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Investigation of transfer ionization in collisions of partially stripped carbon ions with helium at low to intermediate velocities*

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The ratios of transfer ionization (TI) to single-electron capture (SC) cross sections have been measured for the collisions of partially stripped C^{q+} ions ($q = 1$–4) with He. The collision velocity ranges from 0.7 to 4.4 v_0 (v_0 is the Bohr velocity). The projectile-ion and recoil-ion coincidence technique is used to separate the processes of TI and SC. The ratios reach the maximum when the velocity is about 3.7 v_0. This can be explained qualitatively based on the two-step mechanism. The experimental results are also compared with the results calculated using the classical trajectory Monte Carlo (CTMC) method. The CTMC results are in agreement with the experimental data basically. The discrepancies in higher velocity region are interpreted by the effective charge effect.

Keywords: ion–atom collision, transfer ionization, electron capture, cross-section ratios
PACC: 5220H, 3450H, 3470

1. Introduction

The investigation of various processes in ion–atom collisions is important not only in basic atomic collision physics but also for applications in many diverse fields: e.g., plasma physics, controllable thermonuclear fusion, astrophysics.[1,2] Electron-capture by projectile is one of the most important processes and has been studied for many years.[3−5] In general, the process of electron capture is described by the reaction

$$A^{q+} + B \rightarrow A^{(q-k)+} + B^{r+} + (r-k)e^{-}, \qquad (1)$$

where q is the initial charge state of the projectile and r is the final charge state of the recoil ion. If $r = k$, the pure electron capture takes place, whereas for $r > k$, Eq.(1) describes the transfer ionization(TI). In this process the projectile captures only some of the electrons released from the target atom while the others are emitted to the continuum. In the early experiments, only the charge states of the outgoing projectiles are analysed without determining the final recoil charge. So these early results could not separate single-electron capture (SC) and TI.[6,7] Until the projectile-ion and recoil-ion coincidence technique is used, TI was not separated from the total single-electron capture process. Then the multielectron process of TI received much attention for it contains the information of electron–electron correlation. In theory, single-electron processes are well understood quantitatively in many cases,[8,9] while multielectron processes are not so well understood for they are too difficult to describe even qualitatively. He is the simplest target used to investigate the multielectron process and electron–electron correlation, and its multielectron processes can be definitely defined without Auger process.

Theoretical descriptions of the TI process include various special mechanisms in different collision-velocity regions. In the lower velocity region ($\leq$1 eV/u), Niehaus[10] has shown that TI can result from autoionization of the quasimolecule formed during the collision. At higher velocities, when more than one electron is captured, an approach to TI based on the statistical sharing of the available energy among target electrons has been used to calculate multiple

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ionization probabilities by Müller *et al.*[11] At velocities near 100 keV/u, Andersen *et al*[12] have obtained evidence that TI of the He target is due to the transfer of two electrons to a highly correlated state of the highly charged projectile followed by the loss of one of the electrons to the continuum. At high velocities ($\geq$1 MeV/u), TI can be treated as a single electron capture and an impact ionization of the target electrons separately.

Collisions of C ions with He have been investigated by several researchers. Shinpaugh *et al*[13] measured the ratio of TI to SC of bare C ions with He in the velocity range of 0.5–1 MeV/u. The ratios ranged from about 1 to 1.6. DuBois[1] measured the forward electron emission in C^{q+}+He (q = 0–4) collisions and demonstrated that the TI process is important in the multielectron transitions. Recently, high-resolution cold-target recoil-ion momentum spectroscopy has been used to study the electron capture processes. Kamber *et al*[14] measured the state-selective electron capture in 0.5–50 keV/u C^{5+}+He collisions and showed that TI occurs predominantly in the symmetrical states of double-electron-capture at a lowest collision energy.

In the present paper, the ratios of TI to SC for C^{q+}+He (q = 1–4) collisions are measured. The collision velocity ranges from 0.7 to 4.4 v_0. These studies are very interesting because the velocities are comparable to the classical orbiting velocities of the bound electrons of He. It is complicated to deal with in theory because intermediate energy collisions are too slow to fulfill the conditions required for using first-order perturbation theories,[15] but too fast to use molecular-orbital models.[16] The classical trajectory Monte Carlo (CTMC) method has been proved to be valid in a wide energy range.[17] We will compare our experimental data with the results of CTMC and discuss the similarities and differences between them. By taking the ratios of TI to SC cross sections, the effects of the one-electron transition mechanism tend to cancel so that the two-electron mechanism becomes more apparent.

