Vol 13 No 10, October 2004
1009-1963/2004/13(10)/1679-05

Chinese Physics

© 2004 Chin. Phys. Soc.
and IOP Publishing Ltd

Transfer ionization of the isocharge sequence ion and Ar collisions*

Cai Xiao-Hong(蔡晓红)[a)], Yu De-Yang(于得洋)[a)], Cao Zhu-Rong(曹柱荣)[a)],
Lu Rong-Chun(卢荣春)[a)], Yang Wei(杨 威)[a)],
Shao Cao-Jie(邵曹杰)[a)], and Chen Xi-Meng(陈熙萌)[b)]

[a]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou* 730000, *China*

[b]*Department of Modern Physics, Lanzhou University, Lanzhou* 730000, *China*

(Received 15 December 2003; revised manuscript received 1 June 2004)

The ratios of transfer ionization to single capture for isocharge C^{q+}, N^{q+}, O^{q+}, Ne^{q+} ions on Ar atoms are measured by using position-sensitive and time-of-flight techniques. It is found that the ratio R_1 increases with nuclear charge Z in a q=4 sequence, and the ratio R_1 sequences have the minimum values at Z=7 and Z=8 in q=5 and q=6 sequences, respectively, and the ratio R_1 decreases with the increase in the nuclear charge Z in a q=7 sequence. The results may be explained within the frame of the statistical model. It may be concluded that the transfer ionization depends remarkably upon the electronic structure of the projectile. The projectiles used in this study have the same charge state and velocity, but different electronic structures. The dependence of the ratio R_1 on q is studied for Ne^{q+}-Ar collisions. The ratio R_1 is found to increase as q increases for Ne^{q+}–Ar collisions. The measured dependence of the ratio R_1 on q is compared with the calculation using the molecular Coulomb over-barrier model.

Keywords: charge transfer, transfer ionization
PACC: 3470, 8230F

1. Introduction

The study of multi-electron process has been a very active area of atomic physics research.[1–4] The simultaneous electron emission and electron transfer is one of the most interesting two-electron processes in the study of ion–atom collisions.[5] In the last decade much experimental and theoretical attention has been paid to the process named as transfer ionization (TI). This process is normally considered as the successive process of the single electron capture and the ionization of the second or more target electrons. The studies of transfer ionization are motivated by the understanding of the role of the electron correlation in ion–atom collisions which is of great interest in basic atomic physics and may provide important information for the applications in both astrophysics and fusion plasma researches. A number of authors have investigated the transfer ionization process by measuring the angular distribution of the emitted electrons.[5–7] It was found that the second electron recoils at a speed of the projectile ion v_p, resulting in a pronounced peak at about 90° in the angular distribution of the electrons emitted with a matching velocity $v_e = v_p$. The peak was found in 1MeV proton on He collisions by Pálinkás *et al.*[6] Mergel *et al*[7] found further evidence of correlated motion of the emitted and captured electrons for the same collision system. Sarkadi *et al*[5] observed the electron cusp in 100–300keV He^{2+}–He collisions, and identified the processes of electron capture to the continuum (ECC), and ECC accompanied by bound-state capture (transfer ionization) by detecting the electrons in coincidence with the charge-state-analysed outgoing He^{2+} and He^{+} ions. The above experiments were all at intermediate (several hundred keV) and high (MeV) energies. The studies provided the strong evidence for the electron correlation in transfer ionization.

For the ion–atom collisions at low energies, the major processes have been understood, and can be described by the classical over-barrier model[8,9] and coupled channel treatment.[10] For larger numbers of active electrons and for higher projectile charges a full quantum mechanical treatment of the charge transfer

*Project supported by the National Natural Science Foundation of China (Grant Nos 10134010, 10375080 and 10304019).

process becomes difficult due to the large number of reaction channels involved. Up to now, the systematic study of the transfer ionization and the dependence of these processes on the collision parameters for the low-energy ion–atom collisions has still rarely been reported in the literature.[11,12] In the present work the dependence of the transfer ionization process on the electronic structure of projectile is investigated for the isocharge ion sequences A^{q+} (q=4,5,6,7,8,9) on argon target. Different projectile sequences (C, N, O and Ne) with the same charge state are used to interpret the electron correlation in the case of low-energy collisions and the dependence of transfer ionization upon the electronic structure of the impinging ions.

