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Cross sections of Ne^{i+} recoil-ion production through pure ionization, electron loss, and electron capture of projectiles in 1.05-MeV/amu $Ar^{q+}+Ne$ collisions

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The charge-state distributions and production cross sections of Ne recoil ions produced through pure ionization, electron capture, and electron loss processes of projectile Ar ions have been determined for 1.05-MeV/amu $Ar^{q+}+Ne$ ($q=4$, 6, 8, 10, 12, 14, and 16) collisions using a projectile-ion-recoil-ion coincidence technique. Recoil ions in low charge states, in particular, singly charged ions, are produced predominantly through pure ionization without any change of projectile charge. Electron loss or capture processes of projectiles, though weak relative to the pure ionization, are found to result in an enhancement of the multiply charged recoil ions. The average charge $\langle i\rangle_{q,q'}$ of recoil ions in a specific process, $Ar^{q+}+Ne\rightarrow Ar^{q'+}+Ne^{i+}$, is found to increase with increasing projectile charge q and with the number of the lost or captured electrons from or into projectiles.

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I. INTRODUCTION

It is now confirmed that the collisions of an energetic (>0.5 MeV/amu) heavy ion with a neutral atomic target can produce slow recoil ions in very high charge states [1]. In particular, when projectile ions have inner-shell vacancies, the production of multiply charged recoil ions is significantly enhanced. This is thought to be due to inner-shell electron transfer from target atoms to projectile vacancies. Also the production of highly charged recoil ions is enhanced when the collision involves electron loss of projectiles. Coincidence measurements between projectile ion and recoil ion are therefore expected to provide useful information on the mechanisms of secondary-ion production following heavy-ion impact on gas atom targets, and such coincidence measurements have already been carried out by several research groups [2–8]. We previously reported charge-state distributions and production cross sections of recoil ions accompanied by electron loss and capture processes in symmetric 1.05-MeV/amu $Ar^{q+}+Ar$ and 1.05-MeV/amu $Ne^{q+}+Ne$ collisions [9,10].

In the present work, we extend our previous method to study the production of recoil Ne^{i+} ions in the following asymmetric collision system;

$$1.05\text{-MeV/amu } Ar^{q+}+Ne\rightarrow Ar^{q'+}+Ne^{i+} \quad (q=4,\ 6,\ 8,\ 10,\ 12,\ 14,\ \text{and } 16)\ , \qquad (1)$$

to clarify the mechanisms of multiple ionization of target atoms through pure ionization as well as ionization accompanied simultaneously with electron loss (so-called loss ionization) and electron capture (transfer ionization) of projectiles.

II. EXPERIMENTAL SETUP AND METHODS

A. Apparatus

A detailed description of the experimental setup and procedure has been given elsewhere [9]. The projectile 1.05-MeV/amu Ar^{q+} ions were provided from the heavy-ion linear accelerator of the Institute of Physical and Chemical Research (RIKEN). The ion beams were collimated with a 1-mm-high and 0.4-mm-wide aperture and then directed into a target gas cell. After passing through the collision cell, projectile ions were charge analyzed with an electrostatic charge separator and finally detected with a position-sensitive parallel-plate avalanche counter. On the other hand, slow recoil Ne^{i+} ions produced by the collisions were extracted perpendicularly to the projectile beam and detected with a channeltron detector located at about 15 cm from the target cell. The charge-selected projectile-recoil-ion spectra were accumulated in a computer using a list mode.

B. Coincidence spectra

Typical coincidence charge spectra of Ne recoil ions and projectile Ar ions in Ar^{12+} incidence are shown in Fig. 1. Figure 1(a) shows the final charge-state distribution q' of the projectile Ar ions in coincidence with all recoil Ne^{i+} ions, indicating that recoil ions are produced through either the electron capture ($q'=10,11$), pure ionization ($q'=12$), or electron loss ($q'=13$) processes. Figures 1(b)–1(d) show the recoil Ne^{i+} ion spectra accompanied with pure ionization, one-electron capture and one-electron loss of projectile ions, respectively.

