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The direct ionization processes in the collisions of partially stripped carbon and oxygen ions with helium atoms at low-to-intermediate energies*

Zhou Chun-Lin(周春林), Shao Jian-Xiong(邵剑雄), Chen Xi-Meng(陈熙萌)†,
Sun Guang-Zhi(孙光智), and Zou Xian-Rong(邹贤容)

School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, *China*

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The values of direct double- to-single ionization ratio R of helium atoms induced by C^{q+}, O^{q+} $(q = 1-4)$ ions at incident energies from 0.2 to 8.5MeV are measured. Based on the existing model (Shao J X, Chen X M and Ding B W 2007 *Phys. Rev.* A **75** 012701) the effective charge of the projectile is introduced to theoretically estimate the value of R for the partially stripped ions impacting on helium atoms. The results calculated from our "effective charge" model are in good agreement with the experimental data, and the dependence of the effective charge on the ionization energy of the projectile is also discussed qualitatively.

Keywords: effective charge, partially stripped ions, cross-section ratio, direct ionization
PACC: 3450

1. Introduction

Ion–atom collisions play an important role in atomic physics，and they are closely related to many applications, such as the heavy ion inertial fusion,[1] collisional and radiative processes in the Earth's upper atmosphere,[2] ion beam lifetimes in accelerators,[3] atomic spectroscopy[4] and ion stopping in matters.[5]

The double-to-single ionization ratio R for helium target induced by heavy ions has led to a further understanding of multiple ionizations.[6−16] In low velocity ($v \leq v_{\rm Bohr}$) ranges, the multiple ionization of target can be understood well by the classical over-barrier model (COBM),[17] and R is expected to be independent of the incident velocity v. For higher velocities ($v \geq 10\,v_{\rm Bohr}$), the "shake-off" mechanism proposed by McGuire[10] shows that R was independent of the charge state q and the velocity v. The ratio R reached the maximum in a low-to-intermediate velocity range ($v_{\rm Bohr} \leq v_{\rm ion} \leq 10\,v_{\rm Bohr}$). The model[18] predicted that the maxima value of R appeared when the velocity was about 2–3 $v_{\rm Bhor}$, which is in agreement with experimental result. However, some obvious differences between theory prediction and the experimental data for partially stripped ions from the same charge state to the bare ions are unable to be explained by the model in Ref.[18] In the present work, the values of double-to-single ionization ratio R of helium atoms bombarded by 0.2–8.5 MeV C^{q+}, O^{q+} $(q = 1-4)$ are measured. Based on the model in Ref.[18], the effective charge for the partially stripped ion is adopted to explain the difference in R between bare and partially stripped ions. The electrons of helium target will be excited or ionized by the partially stripped ion impact. Meanwhile, electron loss and electron relaxation from the projectile can also occur, so that the core charge of the projectile seen by the second electron of a helium atom should be larger than that seen by the first one. Thus, the introduction of effective charge of the projectile should be regarded as the modification of the model in Ref.[18], and it is presented in this paper. It is found that the modified model describes the experimental data well.

The remainder of the present paper is organized as follows. The experimental method is discussed in Section 2. The experimental data and the details of our model are presented in Section 3. A qualitative interpretation of the 'effective charge' is given in Section 4.

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†Corresponding author. E-mail: chenxm@lzu.edu.cn

2. Experimental method

The ion beams are provided by the 2×1.7 MV tandem accelerator at Lanzhou University.[19] The energies and charge states of C^{q+}, O^{q+} $(q = 1 - 4)$ ions are selected by using a 30 degree bending magnet. The projectiles pass through a chamber, colliding with helium atoms. The pressure in target chamber is kept at 6.4×10^{-2} Pa, thereby avoiding the multi-collision between the projectiles and helium atoms. The beam intensity is less than 1pA in order to reduce the random coincidence counting rate. Recoil ions are accelerated by an electrostatic field and detected by an MCP detector to provide a start signal for a time-to-amplitude converter (TAC). The scattered projectiles with different charge states are separated by a parallel plate electrostatic field and detected by a one-dimensional position-sensitive detector to provide a stop signal for TAC. The charge states of these recoil ions are distinguished by time-of-flight analysis. After the coincidence between the time-signals for recoil ions with different charge states and the position-signals for scattered ions with different charge states, the information about every reaction channel is obtained by an MPA-3 data acquisition system, which is shown in Fig.1.

