Energy-spectroscopic studies of electron-capture processes by low-energy, highly stripped C, N, and O ions from He

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Translation-energy spectra of charge-state-changed projectile ions scattered in the forward direction in collisions of C^{q+} ($q=5,4$), N^{q+} ($q=6,5$), and O^{q+} ($q=6$) ions with He atoms have been measured at collision energies of q and $2q$ keV. All the product peaks observed in the spectra come from exothermic electron-capture processes. From the measured energy gains of the product $(q-1)$—charge-state ions, it has been found that an electron is captured selectively into a single shell with a particular principal quantum number $n=2$ for the incident C^{4+} ion and $n=3$ for the incident C^{5+}, N^{5+}, N^{6+}, and O^{6+} ions. This fact is in accord with the prediction of the one-electron classical theory. It has also been revealed that there is good similarity among the energy-spectral patterns obtained for the ions having the same charge $+q$, irrespective of ionic species; such a similarity results from the similarity among diabatic potential curves for the collision systems of the q—charge-state ions and He. In the case of $C^{4+}+He$ collision, the two-electron—capture process into the ground state of C^{2+} occurs more efficiently than the one-electron—capture process at the low energies studied.

I. INTRODUCTION

Recently one-electron—capture cross sections from neutral He atoms by multiply charged B, C, N, O, F, Ne, and S ions including fully stripped ions have been measured at collision energies below 1.5 keV/amu.[1] A remarkable oscillation of cross sections with incident-ionic charge q was found. Similar oscillation was predicted by Ryufuku, Sasaki, and Watanabe for the case of the H atom target using a classical model of charge transfer.[2] The oscillation has been interpreted as follows. The transferred electron is captured selectively into a shell having a principal quantum number n. This quantum number changes from n to $n+1$ at some value of q as q is increased, with an accompanying drastic increase in cross section. Before the quantum number n changes, the larger q gives the smaller interaction distance, leading instead to a gradual decrease in cross section. After all, the cross sections show a sawtooth type oscillation with the change of ionic charge q. Though the classical model may be crude, the model has been found to be adequate also for the case of the He target.[1] The essential assumption of this model is that the electron is captured only into a single shell. We have made a series of experiments intending to find some evidence for it and to determine into which shell the transferred electron goes. The results obtained should be most important for basic understanding of charge transfer involving multiply charged ions and useful for development of x-ray laser and controlled-thermonuclear-fusion research.

In our preceding papers,[3,4] energy gains of the charge-state changed projectile ions scattered into the forward direction for the collisions of fully stripped C^{6+}, N^{7+}, and O^{8+} with neutral He atoms have been reported, and it has been verified that an electron is captured selectively into a shell of principal quantum number $n=3$, 4, and 4 of the product C^{5+}, N^{6+}, and O^{7+} ions, respectively. In the continuation of the previous experiments for fully stripped ions, energy-spectroscopic studies of collisions of hydrogenlike and heliumlike ions of carbon, nitrogen, and oxygen with neutral He atoms have been made systematically. The two-electron—capture process and the transfer ionization process have also been studied in addition to the one-electron—capture process; among these, the transfer ionization process has been reported[4] for the collision systems of N^{7+} + He and O^{7+} + He.

In the present paper, we report mainly on the one-electron—capture process at keV collision energies. The experimental details are described in Sec. II. The measured translation-energy spectra are displayed and similarity among the spectral patterns for ions having the same charge q is discussed in relation to diabatic potential curves concerned in Sec. III. Concluding remarks follow in Sec. IV, where the results obtained from the series of energy-spectroscopic measurements including fully stripped ions are compared with the classical one-electron theory.[2]

II. EXPERIMENTS

The apparatus used and the experimental procedure have been reported in Ref. 3. Therefore, we describe here the principle of translation-energy spectroscopy and the related problems such as determination of the parameter depending on the apparatus geometry and the energy resolution in detail. A brief description of the experimental setup is given.