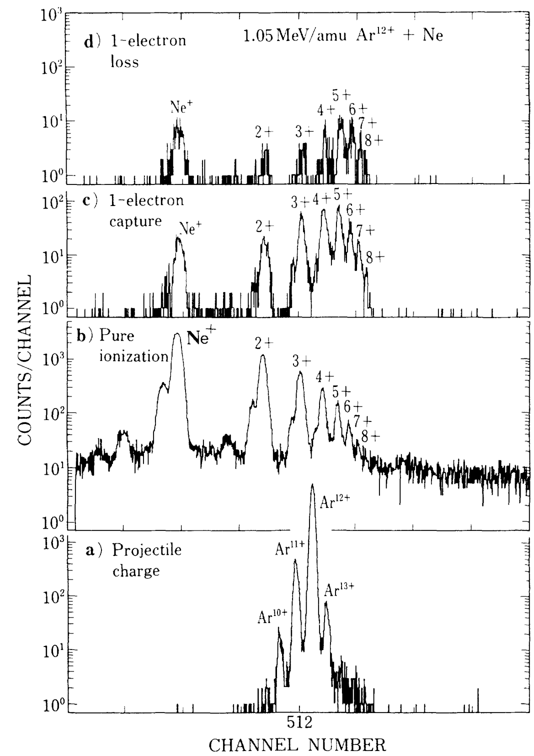

FIG. 1. Charge spectra of projectile and recoil ions in 1.05-MeV/amu Ar^{12+}+Ne collisions. (a) Projectile charge spectrum and (b)–(d) recoil-ion charge spectra for final projectile charge state $q'=12$ (pure ionization), for $q'=11$ (one-electron capture), and for $q'=13$ (one-electron-loss ionization), respectively.

It should be noted here that in electron-capture and electron-loss processes, recoil-ion yields with low charge states, especially singly charged ions, are enhanced through double collisions of the incident particles. Since the cross sections for pure ionization are more than two orders of magnitude larger than the cross sections for electron loss or electron capture, a small fraction of projectiles can capture or lose an electron somewhere in the beam line before or after the target chamber. These ions can produce recoil ions in an additional collision in the target without changing their charge and give a contribution in a spectrum.

As described previously by Tonuma *et al.* [9], such contributions can be evaluated using following equation,

$$\frac{I_b}{I_{q,q'}}=\frac{1-f}{2}\frac{N_{q'}}{N_q}\frac{\sigma_{q,q}+\sigma_{q',q'}}{\sigma_{q,q'}} , \tag{2}$$

where I_b and $I_{q,q'}$ are the number of background recoil ions due to secondary collisions and the total number of true recoil ions due to the process of interest accompanying the projectile charge change from q to q', respectively. $N_{q'}$ and N_q are the total number of projectile ions charge—changed to q' and total number of incident projectile ions of the charge q, respectively. $\sigma_{q,q}$ (also $\sigma_{q',q'}$) and $\sigma_{q,q'}$ are the cross sections for pure ionization due to a projectile with the charge q (q') and for charge transfer from q to q', respectively. Finally, f is the ratio of true target thickness of the collision region to total thickness along the beam path (estimated to be 0.2 in the present work) [9].

Absolute partial production cross sections of Ne^{i+} recoil ions for the collision process (1) were determined through these corrected coincidence data and normalized to the previous net ionization cross sections [11]. Typical uncertainties of the cross sections are given in Table I.

TABLE I. Typical uncertainties of cross sections $\sigma^i_{q,q'}$ (in units of cm^2) determined.

