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Single-and-double electron loss of O^{2+} in collisions with argon and helium*

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This paper reports that the ratios of double to single electron loss cross-section (R) of O^{2+} in collision with Ar and He at the velocity of 1–4ν_0 (ν_0 is the Bohr velocity) have been obtained by the coincidence technique. The trend of $R-V$ in the experiment indicates that the effective charge varies with injected velocity. The effective charge can be obtained by the n-body classical trajectory Monte Carlo method, which is interpreted by the molecular Coulomb over barrier model.

Keywords: ion–atom collision, cross-section, electron-loss, effective charge
PACC: 5220H, 3450H, 3470

1. Introduction

Many studies involved in ion–atom collision have been motivated by the challenge to understand multi-body interactions. It is evident that the remarkable progress has been made for understanding electron production mechanisms in the ion–atom collision. Various fundamental mechanisms have been identified and successfully modelled, such as the Bohr–Lindhardt model,[1] the over barrier model[2] and the molecular Coulomb over barrier model (MCBM).[3] All of them are based on the independent electron model. In the process, it is beneficial to consider the concept of collision centres when heavy particles strongly interact with electrons. The concept takes into account the specific features of ion–atom collision systems consisting of two heavy particles and one or more electrons. According to the concept of collision centres, electron emission in soft and close collisions can be easily understood as antipodal mechanisms involving a single centre associated with the target and the projectile, respectively. The n-body classical trajectory Monte Carlo method (nCTMC)[4] has gained considerable success in the past years, but its deficiency is found when dressed projectiles are used. So far, there is no theory or model that can be used to understand the electron-loss process of projectile-ion. Therefore the investigation of effective charge for dressed ions and atom is of great importance when the interaction force needs to be calculated.

The electron-loss process of projectile-ion is mainly due to the Coulomb interaction between the target nucleus and active electron of projectile-ion. However, the target electrons play the dual role. When they stay in the ground state during the collision, they screen the target nucleus, the electron-loss cross section of projectile-ion decreases, and this is the so called screening effect. On the other hand, when they are excited or ionized, they can produce additional electron-loss, the electron-loss cross section increases, and this is the so called antiscreening effect. These effects have been studied experimentally[5,6] and theoretically[7−10] in the past years. This work mainly studies the electron-loss of O^{2+} in the collisions with argon and helium in the presence of other unavoidable collision channels, for example the electron-capture channel of O^{2+}.

2. Experimental technique

This work was performed on the 2×1.7 MV tandem accelerator at Lanzhou University. The techniques was described previously.[11−13] A schematic diagram of the experimental setup is shown in Fig.1. After passing through two sets of slits, the O^{2+} pro-

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jectiles were directed into the collision chamber where they collided with the helium or argon target atoms. The pressure in the collision chamber was measured with a capacitance manometer. Outgoing charge-changed projectiles were separated by a transverse electrostatic field, and detected by a position-sensitive detector. The recoil ions were accelerated by a transverse electric field into a detector with a microchannel plate. The time that the recoil ion needs to reach the detector depends on the charge state of the recoil-ion. Therefore coincidence events can distinguish the charge states of every ion. The two-dimensional spectra with different charge states of recoil ions and outgoing projectiles were recorded by a Multiparameter Multichannel Analyser System (MPA) data acquisition system.

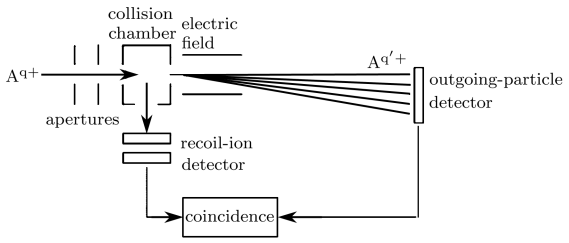


Fig.1. Schematic plot of experimental arrangement.

