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Multi-electron processes in large-angle scattering between slow Ne^{q+} (q = 1, 2 and 3) and Ar

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Abstract

The charge states of the scattered and recoil ions were simultaneously measured at a large scattering angle (Θ_{CM} = 40°) in single collisions of Ne ions with Ar atoms at an energy of 5 keV (relative velocity v = 0.10 a.u.). The incident charge (q) dependence of the charge state correlations between Ne and Ar ions are discussed for q = 1, 2 and 3. It was found that the mean charge state of Ne ions ($\bar{q}_{Ne}$) and Ar ions ($\bar{q}_{Ar}$) increased with q, while the number of emitted electrons ($\bar{q}_{Ne} + \bar{q}_{Ar} - q$) was independent of q.

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Keywords: Multi-electron processes; Large-angle scattering; Slow ions

1. Introduction

Collision processes between slow highly-charged ions and atomic targets have been intensively investigated [1]. In slow collisions where the relative velocity is much smaller than that of the orbital electrons of the collision partners, collision processes are described by electron transition between the quasi-molecular orbitals as a function of their internuclear distance. A simplified description of electron transfer in highly-charged ion – atom collisions is given by the over-barrier model [2]. This model has been successfully describing single electron capture in peripheral collisions, where most of the cross section can be found. Single-electron capture processes in collision of slow highly charged ions with atoms were investigated by many groups and now rather well understood [3].

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A very small amount of the differential cross-section is at large scattering angles. There, however, multi-electron capture processes can be expected to become dominant. Not only the electron capture but also ionization processes could occur even at very low collision velocities. Information on the multi-electron processes at large-angle scattering plays an important role for a detailed understanding of neutralization in ion-surface interactions [4–6] and for the possible formation of hollow atoms in ion–atom collisions.

Early experimental studies of large-angle scattering were done with singly charged ions: Morgan and Everhart [7] measured the inelastic energy loss in collisions of 3–100 keV Ar^+ ions with Ar atoms between ~6° and 38°. Everhart and Kessel [8] also measured the charge state correlation in single collisions of Ar^+ on Ar at 25–150 keV and 15°. Kessel et al. [9] reported the inelastic energy loss in close, single collisions of 6–400 keV Ne^+ ions with Ne atoms and 8° to 40°. On the other hand, only a few measurements of charge state correlation have been reported using slow highly-charged ions at relatively small scattering angle range: for example Schmidt-Böcking et al. [10] measured the charge state correlation for 90 keV Ne^{7+}–Ne system and at angles up to 1.2° and Herrmann et al. [11] for Ne^{9+}–Ne at 90 keV up to 4.3°. According to these experiments, at large-angle scattering of slow ions on atoms, the reaction channel is different between singly and highly charged ions; the ionization channel is dominant in the former, while multi-electron transfer in the latter. However, there is no experimental data of systematic incident charge dependence of outgoing charge states.

In order to study the multi-electron processes in large-angle scattering, we have measured the incident charge dependence of the scattered and recoil ions in the collision of 5 keV $Ne^{q+}(q = 1, 2, 3)$ with Ar atoms at $\Theta_{CM} = 40°$. The corresponding distance of closest approach is about 0.6 a.u. [12], which is by one order of magnitude smaller than the critical distance of electron capture from the over-barrier model [2].

2. Experiment

The experiment was carried out at the slow highly-charged ion-beam facility in RIKEN [13]. The ion beam extracted from a caprice-type ECR ion source was momentum-analyzed by a dipole magnet, and focused by a magnetic quadrupole triplet lens into a collision chamber.

A schematic view of our time-of-flight apparatus is shown in Fig. 1. The ion beam collimated by the entrance slit (2 mm width and 4 mm height) was introduced in a differentially-pumped Ar gas target. The scattered Ne ions and the recoil Ar ions were detected with the detection telescopes in Fig. 1 at 27° and 70°, respectively. This angle combination is expected from kinematics of elastic scattering. Each ion detection telescope consists of a time-of-flight (TOF) drift tube, DT-S for scattered and DT-R for recoil and a two-dimensional position-sensitive detector (2D-PSD) with a microchannel plate (MCP) and a wedge-and-strip anode [14]. The telescope covered an angular range of 10°. The ion beam current, monitored by a Faraday cup, was typically ~2.0 nA.