$-\log_{10}(\sigma^i_{q,q'})$	Uncertainties (%)
>16	<4
16–17	4–12
17–18	12–40
18–19	40–110

III. RESULTS AND DISCUSSION

A. Partial-ionization cross section

Partial-ionization cross sections $\sigma^i_{q,q'}$ of Ne^{i+} recoil-ion production are illustrated in Fig. 2. They are represented as a function of the charge state i of the recoil ions, with the projectile final charge state q' as a parameter. In all projectile charge states q studied here, the cross sections for pure ionization without any change of projectile charge decrease rapidly as the recoil-ion charge i increases. On the other hand, the production cross sections of the recoil ions in the loss or transfer ionization, where the projectiles change their charge from q to q', are found to be strongly correlated with the final charge q' and show quite different features from those due to pure ionization mentioned above.

B. Pure ionization

Figure 3 shows the pure ionization cross sections of Ne^{i+} ions as a function of their charge i for projectile charges $q=4$, 6, 8, 10, and 14. In the analysis of these results we have applied the independent-electron approximation (IEA) proposed by McGuire and Weaver [12]. When the projectiles do not change their charge state q, the partial cross section for i electron ionization in the L shell of Ne atoms can be calculated by integrating over the impact parameter b,

$$\sigma^i_{q,q}=2\pi\int_0^\infty \binom{8}{i}[P_L(b)]^i[1-P_L(b)]^{8-i}b\,db , \tag{3}$$

where $\binom{8}{i}$ is the binomial coefficient. $P_L(b)$ is the ionization probability of a single L-shell electron for impact parameter b and can be determined from the experimental data by assuming the following form,

$$P_L(b)=P_L(0)\exp(-b/r_L) , \tag{4}$$

which has been proved to be adequate for large impact parameter collisions [12]. $P_L(0)$ and r_L can be determined by fitting Eq. (3) to the experimental data. The