A. Principle of translation-energy spectroscopy

We consider the following electron-capture process at low energies:

$$A^{q+}+B \rightarrow A^{q'+}+B^{r+}+Q, \quad q=q'+r \tag{1}$$

where Q is the total inelastic energy gain. In this inelastic electron-capture process, the incident projectile ion A^{q+} with the mass M_1 and the energy E_q is scattered into an angle of θ with the energy $E_{q'}$; meanwhile the neutral target B atom with the mass M_2 is recoiled with the energy E_r. Then, the total gain Q is defined as

$$Q=(E_{q'}+E_r)-E_q \ . \tag{2}$$

In this energy spectroscopy, the gain of the kinetic energy of the scattered ion, $\Delta E=E_{q'}-E_q$, may be measured at the scattering angle θ. The kinematical consideration leads to the following relation:

$$\Delta E(E_q,Q,\theta)=\frac{2M_1M_2}{(M_1+M_2)^2}E_q\left\{1+\frac{M_1}{M_2}\sin^2\theta+\frac{M_1+M_2}{M_1}\frac{Q}{2E_q}-\cos\theta\left[1-\left[\frac{M_1}{M_2}\right]^2\sin^2\theta-\frac{M_1+M_2}{M_2}\frac{Q}{E_q}\right]^{1/2}\right\} . \tag{3}$$

If it is assumed that the energy gain is much smaller than the incident kinetic energy of the projectile ion, that is, $Q \ll E_q$, the energy gain of the projectile ion scattered into the zero-degree direction ($\theta \simeq 0°$) becomes independent of E_q as follows:

$$\Delta E(\theta \simeq 0°) \simeq Q \ . \tag{4}$$

That is, by measuring the energy gain ΔE of the projectile ion (energy gain spectroscopy) scattered into the forward direction, we can determine straightforwardly the reaction energy Q which provides important information on mechanisms in the inelastic collision processes.

In order to get good energy resolution, the energy of the projectile ions should be reduced before they enter an electrostatic energy analyzer as shown schematically in Fig. 1. If the decelerating potential to the projectile ion is V_R, the energy of the incident projectile ion is reduced to E_q-qV_R at the entrance of the energy analyzer. When the ion is to pass through the analyzer of which the deflection voltage is V_D and to reach a detector, the following relation should be fulfilled:

$$E_q-qV_R=qKV_D \ , \tag{5}$$

where K is a constant depending mainly on the geometry of the analyzer and probably on the deflection voltage of the analyzer V_D. On the other hand, the energy of the charge-state-changed projectile ion ($A^{q'+}$) with the charge $+q'$ has to be decelerated through V_R', which is different from V_R for the incident projectile in order to pass through the analyzer with the same deflection voltage V_D as that for the incident projection ion and to reach the detector. Then, the following condition is necessary:

$$E_{q'}-q'V_R'=q'KV_D \ . \tag{6}$$

From the energy conservation, we obtain the following relation:

$$V_R'=(q/q')V_R+[(q-q')/q']KV_D+(1/q')\Delta E \ . \tag{7}$$

That is, we can determine the energy change ΔE in the absolute scale by scanning the decelerating potential V_R' for the charge-state-changed projectile ions while keeping the deflection voltage V_D constant, provided that K is known.

B. Experimental setup and determination of the parameter K

Actually, projectile ions are produced in an EBIS-type ion source called NICE-1 and are injected into a collision cell after acceleration and mass-charge analysis. Ions passing through the cell are decelerated through electrostatic lenses, are energy analyzed by an electrostatic 127° cylindrical analyzer, and finally reach a Channeltron-type detector as shown in Fig. 1. The decelerating lens system having 14 electrodes consists of a part of linear field distribution, an einzel lens, and a pair of deflection electrodes to control the position of projectile ions and to optimize the transmission through the energy analyzer as well as to obtain good energy resolution. Dimensions of the present apparatus are as follows: The collision cell is 2 cm in length and its entrance and exit apertures are 0.8 and 1.0 mm in diameter, respectively; the first decelerating electrode is located 22 mm behind the cell; the entrance and exit slit widths of the analyzer with the mean radius of 125 mm are 1.0 and 1.5 mm, respectively. This geometry enables one to detect the ions scattered only into an extremely forward direction.

