Production of recoil Ne^{i+} ions accompanied by electron loss and capture of 1.05-MeV/amu Ne^{q+} ($q=2$, 4, 6, 8, and 10) ions

H. Tawara
National Institute for Fusion Science, Nagoya 464-01, Japan

T. Tonuma and H. Kumagai
Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-01, Japan

T. Matsuo
Department of Pathology, Tokyo Medical and Dental University, Yushima, Tokyo 113, Japan

(Received 21 March 1989; revised manuscript received 17 July 1989)

The charge distributions and production cross sections of recoil ions accompanied by projectile electron loss and capture have been compared in 1.05-MeV/amu Ne^{q+} ($q=2$, 4, 6, 8, and 10) +Ne collisions. While singly charged recoil ions are dominant in pure ionization processes, the production of highly charged recoil ions is strongly enhanced in collisions involving simultaneous charge change (by both electron loss and capture) of projectiles, and the charge distributions of recoil ions are found to be similar for both projectile loss and capture processes. These results have been analyzed with an independent-electron model and indicate that the dominant contribution to the production of higher-charge recoil ions comes from L-shell ionization, with some contribution from K-shell ionization of targets, accompanied by violent multiple ionization of projectiles.

I. INTRODUCTION

It is known that, under highly charged, energetic heavy-ion impact, multiply charged recoil ions are copiously produced, in contrast to structureless particle (electron or proton) impact, where singly charged ions are dominant. In particular, in collisions with heavy ions having inner-shell vacancies, the production of multiply charged recoil ions is significantly enhanced. This is understood qualitatively as well as, to some extent, quantitatively to be due to inner-shell electron transfer from target atoms into projectile vacancies, which is followed by autoionization. In fact, Gray, Cocke, and Justiniano[1] and Kelbch *et al.*,[2] for example, have shown that the charge distributions of recoil ions are shifted toward higher-charge states with an increasing degree of electron capture by projectile ions. Their measurements indicate that, while the cross sections for pure ionization (without any change of projectile charge q) are far larger for singly charged recoil ions (single ionization) and decrease drastically with increasing recoil-ion charge, the cross sections for target ionization, accompanied by one- and two-electron capture into projectile ions (transfer ionization), show their maximum for higher recoil-ion charge, with very weak singly or doubly ionized recoil ions. Furthermore, the mean charge of recoil ions following two-electron projectile capture is roughly two units higher than that following one-electron projectile capture. Theoretical treatments of such multiple ionization are quite complicated. For pure ionization without any charge change of the projectiles, Olson[3] has developed a classical-trajectory Monte Carlo technique and calculated the cross sections for multiple ionization in the 1-MeV/amu collision energy region using an independent-electron model. His results generally reproduce a number of experimental results, but some disagreement is observed. For example, Olson's results overestimate cross sections for higher target ionization because the theory does not take into account the increased binding energies that result from multiple ionization. Olson also points out that such multiple ionization of target atoms by highly charged projectiles occurs at impact parameters which are 5–10 times larger than the shell radius involved because of the strong Coulomb force produced by high-q projectiles.

By taking into account the importance of transfer ionization in which a projectile captures electrons from a target atom in addition to producing direct ionization, thereby resulting in the production of multiply charged recoil ions, Horbatsch[4–6] has developed a quantum-statistical time-dependent mean-field theory and calculated cross sections for transfer ionization as well as for pure ionization over a collision energy range of 50 keV/amu to 5 MeV/amu for projectiles having an ionic charge of 6, 12, and 20 units. This calculation suggests that the contribution of transfer-ionization processes becomes more significant relative to pure ionization at lower energies. It should be pointed out here that both calculations have been made only for bare projectile ions, while most experiments have been performed with partially stripped projectile ions.

