Investigation of the transfer ionization process in collisions of partially stripped ions on He

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In this paper a projectile ion-recoil ion coincidence technique is used to investigate the transfer ionization processes in collisions of 0.22–6.30 MeV C^{q+} ions and 0.25–6.35 MeV O^{q+} ions ($q = 1, 2, 3, 4$) with the He atom separately. The cross section ratio f of transfer ionization to single electron transfer is measured, and the dependence of f on both charge state q and energy E of the projectiles is investigated. The electron-structure and the mechanisms leading to transfer ionization affect the dependence of f on q and E. Our measurements, along with other data published previously, suggest a similar dependence of f on charge state and energy of projectile for partially stripped ions over a large energy range. The maximum value of f is approximately $0.17q^{0.60}$; the energy corresponding to maximum f is about $160q^{0.60}$ keV/u.

Keywords: ion–atom collision, transfer ionization, single electron transfer

PACC: 3470, 3450

1. Introduction

In the collision of the ion A^{q+} with atomic He, the transfer ionization (TI) process and the single electron capture (SC) process may be indicated schematically by

$$A^{q+} + \mathrm{He} \rightarrow A^{(q-1)+} + \mathrm{He}^{2+} + e \ \text{(TI)}, \quad (1)$$

$$A^{q+} + \mathrm{He} \rightarrow A^{(q-1)+} + \mathrm{He}^{+} \ \text{(SC)}. \quad (2)$$

The sum of TI and SC cross sections is the single electron transfer cross section.

The collision of a charged ion with He is a classical multi-electron and multi-body problem, which is central to the understanding of various areas of physics, chemistry and biology. More experimental[1,2] and theoretical studies[3,4] of the single electron process in collisions of ions and atomic He have been done, and they are in good agreement. Much attention has been paid to multi-electron transition in atomic collisions in recent years to understand the electron–electron correlation in these processes. The simplest case where we can study these effects is a collision in which a bare nucleus P of charge Z_P is impinging upon a helium-like atomic system consisting of two electrons e_1 and e_2 initially bound to the target nucleus T of charge Z_T, i.e. $Z_P + (Z_T; e_1, e_2)$. In such collisions, TI is an important two-electron process. In order to understand the role of the electron correlation in ion–atom collisions, which is of great interest in basic atomic physics and may provide important information on the applications in both astrophysics and fusion plasma research, several investigators have studied this process both theoretically and experimentally in ion–atom collisions over the last few decades.[5−14] In these theories and experiments, different mechanisms of TI were proposed. The previous measurements of TI at very slow collisions ($\leq$1 eV/u) have shown that auto-ionization of the quasi-molecule formed during the collision can be important.[6] Auto-ionization of the projectile after double capture has also been proposed as a mechanism.[5,8] For high-charge ions on a high-Z target, multiple-ionization accompanied by multiple charge transfer has been observed and attributed to a statistical sharing of neutralization energy.[7] At intermediate and low impact energies, TI is normally considered to be an independent two-step process for ionization and capture.[10,11] Another model for TI involves the transfer of one or more electrons to a bound state accompanied by capture to a continuum state of the projectile.[9,14]

For ion–atom collisions at low energies, the major processes have been extensively studied by the classical over-barrier model,[6,15] and detailed insight into these reactions has been gained. The TI induced by

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slow ions has been intensively researched, but no functions were deduced definitely. The TI of atomic He induced by fast bare ions is also well understood and can be satisfactorily described theoretically. Good agreement is achieved between experimental results and theoretical results.[10,11] At intermediate collision velocities, TI may proceed via a few channels; most of the mechanisms are sensitive to collision energy. Though the channels leading to TI have been identified using advanced experimental methods and technologies, how much every channel contributes to TI remains unknown for all impinging charge states and energies. Up to now, there has been no suitable theory or model to perfectly describe the TI process in this region. Introduction of partially stripped ions in collisions makes the situation more complicated. Due to so many difficulties, the TI process has not been well explored experimentally and theoretically in this energy regime.

In this work, the coincidence event counts of TI and SC are measured in collisions of 17.92–120.03 keV/u C^+, 30.01–321.41 keV/u C^{2+}, 71.67–437.47 keV/u C^{3+}, 286.69–524.77 keV/u C^{4+}, 15.87–80.35 keV/u O^+, 30.01–253.95 keV/u O^{2+}, 63.49–321.41 keV/u O^{3+}, and 286.69–396.80 keV/u O^{4+} with He. In order to compare our measurements with the previously published results easily, the values of cross section ratio f of TI to single electron transfer other than the cross section ratio of TI to SC are given, and the dependence of f on the projectile charged state q and energy E (keV/u) is investigated empirically.