By the use of 10-keV C^{5+} ions, the energy resolution of the present analyzer was tested as a function of the deflection voltage V_D. When the voltage V_D is reduced, the resolution becomes high and then tends to be nearly constant; a typical operating resolution was about $0.8\times5=4.0$ eV with the deflection voltage V_D of 25—35 V after the ion energy was decelerated by about 90% of the original acceleration energy. Therefore, the deflection voltage V_D was usually set at 30 V throughout the present experiment. From these experiments it was found that the energy resolution is mainly limited by the energy spread of extracted ions from the NICE-1 and it was estimated to be smaller than $0.8\times q$ eV under the continuous operation mode,[5] which is much smaller than that prevailed in the litera-

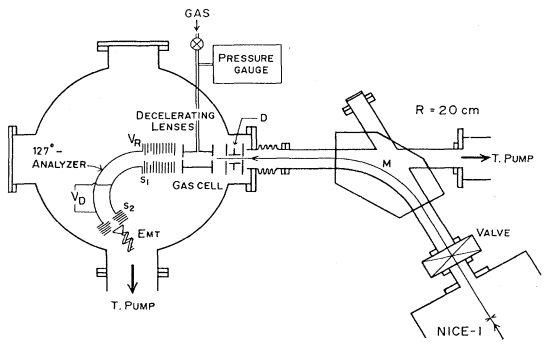

FIG. 1. Schematic view of the apparatus used for translation-energy spectroscopy.

tures.[6]

The translation-energy spectra of the charge-state-changed projectile ions are obtained by scanning the decelerating voltage V_R' while the deflection voltage V_D of the analyzer is kept at the same voltage, 30 V, as that for the incident projectile ions. In order to obtain the absolute scale of the energy in the energy spectra, the parameter K in Eq. (7) has to be determined. First, we determined K using a Li^+-ion beam which is generated from a thermal-emission—type ion source. In this case the ion energy is entirely determined by the acceleration voltage, and then K is found to be equal to 1.21. This number is very close to that estimated from the geometry of the analyzer ($K=1.24$). Secondly, we have checked this number by measuring the relationship between the deflection voltage V_D and the decelerating voltage V_R based upon Eq. (5). It was found that V_D changes very much linearly with V_R, resulting in $K=1.213\pm0.003$ for the deflection voltage ranging from 20 to 40 V, which is very close to the number obtained with Li^+-ion beams. Therefore, $K=1.21$ is used in the present energy analysis.

The stable-isotope gases $^{18}O_2$, $^{15}N_2$, and ^{13}CO are used for source gases in order to separate the highly stripped ions from impurity ions. The helium gas used for the target is in a research grade with 99.999% purity. Background pressures were less than 10^{-10} Torr at the ion source and 10^{-7} Torr at the outside of the collision cell. Under the operation condition, the source pressure was around 10^{-9} Torr, the target pressure in the cell was kept at about 10^{-4} Torr, and the pressure outside the cell was about 10^{-6} Torr.