The ratios of transfer ionization to single capture are measured for isocharge C^{q+}, N^{q+}, O^{q+}, Ne^{q+} ions on Ar atoms by using position-sensitive and time-of-flight techniques. For an isocharge ion sequence the velocities of the ions are selected to be the same in order to clarify the dependence of the ratio on the electronic structure of projectile, as mentioned above. It is found that the ratio R_1 of transfer ionization to single capture increases as the nuclear charge Z increases in a q=4 sequence, and the ratio R_1 sequences have the minimum values for Z=7 and Z=8 in q=5 and q=6 sequences, respectively, and the ratio R_1 decreases with the increase of the nuclear charge Z in a q=7 sequence. It may be concluded that the transfer ionization depends remarkably upon the electronic structure of the projectile. The projectiles used have the same charge state and velocity, but different electronic structures. The dependence of the ratio R_1 on q is studied for Ne^{q+}–Ar collisions. The ratio R_1 is found to increase as q increases for Ne^{q+}–Ar collisions. The measured dependence of the ratio R_1 on q is compared with the calculation using the molecular Coulomb over-barrier model.

2. Experimental technique

The experiments have been performed at the 14.5GHz ECR platform at the Institute of Modern Physics, Chinese Academy of Sciences. Highly charged ions produced in an ion source are extracted and m/q-selected (where m is the ion mass and q is the ion charge) by the analysing magnet. The high voltage of the ECR source is 25kV for the maximum extraction, and the voltage can be changed between 10–25kV. The ion beam is collimated by two two-dimensional collimators to a size less than 0.3mm×0.3mm. The ion beams are charge state selected again before entering the target chamber by a 64° coaxial static analyser to ensure the purity of the charge state of the projectile. The ion beam interacts with a gas jet at the centre of the target chamber. The recoil ions are extracted from the interacting zone by a static electric field and detected by a channel electron multiplier after passing through a field-free tube. The scattered ions are analysed according to their charged states by a parallel plate field and then detected by a position-sensitive channel plate detector. The charge state of the recoil ions can be determined by measuring the differences in the time-of-flight between the scattered ions and the recoil ions. A multi-parameter acquisition system is used to measure the time-of-flight spectra of the scattered and recoil ions.[2,4]

Isocharge ion sequences C^{q+}, N^{q+}, O^{q+}, Ne^{q+} are used. The ion velocities of the same ion sequence are selected to be the same in order to clarify the dependence of the ratio R_1 on the electronic structure, as mentioned above. In this work the energies of the ion sequence are selected to be 4keV/u, 5keV/u, 6keV/u and 7keV/u for projectile charge states 4, 5, 6 and 7 which correspond to the ion velocities of 0.21a.u., 0.24a.u., 0.26a.u. and 0.28 a.u., respectively.

3. Results and discussion

The ratios R_1 for A^{q+} ions on Ar atoms are shown in Figs.1–4. The charge states are selected to be 4 and 5 for carbon projectile; and q=4, 5, 6 for nitrogen projectile; q=5, 6, 7 for oxygen projectile; and q=4, 6, 7, 8, 9 for neon projectile. The fully stripped ions of C^{6+}, N^{7+}, O^{8+} and Ne^{10+} are not used because these ions have a charge-to-mass ratio of 1/2 and cannot be separated from the complex of the ions with a charge-to-mass ratio of 1/2 for the ECR ion source.

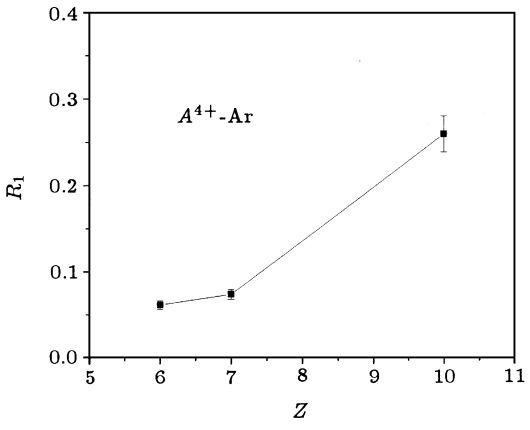


Fig.1. Ratio R_1 of transfer ionization to single capture for C^{4+}, N^{4+} and Ne^{4+} on Ar atom.

