization accompanied by electron loss and electron capture by the projectile requires a small impact parameter collision. Based on

Bohr–Lindhard model,[26] the cross section for capture of electrons from heavy ions is given by the expression (for high velocities)

$$\sigma_{\text{capture}} = 8\pi Z_A^3 \Big(\frac{u_n}{a_n}\Big) v^{-7}, \qquad (1)$$

where Z_A is the nuclear charge of the projectile, v is the impact velocity, a_n and u_n are the Bohr-radius and the Bohr-velocity respectively.

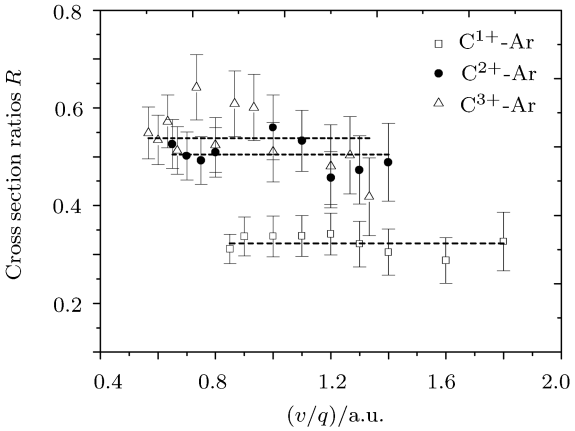


Fig.8. Ratios of double to single ionization cross section associated with single electron capture for $C^{1,2,3+}$-Ar. The dashed lines are the least-squares fitted curves for $C^{1,2,3+}$ ions.

The pure capture cross section decreases monotonically with the increasing impact velocities, and the multiple ionization cross section associated with single electron capture by the projectile has a maximum in the present energy region,[24,25,27] so the ratio R_{n1}^{SC} $(n = 1-3)$ increases first and then decreases as velocities increase. On the other hand, within the frame of the independent electron model, transfer ionization probability is the product of pure single capture probability and pure multiple ionization probability. So the ratio R_{n1}^{SC} $(n = 1-3)$ is proportional to the cross section of pure multiple ionization, which has a maximum at the present region [24,25,27] and since the multiple ionization cross section is proportional to the projectile charge state, the ratio R_{n1}^{SC} $(n = 1-3)$ thus increases with the increasing projectile charge state.

In Fig.8 for the cross section ratios of double to single ionization versus (v/q), these dashed lines are the fitted lines using $R = 0.32 =$ constant for C^{1+} ions and 0.50, 0.54 for C^{2+}, C^{3+} ions respectively. It can be found that the cross section ratios were in agreement with the fitted dashed lines within the experimental uncertainty of about 15%. It may suggest that the single ionization process accompanied by double ionization process results from auto-ionization effect of multi-electron target in the case of single electron capture by the projectile.

4. Conclusions

The partially cross section ratios of the double, triple, quadruplicate ionization to the single ionization (or the single capture) of argon associated with single electron loss (or single electron capture) by the projectile are measured for 0.22–6.35 MeV C^{q+}-Ar $(q = 1-4)$ collisions. We get empirical scaling laws for the ionization cross section ratios corresponding to electron loss by the projectile. It is observed that the ratios of ionization cross section R associated with single electron loss and single electron capture depend strongly on the charge states of the projectile and vary significantly with different reaction channels with the increasing impact energy in the present experiment, which is in good agreement with the results of the earlier work. These features are different from those due to pure ionization in which the direct ionization cross section ratios are independent of the charge state of the projectile, only dependent on the nuclear charge of the projectile. We also find that the ratio of the double ionization to the single ionization associated with single electron capture by the projectile keeps a constant in the present energy range.

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