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Transfer Ionization of Helium in Collisions with C^{q+} and O^{q+} $(q = 1 - 3)$ *

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Cross-section ratios $\sigma_{\rm TI}/\sigma_{\rm SC}$ of transfer ionization (TI) to single capture (SC) of C^{q+}- and O^{q+}-He $(q = 1 - 3)$ collisions in the energy range of 15–440 keV/u (0.8–4.2 $v_{\rm Bohr}$) are experimentally determined. It is shown that $\sigma_{\rm TI}/\sigma_{\rm SC}$ strongly depends on the projectile velocity, and there is a maximum for $E({\rm keV/u})/q^{1/2} \approx 150$. Combining the Bohr–Lindhard model and the statistical model, a theoretical estimate is presented, in reasonable agreement with the experimental data when $E({\rm keV/u})/q^{1/2} > 35$.

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The study of interactions between ions and atoms plays an essential role[1−3] in developing models and providing important cross-section data to other scientific branches of physics, such as plasma physics, astrophysics, nuclear physics and solid state physics, as well as in other sciences such as chemistry, biophysics and medicament. The collision processes depend critically on the impact velocity v_p of an incident ion. At very high velocities ($v_p \gg v_e$) compared to the target electrons' velocities, ionization is the dominant channel, while electron capture is dominant at very low velocities ($v_p \ll v_e$). However, at low to intermediate velocities ($v_p \sim v_e$), it is difficult to single out a dominant channel, because the ionization, the electron capture as well as the transfer ionization processes are comparative and also strongly couple each other. So far, both the experiment and theory have not been well explored for multi-electron systems yet.[4,5] In collisions of an energetic ion A^{q+} with a helium target, single capture (SC) and transfer ionization (TI) processes of helium can be described by

$$\text{SC: } A^{q+} + He \rightarrow A^{(q-1)+} + He^{+}, \quad (1)$$

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

and TI and SC cross sections have been measured by Shah and Gilbody[6] for He^{2+}, Li^{3+} + He collisions in the energy range of 50–2380 keV/u. DuBois[7,8] reported the similar measurements for He^{+} and He^{2+} on He collisions in the energy range of 3–500 keV/u. Later, Forest *et al.*[9] extended the energy range up to 3000 keV/u for He^{+} + He collisions. The ratios of TI to SC were also measured by Woitke *et al.*[10] for Li^{q+} + He $(q = 1-3)$ collisions in the 285–2000 keV/u energy range.

In this Letter, we report the experimental cross-section ratios of TI to SC, $\sigma_{\rm TI}/\sigma_{\rm SC}$, of helium by C^{q+} and O^{q+} $(q = 1 - 3)$ in the energy range of 15–440 keV/u (0.8–4.2 $v_{\rm Bohr}$). An estimate based on the Bohr–Lindhard model[11,12] and statistical model[12,13] is presented.

The experiments were performed using the 2×1.7 MV Tandem accelerator at Lanzhou University. A detailed description of the experimental setup has been presented elsewhere.[2,14] In brief, ions produced by the accelerator were selected by a 30° dipole magnet. The selected ion beams were collimated by two sets of adjustable slits and well defined in size smaller than 0.25×0.25 mm. The energetic projectile ions impact on the gas target atoms, which were introduced into the collision region through a needle gas jet, in the target chamber. The pressure was adjusted to ensure single ion-atom collision conditions in experiments. In this work, the background vacuum was better than 8×10^{-6} Pa, and the working pressure in the target region remained around 2×10^{-3} Pa. In this case, single-collision conditions have been verified.[15] The scattered projectile ions, which may or may not have changed their charge states during the collisions, then entered a parallel plate electrostatic charge analyser, and finally were detected by a position-sensitive multi-channel plate (PSMCP) detector. Various charge states of the scattered projectiles were separated. The recoiled target ions were extracted by an electrostatic field (500 V/cm) and accelerated further to the potential of the recoil multi-channel plate (RMCP) detector (−2.2 kV) through a length of 100 mm. The energy signal from PSMCP was used a stop signal to a time-to-amplitude converter (TAC) and the signal from RMCP was used as a start signal. The charge