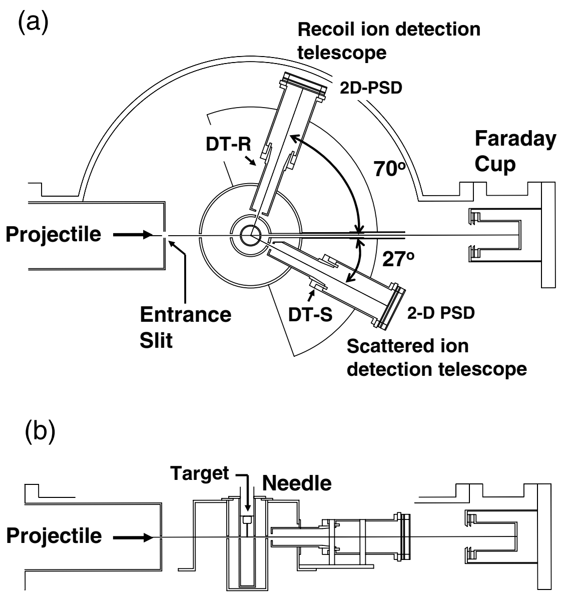

Fig. 1. Schematic view of our time-of-flight coincidence apparatus: (a) top view and (b) side view.

Since we have used the 2D-PSD for ion detection, we can obtain the positions and TOFs of both the scattered and recoil ion as coincidence events. For each coincidence event, the difference between TOFs of the scattered and recoil ion (ΔTOF) was recorded. In present work, the scattered and recoil ion were used to start and stop a time-to-amplitude converter, respectively. With the DT-S and DT-R on an electrostatic potential V, one can vary the velocity of the scattered and recoil ions depending on the charge state. TOF of the scattered Ne (recoil Ar) ion is given by

$$\mathrm{TOF}_{\mathrm{Ne(Ar)}} = \sqrt{\frac{M_{\mathrm{Ne(Ar)}}}{2}}\left(\frac{L_1}{\sqrt{E_{\mathrm{Ne(Ar)}}}} + \frac{L_2}{\sqrt{E_{\mathrm{Ne(Ar)}} - q_{\mathrm{Ne(Ar)}}V}}\right),$$

where L_1 and L_2 show the distance from collision center to the entrance of TOF drift tube and the length of the drift tube, respectively. $M_{\mathrm{Ne(Ar)}}$ and $E_{\mathrm{Ne(Ar)}}$ are the mass of Ne(Ar) ion and the scattered (recoil)-ion energy. $q_{\mathrm{Ne(Ar)}}$ is the charge state of Ne(Ar) product ions. One can determine the charge state of Ne and Ar ions by ΔTOF obtained from this relation.

3. Results

Fig. 2(a)–(c) shows the results for 5 keV Ne^{2+}–Ar collisions: Fig. 2(a) shows the two-dimensional map of ΔTOF versus the projectile scattering angle where the DT-S and DT-R were both biased at −1.8 kV. The events are distributed on bands. The velocity change in the biased drift tubes separated the bands according to the charge-state combination of the scattered Ne ions (q_{Ne}) and the recoil Ar ions (q_{Ar}). The gradient of the bands reflects the kinematical relation between the scattering angle and the scattered-ion energy. Since the angular acceptance is relatively small, we assume a linear dependence between ΔTOF and scattering angle, and compensated ΔTOF for scattering-angle deviation from 27°, so that the bands are parallel to the ordinate. A new abscissa thus obtained is named ΔTOF′. Fig. 2(b) shows the ΔTOF′ spectrum integrated over all scattering angle. Peaks correspond to the charge-state combinations ($q_{\mathrm{Ne}}, q_{\mathrm{Ar}}$). The peak width was about 50 ns