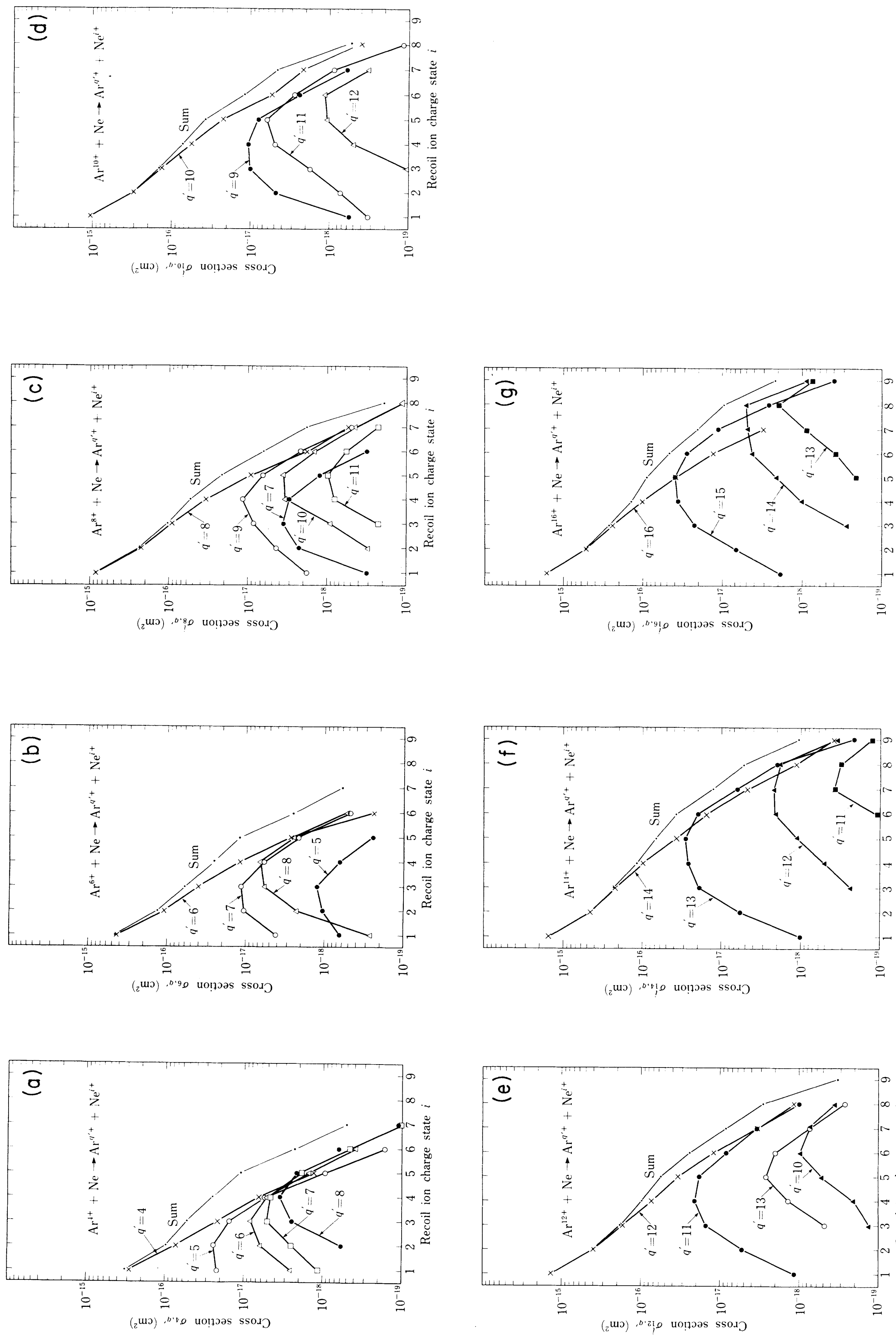

FIG. 2. Cross sections $\sigma^{i}_{q,q'}$ for recoil Ne^{i+} ion production in $Ar^{q+}+Ne\rightarrow Ar^{q'+}+Ne^{i+}$ collisions. Sum denotes total cross sections summed over pure, loss, and transfer ionization processes. The lines connecting data points are drawn for a visual guide.

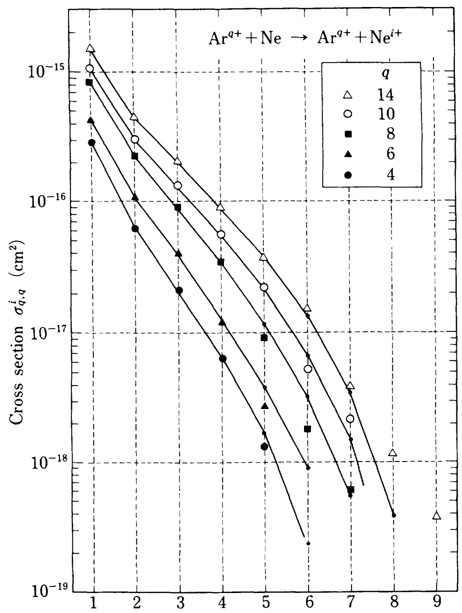

FIG. 3. Cross sections $\sigma^{i}_{q,q'}$ of the recoil Ne^{i+} ion production through pure ionization in $Ar^{q+}+Ne \rightarrow Ar^{q+}+Ne^{i+}$ collisions, in comparison with two-parameter fit in the independent-electron approximation. The points connected by solid lines represent the results obtained by the fitting procedure calculated with parameters given in Table II.

data points connected by solid lines in Fig. 3 represent the results by two-parameter fitting in the IEA model. The values of $P_L(0)$ and r_L thus calculated are listed in Table II.

The IEA model seems to moderately well describe the cross sections in low-charge states (from $i=1$ up to 4) of recoil ions for all $Ar^{q+}+Ne$ collisions investigated. However, for high-charge projectiles with $q \geq 10$, the IEA calculation apparently underestimates the cross sections for the production of highly-charged recoil ions ($i \geq 7$). This suggests that highly-charged Ne recoil ions due to pure ionization are produced not only through direct multiple outer-shell ionization, but also through inner-shell ionization (*K* shell in this case) followed by Auger-electron emission, resulting in the enhancement of highly charged ion production. As pointed out by Kelbch *et al.* [8] the IEA model is considered to be applicable under a restricted condition that direct multiple ionization is the only process of importance for producing *i*-times ionized target atoms.

