Aust. J. Phys., 1996, **49**, 945–51

Effective Charge Effect in 2·0–7·0 MeV Partially Stripped F^{q+}–Helium Collisions

X. Cai,[A,B] *Z. Y. Liu,*[A] *X. M. Chen,*[A] *Z. Y. Shen,*[A]
X. W. Ma,[B] *H. P. Liu*[B] *and M. D. Hou*[B]

[A] Department of Modern Physics, Lanzhou University,
Lanzhou 730 000, P. R. China.
[B] Institute of Modern Physics, Academia Sinica,
PO Box 31, Lanzhou 730 000, P. R. China.

Abstract

The ratio of the double ionisation cross section to that of the single ionisation of helium was measured for 2·0–7·0 MeV F^{q+} ($q = 1, 2, 3, 4$) bombardment. The effective charge effect in partially stripped F^{q+}–helium collisions is studied. It is found that the effective charge $q_{\rm eff}$ increases as the impinging energy increases and that $q_{\rm eff}$ shows almost no dependence upon the projectile charge state in the present energy range.

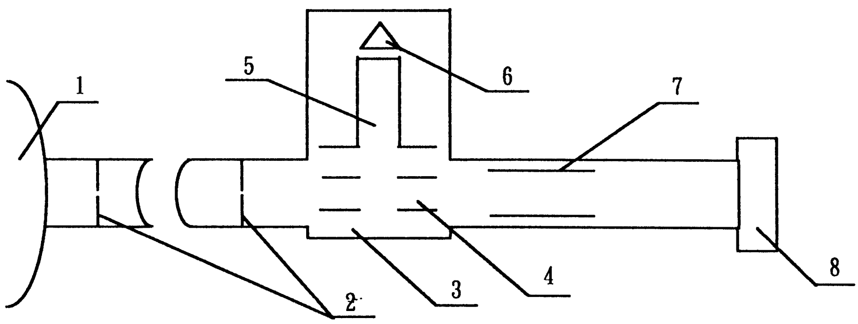
1. Introduction

Much current interest concentrates on the multiple ionisation process of atom impact by fast, fully stripped ions (Knudsen and Reading 1992; Cocke and Olson 1991). Nevertheless, many aspects of the atomic multiple ionisation process still remain unresolved. This is mainly due to the fact that the treatment of multiple electron transitions must go beyond the independent particle model (McGuire and Weaver 1977) and has to take into account the influence of electron–electron correlations, a phenomenon which is not well understood. From the standpoint of theoretical and experimental simplicity, the most ideal system for testing the ideas concerning electron correlation is the two-electron helium atom (Heber *et al.* 1990). The shake-off and the two-step processes are known to be the two main double ionisation mechanisms of helium (Cocke and Olson 1991). For partially stripped ion bombardment the multiple ionisation of the helium atom presents a problem of much increased complexity owing to the effective charge effect. DuBois and Toburen (1988) obtained the average effective charge from the total and double ionisation cross sections of helium impacted by light, nearly fully stripped ions bearing one and two electrons for selected impinging energies. Based on the models of Toburen *et al.* (1981) and McGuire *et al.* (1981), DuBois and Toburen qualitatively discussed the impact parameter dependence of the effective charge. Up to now the projectile and target dependences of the effective charge effect in partially stripped ion–atom collisions have not been well studied over a wide range of projectile energy and projectile charge state.

As the number of bound electrons of the projectile increases, the effective charge effect shows a dependence upon the projectile energy, projectile charge state and the electronic states of the projectile and the target. An investigation

0004-9506/96/050945$05.00

of the effective charge effect may provide important information about the single and double ionisation of helium by low charge-state ions. In the present paper the effective charge effect in partially stripped ion–helium collisions is studied using 2·0–7·0 MeV fluorine ions in charge states of +1 to +4. The projectile charge state, projectile energy, projectile and the target electronic state dependences of the effective charge are presented and discussed. The n-body classical trajectory Monte Carlo (nCTMC) calculations were carried out to investigate the projectile energy dependence of the effective charge effect.



1. magnet; 2. apertures; 3. target chamber; 4. acceleration region;
5. drift tube; 6. channel-electron-multiplier; 7. electric field; 8. PPAD.

Fig. 1. A schematic diagram of the experimental setup.