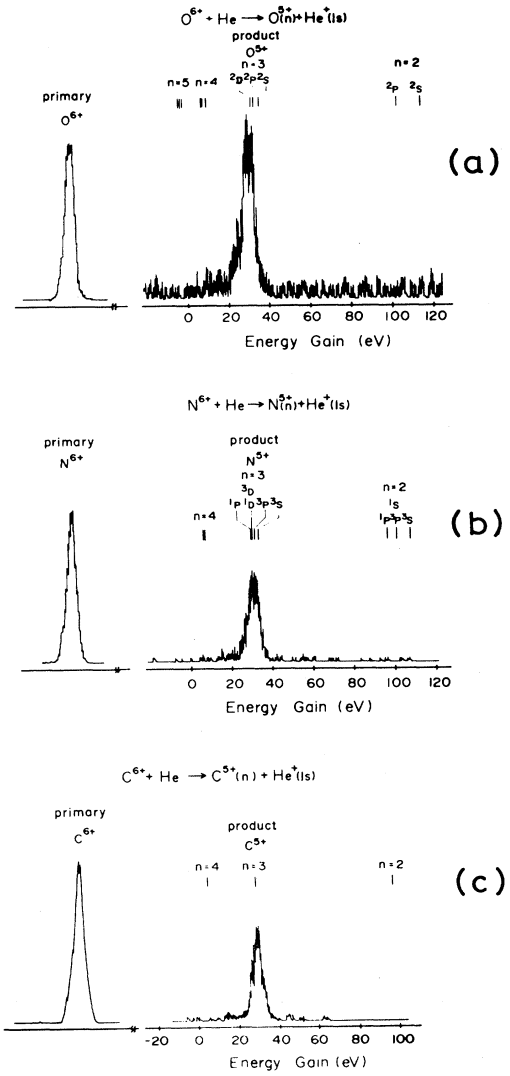

FIG. 2. (a) Typical energy spectrum of O^{5+} ions in the forward direction from the O^{6+} + He collision at 0.33 keV/amu. (b) Typical energy spectrum of N^{5+} ions in the forward direction from the N^{6+} + He collision at 0.30 keV/amu. (c) Typical energy spectrum of C^{5+} ions in the forward direction from the C^{6+} + He collision at 0.46 keV/amu.

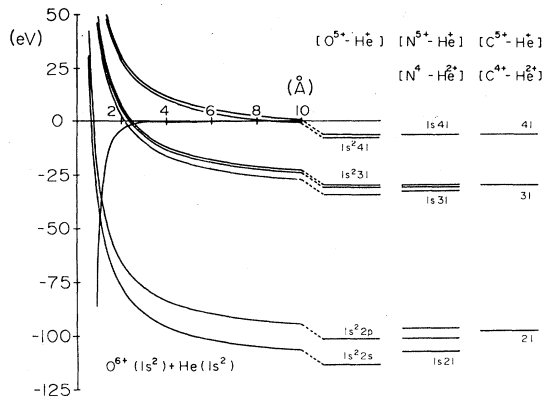

FIG. 3. Diabatic potential curves for the one-electron—capture process, $O^{6+}(1s^2)+He \rightarrow O^{5+}(1s^2nl)+He^+(1s)$, and energy diagrams for channels of the one-electron capture into $O^{5+}(1s^2nl)$, $N^{5+}(1snl)$, and $C^{5+}(nl)$ levels.

III. RESULTS AND DISCUSSION

The energy-spectroscopic measurements have been made for hydrogenlike and heliumlike ions of oxygen, nitrogen, and carbon such as O^{6+}, $N^{6,5+}$, and $C^{5,4+}$ at the energies of q and $2q$ keV, where $q+$ is the charge of the projectile ion incident upon the neutral-helium target. The present experiment has been made in extension of the previous one[3,4] for fully stripped ions colliding with He. In this section, however, the experimental results are presented and classified according as the ionic charge state q rather than the isoelectronic sequence of the incident projectiles, because good similarity is found in the spectra obtained for the ions with the same incident-ionic charge state q. The measured energy gains ΔE of the charge-state-changed projectile ions are compared to the reaction energies Q calculated from the book of Bashkin and Stoner[7] and then the electron-capturing levels of charge-state-changed projectiles are determined.

TABLE I. Observed energy gains and related levels of charge-state-changed projectiles. Energy gain ΔE is determined from the peak position in the energy spectrum measured. The reaction energy Q is calculated with energy levels given by Bashkin and Stoner (Ref. 7). R_c is the crossing distance of diabatic potential curves in consideration of the polarization for the initial channel and the Coulomb repulsion for the final channel; note that R_c is calcuiated by the use of the ionic charge state q. R_x is an internuclear distance limit at which an electron can get over the potential barrier between target and projectile in the classical model [see Eq. (14) in text].

