Experimental study of cross-section ratios in the collisions of C^{q+} and $O^{q+}(q = 1–4)$ on atomic helium in strong-interaction region*

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We have measured the cross-section ratios of helium induced by C^{q+} and O^{q+} ($q = 1–4$) in an energy range from 20 keV/amu to 500 keV/amu, and obtained the two-dimensional spectra by employing the coincidence method combined with the MPA-3 data acquisition system. Hence, we obtain the ratios of total single-ionization cross-sections (SI, SC, SLSI, and DLSI), total double-ionization cross-sections (DI, DC, TI, SLDI, and DLDI) and cross-sections of every process (SI, SC, SLSI, DLSI, DI, DC, TI, SLDI, and DLDI), which induce the single-ionization and double-ionization, to the total cross sections respectively. The competitive relations between the reaction-channels and the experimental data law of each reaction-channel are revealed explicitly, and the qualitative explanations involved in those results are also presented accordingly.

Keywords: ion–atom collisions, strong-interaction region, cross-section ratios, competitive relation

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1. Introduction

The multiple-ionization of atomic helium, produced by highly charged projectiles, has received considerable attention in basic atomic physics in the past decades. Experimental investigations provided more important information for basic theoretical researches in atomic physics such as multi-electron system dynamics,[1] electron–electron correlation,[2–4] and the structure of electron in the extranuclear field.

The ion–atom collision is always a multi-channel reaction, due to the many-body nature of the interaction. The representative collision system is always expressed formally as[5]

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

where A^{q+} is the charge state of projectile, B is the atomic target, $A^{(q-k)+}$ is the scattered ions with k electrons captured, B^{r+} is the recoil ion with r electrons ionized, and $(r-k)e^{-}$ is the δ electrons ejected by the collision system.

Multiple-ionization induced by fully striped ions in many cases has been better understood quantitatively than that induced by partially striped ions. An extensive study has been devoted to the partially-striped-ions-helium collision system in recent years.[6–9] Most of those studies, which have lead to a fuller understanding of the multi-ionization, focused on the double- to single-ionization ratio of helium.[10–18] Comparing with the double- to single-ionization ratio, however, the experimentally measured cross section ratio of multi-channel reaction yielded a smaller statistical error, more brief data analysis procedure and more reliable physics facts reflected by the experimental data. In the present work, we report on our attempts to unravel the complex competitive relations of the reaction-channels by measuring the cross section ratio of multiple-ionization collision. Furthermore, in this paper we also attempt to provide a new visual angle and accumulate the data of the multi-channel reaction bombarded by partially stripped projectiles.

In the present paper, we measure the cross section ratios of total single ionization (SI, SC, SLSI, DLSI *et al.*), total double ionization (DI, DC, TI, SLDI, DLDI *et al.*) and double ionization reaction-channels(SI, SC, SLSI, DLSI, DI, DC, TI, SLDI, DLDI *et al.*) to to-

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tal ionization reaction cross section of helium respectively for 20 keV/amu ∼ 500 keV/amu C^{q+} and O^{q+} ($q = 1 \sim 4$) impact. The rest of the present paper is organized as follows. The experimental method is discussed in Section.2. The details of the experimental data and a qualitative interpretation of the experimental data law are presented in Section.3. Finally, our findings are summarized in Section 4.

2. Experimental method

The ion beams are provided by the 2×1.7 MV tandem accelerator of Lanzhou University[19] and the relevant techniques were described previously.[20,21] The energy states and the charge states of $C^{q+}$and $O^{q+}(q = 1 \sim 4)$ ions are selected by 30° bending magnets when the ions pass through a chamber where they collide with the helium target. Special concern was taken to ensure that single-collision condition is satisfied and reduce the random coincidence counting rates. Therefore, the pressure of helium in the target chamber are kept at 6.4×10^{-2} Pa and the beam intensity is less than 1 pA. Recoil ions are accelerated by an electrostatic field and counted by an MCP detector, the charge states of these recoil ions are distinguished by the flight time in the electric field. The scattered ions are separated by a parallel plate electrostatic field and counted by another MCP detector. The charge states of the scattered ions are analysed by the positions of projectiles on the detector. From the coincidence between the time-signals and the position-signals, we can obtain the information about the counts of each reaction channels, which are shown in the two-dimensional spectra in Fig. 1.