On the other hand, up to now, few experimental investigations have been devoted toward studying the mechanisms of recoil-ion production when the loss of a number of the screening electrons of projectiles is accompanied simultaneously (loss ionization). Ullrich *et al.*[7] have measured cross sections for the production of multiply charged recoil ions in Ne^{q+} ($q=1,2,3$) +Ne collisions

 ©1990 The American Physical Society

at relatively low energies (75–360 keV/amu). Their results show that multiply charged recoil ions are mainly produced in close collisions, whereas low-charge recoil ions are in pure ionization under collisions with large impact parameters. At their collision energy region, two neon collision partners tend to form a quasimolecule, probably within the L-shell orbit. In fact, the observed charge distributions seem to be similar for both projectile and recoil neon ions with the most probable charge of 2–3, indicating that the remaining electrons involved in collisions are equally shared between two collision partners. Extensive measurements of relative charge distributions of various recoil ions accompanied by simultaneous electron capture or loss of projectiles at 1.4 MeV/amu have been recently reported by Muller *et al.*[8–9] On the other hand, no theoretical studies on recoil-ion production involving such projectile electron-loss processes have been reported yet.

In the present work, we report on measurements of the charge distributions of recoil Ne^{i+} ions which are produced in the following collisions of 1.05-MeV/amu Ne^{q+} ($q=2$, 4, 6, 8, and 10) projectile ions with Ne atoms by accompanying simultaneous electron loss ($q<q'$) or electron capture ($q>q'$) of projectile ions, resulting in $Ne^{q'+}$,

$$Ne^{q+}+Ne \rightarrow Ne^{q'}+Ne^{i+} . \tag{1}$$

II. EXPERIMENTAL RESULTS

In the present experiment, a standard time-of-flight technique based upon projectile-recoil-ion coincidence is used. 1.05-MeV/amu Ne^{2+} or Ne^{4+} ions are provided from the RIKEN linear accelerator and, after passing stripping foils and a switching magnet to select their charge, if necessary, sent into a collision chamber. The projectile charge state after collisions is analyzed with an electrostatic charge separator and finally the projectile ions are detected with a position-sensitive parallel-plate avalanche counter. On the other hand, recoil Ne^{i+} ions are detected with a channeltron after flying about 15 cm from the collision region. The charge-selected projectile-recoil-ion coincidence spectra are accumulated through the LIST mode. A detailed description of the present experimental system has been given in a previous paper.[10]

Typical projectile and recoil Ne-ion charge spectra are shown in Fig. 1. Figure 1(a) shows the charge distributions of projectile $Ne^{q'+}$ ions in coincidence with all recoil Ne^{i+} ions in 1.05-MeV/amu Ne^{2+} ion collisions with Ne atoms. It is found that the degree of ionization of projectile Ne ions decreases slowly toward higher ionization stages and ionization of projectiles is far more intense, compared with electron capture of projectiles resulting in Ne^{+} ions. At the present collision energy, the dominant mechanism of the production of low charge ($i=1$–3) recoil ions is believed to be pure ionization without any change of projectile-ion charge where probabilities for multiple ionization decrease drastically with increasing recoil-ion charge [see Fig. 1(b)]. The collisions accompanied by one-electron ionization (loss) of projectiles clearly result in relative enhancement of the production of higher-charge recoil ions, compared with that of lower-charge ions, as seen in Fig. 1(c). Furthermore, two- and more-electron projectile ionization results in successively higher-charge recoil ions [see Figs. 1(d)–1(f)]. In fact, for three- or four-electron ionization of Ne^{2+} projectiles resulting in the final charge of $q'=5$ or 6, Ne^{3+} and Ne^{4+} recoil ions are most intense, with a trace of up to Ne^{7+} ions.

Figures 2(a)–2(e) show the observed cross sections for the production of recoil Ne^{i+} ions in Ne^{q+} ($q=2$, 4, 6, 8, and 10) ion impact, estimated from the present data and normalized to the previous values[11] as a function of the recoil-ion charge. The uncertainties range from 10–20 % for cross sections of 10^{-17} cm^2 or more to 50% for those smaller than 10^{-18} cm^2, in addition to the uncertainties appearing in the original cross sections (15% for larger cross sections and 50% for smaller cross sections).