2. Experiment

The experiments were performed on a 2×1.7 MV tandem accelerator in the Department of Modern Physics, Lanzhou University. The experimental apparatus used in present experiments has been described in detail elsewhere.[16,17] Ions produced by a sputter ion source were accelerated in an accelerating tube and selected by a 30° magnet. After energy- and charge-selections by the magnet, the beams were carefully collimated with two two-dimensional apertures of 0.2×0.2 mm^2 (separated by two meters) to ensure that the divergence of the beam was smaller than 0.01°, and then crossed a thermal beam of target gas emerging from a small hollow needle with inner diameter 1 mm. In order to guarantee the single collision condition, the pressure in the collision region was kept at 2.66×10^{-2} Pa and the background vacuum was maintained at better than 2.66×10^{-4} Pa. The scattered ions were collected by a one-dimensional position-sensitive multi-channel plate (PSMCP) detector after charge separating by a parallel-plate static electric field next to the gas chamber, so that we could deflect the scattered projectiles in different charge states to different positions. The recoil ions produced in the collision were accelerated out of the collision region by an electrostatic field of 1 kV and passed through a field free drift tube. Upon reaching the end of the flight tube, the recoil ions were further accelerated into a micro-channel plate MCP detector in a chevron configuration which was held at a potential of –3 kV and provided start signals for a time-to-amplitude converter (TAC). The scattered ions from the same collision event provided delayed stop signals for the TAC. With the signal of the recoil ions used as a start signal and the delayed scattered projectile signal as a stop signal, a multi-parameter acquisition (MPA) system[13,16,17] was used to record the events of the scattered projectiles and the recoil ions in definite charge states produced in the same collision.

A typical two-dimensional spectrum is shown in Fig. 1 for a 1.03 MeV C^{3+}–He collision. The abscissa is the position coordinate representing the charge state of the scattered projectile. The Y-ordinate is the time coordinate indicating the charge state of the recoil ion. The events of SC and TI can be definitely identified. All peaks in Fig. 1 are well resolved from each other and reside well above the background. In the TI and SC processes, the scattered ions arrive at the same position in the PSMCP, therefore the scattered ion detection efficiencies are the same. The recoil ion detection efficiency $\eta = B_{\rm f}/B_{\rm i}$, where $B_{\rm i}$ is the beam intensity before detecting, and $B_{\rm f}$ is the detected beam intensity. The recoil detection efficiency is different at different places on the MCP. Recoil ions He^+ and He^{2+}

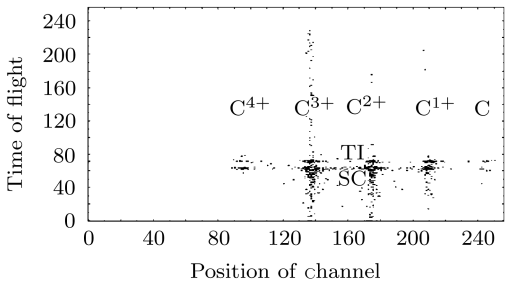


Fig. 1. Two-dimensional spectrum for 1.03 MeV C^{3+}–He.

arrive at two positions on the MCP. Here, η_1 and η_2 are the local detection efficiencies for He^+ and He^{2+} respectively. The recoil ion detection efficiencies are

unknown experimentally in our work. By normalizing our measured cross section ratio of total He^{2+} to total He^{+} for C^{3+}–He at a certain velocity to that of Ref. [18], we have $\eta_2/\eta_1 \approx 0.58$. We define f as the cross section ratio of TI to total one-electron transfer. Ratio f between the cross section of atomic He and a sum of cross sections of C^{q+} and O^{q+} is given by

$$f = \frac{\sigma_{\rm ti}}{\sigma_{\rm sc} + \sigma_{\rm ti}} \tag{3}$$

with

$$\sigma_{\rm ti} = \frac{N_{\rm ti}/\eta_2}{(I/\eta_{\rm p})NLT}, \tag{4}$$

$$\sigma_{\rm sc} = \frac{N_{\rm sc}/\eta_1}{(I/\eta_{\rm p})NLT}, \tag{5}$$

where $N_{\rm ti}$ and $N_{\rm sc}$ are the coincidence event counts of TI and SC respectively, $\eta_{\rm p}$ is the scattered ion detection efficiency, I is the integrated beam intensity, N is the target-gas density, L is the interaction length, and T is the optical transmission of the recoil ion detection system due to the grids used. As mentioned above, scattered ion detection efficiencies are the same for SC and TI, then,

$$f \approx \frac{0.58N_{\rm ti}/N_{\rm sc}}{1 + 0.58N_{\rm ti}/N_{\rm sc}}. \tag{6}$$