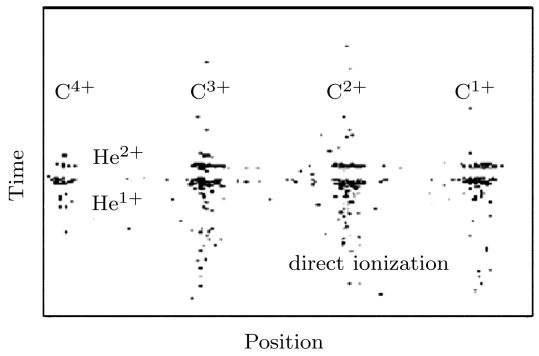


Fig.1. The two-dimensional spectrum for 2.3 MeV C^{2+}–He collisions.

3. Experimental data and theoretical estimation

In Fig.1, 'Position' represents the positional coordinate of the scattered projectile that determines the charge state of the scattered projectile, and 'Time' represents the time coordinate of the recoil ion that determines the charge state of the ionized target atom. In Fig.1 all reaction channels are well resolved from each other, as well as from the background. The values of direct double-to-single ionization ratio R are plotted in Figs.2–9 for helium atoms by 0.2–8.5 MeV C^{q+}, O^{q+} $(q = 1 - 4)$ ions.

Before the effective charge is introduced, it is necessary to review the model in Ref.[18] briefly. The model[18] is based on the COBM of Bohr and Lindhardt, in which the release distance $R_{\rm r}$ and the capture distance $R_{\rm c}$ are introduced, and they satisfy the following relationships:

$$\frac{q}{(R_{\rm r} - a)^2} = \frac{Z}{a^2}, \tag{1}$$

and

$$\frac{q}{R_{\rm c}} = \frac{1}{2} V_{\rm P}^2, \tag{2}$$

where a is the orbital radius of the electron, q is the charge state of the projectile, Z is the atomic number of the target, and $V_{\rm p}$ is the velocity of the ions.

In Bohr's theory of COBM,[17] the electrons that are released but not captured will go back to the target atom after the collision, while in the model[18] it is considered that the released but not captured electrons can ionize the target atom within some distance $R_{\rm I}$, and $R_{\rm I}$ satisfies

$$\frac{q}{R_{\rm I}} \geq I_{\rm n} + \frac{q}{R_{\rm r}}. \tag{3}$$

In the model,[18] the electrons released within the distance $R_{\rm c}$ will be captured, those released between $R_{\rm r}$ and $R_{\rm c}$ will not ionize the target atom until they approach the distance $R_{\rm I}$.

The release probability, the capture probability and the ionization probability of a single-electron system are calculated from $R_{\rm r}$, $R_{\rm c}$ and $R_{\rm I}$, and the direct single and double ionization cross sections, i.e. $\sigma_{\rm SI}$ and $\sigma_{\rm DI}$ of a two-electron system are calculated from these probabilities. For the two electron $(i = 1, 2)$ system, $R_{{\rm r}i}$, $R_{{\rm c}i}$ and $R_{{\rm I}i}$ satisfy the following equations:

$$\frac{q_i}{(R_{{\rm r}i} - a)^2} = \frac{Z_i}{a^2},$$
$$\frac{q_i}{R_{{\rm c}i}} = \frac{1}{2} V_{\rm P}^2,$$

and

$$\frac{q_i}{R_{{\rm I}i}} = I_i + \frac{q_i}{R_{{\rm r}i}}. \tag{4}$$

For a given collision parameter b and velocity $V_{\rm p}$, the probability that the electron will be released is $P_{{\rm r}i}(b) = \dfrac{2\sqrt{R_{{\rm r}i}^2 - b^2}}{V_{\rm P}} \cdot \dfrac{1}{T}$, for $b \leq R_{{\rm r}i}$;