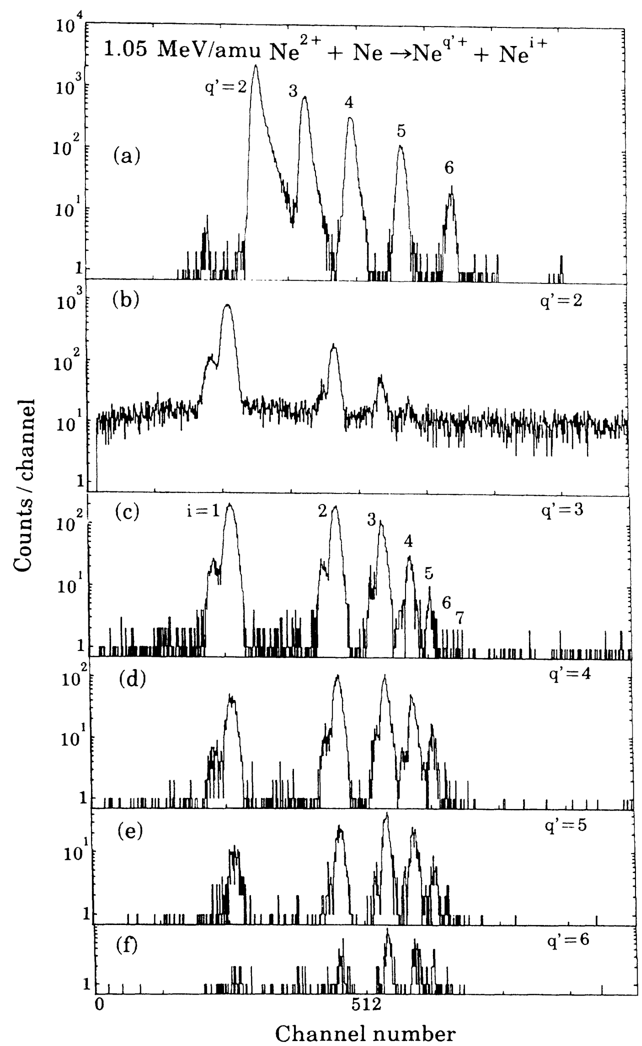

FIG. 1. Charge spectra of projectile and recoil ions in 1.05-MeV/amu $Ne^{2+}+Ne$ collisions. (a) Projectile charge spectrum and (b)–(f) recoil-ion charge spectra for $q'=2$ (pure ionization), for $q'=3$ (one-electron–loss ionization), for $q'=4$ (two-electron–loss ionization), for $q'=5$ (three-electron–loss ionization), and for $q'=6$ (four-electron–loss ionization), respectively.