TABLE II. Fitted parameters $P_L(0)$ and r_L (in angstroms) for pure ionization in the independent electron approximation [12] (*q*: projectile charge state).

q	4	6	8	10	12	14	16
P_L	0.42	0.48	0.55	0.62	0.65	0.68	0.70
r_L	0.51	0.58	0.82	0.94	1.00	1.05	1.10

C. Total charge-changing cross sections of Ar^{q+} projectiles

To obtain information on projectile ionization, we introduced the total charge-changing cross sections of projectiles from q to q', $\sigma_{q,q'}$, including all ionization states of target atoms; that is, total cross sections summed over partial cross sections $\sigma^{i}_{q,q'}$ of Ne recoil ions with different charges i,

$$\sigma_{q,q'} = \sum_{i=1} \sigma^{i}_{q,q'} \; . \tag{5}$$

Figure 4 shows the total charge-changing cross sections as a function of the incident projectile charge q with the number $k(=q'-q)$ of the lost and captured electrons as a parameter. Total cross sections for pure ionization ($k=0$) increase as the projectile charge q increases. As expected, single- and multiple-electron-loss processes ($k>0$) are dominant for low-charge-state projectiles and their cross sections decrease sharply as the projectile charge q increases. On the other hand, electron capture into projectiles ($k<0$) is dominant for high-charge-state projectiles and the cross section increases as q increases. It is also found that in intermediate charge projectiles $q=10$, which corresponds roughly to the equilibrium charge of Ar projectiles in the present collision energy, sum of single- and double-electron-loss cross sections is roughly comparable to that of single- and double-electron capture cross sections, and pure ionization plays a dom-

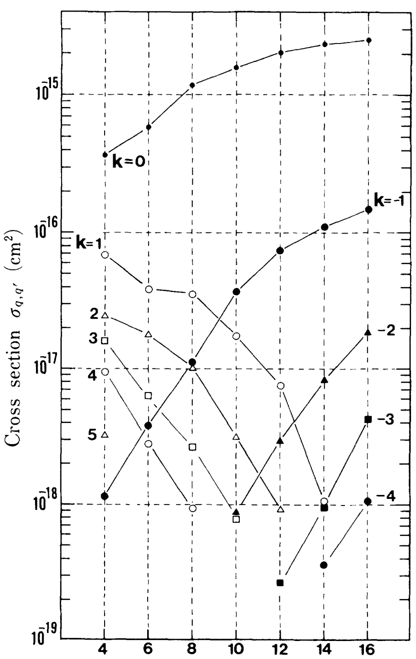

FIG. 4. Total charge-changing cross sections in $Ar^{q+}+Ne \rightarrow Ar^{q'+}+Ne^{i+}$ collisions. $k=q'-q=0$ (●) represent pure ionization cross sections. $k=1$ (○), $k=2$ (△), $k=3$ (□), $k=4$ (○), and $k=5$ (△) represents cross sections for one up to five electron-loss process. $k=-1$ (●), $k=-2$ (▲), $k=-3$ (■), and $k=-4$ (●) denotes cross sections for one up to four electron-capture processes. The solid curves are drawn to guide the eyes.

inant role in the production of highly charged recoil ions as well as low-charge ions over loss and transfer ionization processes (see Fig. 2).