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states of recoils were analysed by a time-of-flight spectrum. We can identify each individual process in ion-atom collisions from the related coincidence spectrum between recoil-ion time of flight and projectile position. For a case of A^{q+} on He, the ratio σ_{TI}/σ_{SC} could be determined by

$$\frac{\sigma_{TI}}{\sigma_{SC}} = \frac{\varepsilon_1}{\varepsilon_2}\frac{N^{02}_{qq-1}}{N^{01}_{qq-1}}, \tag{3}$$

where N^{01}_{qq-1} and N^{02}_{qq-1} are the number of detected He^+ and He^{2+} events undergoing one-electron transfer, respectively, and σ^1 and σ^2 are the detection efficiencies of He^+ and He^{2+}, respectively. The main sources of uncertainties come from the efficiency of RMCP detector (10%), statistical errors, multicollision (< 3%) and the uncertainty of determining the counting region in the two-dimension spectrum (10%). The statistical error is small (< 5%) for the SC and TI channel. Full details of the error analysis have been given in our previous paper.[14]

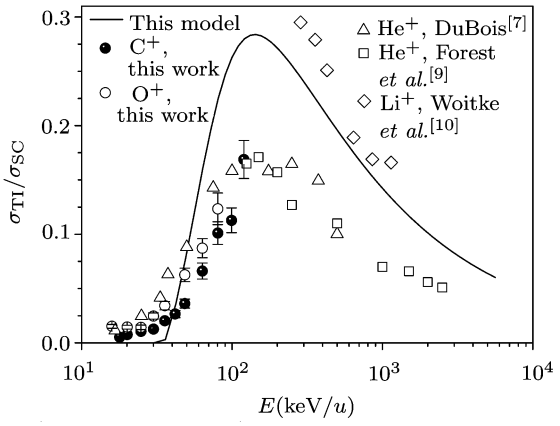


Fig. 1. Energy dependence of the ratios σ_{TI}/σ_{SC} for A^+ + He collisions.

The present results as a function of the energy E (keV/u) as well as previous results on He by other groups [6–10] are shown in Fig. 1–3. All the results show that the ratios σ_{TI}/σ_{SC} are smaller than 0.5, which implies that the SC process is the dominant contributor to total single capture processes. At a given charge state q, the ratios are strongly dependent on the projectile energy and reach a maximum at a certain energy E_{max}. It is obvious that the value of E_{max} moves towards the higher energy with the increasing charge state. As seen from Figs. 2 and 3, E_{max} for the partially stripped ions are slightly larger than that for fully stripped ions with the same charge state, i.e., E_{max} (C^{2+}, O^{2+}) > E_{max} (He^{2+}) and E_{max}(C^{3+}, O^{3+}) > E_{max} (Li^{3+}). This should be attributed to the influence of the projectile electrons. For partially stripped ions, the projectile nucleus is almost fully screened by electrons at distant collisions and the effect charge q_{eff} is approximately equal to the charge state q. At close collisions, the target electrons will be disturbed by an effective charge q_{eff} which is larger than q owing to the orbital interpenetrating. Considering the C^{2+} projectile, the average effective charge q_{eff} is larger than 2. Next, the theoretical estimates for the energy dependence of the ratios based on Bohr–Lindhard model[11,12] and statistical model[12,13] are offered.

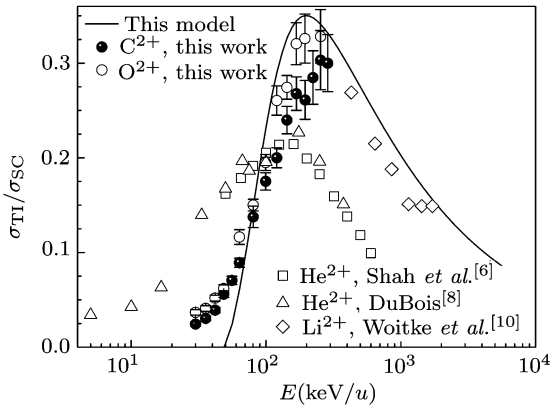


Fig. 2. Energy dependence of the ratios σ_{TI}/σ_{SC} for A^{2+} + He collisions.