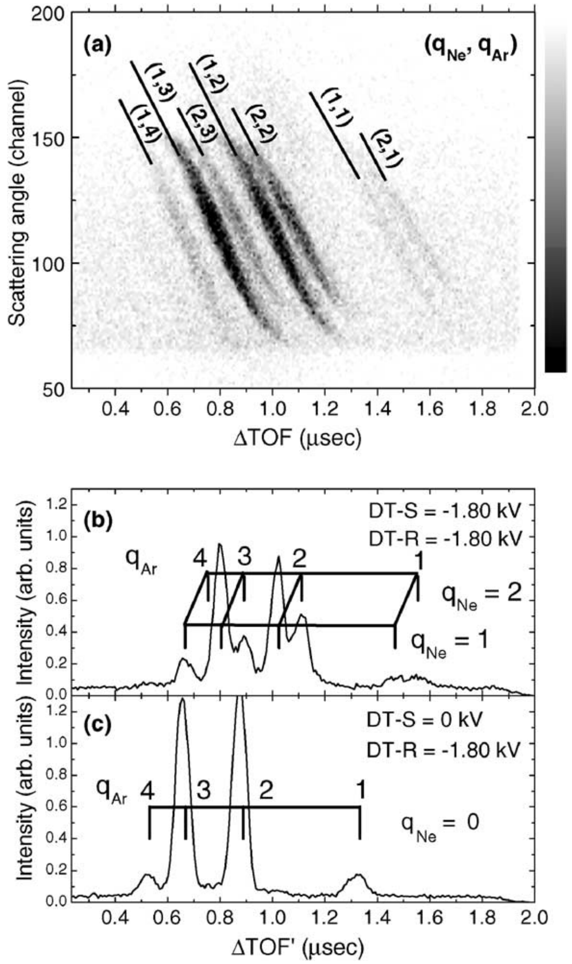

Fig. 2. The ΔTOF spectrum of product ions in Ne^{2+}–Ar collisions at 5 keV: (a) the two-dimensional plot of ΔTOF vs the projectile scattering angle with both DT-S and DT-R biased at −1.8 kV (not calibrated); (b) ΔTOF′ spectrum integrated over the projectile scattering angle and (c) ΔTOF′ spectrum with only DT-R biased at −1.8 kV.

in FWHM. If the width is due to the inelastic energy-loss distribution, the maximum width of the distribution is estimated to be about 10 eV. In order to identify q_{Ne} and q_{Ar}, the position of $q_{\mathrm{Ne}} = 0$ was determined by an additional experiment with the same condition but DT-S grounded. Fig. 2(c) shows the obtained ΔTOF′ spectrum, where the four peaks have been identified as $q_{\mathrm{Ar}} = 1$ to 4 with $q_{\mathrm{Ne}} = 0$. With DT-S biased, each q_{Ar} shifts to the large ΔTOF′ side and splits to different q_{Ne} as shown in Fig. 2(b).

It was found that the most probable combinations were $(q_{Ne}, q_{Ar}) = (1,2)$ and $(1,3)$, which corresponded to single-electron capture with target ionizations.

The charge-state distributions of the Ne and Ar ions in Ne^{q+}–Ar collisions are shown in Fig. 3 for $q = 1,2,3$. For $q = 1$, it was found that pure ionization $(q_{Ne}, q_{Ar}) = (1,2)$ was the maximum fraction. In the case of $q = 2$, q_{Ar} showed a broader distribution and single-electron capture with target ionization $(q_{Ne}, q_{Ar}) = (1,2)$ and $(1,3)$ were the main channels. In the case of $q = 3$, the charge states distributed in $1 \leqslant q_{Ar} \leqslant 5$ and $1 \leqslant q_{Ne} \leqslant 3$ and single-electron capture with target ionization $(q_{Ne}, q_{Ar}) = (2,3)$ was the major channel. Double-electron capture $q_{Ne} = 1$ and pure target ionization channel $q_{Ne} = 3$ were also observed.

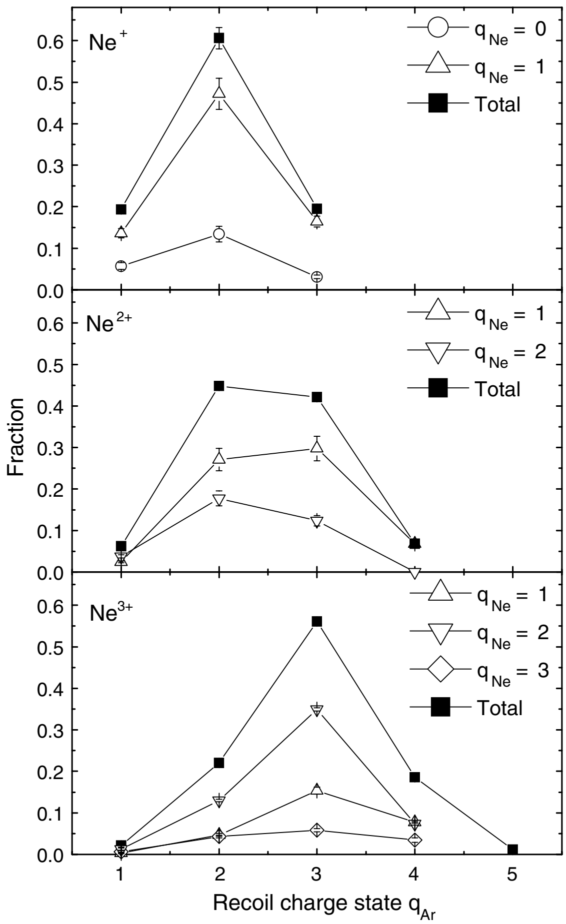

Fig. 3. The charge state distributions of Ne and Ar ions in Ne^{q+} (q = 1, 2 and 3)–Ar collisions at 5 keV.

