Differential Experimental Investigation of Electron Capture for He$^{2+}$ on Helium at Low Energy

X. L. Zhu$^1$, X. Ma$^{1,2}$, B. Li$^{1,2}$, S. F. Zhang$^{1,2}$, W. T. Feng$^{1,2}$, H. P. Liu$^1$, L. F. Chen$^{1,2}$, S. P. Cao$^{1,2}$, D. B. Qian$^{1,2}$, D. C. Zhang$^{1,2}$

1 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000 China
2 Graduate University of Chinese Academy of Sciences, Beijing 100049 China

E-mail: zhuxiaolong@impcas.ac.cn

Abstract. State-selective single- and double-electron capture in He$^{2+}$-He collisions at energies ranging from 20 to 40 keV have been studied experimentally by means of cold target recoil ion momentum spectroscopy. The differential cross sections have been obtained by measuring the longitudinal and transverse momenta of recoil ions. The results show that single electron capture into L shell is the dominant reaction channel, and double-electron capture into the ground state of projectile is by far the dominant process in the incident energy range. The measured state-selective cross sections agree well with the semi-classical close-coupling calculations.

1. Introduction
The collision processes of multiply charged ions with atom/molecules are of fundamental interest because they involve many-body dynamics. Charge transfer processes during keV collisions of multiply charged ions with various atomic and molecular targets play an important role in various fields, such as astrophysical plasmas, accelerator physics [1-4]. The symmetrical He$^{2+}$-He collision system is the simplest two-electron system in which coulomb ion–electron and nuclear-electron interactions, and the correlation between electrons can be studied. This collision system has been studied heavily in experimental [5-14] and theoretical [14-17] works. However, only a few measurements or calculations of differential angular scattering cross sections have been carried out for the He$^{2+}$-He collision system in the energy range from 15 keV to 150 keV.

In this paper, we present measured differential cross-sections for single electron capture (SC),

$$\text{He}_p^{2+} + \text{He}_i \rightarrow \text{He}_p^{+}(n) + \text{He}_i^+(n')$$

(1)

and double-electron capture (DC),

$$\text{He}_p^{2+} + \text{He}_i \rightarrow \text{He}_p^0(nn') + \text{He}_i^{2+}$$

(2)

at 20, 30 and 40keV by using cold target recoil ion momentum spectroscopy (COLTRIMS). Results were compared with theoretical calculations.

2. Experimental setup
The experiments have been performed in the atomic physics platform at the Institute of Modern Physics (IMP) in Lanzhou. Details of the experimental set-up are described in references [18,19].
Briefly, a continuous beam of He\textsuperscript{q+} is extracted from the ECR source, whose extraction voltage of the source was varied from 5 to 23 kV, and the charge state is analysed by a magnet. The ion beam enters the collision chamber through the two-pair collimators with four adjustable slits. The beam-spot size of below 0.4×0.4 mm\textsuperscript{2} at collision point was obtained. The He\textsuperscript{2+}ion beam is crossed with a supersonic He gas target. 20 cm downstream of the interaction point an electrostatic deflector analyses the final projectile charge states. Then, a two-dimensional position-sensitive detector (PSD) with delay-line anode detects the projectile products. The recoil ions generated in the collisions were extracted by an electric field and accelerated toward the recoil PSD. After passing the field-free time-of-flight region, the ions were post-accelerated to a few keV to increase the detection efficiency. Coincidence technique was used between recoil ions and projectiles. Coincident event was recorded by PC-based data acquisition system in even-by-event mode. Figure 1 shows the two-dimension coincidence map of recoil ions with projectiles ions at 30 keV He\textsuperscript{2+}-He collisions. From the map, the different reaction channels can be easily identified.

![Figure 1](image1.png)

**Figure 1.** The two-dimensional coincidence map of recoil ions with the projectiles ions at 40 keV He\textsuperscript{2+}-He collisions.

![Figure 2](image2.png)

**Figure 2.** Recoil ion position image on the detector for SC process at 40 keV He\textsuperscript{2+}-He collisions.

3. Results and discussion

The COLTRIMS collects two classes of information: energy-gain spectra and angular differential cross sections. The former one gives the state-selective information on charge transfer, and the later one gives the information on the dynamics of the populated states. For pure electron captures, according to momentum and energy conservation laws, the longitudinal momentum and transverse momentum of the recoil ion was deduced as follows:

\[
P_{\parallel R} = -Q / v_p - n_e \cdot v_p / 2
\]

\[
P_{\perp R} = m_p \cdot v_p \cdot \theta
\]

where, \(v_p\) is the projectile velocity, \(m_p\) is the projectile mass, \(n_e\) is the number of captured electrons, \(Q\) is the change in binding energy of the active electrons, and \(\theta\) is the scattering angle of the projectile products.