The error of the cross section ratio f originates mainly from statistical error (2%–17%) and uncertainty in the calibration of the detector efficiency ($< 8\%$).

3. Results and discussion

The values of cross section ratio f of TI to total single electron transfer in collisions of 17.92–120.03 keV/u C^{+}, 30.01–321.41 keV/u C^{2+}, 71.67–437.47 keV/u C^{3+}, 286.69–524.77 keV/u C^{4+}, 15.87–80.35 keV/u O^{+}, 30.01–253.95 keV/u O^{2+}, 63.49–321.41 keV/u O^{3+}, and 286.69–396.80 keV/u O^{4+} with atomic He are shown in Figs. 2 and 3 as a function of charge state q and energy per nucleon E (keV/u). It can be seen that for both C^{q+} and O^{q+}, the cross section ratio f exhibits a similar dependence on E and q. It increases first and reaches a maximum with the increase of projectile energy, then decreases at higher velocities. However, for the collisions of C^{+} and O^{+} with He, the energies are not high enough for f to reach their maxima correspondingly; we find from these two figures that the energies corresponding to the maxima of f go to higher values with the increase of projectile charge state.

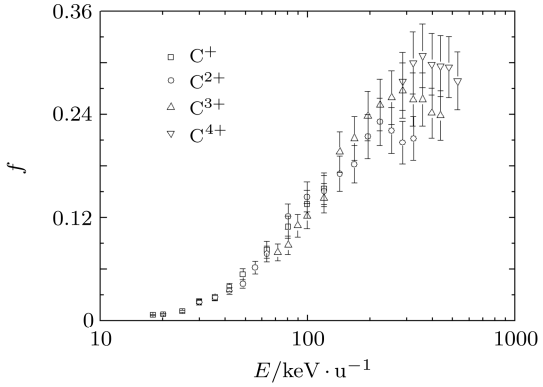


Fig. 2. Curves for ratio f of C^{q+} on He versus E for different values of q.

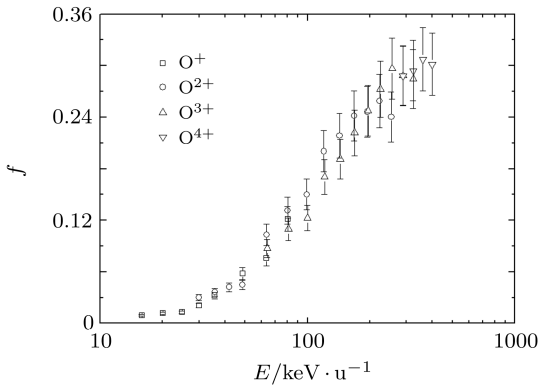


Fig. 3. Curves for ratio f of O^{q+} on He versus E for different values of q.

As is well known, the cross section ratio f is determined by its origin, charge state and projectile structure. For a partially stripped ion, the structure shows its importance not only in effective charge,[19,20] but also in energy deposited in the system.[7,21] The projectile structure influences a reaction involving a low-charge ion much more than that involving a high charge one in a collision. When the projectile charge state goes higher, the electron is bound more tightly to the nucleon of the projectile; the effective charge is close or equal to the net charge of the projectile. Again, the higher the charge state is, the more the energy deposition in the system will be, and also the higher the ratio of TI to SC will be.[21]