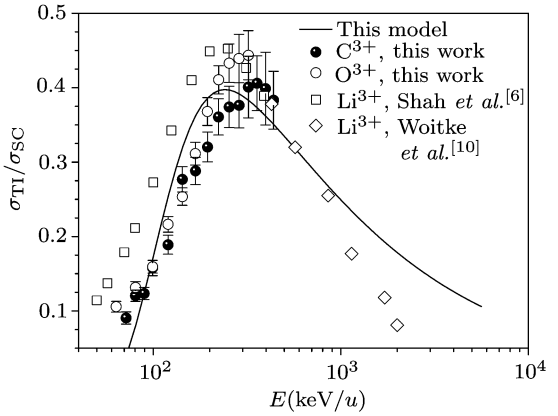


Fig. 3. Energy dependence of the ratios σ_{TI}/σ_{SC} for A^{3+} + He collisions.

One electron can be released from the target when the projectile is close enough in order to overcome the binding force of electron from the target. The release distance R_r is defined by $qe^2/R_r^2 = m_e v_e^2/a$, where q is the projectile charge and m_e, a and v_e are the mass, orbital radius and velocity of the bound electron, respectively. The release distance R_r can be given as

$$R_r = (qaa_0)^{1/2}(v_0/v_e), \tag{4}$$

where $v_0 = e^2/\hbar$ and $a_0 = \hbar^2/m_e e^2$ are the first Bohr orbital velocity and radius, respectively. On the other hand, the capture process takes place when the electron's energy in the projectile rest frame is negative.

The capture distance R_c is given by

$$R_c = 2qa_0(v_0/v_p)^2. \tag{5}$$

When $R_r > R_c$, one released electron from the target can be captured or ionized. Release is a gradual process, which takes place with a probability per unit time of the order of v_e/a. One-electron release probability f_r is proportional to the time that the projectile spends within the R_r distance, i.e. $f_r \propto R_r/v_p$. According to the Bohr–Lindhard model, f_r can be written as

$$f_r = v_e/a \cdot R_r/v_p. \tag{6}$$

In the same way, the capture probability f_c is written as

$$f_c = v_e/a \cdot R_c/v_p. \tag{7}$$

where the unitarized probabilities are used, which are calculated by[16]

$$P_r = 1 - \exp(-f_r), \tag{8}$$

$$P_c = \frac{f_c}{f_r} \cdot P_r, \tag{9}$$

$$P_i = P_r - P_c, \tag{10}$$

where P_r, P_c and P_i are the unitarized release, capture and ionization probabilities, respectively. Within the independent-electron approximation (IEA), the probabilities of SC and TI are determined by

$$P_{\rm SC} = 2P_c \cdot (1 - P_i - P_c), \tag{11}$$

$$P_{\rm TI} = 2P_c \cdot P_i, \tag{12}$$

where $P_{\rm SC}$ and $P_{\rm TI}$ are the probabilities of single capture and transfer ionization, respectively. The cross sections σ are calculated as geometrical cross sections multiplied by the corresponding probability P, i. e.

$$\sigma = \pi R^2 \cdot P. \tag{13}$$

We have to integrate over the electron distribution of the target atom. A statistical distribution[12,13] dn as a function of velocity v_e is given by

$$dn = Z^{1/3}(1/v_0)dv_e, \quad \alpha v_a \le v_e \le \beta z v_0 \tag{14}$$

and $dn = 0$, otherwise. Here, Z is the atomic number, v_a is given by $v_a = (I/I_0)^{1/2}$, I is the atomic ionization potential, and I_0 is the Rydberg energy. For the removal of two electrons, we use the average ionization energy $I = (I_1 + I_2)/2 = 39.5\,\text{eV}$. To account for the existence of electrons moving with velocities smaller than v_a, the adjustable parameter α between 0 and 1 is introduced. We choose $\alpha = 0.5$ in the present calculations. For normalization, the parameter β is given by $\beta = Z^{-1/3} + \alpha Z v_a/v_0$. Orbital velocity v and radius a are connected via $a = a_0 v_0/v_e Z^{1/3}$.