Special concern was taken to ensure that single-collision condition was satisfied and recoil ion did not change its charge state during the period of flight. Therefore, the average pressure in the chamber with gas was controlled at 3.8×10^{-3} Pa and the pressures at the entrance and at the exit of the chamber both were less than 2.7×10^{-4} Pa, however the background pressures without gas were less than 6×10^{-5} Pa. The gas was bled into the chamber through a needle valves, and its flux was monitored by a flowmeter. After collimated with two two-dimensional apertures of $0.2\text{mm}\times0.2\,\text{mm}$ (two metres between them) to ensure that the divergence of the beam was smaller than 0.01°, the ion-beams passed through the collision chamber vertically crossing with argon or helium atoms.

The cross section for any channel $\{Z_P^q+Z_T \rightarrow Z_P^{q'}+Z_T^i+(i+q'-q)e\}$ can be derived by

$$\sigma^{i}_{qq'}=\frac{n^{i}_{qq'}/\eta^{i}_{r}}{\left(I/\eta^{q'}_{p}\right)NlT}. \tag{1}$$

Where $n^{i}_{qq'}$ is the intensity of coincidence event, η^{i}_{r} is the recoil-ion detection efficiency, $\eta^{q'}_{p}$ is the outgoing projectile detection efficiency, I is the integrated beam intensity, N is the target-gas density, l is the effective interaction length, and T is the optical transmission of recoil-ion detection system due to the grids used, i is the charge state of recoil-ion, q is the charge state of injected projectile-ion, q′ is the charge state of outgoing projectile.

In our experiment, the electron-loss process of projectile-ion is described by the reaction channels:

$$O^{2+}+A\rightarrow O^{3+}+A^{i+}+(1+i)e, \tag{2}$$

$$O^{2+}+A\rightarrow O^{4+}+A^{i+}+(2+i)e, \tag{3}$$

where A stands for the target He or Ar, i stands for the electron-loss number of target atom after the collision, the reaction (2) channel is the process of projectile single electron-loss, the reaction (3) channel is the process of projectile double electron-loss.

According to Ref.[14], when the energy per nucleus (E/amu) is larger than 1keV/amu, the detection efficiency is up to 100%. The value of E/amu for the outgoing projectile (O^{3+} or O^{4+}) is larger than 60keV/amu in this work, so the detection efficiency of the outgoing projectile almost equals to 100%. The ratios of double-to-single electron-loss cross-section of O^{2+} are described by the following expression:

$$R^{e,t}=\frac{\sigma_{24}}{\sigma_{23}}=\frac{n_{24}}{n_{23}}. \tag{4}$$

3. Results and discussion

The two-dimensional spectra as a function of the charge states of out-going projectiles and recoil-ions were analysed in our experiment. We obtained the ratios of double-to-single electron-loss cross-section ($R^{e,t}$) of O^{2+} colliding with Ar or He atoms regardless of the charge states of recoil-ions at the projectile-ion velocity of $1-4\nu_0$.

When the effective charge of target atom is taken as S^+, the process of nCTMC method is expressed as

$$A^{s+}+O^{2+}\rightarrow A^{s+}+O^{(2+k)+}+k\text{e}, \tag{5}$$

where k is the number of electron-loss for O^{2+}, A is He or Ar, and the value of S is 0.4, 1 and 2 in this work.

For the sake of performing the calculation of nCTMC, O^{2+} is regarded as the target instead of the projectile, while He or Ar is considered as the projectile with the charge state of S^+ in this work. As a result, the electrons of He or Ar are not considered during the collision, for the electronic structure effect of projectile cannot be calculated in nCTMC.

Then the ratios of double-to-single electron-loss cross-section ($R^{c,s}$) of O^{2+} colliding with Ar or He are obtained through the calculation of nCTMC, when the effective charge of target-atom is regarded as S^+.

The experimental results and calculation results are shown in Figs.2 and 3.