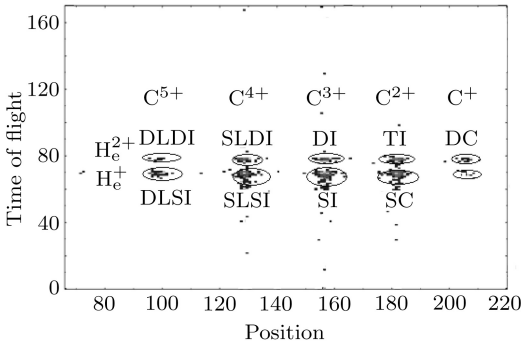


Fig. 1. Two-dimensional spectra of 3.05 MeV C^{3+}-He.

In Fig. 1 all peaks are well resolved from each other, and reside well above the background. The uncertainties are derived mainly from the statistic errors. As shown in Fig. 1, the vertical composition of the orderly peaks corresponds to the same final charge state A^{q+} (q = 1–5) of scattered ions, while the horizontal composition of the orderly peaks corresponds to the same final charge state B^{q+} ($q = 1, 2$) of recoil ions.

In this experiment as shown in Fig. 1, each peak in a two-dimensional spectrum represents a reaction channel in the collision processes. Those reaction channels are as follows:

(1)$C^{3+} + He \rightarrow C^{3+} + He^{+} + e^{-}$, single ionization (SI)
(2)$C^{3+} + He \rightarrow C^{3+} + He^{2+} + 2e^{-}$, double ionization (DI)
(3)$C^{3+} + He \rightarrow C^{2+} + He^{+}$, single capture (SC)
(4)$C^{3+} + He \rightarrow C^{2+} + He^{2+} + e^{-}$, transfer ionization (TI) (double ionization-single capture)
(5)$C^{3+} + He \rightarrow C^{+} + He^{2+}$, double capture (DC)
(6)$C^{3+} + He \rightarrow C^{4+} + He^{+} + 2e^{-}$, single loss-single ionization (SLSI)
(7)$C^{3+} + He \rightarrow C^{4+} + He^{2+} + 3e^{-}$, single loss-double ionization (SLDI)
(8)$C^{3+} + He \rightarrow C^{5+} + He^{+} + 3e^{-}$, double loss-single ionization (DLSI)
(9)$C^{3+} + He \rightarrow C^{5+} + He^{2+} + 4e^{-}$, double loss double ionization (DLDI).

3. Experimental results and discussion

3.1. Cross section ratios of total single ionization and total double ionization to total ionization

We divide the reaction channels (1)–(9) into total single ionization process (SI, SC, SLSI, DLSI *et al.*) and total double ionization process (DI, DC, TI, SLDI, DLDI *et al.*). The corresponding ratios, denoted by R_1 and

R_2, are shown in the following defining formulae:

$$R_1 = \frac{\sigma_1}{\sigma_{\rm total}} = \frac{\varepsilon_1^{-1}(N_{\rm SI} + N_{\rm SC} + N_{\rm SLSI} + \ldots)}{\varepsilon_1^{-1}(N_{\rm SI} + N_{\rm SC} + N_{\rm SLSI} + \ldots) + \varepsilon_2^{-1}(N_{\rm DI} + N_{\rm DC} + N_{\rm TI} + N_{\rm SLDI} \ldots)}$$
$$= \frac{\eta(N_{\rm SI} + N_{\rm SC} + N_{\rm SLSI} + \ldots)}{\eta(N_{\rm SI} + N_{\rm SC} + N_{\rm SLSI} + \ldots) + (N_{\rm DI} + N_{\rm DC} + N_{\rm TI} + N_{\rm SLDI} \ldots)} = \frac{\eta S}{T}, \quad (2)$$

$$R_2 = \frac{\sigma_2}{\sigma_{\rm total}} = \frac{D}{T}. \quad (3)$$

The experimental data, which show the energy dependences of R_1 and R_2 and competitive relation of the couple reaction-channels, are plotted in Figs. 2 and 3.

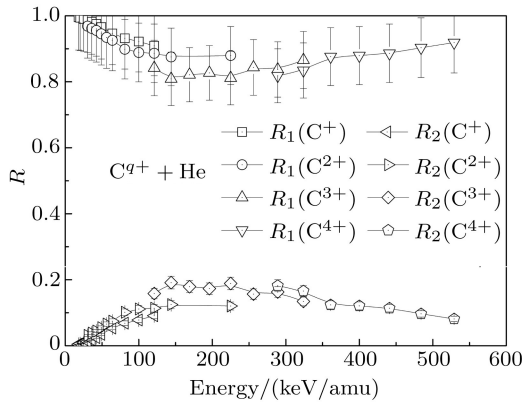


Fig. 2. Projectile energy dependences of R_1 and R_2 for C^{q+} ($q = 1$–4) collision with helium.