The estimates are expected to show the general trend of the ratios following the projectile energies. It is seen that the present theoretical estimates are in reasonable agreement with the experimental results, which indicates that the independent-electron approximation (IEA) is feasible in the present energy range to a certain extent.

Figure 4 shows the present results as functions of the reduced energy $E(\text{kev}/u)/q^{1/2}$ as well as previous results on He by other groups.[4–8] It is obvious that the ratios increase with the increasing charge state for ions with the same atomic number and there is a maximum in $\sigma_{\rm TI}/\sigma_{\rm SC}$ for $E_{\max}(\text{keV}/u)/q^{1/2} \approx 150$. It is well known that $\sigma_{\rm SC}$ monotonously decreases with increasing energy at intermediate velocities, while $\sigma_{\rm TI}$ has a maximum at certain energy $E_{\max,\rm TI}$. As an approximation, from Eqs. (3)–(9), $\sigma_{\rm TI}$ will reach a maximum when $P_i = P_c$, i.e. $f_r = 2f_c$. We have $E_{\max,\rm TI} \propto q^{1/2}$, which is helpful to understand the scaling $q^{1/2}$ dependence of $E_{\max}$ to a certain extent. It is also obvious that when the projectile charge q increases, the maximum value increases. It should be attributed to the increase of the effective interaction range R_r with the increasing charge state q. On the other hand, because the ionization process can not take place for $R_r < R_c$ according to the Bohr–Lindhard model, the estimated values have reached zero at $\text{E}(\text{keV}/u)/q^{1/2} \approx 35$. It may indicate that another mechanism, autoionization (AI) of the projectile after capture of two electrons to a doubly excited state,[17] can contribute to the TI process.

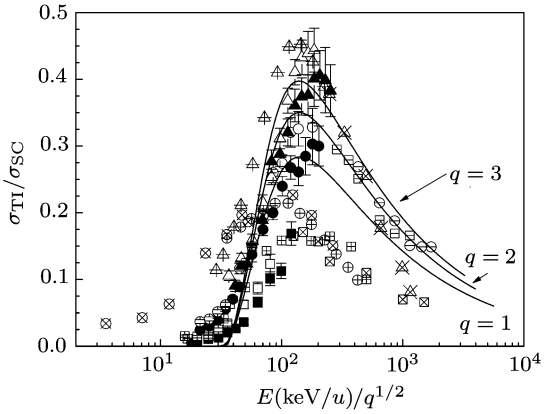


Fig. 4. Ratios $\sigma_{\rm TI}/\sigma_{\rm SC}$ for A^{q+} ($q = 1 - 3$) + He versus $E(\text{keV}/u)/q^{1/2}$. The present estimates: solid lines. Experiment results: the same as Figs. 1–3.

In summary, the ratios $\sigma_{\rm TI}/\sigma_{\rm SC}$ of TI to SC of He by C^{q+} and O^{q+} (q = 1–3) in the energy range of 15–440 keV/u (0.8–4.2 $v_{\rm Bohr}$) have been measured. The present results and the similar measurements show that the ratios are strongly dependent on the projectile energy and there is a maximum at $E_{\max}(\text{keV}/u)/q^{1/2} \approx 150$. We also perform the the-

oretical estimate based on the Bohr–Lindhard model and statistical model. The estimate shows the trend in reasonable agreement with the experimental data when $E(\mathrm{keV}/u)/q^{1/2} > 35$.

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