The capture probability is

$$P_{\mathrm{C}i}(b) = \frac{2\sqrt{R_{\mathrm{C}i}^2 - b^2}}{V_{\mathrm{P}}} \cdot \frac{1}{T}, \quad \text{for} \quad b \le R_{\mathrm{C}i};$$

The ionization probability is

$$P_{\mathrm{I}i}(b) = P_{\mathrm{r}i}(b) - P_{\mathrm{C}i}(b), \quad \text{for} \quad b \le R_{\mathrm{I}i}. \tag{5}$$

Then the direct single-ionization cross section and the direct double-ionization cross section can be calculated within the framework of the independent electron model to be

$$\sigma_{\mathrm{Si}} = 2\pi \int P_{\mathrm{I}1}(b) \cdot (1 - P_{\mathrm{I}2}(B) - P_{\mathrm{C}2}(b)) \cdot b \cdot \mathrm{d}b + 2\pi \int P_{\mathrm{I}2}(b) \cdot (1 - P_{\mathrm{I}1}(b) - P_{\mathrm{C}1}(b)) \cdot b \cdot \mathrm{d}b$$

and

$$\sigma_{\mathrm{DI}} = 2\pi \int P_{\mathrm{I}1}(b) \cdot P_{\mathrm{I}2}(b) \cdot b \cdot \mathrm{d}b.$$

The ratio of direct double-to-single ionization is $\frac{\sigma_{\mathrm{DI}}}{\sigma_{\mathrm{SI}}}$. The ratio for bare ions impacting on helium atoms is described well in this model, but not in good agreement with the experimental data for partially stripped ions. To solve this problem, we consider that the effective charge of the projectile should be taken into account, based on the following fact.

The first released electron is ionized out of the helium atom as the partially stripped ion approaches the distance $R_{\mathrm{I}1}$, which is several times larger than the atomic diameter[20,21], so the charge of the projectile seen by the first electron ionized out of the helium atom should be the initial charge state q. With the further approach of the projectile, the second electron of the helium atom will be released when the helium atom is ionized at a distance of $R_{\mathrm{I}2}$ that is much smaller than one atomic unit. When the projectile approaches the target nucleus further, the projectile will penetrate the orbits of the target electrons so that the screening effect of the bound electrons of the partially stripped projectile is weakened, and some electrons of the projectile should be released or ionized out of the helium atom after the first helium electron is released due to the electron-electron interaction to some extent. Once the projectile electron is released, which means that the screening effect weakens, so the effective charge of the projectile seen by the second target electron will be Δq_{eff} larger than the initial charge state q. At present it is very hard to obtain the accurate analytic expression of Δq_{eff} due to the complex many-body interactions, thus the value of Δq_{eff} could be introduced as a parameter by fitting the experimental data.

So we modify the model[18] in the following way: calculate the direct ionization cross sections of the first electron by using the initial charge states, and calculate the direct ionization cross sections of the second electron by using the effective charges. For the partially stripped C^{q+} and O^{q+} ions, the values of the additional charge Δq_{eff} are determined when the differences between the experimental data and the theoretical fittings are minima. The theoretical fittings of R are also plotted in Figs.2–9.