Incident	ΔE (eV)	product	Q (eV)	R_c (Å)	R_x (Å)
O^{7+}	18.0[a]	$O^{6+}(1s4p\ ^1P)$	16.95	5.13	
		$(1s4d\ ^{1,3}D)$	17.05	5.11	
		$(1s4f\ ^{1,3}F)$	17.12	5.09	
		$(1s4s\ ^3S)$	17.45	4.99	
		$(1s4p\ ^3P)$	17.46	4.99	4.4
N^{7+}	16.8[a]	$N^{6+}(4f\ ^2F)$	17.08	5.10	
		$(4d\ ^2D)$	17.09	5.10	
		$(4s\ ^2S)$	17.10	5.09	
		$(4p\ ^2P)$	17.10	5.09	4.4
O^{6+}	29.5	$O^{5+}(1s^23d\ ^2D)$	29.89	2.53	
		$(1s^23p\ ^2P)$	30.94	2.26	
		$(1s^23s\ ^2S)$	34.18	2.26	4.2
N^{6+}	30.0	$N^{5+}(1s3p\ ^1P)$	29.51	2.56	
		$(1s3d\ ^3D)$	29.89	2.53	
		$(1s3d\ ^1D)$	29.93	2.53	
		$(1s3p\ ^3P)$	30.78	2.47	
		$(1s3s\ ^3S)$	32.66	2.34	4.2
C^{6+}	29.0[b]	$C^{5+}(3d\ ^2D)$	29.84	2.53	
		$(3s\ ^2S)$	29.86	2.53	
		$(3p\ ^2P)$	29.86	2.53	4.1
N^{5+}	16.0	$N^{4+}(1s^23d\ ^2D)$	13.24	4.39	
		$(1s^23p\ ^2P)$	14.07	4.14	
		$(1s^23s\ ^2S)$	16.75	3.50	3.9
C^{5+}	13.6	$C^{4+}(1s3p\ ^1P)$	12.98	4.48	
		$(1s3d\ ^1D)$	13.21	4.40	
		$(1s3d\ ^3D)$	13.24	4.39	
		$(1s3p\ ^3P)$	13.97	4.17	
		$(1s3s\ ^1S)$	14.00	4.16	
		$(1s3s\ ^3S)$	15.44	3.78	3.9
C^{4+}	31	$C^{3+}(1s^22p\ ^2P)$	31.91	1.57	
		$(1s^22s\ ^2S)$	39.91	1.35	3.6

[a]Taken from Ref. 4.
[b]Taken from Ref. 1.

A. O^{6+}, N^{6+} + He collisions

The energy spectra of the product O^{5+} ion in the O^{6+} + He collision and of the product N^{5+} ion in the N^{6+} + He collision are shown in Figs. 2(a) and 2(b), together with the energy profile of the primary ions. Figure 2 clearly demonstrates that the energy-spectral patterns of the product O^{5+} and N^{5+} ions are quite similar not only to each other but also to that of the C^{5+} ion in the C^{6+} + He collision reported previously[3] and is shown in Fig. 2(c) as a reference. In Fig. 2 are indicated the calculated energy levels which correspond to some principal quantum numbers n of the product A^{5+} ions for the one-electron–capture process,

$$A^{6+} + \mathrm{He} \rightarrow A^{5+}(nl) + \mathrm{He}^{+}(1s) .$$

As seen in Fig. 2, the electron is captured into neither the $n=2$ shell nor the $n=4$ shell. In each energy spectrum, only a single peak is observed at the energy gain of around 30 eV and it corresponds to the one-electron capture into the $n=3$ shell of the charge-state-changed projectiles of O^{5+} and N^{5+} as