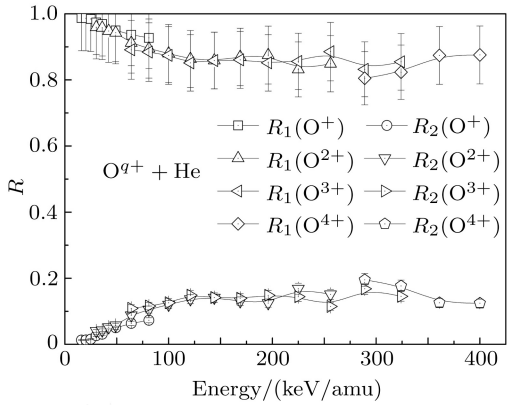


Fig. 3. Projectile energy dependences of R_1 and R_2 for O^{q+} ($q = 1$–4) collision with helium.

From Figs. 2 and 3 it follows that the ratio R_2 is significantly smaller than $R_1$and the maximum value of R_2 is below 0.2 in our experiment. In the low-to-intermediate energy range, R_2 has a maximum value region for C^{q+} and O^{q+} ($q = 1$–4) impact. This phenomenon can be understood qualitatively by matching projectile velocity with the target electron orbital velocity.[22,23] However, it should be noted that the double ionization also depends on the charge state of the projectile,[24] that is why there is not a single peak but a maximum value region for C^{q+} and O^{q+} ($q = 1$–4). Another evident phenomenon that we can see from Figs. 2 and 3 is the energy dependence of the competition between the double and the single ionization reaction channels, which will be further discussed in detail in the next section.

3.2. Cross section ratios of double ionization to total ionization

We define the cross section ratios of double ionization processes, which induce the total double ionization, to the total ionization as follows:

$$R({\rm DI}) = \frac{\sigma_{\rm DI}}{\sigma_{\rm total}} = \frac{N_{\rm DI}}{T},$$

induced by direct ionization process;

$$R({\rm TI + DC}) = \frac{\sigma_{\rm TI} + \sigma_{\rm DC}}{\sigma_{\rm total}} = \frac{N_{\rm TI} + N_{\rm DC}}{T},$$

induced by capture process;

$$R({\rm SLDI + DLDI}) = \frac{\sigma_{\rm SLDI} + \sigma_{\rm DLDI}}{\sigma_{\rm total}} = \frac{N_{\rm SLDI} + N_{\rm DLDI}}{T},$$

induced by electron-loss process of projectile-ion.

The experimental data of competition between the double ionization reaction channels for C^{q+}+He and O^{q+}+He($q = 1$–4) collisions are plotted in Figs. 4–11.

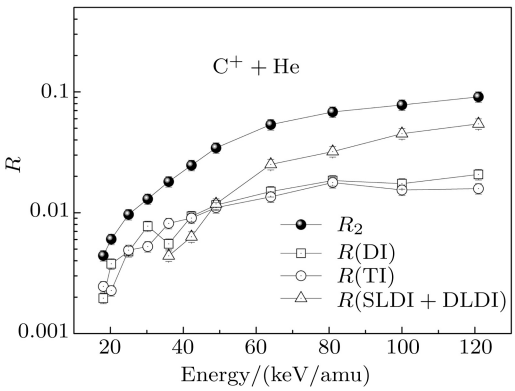


Fig. 4. Projectile energy dependences of R(DI), R(TI) and R(SLDI+DLDI) for C^++He collisions.

Figures 4 and 5 indicate that the values of R(DI), R(TI) and R(SLDI+DLDI) increase with projectile energy. For lower impact energies, the values of the three ratios are small and almost the same, that is to

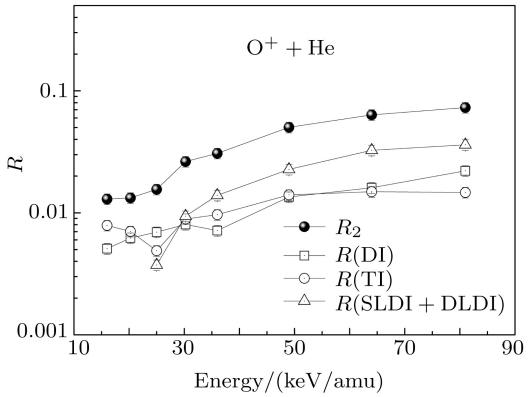


Fig. 5. Projectile energy dependences of R(DI), R(TI) and R(SLDI+DLDI) for O^++He collisions.