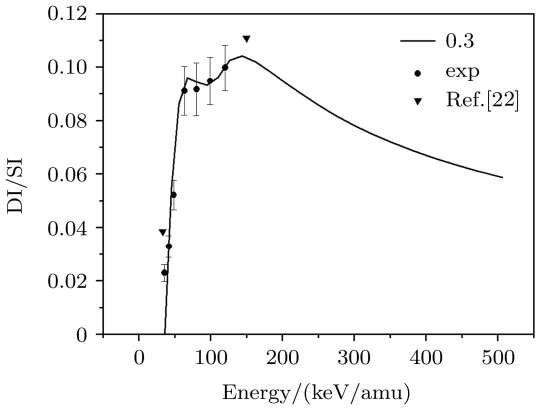


Fig.2. Experimental data of direct double-to-single ionization ratio for C^{+} colliding with He and the theoretical estimate with Δq_{eff} =0.3 (solid line). The data ($\blacktriangledown$: C^{2+}) are adopted from Ref.[22], and the data ($\bullet$: C^{+}) are obtained from the present experiment.

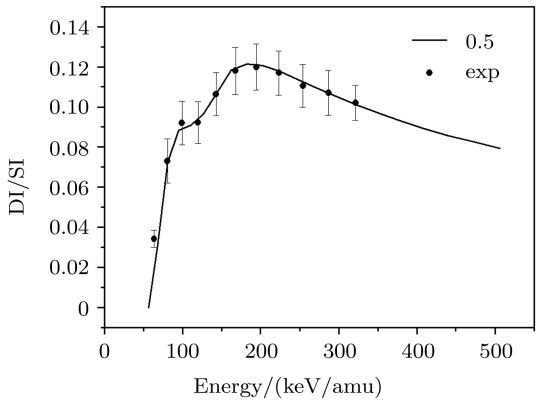


Fig.3. Experimental data of direct double-to-single ionization ratio for C^{2+} colliding with He ($\bullet$: C^{2+}) and the theoretical estimate with Δq_{eff} = 0.5 (solid line).

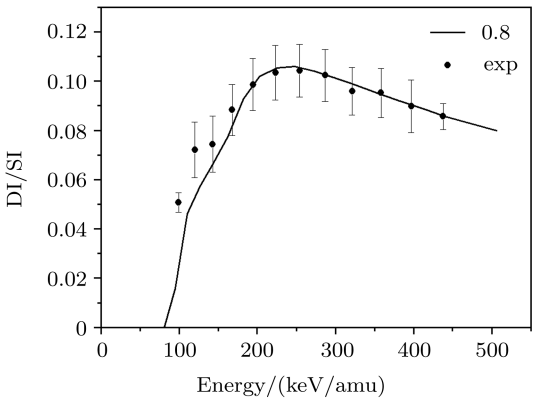


Fig.4. Experimental data of direct double-to-single ionization ratio for C^{3+} colliding with He (●: C^{3+}) and the theoretical estimate with $\Delta q_{\rm eff} = 0.8$ (solid line).

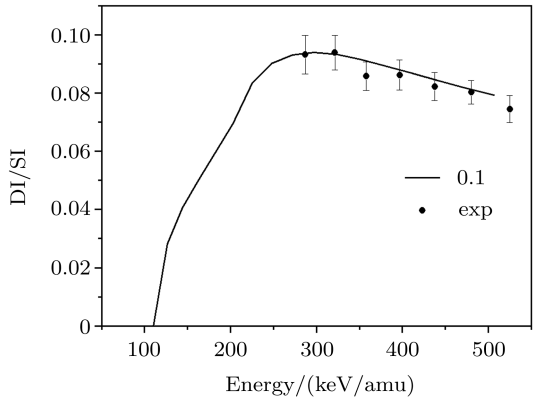


Fig.5. Experimental data of direct double-to-single ionization ratio for C^{4+} colliding with He (●: C^{4+}) and the theoretical estimate with $\Delta q_{\rm eff} = 0.1$ (solid line).