2. Experiment

The experimental apparatus has been described in detail previously[18] and is briefly described here. Ion beams with appropriate energy were provided by the 2 × 1.7 MV tandem accelerator at Lanzhou University. They were charged states selected by a switching magnet and then well focused by two apertures before being directed into the target cell. During the measurement the pressure in the gas cell was maintained at 3×10^{-3} Pa to ensure the single collision condition. A differential pumping system was used to maintain the vacuum outside the gas cell much better. The scattered projectiles were charge-separated by a parallel-plate static electric field and then recorded by a one-dimensional position-sensitive microchannel plate (PSMCP-x) detector, which was housed in a detection chamber placed about 1.7 m downstream the target region. PSMCP-x could measure the charge of the scattered projectile by determining its position x. The time-of-flight (TOF) spectrometer was used to separate the charge states of the recoil ions. The ionized recoil ions produced by the primary beam were accelerated out of the gas cell by an extraction electric field into a flight tube, which consists of an acceleration region (the acceleration voltage is about 1.0 kV) and a field-free drift tube. The length of the drift tube was chosen to accomplish the first-order TOF focusing of the recoil ions. Upon reaching the end of the flight tube, the recoil ions were detected by a microchannel-plate detector, and then the start signals for a time-to-amplitude converter (TAC) were generated. Meanwhile, the stop signals were given by the delayed scattered projectile signals. An MPA-3 data acquisition system was used to record the events of the scattered projectiles and the recoil ions with the definite charge states produced in the same collision.

A typical two-dimensional spectrum of C^{q+}+He collision is shown in Fig.1. The label 'X' is the position-coordinate of the scattered projectiles, which determines the charge state of the scattered projectiles. 'T' is the time-coordinate of the recoil ions which determines the charge state of the recoil ions. The events of SC and TI can be definitely identified.

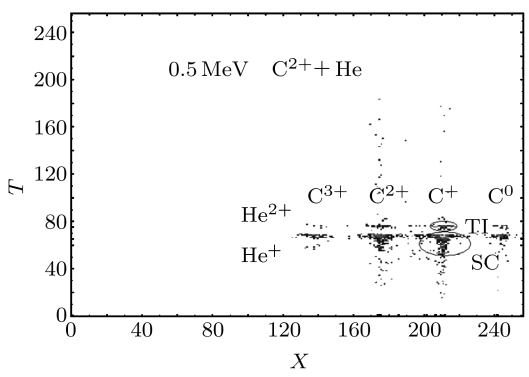


Fig.1. A typical two-dimensional spectrum for 0.5 MeV C^{2+}+He collision.

In order to assess the importance of the two-electron TI process and eliminate most of the experimental uncertainties, the ratios of TI to SC cross sections were measured and studied for He bombarded by C^{q+} ions ($q = 1$–4) at low to intermediate velocities in present work. The uncertainties were derived mainly from the statistic errors.

3. Results and discussion

Figure 2 shows the ratios of TI to SC of He induced by different-charged C^{q+} ions ($q = 1$–4) at velocities from 0.7 to 4.4 v_0. The ratios for all charge states exhibit a similar dependence on the collision velocity. In general, the ratios increase first and reach the maximum when the velocity is around 3.7 v_0, then decrease at higher velocities. For any given velocity less than 2 v_0, the ratios are nearly independent of the projectile charge state. But in the higher energy region, the larger the projectile charge state, the higher the ratios. For highly charged projectiles and in the intermediate energy region, TI may be due to the transfer of two electrons to a highly correlated state of the projectile followed by the loss of one of the two electrons to the continuum.[19] But for the low-charged projectiles, such as the C^{q+} ions ($q = 1$–4), they have not enough potential energy to capture two electrons from the target atom simultaneously. So we suppose that TI is a two-step process[20] which consists of SC and direct single-ionization.

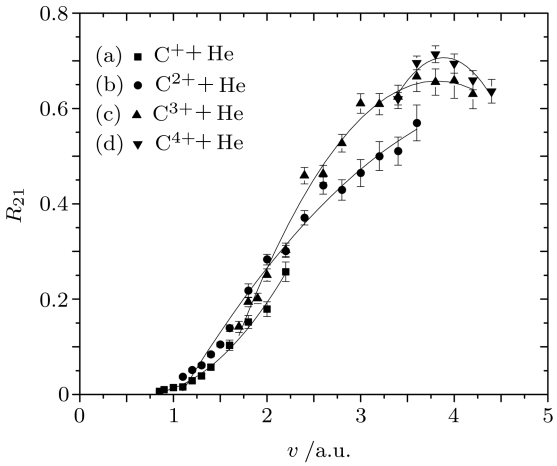


Fig.2. Ratios of TI to SC of He colliding with C^{q+} ions ($q = 1$–4) as functions of projectile velocity v (a.u. is the atomic units) and charge state. The solid lines are drawn to guide the eyes.