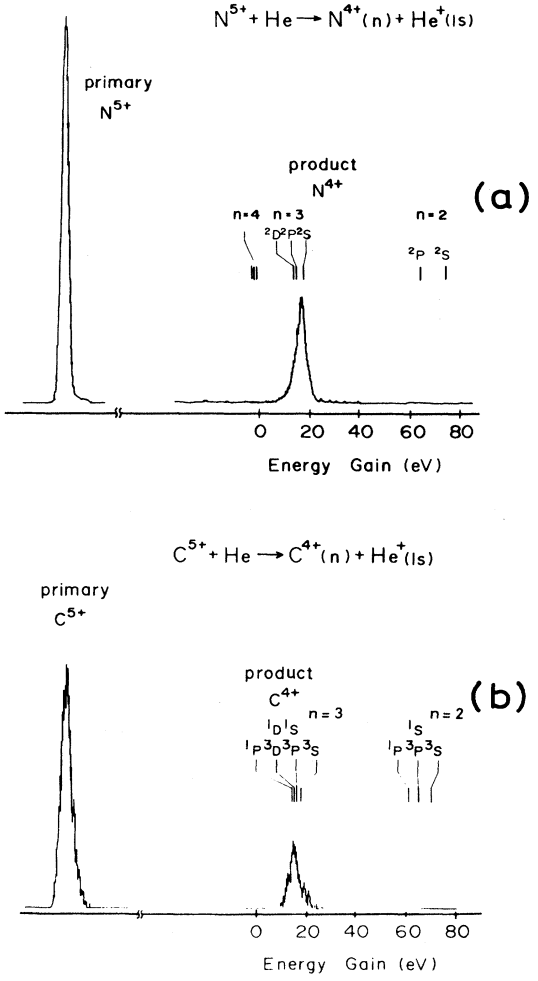

FIG. 4. (a) Typical energy spectrum of N^{4+} ions in the forward direction from the N^{5+} + He collision at 0.33 keV/amu. (b) Typical energy spectrum of C^{4+} ions in the forward direction from the C^{5+} + He collision at 0.38 keV/amu.

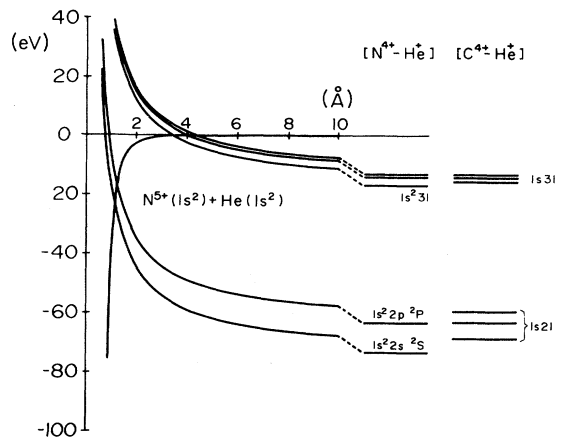

FIG. 5. Diabatic potential curves for the one-electron—capture process, $N^{5+}(1s^2) + He \rightarrow N^{4+}(1s^2nl) + He^+(1s)$, and energy diagrams for channels of one-electron capture into $N^{4+}(1s^2nl)$ and $C^{4+}(1snl)$ levels.

$$O^{6+}(1s^2)+He(1s^2)\rightarrow O^{5+}(1s^2 3l)+He^+(1s)+Q \tag{8}$$

and

$$N^{6+}(1s)+He(1s^2)\rightarrow N^{5+}(1s\,3l)+He^+(1s)+Q\ , \tag{9}$$

where Q is distributed from 29.89 to 34.18 eV for the O^{6+} + He collision and from 29.51 to 32.66 eV for the N^{6+} + He collision. The energy resolution in the present experiment is not high enough to separate the sublevels of the $n=3$ shell.

In consideration of the polarization for the initial channel and the Coulomb repulsion for the final channel, the diabatic potential curves are presented in Fig. 3 for the collision systems of O^{6+} + He and N^{6+} + He, along with the system of O^{6+} + He. This figure illustrates good similarity among the potential curves of these collision systems and such similarity is considered to give the similarity in the energy spectra obtained for the one-electron—capture process by the O, N, and C ions having the same charge $q=6$ from He. The calculated reaction energies Q and the crossing distances R_c in the related channels are listed in Table I.

It is noted here that the values of the R_c are slightly different from those of crossing distances R_n evaluated in Ref. 1; in the present paper, the R_c is calculated by the use of the ionic charge q, whereas the R_n is done by the use of the effective charge Z^* (see Ref. 1 for details).

B. N^{5+}, C^{5+} + He collisions

Good similarity is also observed between the energy spectra obtained in the N^{5+} + He and C^{5+} + He collisions as shown in Figs. 4(a) and 4(b). This is expected from the similarity of the diabatic potential curves presented in Fig. 5.

For the N^{5+} + He collision, as shown in Fig. 4(a), only a single peak is observed at the energy gain of 16 eV, and it corresponds to the one-electron capture into the $n=3$ shell of the product N^{4+} ion as

$$N^{5+}(1s^2)+He(1s^2)\rightarrow N^{4+}(1s^2 3l)+He^+(1s)+Q\ , \tag{10}$$

where Q is distributed from 13.24 to 16.75 eV as listed in Table I. In this case the energy resolution is too poor to allow separation of the sublevels.