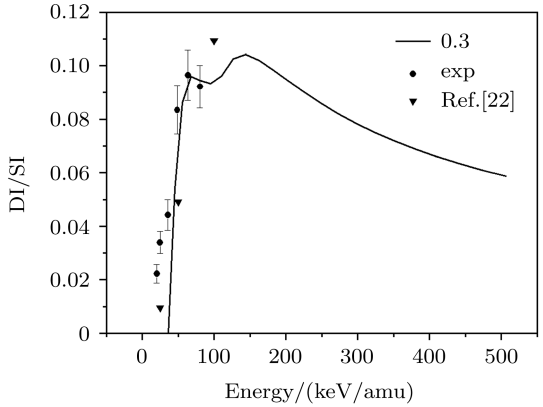


Fig.6. Experimental data of direct double-to-single ionization ratio for O^{+} colliding with He and the theoretical estimate with $\Delta q_{\rm eff} = 0.3$ (solid line).The data (▼: O^{+}) are adopted from Ref.[22], and the data (▼: O^{+}) are obtained from the present experiment.

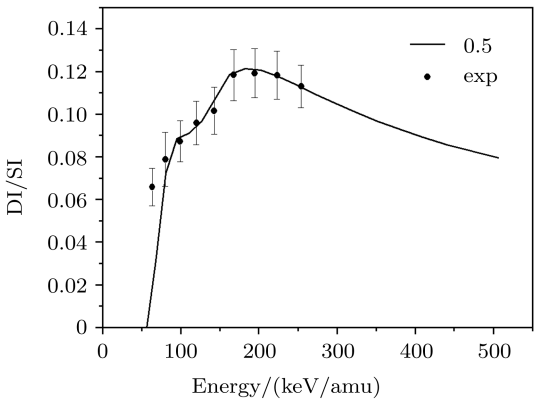


Fig.7. Experimental data of direct double- to-single ionization ratios for O^{2+} colliding with He (●: O^{2+}) and the theoretical estimate with $\Delta q_{\rm eff} = 0.5$ (solid line).

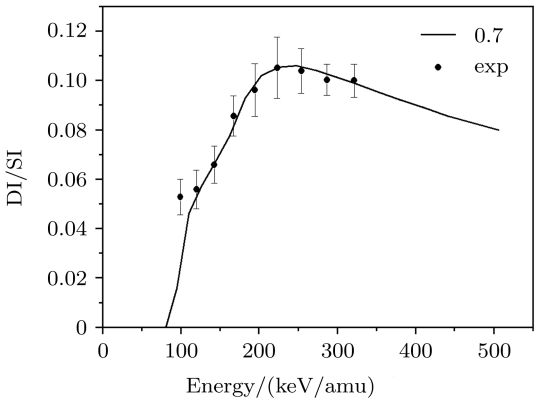


Fig.8. Experimental data of direct double-to-single ionization ratio for O^{3+} colliding with He (●: O^{3+}) and the theoretical estimate with $\Delta q_{\rm eff} = 0.7$ (solid line).

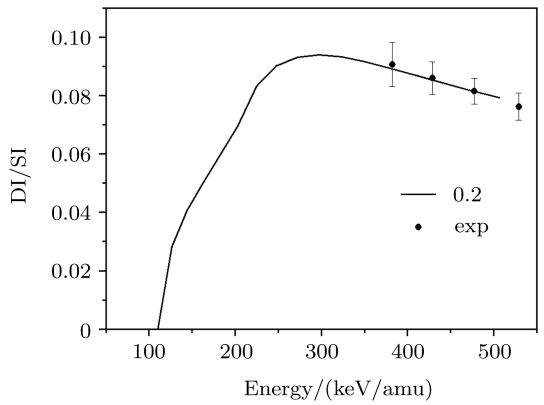


Fig.9. Experimental data of direct double-to-single ionization ratio for O^{4+} colliding with He (●: O^{4+}) and the theoretical estimate with $\Delta q_{\rm eff} = 0.2$ (solid line).