After neglecting the correlation between electrons, the cross sections of TI, capture and ionization per active electron are

$$\sigma_{\rm TI} = 2\pi \int_0^\infty |a_{\rm c} a_{\rm i}|^2 b{\rm d}b, \tag{2}$$

$$\sigma_{\rm c} = 2\pi \int_0^\infty |a_{\rm c}|^2 b{\rm d}b, \tag{3}$$

$$\sigma_{\rm i} = 2\pi \int_0^\infty |a_{\rm i}|^2 b{\rm d}b. \tag{4}$$

where $a_{\rm c}$ and $a_{\rm i}$ are the capture and ionization probability amplitudes per active electron, so we obtain the ratio of TI cross section to SC cross section R_{21} as

$$R_{21} = \frac{\sigma_{\rm TI}}{\sigma_{\rm c}} \propto \sigma_{\rm i}. \tag{5}$$

Janev and Presnyakov[21] have given good calculations of direct ionization cross sections using the close-coupling method, as shown in Fig.3 (Janev).

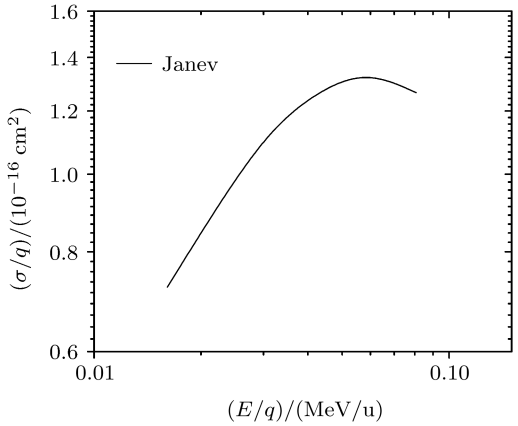


Fig.3. Direct ionization cross section as a function of projectile energy (Ref.[22]). E is the projectile energy per nucleus, q is the projectile charge state and σ is the absolute cross section.

The collision energy of our experiment is within the range from 0.01 to 0.121 MeV/(u·q) in Fig.3. The single ionization (SI) cross section(Janev) in Fig.3 has the maximum value of collision energy almost the same as our experimental results of R_{21}. This fact is in agreement with Eq.(5), which indicates that R_{21} is proportional to the SI cross section. This suggests that the two-step mechanism dominates the TI process for the low-charged projectiles in the low to intermediate energy range.

Figure 2 indicates that when the collision velocity is larger than $2v_0$, the value of R_{21} increases with the projectile charge state. The reason of this is probably that the polarization effect is larger for the higher charge state of projectile. Thus, the ionization cross sections ($\sigma_{\rm i}$) are larger for higher charge state. So does R_{21} according to Eq.(5).

The experimental ratios of TI to SC of He induced by C^{q+} ions (q = 1–4) are compared with the results of CTMC in Fig.4.

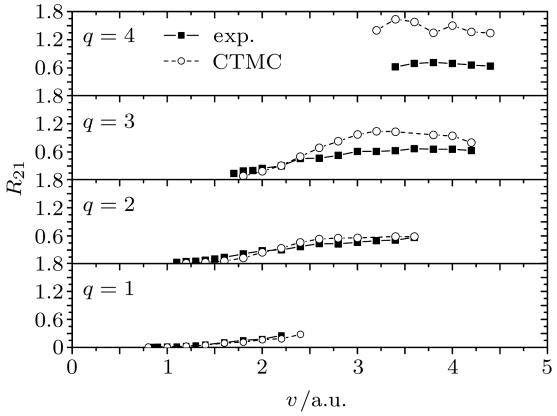


Fig.4. Comparison of ratios of TI to SC between experimental data and results of CTMC for different charged projectiles.

It is found that in the lower energy region the results of CTMC are in good agreement with the experimental results. But in the higher energy region, especially for a highly charged projectile, the results of CTMC are larger than the experimental data. The difference results mainly from the invariable charge state q of the projectile in the CTMC calculation. Because of the capture process, the effective charge state $q_{\rm eff}$ in collision will be smaller than the invariable q in CTMC.[17] According to Eq.(5), the over-estimated charge q will cause the calculated results of CTMC to be higher than the experimental data. Furthermore, neglecting the correlation between target electrons in CTMC may also enlarge the discrepancy.

4. Conclusions

In summary, the ratios of TI to SC cross sections have been investigated experimentally for the collisions of C^{q+} ions (q = 1–4) and He in the velocity range from 0.7 to 4.4 v_0. This ratio for each projectile charge state increases first and reaches the maximum when the velocity is about 3.7 v_0, then decreases with increasing velocity. The analysis shows that the two-step process dominates the TI process within the experimental velocity region for low charge state projectiles. Our experimental data are also compared with the results of CTMC. In general, CTMC method is valid for these collision systems. The difference of q and $q_{\rm eff}$ and the electron–electron correlation effect lead to the discrepancy between the experimental data and the CTMC results.

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