2. Experimental

The experiments were performed on the 2×1·7 MV tandem accelerator of Lanzhou University using well focused beams of 2·0–7·0 MeV fluorine ions having charges of +1 to +4 by means of the time-of-flight procedure (Cai *et al.* 1993). A schematic experimental setup is shown in Fig. 1. The beams were charge-state and energy selected by a magnet and then carefully collimated with two two-dimensional apertures. The apertures were set to be 0·1×0·1 mm^2 to ensure that the divergence of the beam is smaller than 0·1 mrad. The gas cell pressure was maintained at 2×10^{-4} Torr to ensure the single collision process. A differential pumping system was used to keep the pressure out of the gas cell to better than 2×10^{-6} Torr. Recoil helium ions produced in partially stripped ion–helium collisions were accelerated out of the gas cell by an electric field oriented transverse to the beam axis into a 7 cm flight tube. Upon reaching the end of the flight tube, the recoil ions were further accelerated into a channel-electron-multiplier (CEM) where they generated start signals for a time-to-amplitude converter (TAC). The TAC was stopped by delayed signals from the parallel-plate avalanche detector (PPAD), which detected the scattered projectiles during the collisions. The beam current was kept below 1×10^{-12} A in order to get reasonable signal-to-noise ratios of the time-of-flight spectra. The TOF spectra generally required accumulation times of 2 to 4 hours to obtain good counting statistics for He^{2+} peaks. A typical

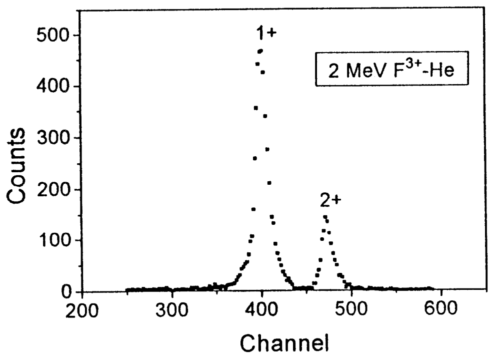


Fig. 2. A time-of-flight spectrum of helium ions produced in collisions with 2 MeV F^{3+} ions.

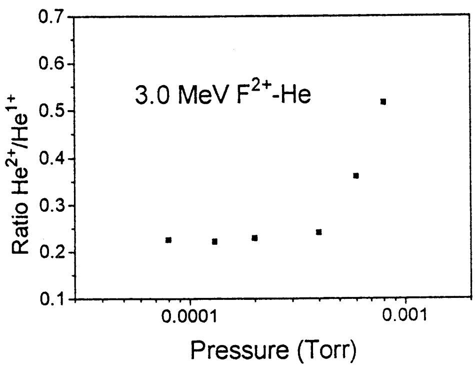


Fig. 3. The measured He^{2+}/He^{1+} ratio for 3·0 MeV F^{2+} on He at different gas cell pressures.

TOF spectrum is shown in Fig. 2 for 2 MeV F^{3+} on He. It is apparent from this figure that the He^{1+} and He^{2+} peaks are well resolved from each other and reside well above the background.

Several tests were performed to minimise the possibility of systematic uncertainties in the experiments. When the gas cell pressure is too high, the measured He^{2+}/He^{1+} ratio may be larger than the cross section ratio of helium induced by the direct double and single ionisation, due to the multiple collision process. The change of the measured He^{2+}/He^{1+} ratios with the gas cell pressure was studied for 3·0 MeV F^{2+} on He, shown in Fig. 3. The He^{2+}/He^{1+} ratio is found to remain constant when the pressure is lower than 4×10^{-4} Torr. This ratio increases a lot as the pressure increases from 4×10^{-4} to $1\cdot0\times10^{-3}$ Torr. To avoid the multiple collision process the gas cell pressure of 2×10^{-4} Torr was used in the present experiment. The efficiency of the TOF spectrometer was checked by comparing our measured He^{2+}/He^{1+} ratios with the experimental cross section ratios of Knudsen *et al.* (1984) using fully stripped Li^{3+} ion impact. For Li^{3+} ion impact, our measured He^{2+}/He^{1+} ratios agree with the cross section ratios of Knudsen *et al.* (1984) within the errors of 6%.

Finally, the measurements of He^{2+}/He^{1+} ratios were carried out using the TOF procedure for 2·0–7·0 MeV impinging fluorine ions in charge states of +1 to +4. The measured data were compared with those from fully stripped ion bombardment by Knudsen *et al.* (1984) to get the values of the effective charge, following the method of DuBois and Toburen (1988). The procedure used was to fit the data of the cross section ratios for fully stripped ion impact against v/q of the projectile using polynomial least-squares fitting; here v and q are the velocity and charge state of the projectile respectively. The fitted result is shown in Fig. 4. Then the cross section ratios for partially stripped ion impact were placed on the fitted curves according to the magnitude of the cross section ratios. At this point, values for the effective charge were obtained by referring to the abscissa.