D. Average charge state of recoil ions

To visualize general trends of the degree of target ionization, we introduced the average charge $\langle i \rangle$ of recoil ions. The average charge $\langle i \rangle_{q,q'}$ for a specific collision process is obtained from the measured partial cross sections $\sigma^i_{q,q'}$ by

$$\langle i \rangle_{q,q'} = \sum_{i=1} i\sigma^i_{q,q'}/\sigma_{q,q'} \ , \qquad (6)$$

where $\sigma_{q,q'}$ is the projectile charge-changing cross sections represented by Eq. (5). Figure 5 shows $\langle i \rangle_{q,q'}$ as a function of the incident projectile charge q with the number $k = q' - q$ of the lost or captured electrons as a parameter. The average charge $\langle i \rangle_{q,q}$ of recoil ions for pure ionization ($k=0$) increases only slightly from 1.35 to 1.63 as the projectile charge q increases from 4 to 16, indicating that the recoil ions of low-charge states, in particular singly charged ions, are produced dominantly in the pure ionization process.

In both electron-loss and -capture processes, the average charge $\langle i \rangle$ increases significantly with projectile charge. It should be noted that in projectiles with charge states $q = 12$, 14, and 16, the average charge $\langle i \rangle$ for two-electron-capture processes shifts toward higher charges by about two charge units over that in single-electron capture. This fact suggests that such a shift might be due to target K-shell ionization followed by Auger electron emission, resulting in the final two-electron emission. On the other hand, the mean charge of recoil ions produced in the three-electron capture process is shifted higher by only the unit charge, indicating that the third electron involved might be another L-shell electron, corresponding to double L-shell electron transfer.

In the Ar^{4+}, Ar^{6+}, and Ar^{8+} projectile ions, electron-loss processes are dominant over electron-capture processes. In these cases, the average charges for electron-loss processes $k=1$ and 2 differ by about unit charges, indicating that the two-electron loss might proceed with an additional electron ionization in the same shell (L shell) of the Ne target as that in the one-electron-loss process. In the meantime, the average charges of three-electron-loss ($k=3$) processes increase by only 0.3–0.4 unit charges compared with those of two-electron loss, indicating that $k=3$ processes might accompany, in part, an additional electron ionization in the same L shell of the target as that in $k=2$ processes.

E. Production of highly-charged recoil ions

The production cross sections σ^i_q $(=\sum_{q'}\sigma^i_{q,q'})$ of highly-charged Ne^{i+} $(i \geq 5)$ recoil ions in 1.05-MeV/amu $Ar^{q+} + Ne$ collisions are summarized in Fig. 6 as well as those in 1.05-MeV/amu $Ne^{q+} + Ne$ collisions reported previously [10,13]. It is noted that the cross sections for Ne^{i+} $(i = 5-7)$ recoil-ion production by Ar^{q+} impact are quite similar to those by Ne^{q+} impact when compared under the same projectile charge. This confirms the previous results measured by a noncoincidence method [13,14], in which the partial cross sections of Ne^{i+} recoil ions produced in 1.05 MeV/amu Ar^{q+} and 1.05-MeV/amu Ne^{q+} collisions with Ne atoms are dependent

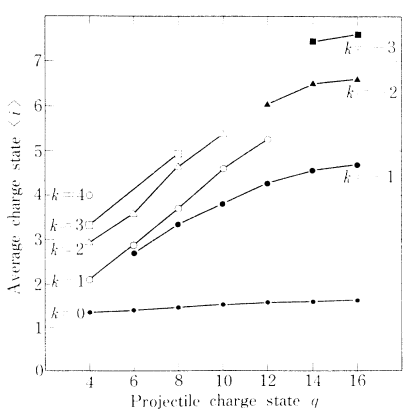

FIG. 5. Average recoil-ion charges $\langle i \rangle$ as a function of the projectile charge state q in $Ar^{q+} + Ne \rightarrow Ar^{q'+} + Ne^{i+}$ collisions. They are shown as $k = q' - q$ as a parameter. $k=0$ (●) represents the average charge for pure ionization. $k=1$ (○), $k=2$ (△), $k=3$ (□), and $k=4$ (○) represent average charges for one up to four electron-loss processes. $k=-1$ (●), $k=-2$ (▲), and $k=-3$ (■) denote those for one up to three electron-capture processes. The solid curves are drawn to guide the eyes.