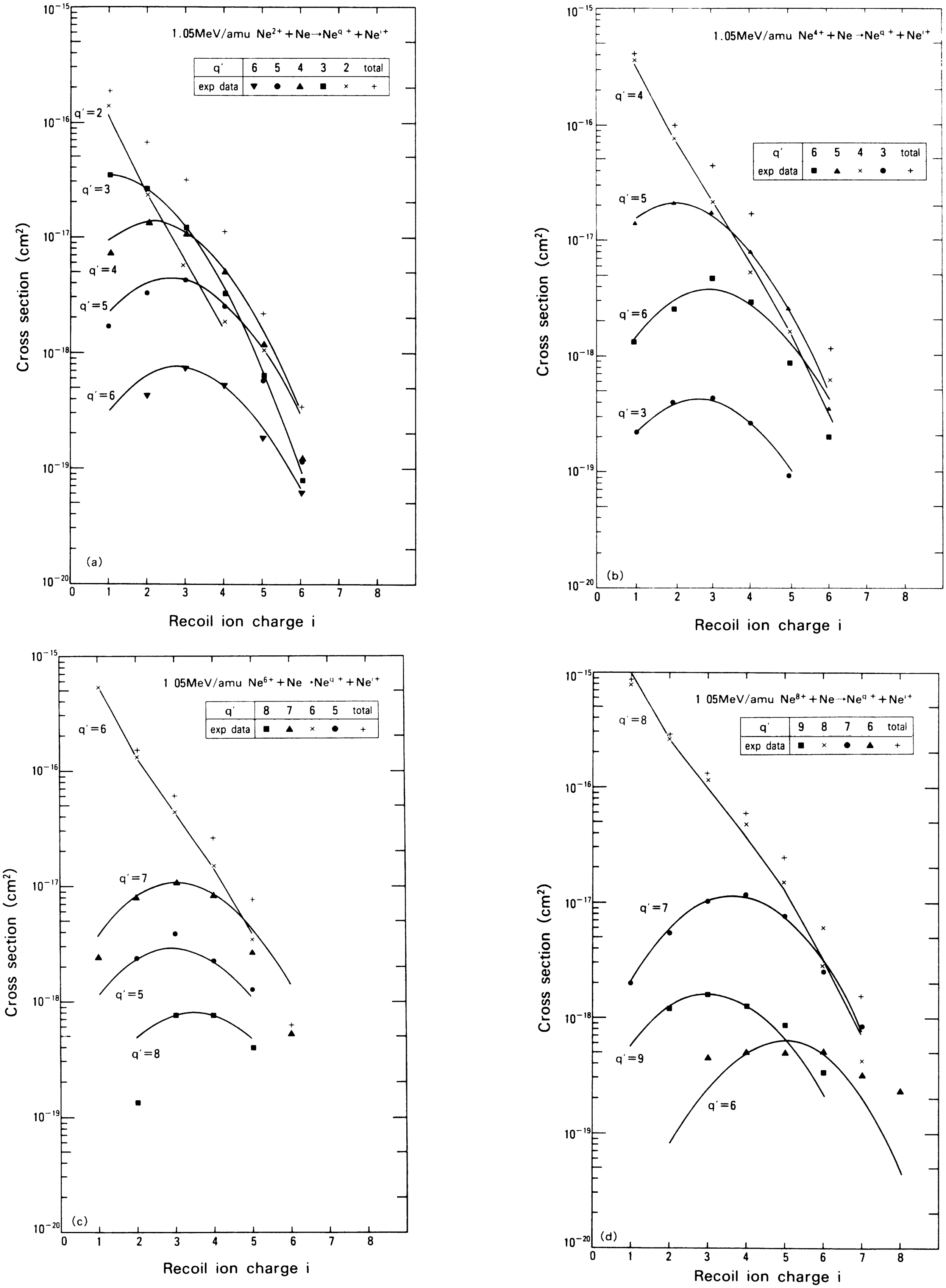

FIG. 2. Cross sections for recoil-Ne^{i+}-ion production in 1.05-MeV/amu Ne^{q+}+Ne$\rightarrow$Ne$^{q'+}$+Ne^{i+} collisions. The solid lines represent the fitted values. The fitted two parameters are given in Tables II (pure ionization) and I (electron loss and capture). (a) $q=2$; (b) $q=4$; (c) $q=6$; (d) $q=8$; (e) $q=10$.

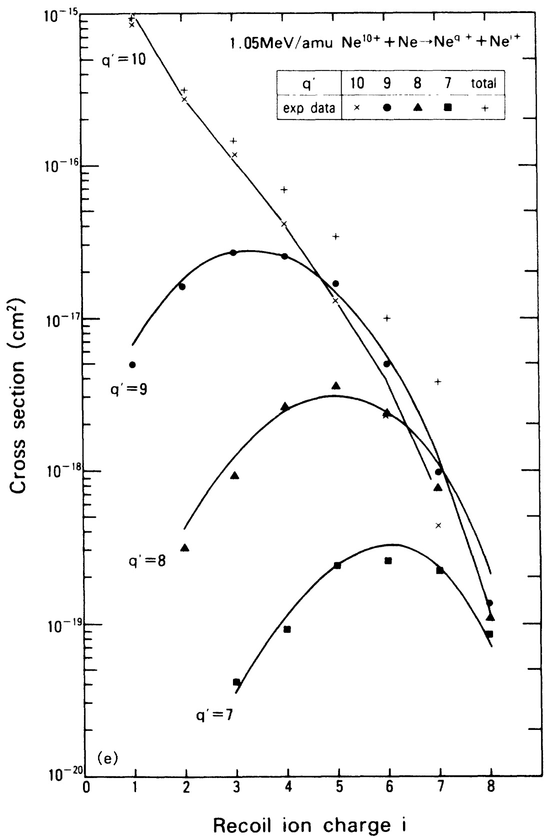

FIG. 2. (*Continued*).

These data clearly show that, by increasing the number of loss electrons of low-charge projectiles and that of electron capture of projectiles, the production of higher-charge recoil ions is significantly enhanced. The present data for singly charged recoil ions, in particular those in multiple-electron change of projectiles, might be overestimated due to double collisions. As pointed out by Gray, Cocke, and Justiniano,[1] a part of the projectiles have unavoidably changed their charge due to collisions with gas atoms effused from the collision region, and these charge-changed projectiles can produce recoil ions through pure ionization which are coincident with the projectiles charge changed inside the collision region. This effect is significant for lower-charge recoil ions, in particular, for singly charged ions. This effect can be estimated through interpolation or separate experiments of pure ionization cross sections for the corresponding charge-changed projectile ions. A detailed correction method has been described elsewhere.[10] Though such detailed features have been found to be dependent on various collision parameters, the contribution of these projectiles charge changed outside the collision region has been found to range from a few percent to nearly 100% for singly charged recoil ions.