Now there have been many papers dealing with the mechanisms that lead to TI at intermediate velocities. The two-step process where one electron is captured and the other is ionized by the impact ionization is the main channel. In the framework of the independent electron approximation,[22] the TI cross section coming from the direct (two-step) process may

be written as

$$\sigma_{\rm ti} = 4\pi \int p_{\rm c}(b) p_{\rm i}(b) b {\rm d}b, \tag{7}$$

where $p_{\rm c}(b)$ and $p_{\rm i}(b)$ are the electron capture and the ionization transition probabilities. Neglecting the correlation between the two electrons, we have

$$\frac{\sigma_{\rm ti}}{\sigma_{\rm sc}} = \frac{4\pi \int p_{\rm c}(b) p_{\rm i}(b) b {\rm d}b}{4\pi \int p_{\rm c}(b)[1 - p_{\rm c}(b) - p_{\rm i}(b)] b {\rm d}b} \approx \frac{\sigma_{\rm ion}}{1 - p_{\rm c}(b) - p_{\rm i}(b)}. \tag{8}$$

Combining Eq. (3) with Eq. (7), we deduce that in the two-step process the trend of cross section ratio f of TI to total single electron transfer is similar to that for the case of the ionization cross section. Double capture to doubly excited state can also contribute to TI at the low energies considered here. With the increase of projectile charge state, it becomes more and more important to TI. In the collisions of 25 keV/u He^{2+} on He, the contribution of autoionization after doubly excited capture (ADC) is 5%.[23] For high-charge ions, ADC contributes significantly to TI, even more important than the direct mechanism.[24,25] The cross section ratio $R_{\rm ADC}$ ($R_{\rm ADC} = \sigma_{\rm ADC}/\sigma_{\rm sc}$) increases with the increase of projectile energy E at low energies.[25,26] TI originating from the capture of one electron to the projectile bound state accompanied by the capture of the others to the continuum (ECC) is studied via cusp-electron emission.[14,27] In the collision of He^{2+} on He, the cross section ratio between cusp-electron production cross sections for TI and ECC decreases when $E \geq 50$ keV/u.[27]

In our work, mechanisms leading to TI cannot be separated experimentally, and the investigations conducted by others are not systematic. From the previous measurements for some charge states at only several energy points, we cannot speculate on the dependence of the cross section ratio f of TI to single electron transfer on q and E. In order to investigate the behaviour of TI over wider ranges of q and $E(V_p)$ for partially stripped ions, we choose parameters $f/q^{0.60}$ for the ordinate and $E({\rm keV/u})/q^{0.60}$ for the abscissa after various trial forms have been tested. The resulting scaled data are shown in Figs. 4 and 5. In addition to our measured values for C^{q+} and O^{q+}, the values of Dubois[28] for He^+ with energies $E = 16.7$–500 keV/u and three points of Sander[29] for Li^{2+}, as well as the measurements by Chen[30] for F^{3+} with energy ranging from 46 keV/u to 350 keV/u are also displayed. Some data for $O^{5,6,7+}$ in an energy range from 0.5 MeV/u to 1.5 MeV/u measured by Tanis *et al.*[31] are also available. The data of Datz *et al.*[32] for $I^{5,6,7,8,10+}$ at 100 keV/u and $I^{9,10+}$ at 250 keV/u are also plotted. Figures 4 and 5 suggest that there is a maximum in $f/q^{0.60}$ at about $E/q^{0.60} \sim 160$ keV/u; the maximum value of f is approximately $0.17q^{0.60}$.

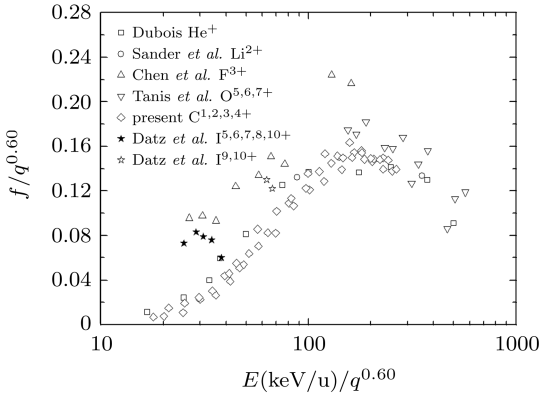


Fig. 4. Curves for $f/q^{0.60}$ versus $E({\rm keV/u})/q^{0.60}$ for C^{q+}. Previously published data are as follows: Dubois (Ref. [28]) (□ : He^+), Sander (Ref. [10] in Ref. [29]) (◯ : Li^{2+}), Chen *et al.* (Ref. [30]) (△: F^{3+}), Tanis *et al.* (Ref. [31]) (▽ : $O^{5,6,7+}$), Datz *et al.* (Ref. [32] (⋆ : $I^{5,6,7,8,10+}$ at 100 keV/u, ☆: $I^{9,10+}$ at 250 keV/u).