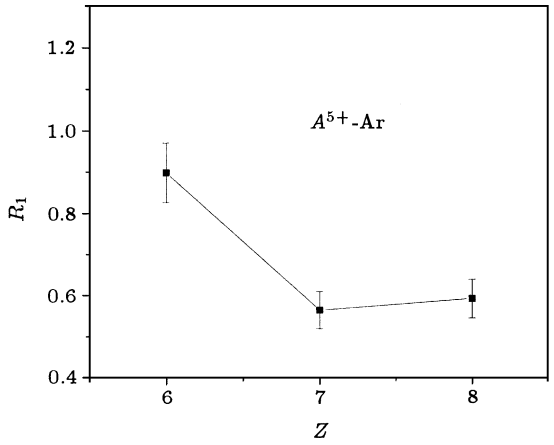


Fig.2. Ratio R_1 of transfer ionization to single capture for C^{5+}, N^{5+} and O^{5+} on Ar atom.

From Figs.1–4 it can be seen that the ratio R_1 increases as the nuclear charge Z increases for q=4 sequence, and the ratio R_1 sequences have minimum values for Z=7 and Z=8 in q=5 and q=6 sequences, respectively, and the ratio R_1 decreases with the increase of nuclear charge Z in a q=7 sequence.

To explain the results we may use the concepts of the statistical model.[13–15] The electron capture process is an exoergic reaction, and the target electron will gain energy during the single capture. In the statistical model the energy deposition to the target atom is considered to be distributed statistically among the electrons that initially belong to the target.[13] One or more electrons may then be evaporated. The probability that electrons gain enough energy to overcome the binding energy and escape from the target atom is proportional to the energy gain. If we consider the transfer ionization in a two-step regime the transfer ionization is a successive process of the single electron capture and the ionization of the second (or more) target electron. In the first-order approximation the probability of the transfer ionization may be considered as the product of the probability of the single capture and the probability of the ionization of the second electron. So the ratio R_1 may be considered to be approximately proportional to the ionization cross-section of the second electron. As mentioned above, the second electron may be ionized or 'evaporated' if gaining enough energy. The maximum energy deposition $\Delta E_{\rm m}$ is the difference between the ionization energy of the projectile A^{q+} and the first ionization energy $I_{\rm Ar}^{(1)}$ of the target atom, i.e $\Delta E_{\rm m} = I_A^{(q)} - I_{\rm Ar}^{(1)}$.[13] The first ionization energy of argon $I_{\rm Ar}^{(1)}$ is equal to 15.76eV,[16] so the maximum energy deposition is determined by the ionization energy of the projectile A^{q+}. After the first electron of the argon atom is captured by the projectile, the binding energy of the remaining target electrons will be increased due to the decrease of the screening, and the ionization energy of the second argon electron increases to 27.63eV.[16] If the maximum energy deposition $\Delta E_{\rm m} \geq$27.63eV, the second target electron may then be ionized.

For the ion sequence of q=4, the fourth ionization energies of carbon, nitrogen and neon are 64.49eV, 77.47eV and 97.12eV, and the maximum energy depositions are then 48.73eV, 61.17eV and 81.36eV, respectively. That is to say, for carbon, nitrogen and neon the fourth ionization energy increases with the nuclear charge number. The maximum energy deposition $\Delta E_{\rm m}$ increases with the nuclear charge number Z. Since $\Delta E_{\rm m}$ is larger for carbon, nitrogen and neon ions than the ionization energy of the second electron of argon, the second electron may be ionized. According to the above discussion, the ionization probability of the second target electron then increases as the nuclear charge number increases. This supports the present results that the ratio R_1 increases as the nuclear charge number increases for the collisions of C^{4+}, N^{4+} and Ne^{4+} ions with argon atoms (Fig.1). The 5th ionization energies of carbon, nitrogen and oxygen are 392.09eV, 97.89eV and 113.90eV,[16] respectively. Nitrogen has the smallest ionization energy compared with carbon and neon. For the same reason mentioned above, one may expect that the ratio R_1 has a minimum for nitrogen and this is in agreement with the result from the present experiment (Fig.2). The 6th ionization energies of nitrogen, oxygen and neon are 552.08eV, 138.12eV and 157.93eV.[16] Among them there is a minimum at Z=8 (oxygen), too. This suggests that the ratio R_1 has a minimum at Z=8, which agrees with the results shown in Fig.3. The 7th

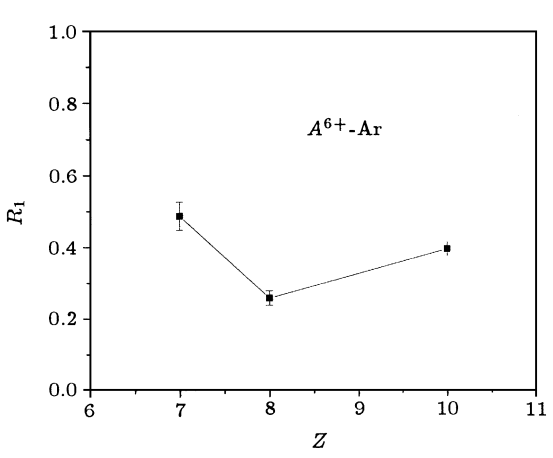


Fig.3. Ratio R_1 of transfer ionization to single capture for N^{6+}, O^{6+} and Ne^{6+} on Ar atom.