Another important feature observed in the present work is the fact that the charge distributions of recoil ions are similar in both projectile electron-loss and -capture processes, although cross sections strongly depend upon their initial charge states, suggesting that some similar mechanisms do work in the production of higher-charge recoil ions in two different types of collisions of projectiles. Similar features in 0.7-MeV/amu $Cl^{q+}+Ar$ collisions have recently been reported by Levin *et al.*[12]

III. DISCUSSION

A. Recoil-ion production cross sections by different charge projectiles

Although no complete understanding of multiple ionization of atoms by energetic, heavy-ion impact is possible at present, some reasonable description of such a process can be made, based upon an independent-electron model.[1] It is for the moment assumed that, in multiple ionization of Ne atoms, eight electrons in the L shell play a main role, while two K-shell electrons play a minor role. According to this independent-electron model, the cross sections for multiple ionization of Ne atoms in the process defined above in Eq. (1) can be expressed as follows:

$$\sigma(q,q';i)=\int \binom{8}{i} P_L^i(1-P_L)^{8-i}2\pi b\, db \ , \tag{2}$$

where P_L is the ionization probability of one of the L-shell electrons, i represents the number of ionized electrons, and b is the impact parameter of collisions. Though P_L is usually dependent upon the impact parameter b, P_L is assumed to be constant inside an impact parameter r_L and zero outside. Then, the cross sections for multiple ionization of Ne atoms can be expressed as follows (see further discussion later):

$$\sigma(q,q';i)=\binom{8}{i} P_L^i(1-P_L)^{8-i}r_L^2\pi \ . \tag{3}$$

As seen in this equation, the charge distributions of recoil Ne^{i+} ions are mainly determined by P_L, whereas the sizes of the cross sections are determined by the impact parameter b. By fitting the observed data, these two parameters P_L and r_L can be estimated as given in Table I. The solid lines for the charge-changed projectiles shown in Fig. 2 correspond to the estimated values based upon these fitted parameters in Table I. It is found that fittings are generally good for all the charge states investigated except for those of singly charged recoil ions where significant contributions from double collisions cannot be completely excluded.

It should be noted that data for pure ionization cannot be reproduced through this simple impact-parameter dependence, but are better reproduced through the following exponential dependence:

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

where $P_L(0)$ represents the ionization probabilities of L-shell electrons at the impact parameter $b=0$. This fact might be due to the difference in the dependence of ionization probabilities on the impact parameter in two

TABLE I. Fitted parameters P_L and r_L (in angstroms) for electron-loss and -capture ionization processes (note that the mean radius of the L-shell orbit of Ne is 0.32 Å).

q	2				4			6			8			10		
q'	3	4	5	6	3	5	6	5	7	8	6	7	9	7	8	9
P_L	0.19	0.28	0.34	0.36	0.34	0.28	0.38	0.38	0.39	0.44	0.61	0.46	0.39	0.72	0.61	0.43
r_L	0.49	0.36	0.22	0.09	0.07	0.45	0.20	0.18	0.34	0.10	0.08	0.36	0.13	0.06	0.19	0.57

different processes, as seen in the calculated results by Horbatsch,[4] which indicate that probabilities for pure ionization tend to extend toward large impact parameters, while those for electron capture tend to diminish rapidly outside some impact parameters. On the other hand, no theoretical calculation is presently available of the impact-parameter dependence of target multiple ionization accompanied by the projectile electron-loss process. After fitting the observed data, the solid lines for pure ionization in Fig. 2 are calculated from such parameters $P_L(0)$ and r_L which are given in Table II.