say, the double ionization processes have almost equal contributions to the total double ionization, which is significantly smaller than single ionization as shown above (see Figs. 2 and 3). At higher impact energies, it is demonstrated in Figs. 4 and 5 that the double ionization components of the TI and SLDI+DLDI channels become important as the projectile ion velocity increases.[25] And we can obtain the experimental law R(SLDI+DLDI)> R(DI)> R (TI+DC) explicitly. The tendency that the SLDI+DLDI channel dominates the double ionization process has been shown as a common property for low charged ion–atom collision.[26]

For the behaviour of C^{2+}+He collision system from Fig. 6, it is deferent from that of C^++ He collision system, which implies that the projectile charge

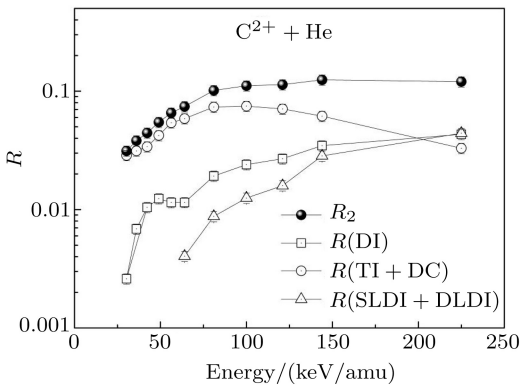


Fig. 6. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for C^{2+}+He collisions.

state begins to affect the double ionization process by capturing the outer-shell electrons of atomic helium at low projectile energies, and the transfer ionization and the double capture process predominate over the double ionization of the target. Therefore, we can obtain the relation of the three channels as R(TI+DC)> R(DI)> R(SLDI+DLDI). With more attendant electrons than C^{2+}, the O^{2+}+He system in Fig. 7 has the same experimental law as that for the C^{2+}+He system and enters into a strong-interaction region at significantly lower energies.[2,21] With the energy increasing in the strong-interaction region, the electron losing channel dominates the double ionization gradually and R(SLDI+DLDI) exceeds R(DI) in some energy region, furthermore, it exceeds R(TI+DC) in a higher energy region.

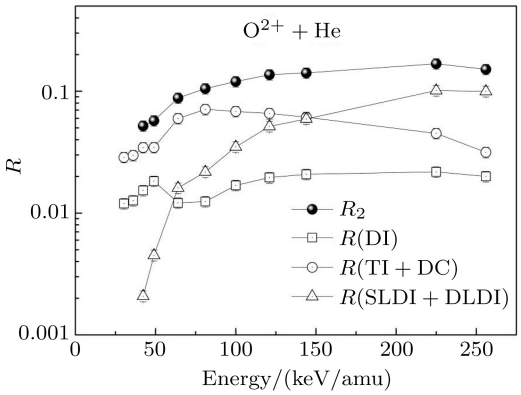


Fig. 7. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for O^{2+}+He collisions.

As shown in Figs. 8 and 9, it is evident that the double capture predominates the reaction in the whole experimental energy region for the higher charged projectiles, and the law the same as C^{2+}+He$\sim$ R(TI+DC)> R(DI)> R(SLDI+DLDI) is obtained

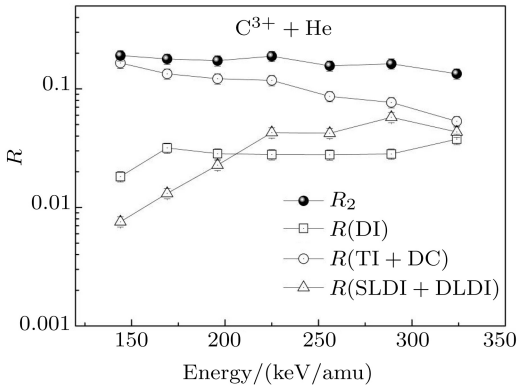


Fig. 8. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for C^{3+}+He collisions.

in a low energy region. From Figs. 8 and 9, the R(DI) keeps almost an invariable value during the increase of

projectile energy, and it seems that the losing of channel will significantly affect the double ionization process. From the tendencies shown in Figs. 8 and 9, the R(SLDI+DLDI) is more likely to become invariable too, and the direct ionization process will predominate in the double ionization in some higher energy range, which is beyond our experiment.[8]

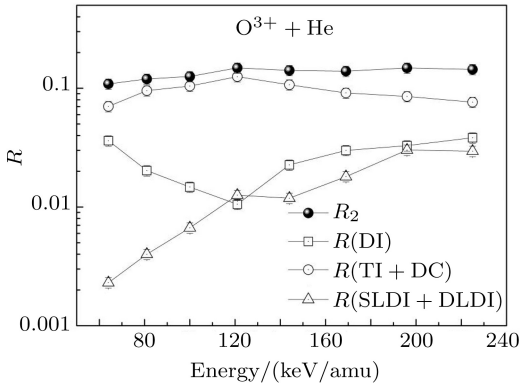


Fig. 9. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for O^{3+}+He collisions.