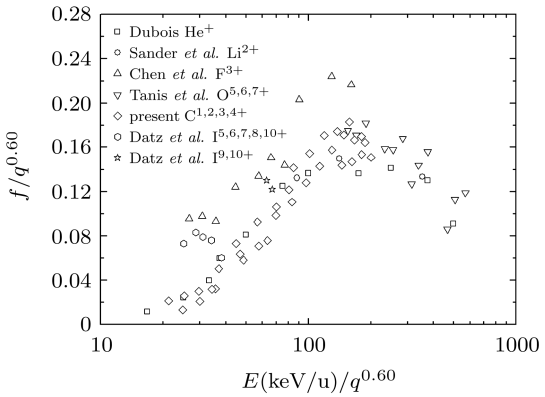


Fig. 5. Curves for $f/q^{0.60}$ versus $E/q^{0.60}$ for C^{q+}. Previously published data are as follows: Dubois (Ref. [28]) (□ : He^+), Sander (Ref. [10] in Ref. [29]) (◯ : Li^{2+}), Chen *et al.* (Ref. [30]) (△: F^{3+}), Tanis *et al.* (Ref. [31]) (▽ : $O^{5,6,7+}$), Datz *et al.* (Ref. [32] (⋆ : $I^{5,6,7,8,10+}$ at 100 keV/u, ☆: $I^{9,10+}$ at 250 keV/u).

The ionization cross section is known experimentally to vary as $q^{1.3}$ and to have a maximum at $E({\rm keV/u})/q^{0.65} \approx 100$.[31] In our experiments, the magnitude of f at the maximum $\sim 0.17q^{0.60}$ is found to increase more slowly than for the case of the ionization cross section, and its maximum of f is at

E(keV/u)/$q^{0.60}$ ≈160, shifting toward higher energies. Such a difference probably reflects the influence of the effective charge and the additional contributions to f of the ADC and the mechanism involving a bound state capture accompanied by a continuum capture. The charge states of the ions shown in Figs. 4 and 5 vary from 1 to 10. For a collision system of low-charge ions (such as He^{+}, Li^{2+}, $C^{1,2,3+}$, $O^{1,2,3+}$ and F^{3+}) and He, TI contributed from the ADC can be omitted; the contribution of ADC to TI cannot change the dependence of f on energy and charge appreciably. For high-charge ions, the data of Tanis[31] for $O^{5,6,7+}$ are measured at high energies which are beyond the point where maximum f appears, and the measurements of Datz[32] for I^{q+} at relatively low energies are not for the system that is required for the present purpose. From these two sets of data, we cannot draw a definite conclusion on how much the ADC contributes to TI. On the other hand, we know that the structure of the ions will affect the effective charge much more for low-charge ions and less for high-charge ions.[19,20] The mechanism leading to TI and the impinging ion structure together result in the different dependence of f on q and E from that in Refs. [32] and [33].

4. Conclusion

The cross section ratios of transfer ionization to single-electron transfer of atomic He by 17.92–120.03 keV/u C^{+}, 30.01–321.41 keV/u C^{2+}, 71.67–437.47 keV/u C^{3+}, 286.69–524.77 keV/u C^{4+}, 15.87–80.35 keV/u O^{+}, 30.01–253.95 keV/u O^{2+} , 63.49–321.41 keV/u O^{3+}, and 286.69–396.80 keV/u O^{4+} are measured using a projectile ion-recoil ion coincidence technique. The dependence of the fraction f on projectile charge state q and energy E (keV/u) is investigated. In general, the ratio f increases first and reaches a maximum at a certain energy, then decreases with the increase of incoming energy; it is also observed that the cross section ratio f is independent of q at lower energies and increases with q at higher energies, and that the maximum f shifts toward higher energies with the increase of q. The present measurements, along with the previously published data for a partially stripped projectile, suggest a maximum f ≈$0.17q^{0.60}$ at $E/q^{0.60}$ ≈160 keV/u. Due to the additional channel leading to TI and the screening (anti-screening) effect of the projectile electron, the dependence of maximum f on q is weaker than that of the ionization cross section which is known experimentally to vary as $q^{1.3}$, and the energy corresponding to the maximum f goes higher to 160(keV/u)$q^{0.60}$.

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