B. P_L and r_L in the independent-electron model

For pure ionization, by increasing the incident projectile charge both parameters $P_L(0)$ and r_L are found to increase and relative enhancement of higher-charge recoil ions is observed (see Table II), suggesting the enhanced production of higher-charge recoil ions as well as the increased cross sections. On the other hand, with an increase of the number of projectile electrons changed through either the loss or the capture process, P_L becomes large, resulting in the shift of recoil-ion charge distributions toward higher charges, while r_L decreases, resulting in a reduction of cross sections (see Table I).

Generally, the variation of the same number of projectile electrons through either the loss or the capture process has been found to result in practically the same values of P_L, indicating similar charge distributions of recoil ions in both processes. However, if the incident projectile charge q is larger than the equilibrium charge $\tilde{q}$, r_L for the electron-loss process is smaller than that for electron capture. In fact, the measured cross sections for the electron-loss process are smaller than those for electron capture. If $q<\tilde{q}$, the situation is reversed and r_L in the loss process becomes larger than that of the electron-capture process, indicating that the electron-loss process is more likely to occur than the electron-capture process.

The dependence of these two parameters on the incident projectile charge is shown in Figs. 3(a) and 3(b). Generally speaking, P_L increases with increasing incident charge for both electron-loss and -capture processes, indicating that the charge distributions of recoil ions are shifted toward higher charges, and then levels off at the highest incident charge. Another feature in r_L dependence on q is interesting, as seen in Fig. 3(b) where r_L for both one- and two-electron-loss processes crosses that for the corresponding electron-capture processes at about $q=7$, which is close to the equilibrium charge $\tilde{q}$ of Ne projectile ions at the present energy.

TABLE II. Fitted parameters $P_L(0)$ and r_L (in angstroms) for pure ionization ($q=q'$).

q	2	4	6	8	10
$P_L(0)$	0.35	0.40	0.45	0.55	0.55
r_L	0.33	0.55	0.68	0.87	0.90

C. Contribution of K-shell ionization

As already pointed out, the inner-shell ionization process contributes significantly to the production of higher-charge recoil ions. However, in the $Ne^{q+}+Ne$ collision system, K-shell ionization cross sections for Ne atoms at the present energy region are estimated to be $(2-4)\times10^{-18}$ cm^2, with the enhancement of a factor of 2–4 for projectile ions with one K-shell vacancy due to K-shell to K-shell electron transfer, based upon those by F^{q+} ion impact.[13] As far as total cross sections are concerned, the contribution of K-shell ionization seems to become important only in collisions accompanied by a two- or more-electron change of projectiles.

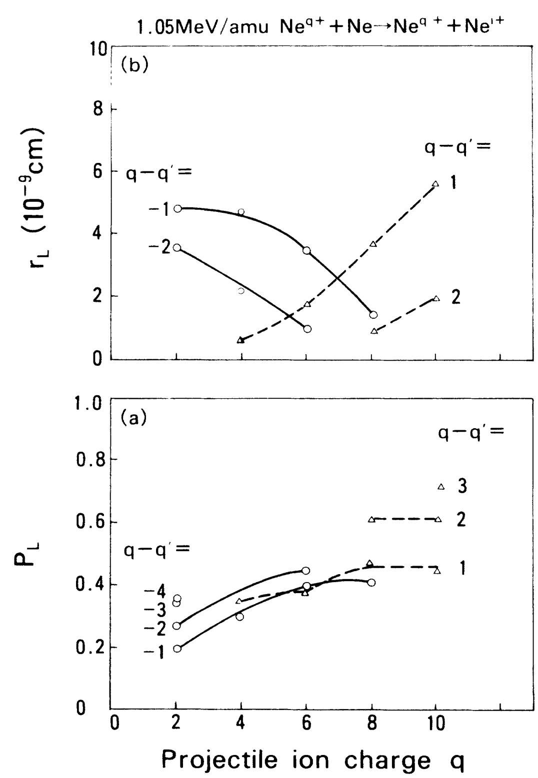

FIG. 3. Fitted parameters as a function of the incident projectile charge. (a) P_L; (b) r_L. The lines are drawn to guide the eye.