ionization energies of oxygen and neon are 739.29eV and 207.28eV, respectively.[16] The ratio R_1 for O^{7+}–Ar collision will then be higher than that for the Ne^{7+}–Ar collision, just as shown in Fig.4.

The above discussion suggests that the transfer ionization depends upon the nuclear charge number of the projectile for the collision of the isocharge sequence ion with argon. The ions in an isocharge sequence have the same charge state but different electronic structure. For example, in a q=4 sequence the electronic configurations are $1s^2$, $1s^22s$, $1s^22s^22p^2$ for C^{4+}, N^{4+} and Ne^{4+} ions, respectively. And just due to the difference in electronic structures the ions behave differently in the collisions with the target atom, resulting in the difference in the ratios R_1. It may be concluded that the transfer ionization depends remarkably upon the electronic structure of the projectile. The projectiles used in this study have the same charge state and velocity, but different electronic structures, further study of which is beyond the description of the over-barrier-model which predicts only the dependence of the transfer cross-section on q. The transfer ionization may be considered as a successive process of the single electron capture and the ionization of the second (or more) target electron. The dependence of the ratio R_1 on the electronic structure of projectile may be explained within the frame of the statistical model.

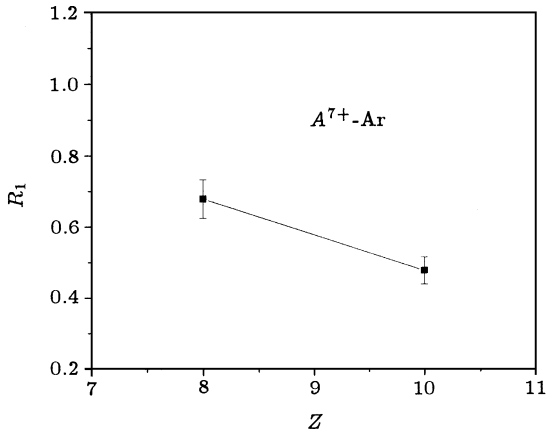


Fig.4. Ratio R_1 of transfer ionization to single capture for O^{7+} and Ne^{7+} on Ar atom.

To study the dependence of the ratio R_1 on q, we use the MCBM (molecular Coulomb over-barrier model)[8] to calculate the ratio R_1 theoretically. The statistical model is included in the treatment of the transfer ionization cross-section. The probability that electrons gain enough energy to overcome the binding energy and escape from the target atom may be calculated with the equation of Russek and Meli[15] for describing the ionization processes in ion–atom collisions. The calculated dependence of the ratio R_1 on q for Ne^{q+}–Ar collisions (open circles) together with the experimental data (solid rectangles) is shown in Fig.5. Figure 5 shows that the ratio R_1 increases as q increases for Ne^{q+}–Ar collisions, and this is in agreement with the calculation using MCBM. Since the single capture probability increases as q increases, it may be suggested that the transfer ionization probability has a higher order of magnitude of dependence upon q than the single capture probability. By applying the statistical interpretation model to the transfer ionization, the maximum energy deposition ΔE_m is found to increase with q. This suggests that the ionization probability of the second electron will be larger in the case of the higher charge state (q), and that the ratio R_1 will also increase with the charge q. From the above discussion it may be concluded that the ionization of the second target electron in the transfer ionization process depends obviously upon the projectile charge state, which is in agreement with the prediction by MCBM.

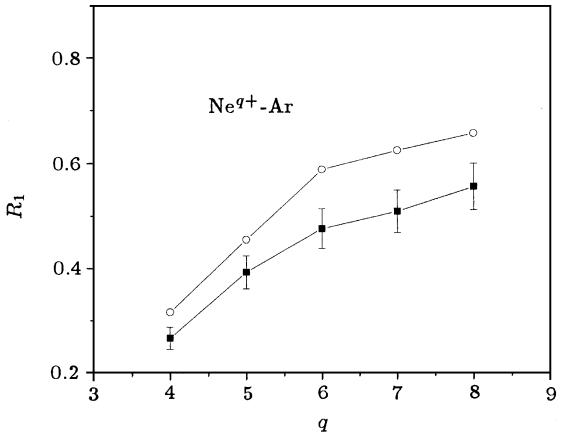


Fig.5. Ratio R_1 of transfer ionization to single capture for Ne^{q+}, (q=4, 6, 7, 8, 9) on Ar atom Solid rectangles: present experiments; open circles: MCBM calculations.