Typical energy spectrum obtained in the C^{5+} + He collision is shown in Fig. 4(b). Only a single peak is observed at the energy gain of 13.6 eV and it corresponds to the one-electron—capture process

$$C^{5+}(1s)+He(1s^2)\rightarrow C^{4+}(1s\,3l)+He^+(1s)+Q\ . \tag{11}$$

The Q values are distributed from 12.98 to 15.44 eV for the $1s\,3l$ states as listed in Table I. The observed peak re-

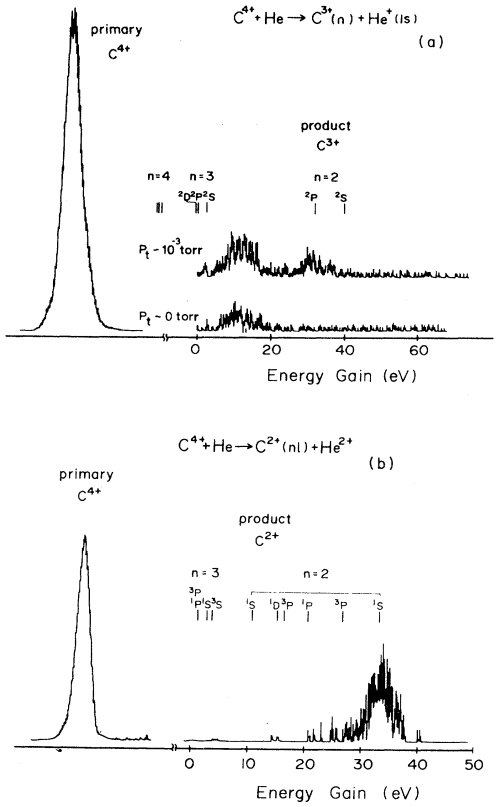

FIG. 6. (a) Typical energy spectrum of C^{3+} ions in the forward direction from the C^{4+} + He collision at 0.31 keV/amu. (b) Typical energy spectrum of C^{2+} ions in the forward direction from the C^{4+} + He collision at 0.31 keV/amu.

sults from these states, though the preferentially capturing sublevels cannot be definitely assigned.

C. C^{4+} + He collision

In the energy gain spectra of the charge-state-changed C^{3+} ion in the C^{4+} + He collision, two peaks are observed at around 12 and 31 eV as shown in Fig. 6(a). The former peak at 12 eV is considered to be due to collisions with background gases because it is still observed without the He target gas.

The latter peak at 31 eV increases with an increase of the target pressure of He gas and is originated from the charge-state-changed C^{3+} ion in the one-electron—capture process by C^{4+} from He. The energy spectrum of the product C^{3+} ion reveals clearly that an electron is not captured into the $C^{3+}(1s^2 2s\ ^2S)$ but into the $C^{3+}(1s^2 2p\ ^2P)$ level in the reaction such as

$$C^{4+}(1s^2)+He(1s^2) \rightarrow C^{3+}(1s^2 2p\ ^2P)+He^{+}(1s) + 31.91 \text{ eV} . \quad (12)$$

In Fig. 7 are shown the diabatic potential curves for one- and two-electron—capture processes. The small value of the observed cross section[8] of reaction (12) may be related to the very short crossing distance (1.57 Å). There are some potential curve crossings at around 2 Å for the two-electron—capture process. The C^{2+} product peak is observed in the C^{4+} + He collision as shown in Fig. 6(b) and it corresponds to the ground state of the C^{2+} ion in the two-electron—capture process

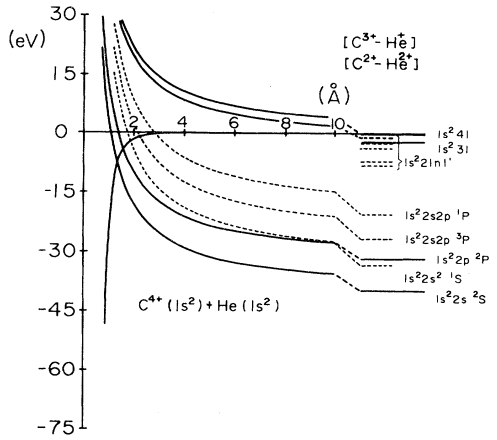

FIG. 7. Diabatic potential curves for the C^{4+} + He collision and energy diagrams. Solid and dashed lines are for one- and two-electron—capture channels into $C^{3+}(1s^2 nl)$ and $C^{2+}(1s^2 2l 2l')$ levels, respectively.