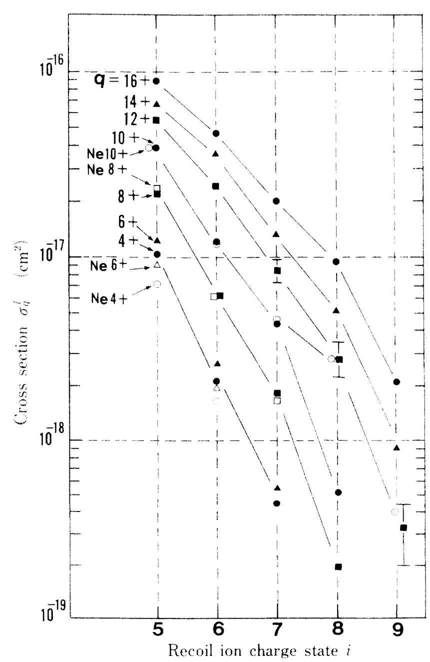

FIG. 6. Cross sections for high-charge-state Ne^{i+} $(i \geq 5)$ ions produced in 1.05-MeV/amu $Ar^{q+} + Ne$ collisions (closed marks), in comparison with those in 1.05-MeV/amu $Ne^{q+} + Ne$ collisions (○: Ne^{10+}, □: Ne^{8+} [13] and △: Ne^{6+}, ○: Ne^{4+} [10]). Typical uncertainties of the cross sections are indicated in the data for $q=12$.

on the charge state q of projectile ions but almost independent on projectiles themselves up to recoil-ion charge state $i=7$.

It is remarkable that the production of highly charged Ne^{8+} and Ne^{9+} recoil ions is largely enhanced in Ar^{14+} and Ar^{16+} projectiles. This might be ascribed to the rapid increase of the two- and three-electron-capture probabilities of projectiles as the projectile charge q increases (see Fig. 4). As pointed out in the preceding section, in the two- and three-electron-transfer ionization processes, at least one target K-shell electron is expected to be involved in addition to the L-shell electron transfer. The importance of transfer processes of K-shell electrons between projectile ions and target atoms has been suggested in production of high-charge-state Ne^{i+} ($i \geq 8$) recoil ions as a result of 1.05-MeV/amu Ne^{10+}+Ne collisions [13].

IV. CONCLUDING REMARKS

We have measured recoil Ne^{i+} ion production cross sections in coincidence with 1.05-MeV/amu Ar^{q+} projectile ions in a wide range of projectile charge state q. The pure ionization was found to dominate the production of low-charge recoil ions ($i=1,2$ and 3), in any of the projectile charge studied here. In the loss ionization ($k=q'-q>0$), which is important for low-charge projectile impact ($q<8$), the average-charge states $\langle i \rangle_{q,q'}$ of recoil ions shift toward higher values with increasing projectile charge q and the number k of the lost electrons, whereas the corresponding cross sections $\sigma_{q,q'}$ decrease rapidly with increasing q and k. On the other hand, in the transfer ionization ($k<0$), which is important for higher charge projectile impact ($q>12$), the average charges $\langle i \rangle_{q,q'}$ as well as the cross sections $\sigma_{q,q'}$ increase with the projectile charge q. In intermediate charge projectiles ($q=10$), the probabilities of loss and capture processes are roughly comparable and the pure ionization play a dominant role in production of high-charge recoil ions as well as low-charge ions. These features of the Ne^{i+} (i=up to 7) recoil-ion production are quite similar to those in symmetric 1.05-MeV/amu Ne^{q+}+Ne collisions.

In addition to further accumulation of experimental data similar to the present work, it would be important to know impact-parameter dependence of the probabilities of multiple ionization for understanding the mechanisms of recoil-ion production in energetic impact of partially stripped ions. Furthermore, x-ray (or Auger-electron) recoil-ion coincidence experiments would provide important information in the contribution of inner-shell ionization processes.

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