In $Ne^{10+}+Ne$ collisions, for example, the charge distributions or mean charges of recoil Ne ions produced through double-electron capture are found to shift 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 autoionization, finally resulting in two-electron emission. Thus, in the production of recoil ions through the double-electron-capture process, at least one K-shell electron is expected to be involved, in addition to one L-shell capture of projectiles and multiple L-shell electron ionization. Total cross sections for Ne K-shell ionization are estimated[13] to be about $(1-2)\times10^{-17}$ cm^2 which is comparable to the measured total cross sections of recoil-ion production through double-electron capture [$\cong1\times10^{-17}$ cm^2, see Fig. 2(e)]. On the other hand, the mean charge of recoil ions produced through the three-electron capture process is shifted to higher sides only by unit charge, indicating that the third electron involved might be another L-shell electron corresponding to double L-shell electron transfer. In fact, according to Auger hypersatellite measurements,[14] the contribution of double K-shell electron transfer into Ne^{10+} projectiles ($\cong7\times10^{-19}$ cm^2) to the production of recoil ions is believed to be not dominant, though it may become significant for very-high-charge recoil-ion production such as Ne^{8+} and above. It should also be noted that Ne hypersatellites due to double K-shell ionization have been observed only in bare (F^{9+}) ion impact.[14] Then, other collision systems involving partially ionized Ne projectiles in the present work should have only a minor contribution of double K-shell electron transfer into projectiles.

Similar situations are observed in charge distributions of recoil ions produced through single- and double-electron-capture processes in $Ne^{8+}+Ne$ collisions [see Fig. 2(d)]. As Ne^{8+} could contain some fraction of metastable $1s2s3p$ state beams, K-shell to K-shell electron transfer becomes possible.

In the meantime, no such clear difference is observed in $Ne^{6+}+Ne$ collisions. The mean charge of recoil ions produced through projectile double-electron loss is at best by a unit charge higher than that by a single-electron loss process. This might suggest that in this collision the contribution of target K-shell ionization is not dominant in the production of the main parts of recoil ions [see Figs. 2(c)].

In $Ne^{2+}+Ne$ [Fig. 2(a)] and $Ne^{4+}+Ne$ [Fig. 2(b)] collisions, projectiles are dominantly ionized. These data show that, by increasing the number of loss electrons from projectiles, the mean charges increase slowly by about half a unit charge for each electron lost from projectiles. This gradual increase of the mean charge should correspond to the increase of the number of the ionized L-shell electrons but the contribution of K-shell ionization should be minor in this collision system, except for the four-electron loss process where target K-shell ionization may contribute to some extent to the production of highly charged recoil ions.

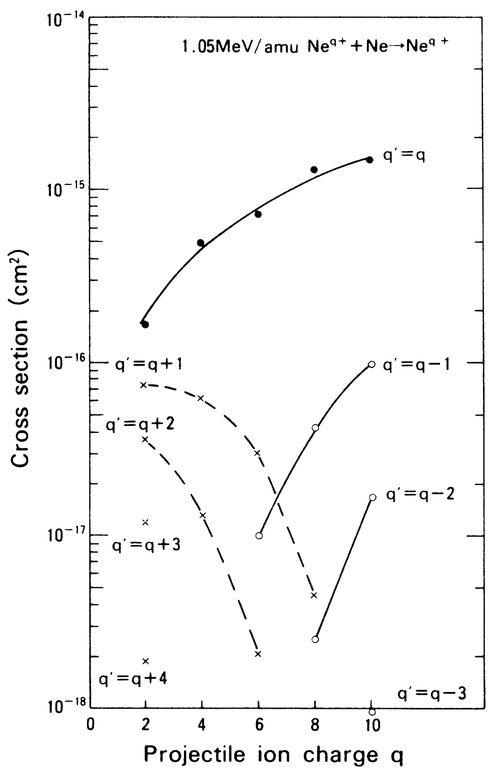

FIG. 4. Total cross sections of pure ionization, electron-loss, and electron-capture processes of 1.05-MeV/amu Ne^{q+} projectile ions in Ne targets as a function of the projectile charge q. The solid lines with closed circles, solid lines with open circles, and dotted lines with crosses represent pure ionization, electron-capture, and electron-loss processes, respectively. The lines are drawn to guide the eye.