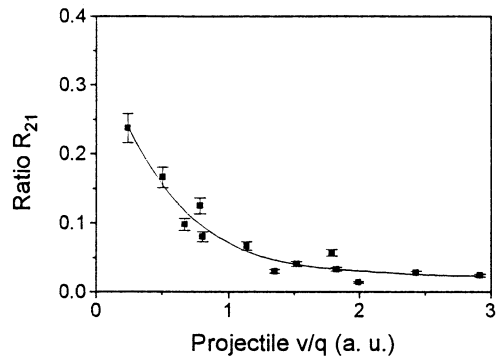


Fig. 4. The fitted curve of the ratio R_{21} for fully stripped ion bombardment (Knudsen *et al.* 1984).

The uncertainty in $q_{\rm eff}$ obtained in this work is estimated to be 10%, which comes mainly from the statistical error (<2%), the uncertainty in the efficiency of the TOF spectrometer (~6%) and the comparison of the measured He^{2+}/He^{1+} ratio with that of the fully stripped ion impact (~8%).

3. Results and Discussion

The effective charge $q_{\rm eff}$ obtained in the present work is shown in Fig. 5. It is evident that $q_{\rm eff}$ increases as the impinging energy increases and within the error bar $q_{\rm eff}$ shows no dependence upon the projectile charge state in the present energy range.

In the partially stripped ion–helium collision process, the bound electrons of the partially stripped projectile screen the interaction of the projectile nucleus and the target electrons. When the projectile is far away from the target nucleus, the target electrons interact with the impinging ion charged with q, the charge state of the partially stripped projectile, due to the full screening of the bound electrons of the partially stripped ion. As the projectile approaches the target nucleus, the target electrons will be disturbed by an effective charge which is larger than q owing to the interpenetration of orbitals. This effect depends upon the impact parameter of the projectile and the electronic structures of

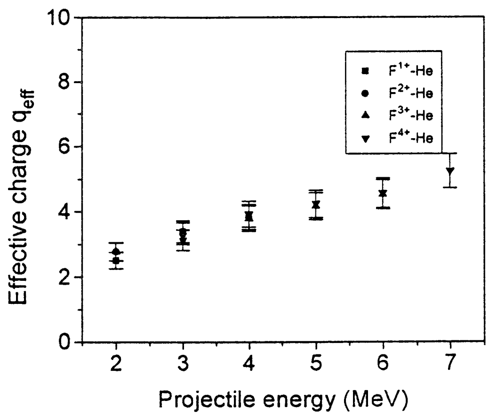


Fig. 5. The effective charge q_{eff} for 2·0–7·0 MeV F^{q+}–helium impact.

the projectile and target atom. The q_{eff} values obtained and referred to in the present work are the average results of different impact parameters.

In the F^{q+}–He system ($q = 1, 2, 3, 4$), the 1s orbit radius of helium is 0·26 Å according to the Bohr theory. The radii of the 1s and 2s orbits of fluorine are 0·06 and 0·24 Å respectively, and the average radius of its 2p orbit is nearly 0·24 Å. As the 1s orbit of fluorine is much smaller than that of the 1s orbit of helium, the 1s electrons of fluorine screen its nucleus completely during the collisions. Thus $q_{\text{eff}} < Z_F - 2$, where Z_F is the nuclear charge number of the fluorine atom. Since the 1s orbit of helium is approximately equal to the radii of the 2s and 2p orbits of fluorine, the 2s and 2p electrons of fluorine screen the fluorine nucleus partially during the collision with helium. As the projectile approaches the target nucleus, the fluorine ion penetrates the 1s orbit of helium and the target electronic states will be disturbed by the penetrating projectile charged with effective charge q_{eff}, which is larger than q but smaller than $Z_F - 2$. For the F^{1+}, F^{2+}, F^{3+} and F^{4+} ions, their 1s and 2s subshells are full of electrons and the 2p subshells have four, three, two and one electrons respectively. Because the screening effect weakens rapidly as the number of electrons in an atomic shell increases (Fisher 1977), the difference in the number of 2p electrons of F^{q+} ($q = 1, 2, 3, 4$) ions influences a little the screening effect and the q_{eff} shows almost no dependence upon the projectile charge state in the present energy range.