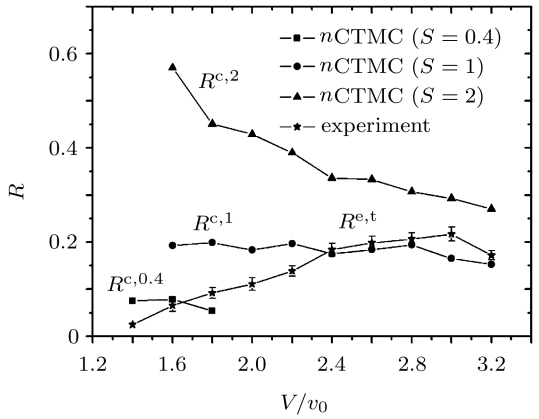


Fig.2. Ratios ($R^{e,t}$) of double-to-single loss cross-sections for O^{2+} in collision with He as a function of the projectile velocity v (a.u. is the atomic unit) and effective charge of target atom. Symbols for data: –★–, this work; –■–, nCTMC results for $S = 0.4$; –●–, nCTMC results for $S = 1$; –▲–, nCTMC results for $S = 2$.

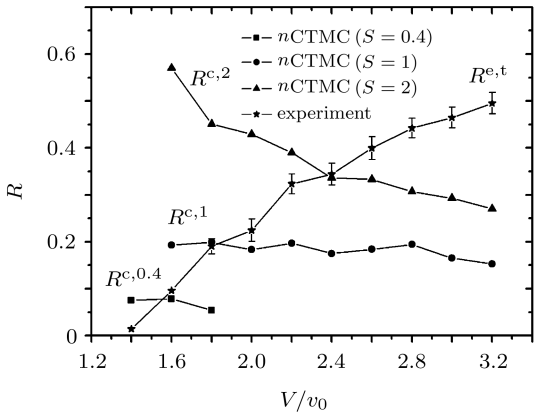


Fig.3. Ratios ($R^{e,t}$) of double-to-single loss cross-sections for O^{2+} in collision with Ar as functions of the projectile velocity v (a.u. is the atomic unit) and effective charge of target-atom. Symbols for data: –★–, this work; –■–, nCTMC results for $S = 0.4$; –●–, nCTMC results for $S = 1$; –▲–, nCTMC results for $S = 2$.

From Fig.2, the experimental $R^{e,t}$ increases with increase of the projectile-ion velocity. For projectile velocity $V = 2.4 - 2.8v_0$, the effective charge of He to O^{2+} is at the range of $1.0 - 1.5$; for $V = 1.6 - 2.4v_0$, it is at the range of $1.0 - 0.4$, and for $V < 1.6v_0$, it is smaller than 0.4; for $V > 3.0v_0$, the effective charge begins to descend from 1.5, and its highest value is 1.5 which is smaller than He nuclear charge 2. From Fig.3, the effective charge of Ar also increases with increasing the projectile velocity, and it is not up to its highest value at the velocity range ($V = 1 - 4v_0$). It is not difficult to come to the conclusion that, the effective charge of target atom is a function of the projectile velocity rather than a constant, and the effective charge of target atom to O^{2+} increases with increasing the injected velocity. In a word, as the collision parameter decreases with increasing the projectile velocity, the effective charge of target-atom which the projectile suffers increases at the velocity of 1–4 v_0.

Experimental data show that there is a threshold of injected velocity for the electron-loss of projectile-ion in ion–atom collisions, and the threshold for He or Ar approximately equals to $1.4v_0$. This can be interpreted by the MCBM model. From the viewpoint of the MCBM model, larger the velocity of projectile-ion is, smaller the minimum distance between the particle-ion and target-atom is, thus the potential barrier between the two nuclear centres will become lower, so that it is easier to form a quasi-molecule. Consequently it is more probable to lose electrons. Notice that the capture distribution is excluded because the investigation only aims at the electron-loss of projectile-ion and target-atom. On the other hand, if the injected velocity is less than the threshold, projectile-ion and target-atom cannot form a quasi-molecule. As a result, no electron will be lost. The velocity threshold varies with the charge state of projectile-ion and the binding energy of each electron. Therefore the velocity thresholds of the inner-shell electrons are higher. These will explain that $R^{e,t}$ increases with increasing the projectile-ion velocities until the single ionization tends to its maximum.

In summary, comparing with the experimental data and nCTMC results, we obtain the target effective charge during ion–atom collisions at a certain velocity and projectile charge state. At the same time, it is found that the effective charge of target-atom depends on the relative velocity between the target and projectile, and there is a velocity threshold of electron-loss during ion–atom collision at the energy region.

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