4. Discussion

From Fig.2 to Fig.9, it is found that the theoretical results calculated by our model are in good

agreement with the experimental data. Note that the effective charges seen by the second target electron are determined by the fitting parameter $\Delta q_{\rm eff}$. In the collision process, the out-shell electrons of these partially stripped ions may be released and lose their screening effect, so the charge seen by the second target electron will be larger than the initial charge state of the projectile. From Fig.2 to Fig.9, it can be seen that the fitting parameter $\Delta q_{\rm eff}$ increases with the increase of charge state q for carbon ions and so does the circumstance for oxygen ions, except the ions with charge state $q = 4$. For carbon ions in Figs.2–5, the values of fitting parameter $\Delta q_{\rm eff}$ are 0.3, 0.5, 0.8, and 0.1, and the values of effective charge $q_{\rm eff}$ are 1.3, 2.5, 3.8, and 4.1. For oxygen in Figs.6–9, the values of fitting parameter $\Delta q_{\rm eff}$ are 0.3, 0.5, 0.7, and 0.2, and the values of effective charges $q_{\rm eff}$ are 1.3, 2.5, 3.7, and 4.2.

In Fig.10, the 2nd–5th ionization energies of these ions as well as the ionization energies of helium are plotted. The 2nd–4th ionization energies of carbon and oxygen ions are very close to the 1st and 2nd ionization energies of helium. In close collision, after the first electron of a helium atom has been released, some electrons of the ion will also be released accompanied with the release of the second target electron. The probability for the projectile electron-loss is about $\Delta t/T$, where Δt is the collision time and T is the orbital period of the projectile electron. The electron orbital period of the projectile with charge state q is $T = 2\pi n^3/q^2$, which decreases with the increase of charge state q. So the release probability of the projectile electron increases with the increase of charge state q. Thus, the effective charge seen by the second electron of helium target also increases with the increase of the projectile charge state. However, for the ion with charge state 4+, that is another story. The 5th ionization energy of the projectile is much larger than the 2nd ionization energy of the helium atom, so the release distance for the 5th electron will be much smaller than that for 2nd–4th electrons, and the release probability of the 5th electron should be much smaller. So the additional effective charge $\Delta q_{\rm eff}$ for the projectile with charge state $q = 4$ will be much smaller than that of ions with charge state $q = 3$. The parameter $\Delta q_{\rm eff}$ for O^{4+} is 0.2, a bit larger than 0.1 for C^{4+}, which also can be explained by our model: the 5th ionization energy for O^{4+} ion is smaller than that for C^{4+} ion, so the release probability of the 5th electron for O^{4+} ion will be larger than that for C^{4+} ion.

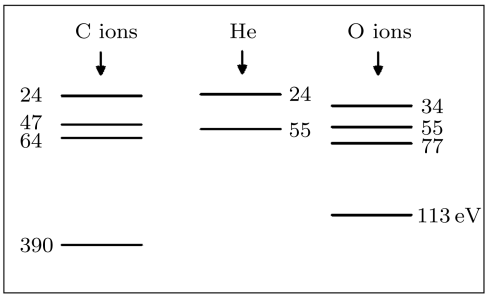


Fig.10. Ionization energies for C^{q+} , O^{q+} ions and Helium target (unit : eV).

Generally, in the collisions of the partially stripped ions with helium atoms, the released but uncaptured electrons are ionized out of helium atoms at some distance $R_{\rm I}$. After the first target electron has been released, some of the out-shell electrons of the projectile can also be released and lose their screening effect, so the charge seen by the second electron of the helium target will be larger than the initial charge state of the projectile. Based on this fact, we modify the model[18] by introducing an effective charge to estimate the values of direct double-to-single ionization ratio for partially stripped ion impact.

5. Summary

The double-to-single ionization ratios of helium atoms bombarded by C^{q+}, O^{q+} $(q = 1 - 4)$ ions are measured in an energy range from 25 to 500 keV/amu. We modify the model[18] by introducing an effective charge seen by the second target electron to estimate these ratios for partially stripped ions impact. The theoretical results from our model are in good agreement with the experimental data and the trend of the fitting parameter varying with the projectile charge state q is also interpreted qualitatively.

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