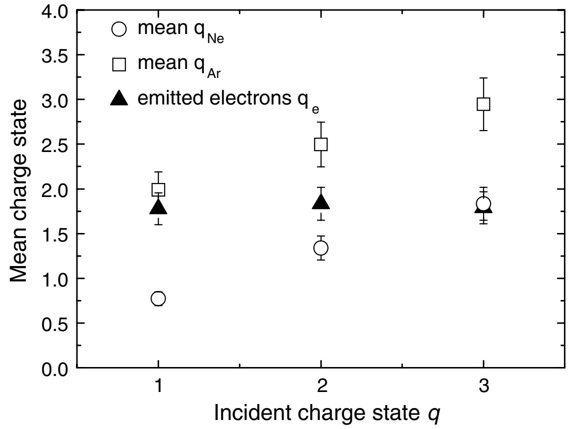

Fig. 4. The incident charge dependence of the mean charge state of the scattered ($\bar{q}_{Ne}$), recoil ($\bar{q}_{Ar}$) ions and the number of emitted electron ($q_e = \bar{q}_{Ne} + \bar{q}_{Ar} - q$) for $q = 1,2,3$.

Fig. 4 shows the mean charge state of both the scattered Ne ($\bar{q}_{Ne}$) and recoil Ar ($\bar{q}_{Ar}$) ions, and the number of emitted electrons ($q_e = \bar{q}_{Ne} + \bar{q}_{Ar} - q$) as a function of incident charge state q. It was found that the mean charge states $\bar{q}_{Ne}$ and $\bar{q}_{Ar}$ increased with q, while the number of emitted electrons q_e appeared almost independent of q.

4. Summary

We observed the charge state combination of scattered and recoil ions for large-angle scattering ($\Theta_{CM} = 40°$) between Ne^{q+} (q = 1, 2 and 3) ions and Ar atoms at 5 keV (velocity $v = 0.10$ a.u.). In the case of Ne^{+} impact, pure target ionization was dominant. For Ne^{2+} and Ne^{3+} impacts, single-electron capture with target ionization was the most important channel. It was found that the mean charge states of both the scattered ions and recoil ions increased with q. However, the number of emitted electrons was approximately 1.7 and almost independent of q.

References

[1] R.K. Janev, H.P. Winter, Phys. Rep. 117 (1985) 265.
[2] A. Niehaus, J. Phys. B 19 (1986) 2925.

[3] M. Barat, P. Roncin, J. Phys. B 25 (1992) 2205.
[4] W. Huang, H. Lebius, R. Schuch, M. Grether, N. Stolterfoht, Phys. Rev. A 58 (1998) 2962.
[5] Z.D. Pešić, H. Lebius, R. Schuch, Gy. Víkor, V. Hoffman, D. Niemann, N. Stolterfoht, Nucl. Instr. and Meth. B 164–165 (2000) 511.
[6] F.W. Meyer, H.F. Krause, V.A. Morozov, C.R. Vane, L.I. Vergara, Phys. Scr. T 110 (2004) 403.
[7] G.H. Morgan, E. Everhart, Phys. Rev. 128 (1962) 667.
[8] E. Everhart, Q.C. Kessel, Phys. Rev. Lett. 14 (1965) 247.
[9] Q.C. Kessel, M.P. McCaughey, E. Everhart, Phys. Rev. Lett. 16 (1966) 1189.
[10] H. Schmidt-Böcking, M.H. Prior, R. Dörner, H. Berg, J.O.K. Pedersen, C.L. Cocke, M. Stockli, A.S. Schlachter, Phys. Rev. A 37 (1988) 4640.
[11] R. Herrmann, M.H. Prior, R. Dörner, H. Schmidt-Böcking, C.M. Lyneis, U. Wille, Phys. Rev. A 46 (1992) 5631.
[12] E. Everhart, G. Stone, R.J. Carbone, Phys. Rev. 99 (1955) 1287.
[13] Y. Kanai, D. Dumitriu, Y. Iwai, T. Kambara, T.M. Kojima, A. Mohri, Y. Morishita, Y. Nakai, H. Oyama, N. Oshima, et al., Phys. Scr. T 92 (2001) 467.
[14] C. Martin, P. Jenlinsky, M. Lampton, R.F. Malina, H.O. Anger, Rev. Sci. Instrum. 52 (1981) 1067.