D. Electron-capture and -loss cross sections of projectiles

By summing up all the observed partial cross sections of multiple ionization for the incident projectile charge states, electron-capture and -loss cross sections of projectile Ne^{q+} ions can be estimated and the results are summarized in Fig. 4. Though no data are available for direct comparison, the estimated cross sections are in reasonable agreement with values extrapolated from those previously reported, for example, by Macdonald *et al.*[15] As seen in Fig. 4, with increasing projectile charge q, cross sections for single- and double-electron capture increase drastically, whereas those for single- and double-electron-loss decrease. Those for pure ionization are found to increase as $q^{1.35}$, similar to the net ionization cross sections of Ne which were determined to increase as $q^{1.67}$ by Be *et al.*[16]

IV. CONCLUDING REMARKS

Recoil-Ne^{i+}-ion production cross sections have been measured in coincidence with 1.05-MeV/amu Ne^{q+} projectile ions over a wide range of q and analyzed with an independent-electron model. It is found that at a lower-charge projectile impact where the electron-loss process is dominant the charge distributions of recoil ion shift toward higher sides with an increase of the number of electrons lost from projectiles, and the impact parameters contributing most to the ionization shrink accordingly. For intermediate-charge projectile ions where both electron-loss and -capture processes can occur with comparable probabilities, the recoil-ion charge distributions are similar (but not the same) when these projectiles change their charge state either through electron loss or through electron capture, suggesting that some common interaction mechanisms prevail in both collision processes, although cross sections themselves depend strongly upon the initial and final projectile charges. These observed features are found to be understood with the independent-electron model, which predicts that the dominant contribution to the production of highly charged recoil ions comes from multiple L-shell ionization, while K-shell ionization seems to be non-negligible only in the production of very highly charged recoil ions, in particular, in double- and three-electron capture processes of Ne^{10+} ions.

In addition to further measurements of absolute cross sections of highly charged recoil-ion production accompanied by the electron loss and capture of projectiles, it would be important to know the impact-parameter dependence of the probabilities of multiple ionization. Furthermore, x-ray (or Auger electron) recoil-ion coincidence experiments should be performed to clarify the contribution of inner-shell ionization processes, though either electron transfer or ionization to continuum, to the production of highly charged recoil ions.

[1]T. J. Gray, C. L. Cocke, and E. Justiniano, Phys. Rev. A **22**, 849 (1980).

[2]S. Kelbch, J. Ullrich, R. Mann, P. Richard, and H. Schmidt-Böcking, J. Phys. B **18**, 323 (1985).

[3]R. E. Olson, J. Phys. B **12**, 1843 (1979).

[4]M. Horbatsch, J. Phys. B **19**, L193 (1986).

[5]M. Horbatsch, Z. Phys. D **1**, 337 (1986).

[6]M. Horbatsch and R. M. Dreizler, Z. Phys. D **2**, 183 (1986).

[7]J. Ullrich, K. Bethge, S. Kelbch, W. Schadt, H. Schmidt-Böcking, and K. E. Stiebing, J. Phys. B **19**, 448 (1986).

[8]A. Muller, B. Schuch, W. Groh, and E. Salzborn, Z. Phys. D **7**, 251 (1987).

[9]A. Muller, B. Schuch, W. Groh, E. Salzborn, H. F. Beyer, P. H. Mokler, and R. E. Olson, Phys. Rev. A **33**, 3010 (1986).

[10]T. Tonuma, H. Kumagai, T. Matsuo, and H. Tawara, Phys. Rev. A **40**, 6238 (1989).

[11]T. Tonuma, T. Matsuo, M. Kase, T. Kambara, H. Kumagai, S. H. Be, I. Kohno, and H. Tawara, Phys. Rev. A **36**, 1941 (1987).

[12]J. C. Levin, C.-S. O, H. Cederquist, C. Biedermann, and I. A. Sellin, Phys. Rev. A **38**, 2674 (1988).

[13]C. W. Wood, R. L. Kauffmann, K. A. Jamison, N. Stolterfoht, and P. Richard, Phys. Rev. A **13**, 1358 (1976).

[14]C. W. Wood, R. L. Kauffmann, K. A. Jamison, N. Stolterfoht, and P. Richard, Phys. Rev. A **12**, 1393 (1975).

[15]J. R. Macdonald, S. M. Ferguson, T. Chiao, L. D. Ellsworth, and S. A. Savoy, Phys. Rev. A **5**, 1168 (1972).

[16]S. H. Be, T. Tonuma, H. Kumagai, H. Shibata, M. Kase, T. Kambara, I. Kohno, and H. Tawara, J. Phys. B **19**, 1771 (1986).