The He^{2+}/He^{1+} ratios of impinging 2·0 and 7·0 MeV F^{4+} ions were calculated by using the n-body classical trajectory Monte Carlo method (Olson and Solop 1977; Dörner *et al.* 1991) to investigate the energy dependence of the He^{2+}/He^{1+} ratios. In our nCTMC calculations the largest value of the impact parameter (Olson and Solop 1977) for which the ionisation of the target electrons can occur is chosen to be $b_{\text{max}} = 1 \cdot 8$ a.u.; the distances of the start and the stop interaction r_{start} (start point) and r_{stop} (stop point) are chosen to be equal and change from 0·2 to 3·0 a.u., and the number of Monte Carlo cycles is 10 000. The parameters r_{start} and r_{stop} mean that the ionisation of the target atom contributed by the interactions with $r > r_{\text{start}}$ or $r > r_{\text{stop}}$ is neglected in the nCTMC calculation; here r is the radial distance between the projectile and target nucleus. The calculated results are presented in Fig. 6 for the radial

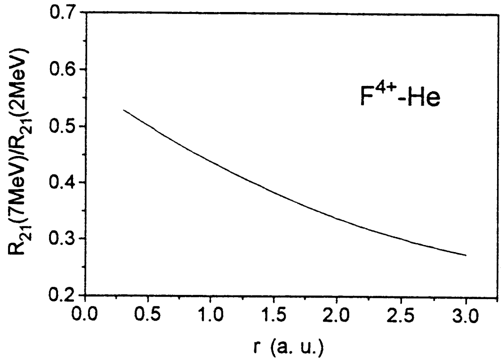


Fig. 6. The calculated relative cross section ratios of helium against the radial distance r for 2·0 and 7·0 MeV F^{4+} bombardment.

distance of the two nuclei, r. The nCTMC calculations shows that the relative He^{2+}/He^{1+} ratios for 7·0 and 2·0 MeV apparently increase as the radial distance r decreases. It suggests that the near interaction of the projectile and target electrons is more important to the double ionisation of helium when the impinging energy is high. For reasons of simplicity we consider here head-on collisions. For a head-on collision at high energies, the projectile approaches the target nucleus more closely, the closest distance becomes relatively smaller and plays a more important role in the double ionisation of helium. A decrease of the closest distance leads to an increase of the effective charge. The average effective charge will then increase as the projectile energy increases.

The direct ionisation and electron capture of the projectile are the two main mechanisms for single and double ionisation of helium. As the He^{2+}/He^{1+} ratio of the capture process has a much sharper velocity dependence ($\propto v^{-12}$) than the direct ionisation process ($\propto v^{-2}$), the electron capture process may be negligible for ionisation of helium by fluorine ion impact in the present energy range.

4. Conclusion

In conclusion, the effective charge effect in partially stripped F^{q+}–helium collisions has been studied for the projectile energy range 2·0–7·0 MeV and charge states of +1 to +4. By introducing the effective charge, the partially stripped projectile can be considered as a structureless particle charged with $q_{\rm eff}$. The projectile charge state, and the projectile and target electron state dependences of the effective charge can be explained using the orbital interpenetration model.

Acknowledgments

We thank H. Schmidt-Böcking and R. Dörner (Frankfurt, Germany) for their help in setting up the experimental facilities and R. E. Olson (Rolla, USA) for providing the nCTMC program. This work was supported by the National Science Foundation of China.

References

Cai, X., Chen, X. M., Feng, J. Z., and Liu, Z. Y. (1993). *Chin. J. Atom. Mol. Phys.* **10**, 2982.
Cocke, C. L., and Olson, R. E. (1991). *Phys. Rep.* **205**, 153.
Dörner, R., Ullrich, J., and Schmidt-Böcking, H. (1991). Dynamik der Einfach- und Doppelionisation von Helium in schnellen Protonenstössen. GSI Rep. GSI-91-28.
DuBois, R. D., and Toburen, L. H. (1988). *Phys. Rev.* A **38**, 3960.
Fischer, C. F. (1977). 'The Hartree–Fock Method for Atoms', p. 276 (Wiley–Interscience: New York).
Heber, O., Bandong, B. B., Sampoll, G., and Watson, R. L. (1990). *Phys. Rev. Lett.* **64**, 851.
Knudsen, H., and Reading, J. F. (1992). *Phys. Rep.* **212**, 107.
Knudsen, H., Andersen, L. H., Hvelplund, P., Astner, G., Cederquist, H., Danared, H., Liljeby, L., and Rensfelt, K.-G. (1984). *J. Phys.* B **17**, 3545.
McGuire, J. H., and Weaver, L. (1977). *Phys. Rev.* A **16**, 41.
McGuire, J. H., Stolterfoht, N., and Simony, P. R. (1981). *Phys. Rev.* A **24**, 97.
Olson, R. E., and Solop, A. (1977). *Phys. Rev.* A **16**, 531.
Toburen, L. H., Stolterfoht, N., Ziem, P., and Schneider, D. (1981). *Phys. Rev.* A **24**, 174.

Manuscript received 8 November 1995, accepted 25 January 1996