3.1.1. Single electron capture

Figure 2 shows the distribution of He\textsuperscript{+} recoil ions on the recoil ion detector for SC processes at 40 keV impact energy. From figure 2, electron capture into the different final bound states was clearly distinguished. The single electron capture into L shell is the dominant reaction channel. The experimental state-selective cross sections are deduced by normalizing the total single electron capture cross sections to the data of references [8,9].
Figure 3. State-selective capture cross sections for SC process of He$^{2+}$ on He collisions.

Figure 4. Differential state-selective capture cross sections for SC process of He$^{2+}$ on He collisions.

Figure 5. The longitudinal momentum spectra of recoil He$^{2+}$ ion for DC processes.
3.1.2. Double electron capture

Figure 5 shows the longitudinal momentum spectrum obtained for double-electron capture by He\(^{2+}\) ions on helium at 40 keV. According to Eq. (3), the peak in figure 5 can easily be identified. The left peak in the spectrum corresponds to the double-electron capture into the ground state of the projectile; the right peak corresponds to the case of one of the two electrons captured into the ground state and the other one captured into excited states. It is clearly found that double electron captured into the ground state is by far the dominant reaction channel.

4. Summary

We have experimentally studied the state-selective single- and double-electron capture processes for slow He\(^{2+}\) on helium collisions between 20 keV and 40 keV. COLTRIMS technique was utilized. Differential cross sections have been obtained by the measurement of the recoil ion momentum vector. At low energies between 20 and 40 keV, the experimental results show that single electron capture into L shell is the main reaction channel, and double-electron capture into the ground state of projectile is by far the dominant process. The measured data is reasonably described by semi-classical close-coupling calculations.

Acknowledgments

This work is supported by the Natural Science Foundation of China (Grant No. 10434100).

References

[1] M. Barat, P. Roncin, 1992 J. Phys. B 25 2205
[2] D. Mathur, 1988 Phys. Rep. 225 193
[3] M. Ehrich, B. Siegmann, U. Werner and H. Lebius, 2003 Radiat. Phys. Chem. 68 127
[4] R. K. Janev, T. Kato and J. Wang, 2000 Phys. Plasmas 7 4364
[5] V. V. Afrosimov, A. A. Basalaev, G. A. Leiko and M. N. Panov, 1978 Sov. Phys. JETP 47 837
[6] M. E. Rudd, T. V. Goffe and A. Itoh, 1985 Phys. Rev. A 32 2128
[7] R. D. Dubois, 1986 Phys. Rev. A 33 1595
[8] R. D. Dubois, 1987 Phys. Rev. A 36 2585
[9] M. B. Shah, P. McCallion and H. B. Gillbody, 1989 J. Phys. B: At. Mol. Opt. Phys. 22 3037
[10] H. O. Folkerts, F. W. Böck, L. Meng, R. E. Olson, R. Morgenstern, M. V. Von Hellermann, H. P. Summers and R. Hoekstra, 1994 J. Phys. B: At. Mol. Opt. Phys. 27 3475
[11] V. Mergel, R. Dörner, J. Ullrich, O. Jagutzki, S. Lencinas, S. Nüttgens, L. Spielberger, M. Unverzagt, C. L. Cocke, R. E. Olson, M. Schulz, U. Buck, E. Zanger, W. Theisinger, M. Isser, S. Geis and H. Schmidt-Böcking, 1995 Phys. Rev. Lett. 74 2200
[12] R. Dörner, V. Mergel, L. Spielberger, O. Jagutzki, J. Ullrich and H. Schmidt-Böcking, 1998 Phys. Rev. A 57 312
[13] R. Dörner, V. Mergel, O. Jagutzki, L. Spielberger, J. Ullrich, R. Moshammer and Schmidt-Böcking, 2000 Phys. Rev. A 330 95
[14] R. S. Gao, C. M. Dutta, N. F. Lane, K. A. Smith, R. F. Stebbings and M. Kimura, 1992 Phys. Rev. A 45 6388
[15] W. Fritsch, 1994 J. Phys. B: At. Mol. Opt. Phys. 27 3461
[16] Ashok Jain, C. D. Lin and W. Fritsch, 1989 Phys. Rev. A 39 1741
[17] Wu Yong, Yan Bin, Liu Ling and Wang Jian-guo, 2007 Chin. Phys. Lett. 24 1999
[18] Zhu Xiao-long, Ma Xin-wen, Li Bin, Liu Hui-ping, Chen Lan-fang, Zhang Shao-feng, Qian Dong-bin, Feng Wen-tian, Cao Shi-pin, Sha Shan and Zhang Da-cheng, 2006 Chin. Phys. Lett. 23 587
[19] Ma Xin-wen, Zhu Xiao-long, Liu Hui-ping, Li Bin, Zhang Shao-feng, Cao Shi-pin, Feng Wen-tian, Xu Shen-yue, 2008 Science in China Series G: Physics, Mechanics & Astronomy 51 755
[20] W. C. Keever and E. Everhart, 1966 Phys. Rev. 150 43