Figure 5 shows the overestimated calculations of the R_1 ratios. Their relative discrepancies are about 20%. In our calculations the maximum energy deposition ΔE_m is calculated by assuming that the electrons are always captured into the lowest unoccupied energy levels, but in fact the electrons are mostly captured into the higher excited energy levels. This assumption will lead to the overestimation of both ΔE_m and the transfer ionization probability. So the calculated R_1 ratios will be larger than the measured ones.

The experimental uncertainty in Figs.1–5 is within 10% which comes mainly from the statistic error.

4. Summary

The dependence of the ratio R_1 upon the electronic structure of the projectile for C^{q+}, N^{q+}, O^{q+}, Ne^{q+} ions on Ar target is studied by using position-sensitive and time-of-flight techniques. For an isocharge ion sequence the ion velocities are selected to be the same in order to clarify the dependence of the ratio R_1 on the electronic structure of the projectile, as mentioned above. It is found that the ratio R_1 increases with the nuclear charge Z in a q=4 sequence, and the ratio R_1 sequences have minimum values for Z=7 and Z=8 in q=5 and q=6 sequences, respectively, and the ratio R_1 decreases as the nuclear charge Z increases in a q=7 sequence. The above results may be well explained within the concepts of the statistical model. It may be concluded that the transfer ionization depends remarkably upon the electronic structure of the projectile. The projectiles used have the same charge state and velocity, but different electronic structures. Further study of this problem is beyond the description of the over-barrier-model which predicts only the dependence of the transfer cross-section on q.

The dependence of the ratio R_1 on q is studied for Ne^{q+}–Ar collisions. The ratio R_1 is found to increase as q increases for Ne^{q+}-Ar collisions. The measured dependence of the ratio R_1 on q is compared with the calculation using the MCBM. The discrepancy between the experimental data and the calculation results is discussed. It may be concluded that the ionization of the second target electron in the transfer ionization process depends obviously upon the projectile charge state, which is in agreement with the MCBM prediction.

Acknowledgment

We are grateful to the staff of the ECR laboratory at the Institute of Modern Physics, Chinese Academy of Sciences for their help during the experiment.

References

[1] Bliman S, Bruch R, Cornille M, Langereis A and Nordgren J 2002 *Phys. Rev.* A **66** 052707
[2] Cai X, Chen X, Liu Z, Shen Z, Yu D, Wang S and Ma X 1999 *Eur. Phys. J.* D **6** 23
[3] Zhou X X and Li B W1999 *Acta Phys. Sin.* **48** 1426 (in Chinese)
[4] Cai X H *et al* 1997 *Acta Phys. Sin.* (Overseas Edition) **6** 6
[5] Sarkadi L, Lugosi L, Tokési K, Gulyás L and Kövér Á 2001 *J. Phys.* B **34** 4901
[6] Pálinkás J, Schuch R, Cerderquist H and Gustafsson O 1989 *Phys. Rev. Lett.* **63** 2464
[7] Mergel, V Dörner R, Khayyat Kh, Achler M, Weber T, Jagutzki O, Lüdde H J, Cocke C L and Schmidt-Böcking H 2001 *Phys. Rev. Lett.* **86** 2257
[8] Niehaus A 1986 *J. Phys.* B **19** 2925
[9] Sattin F 2000 *J. Phys.* B **33** 861
[10] Bransden B H and McDowell M R C 1992 *Charge Exchange and the Theory of Ion–Atom Collisions* (Oxford: Clarendon)
[11] Selberg N, Biedermann C and Cederquist H 1997 *Phys. Rev.* A **56** 4623
[12] Lubinski G, Juhász Z, Morgenstern R and Hoekstra R 2001 *Phys. Rev. Lett.* **86** 616
[13] Müller A, Groh W and Salzborn E 1983 *Phys. Rev. Lett.* **51** 107
[14] Russek A 1963 *Phys. Rev.* **132** 246
[15] Russek A and Meli J 1970 *Physica* **46** 222
[16] Lide D R 2000 *Handbook of Chemistry and Physics* (80th Edition) (Boca Raton, FL: CRC Press) p10