From Figs. 10 and 11, a similar law to that for the C^{3+}+He system, i.e., R(TI+DC)> R(DI)> R(SLDI+DLDI) is obtained, and the C^{4+}+He system comes into a strong-interaction region at higher energy than those of C^{1+} C^{2+} C^{3+}.[21] Under the condition of higher energy and charge states, the experimental data indicate that the ratios of three reaction channels slightly decline with the further increase of projectile energy. In contrast with the cases of C^{1+}, C^{2+} and C^{3+}in Figs. 2 and 3, where total single ionization increases with energy and the total double ionization declines as the energy increases. This phenomenon evidently shows that the single ionization process has a tendency to predominate in the ionization reaction.

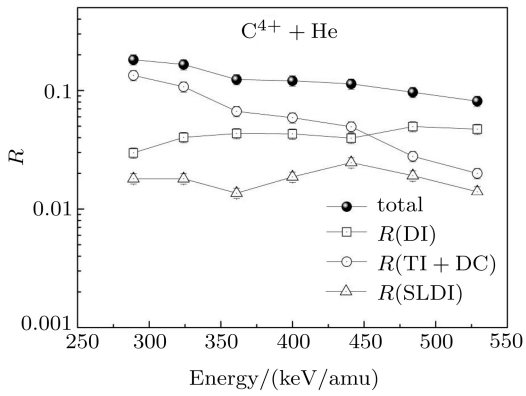


Fig. 10. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for C^{4+}+He collisions.

We find the evidence of competition relations between the reaction channels for partially stripped ion–atom collisions, which involve the charge state q and energy E of the projectile. In the present work, we discuss the experimental results by dividing the reaction channels in our experiment into single ionization and double ionization by the ionization states of atomic helium, and obtain that single ionization dominates the collisions, thus the double ionization occurs at a low probability.[27,28]

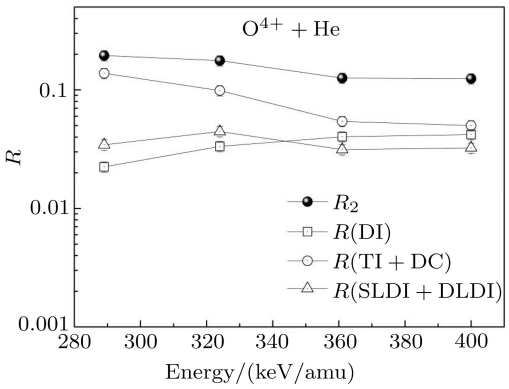


Fig. 11. Projectile energy dependences of R(DI), R(TI+DC) and R(SLDI+DLDI) for O^{4+}+He collisions.

We also discuss that the double ionization divides the reaction channels in our experiment into the direct ionization process, electron capture process, and projectile losing electron process by the change of charge state of projectile. In the low energy range, the electron capture dominates the reaction, and the ratio of electron loss is significantly low. With energy increasing, the reaction comes into a so-called strong-interaction region, [2,21] the ratios of the three reaction channel are identical with each other in generally. In a higher energy region, which process predominates the reaction is determined by the charge state of projectile. With a low charge state ($q = 1$), electron losing process predominates in the process. However, when the charge state is higher than previous ones ($q = 2$–4), the direct ionization predominates in the reaction and the ratio of capture channel is significantly low.

4. Summary

By employing coincidence method combined with the MPA-3 data acquisition system, we have measured the cross-section ratios of helium induced by C^{q+} and O^{q+} ($q = 1$–4) with the energies ranging from 20 keV/amu to 500 keV/amu. we obtain the ratios of total single-ionization cross-sections (SI, SC, SLSI, and DLSI), total double-ionization cross-sections (DI, DC, TI, SLDI, and DLDI) and cross-sections of every

process (SI, SC, SLSI, DLSI, DI, DC, TI, SLDI, and DLDI) to the total cross sections respectively. The competitive relation of the reaction-channels and the experimental data laws of each reaction-channel are obtained and the relevant results are also interpreted qualitatively. Considering that some basic problems exist in the collision system, such as multiply-body problem), it is worth finding out the scaling laws of those cross-section ratios.

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