$$C^{4+}(1s^2)+He(1s^2) \rightarrow C^{2+}(1s^2 2s^2\ ^1S)+He^{2+} + 33.37 \text{ eV} . \quad (13)$$

The two-electron—capture process takes place more efficiently than the one-electron capture at the low-energy region as reported by Crandall.[9] From the comparison between the peak heights of the C^{3+} and C^{2+} product ions we estimated that the total cross section of two-electron capture by C^{4+} from He is about thirty times larger than that of one-electron capture at 0.31 keV/amu. This ratio agrees roughly with that calculated by Shipsey *et al.*[10]

Finally, we add mention of the O^{7+} + He and N^{7+} + He collisions which have been reported in connection with the transfer ionization process.[4] Patterns of the energy spectra obtained in both the collisions are very similar to each other (see Figs. 3 and 4 in Ref. 4) as expected from the similarity in the diabatic potential curves concerned. Dominant peaks in the energy spectra are observed at the energy gains of about 17—18 eV and they correspond to the one-electron capture into the $n=4$ shell of the product O^{6+} and N^{6+} ions. The reaction energies Q and the crossing distances R_c in the related channels are listed in Table I.

IV. CONCLUDING REMARKS

In this paper, we classified the experimental results according to the ionic charge state q rather than the isoelectronic sequence of the incident projectiles. There is good similarity among the energy spectra for ions having the same charge state q. This is quite natural because the diabatic potential curves are not very dependent on the num-

ber of core electrons of incident ions and, as a result, are very similar for ions with the same charge state q.

It is clearly demonstrated that all the observed peaks in the energy spectra obtained in the forward direction are originated from the exothermic channels in the electron-capture processes without the excitation of the He^+ ion, and no signals due to the endothermic processes are found over noise levels in any energy spectra. In the one-electron—capture processes by fully stripped, hydrogenlike and heliumlike ions, O^{q+}, N^{q+}, and C^{q+}, from the neutral He atom, it is confirmed experimentally that an electron is captured selectively into only a single shell of charge-state-changed projectiles. As summarized in Table II, the principal quantum numbers n of the capturing levels of charge-state-changed ions are determined as $n=4$ for O^{8+}, O^{7+}, and N^{7+} + He collisions, $n=3$ for O^{6+}, N^{6+}, C^{6+}, N^{5+}, and C^{5+} + He collisions, and $n=2$ for the C^{4+} + He collision.

It is interesting to compare these results with the prediction by the classical one-electron theory.[2] The theory characterizes an internuclear distance R_x at which the attractive force by the multiply charged ion becomes to exceed the binding force for the electron in the target atom. In other words, the R_x gives the outer limit of the internuclear distance where the one-electron—transfer reaction is possible. The R_x is given by

$$R_x=[Z_1^*+2(Z_1^*Z_2^*)^{1/2}]/I_{\mathrm{He}}\ , \tag{14}$$

where Z_1^* and Z_2^* are the effective charges of He^+-ion core and of q—charge-state ion core of the projectile, and I_{He} is the ionization energy of He atom in atomic units. The values of R_x given by Eq. (14) are listed in Table I. It is noted that most of the levels determined experimentally have the crossing distance R_c which is smaller than the R_x but is the largest inside the R_x. In some cases including O^{7+} and N^{7+}, however, the R_c is slightly larger than the R_x.[11] This discrepancy may be due to the crudeness of the classical theory and the inaccuracy of the potential curves. For other cases the classical theory correctly predicts the principal quantum number n of the level into which the electron is captured. The theory could be a criterion for prediction of the electron-capturing levels. It should be most interesting to see what relation exists between the cross sections and the R_c of the reaction channels determined. Unfortunately, the present data are not enough for a discussion of this subject and an effect to accumulate sufficient data for discussion of this subject is now under way.

TABLE II. Principal quantum numbers n of selectively capturing levels of charge-state-changed projectiles $A^{(q-1)+}$ in the A^{q+} + He collision.

A	$q=8$	$q=7$	$q=6$	$q=5$	$q=4$
O	4	4	3		
N		4[a]	3	3	
C			3	3	2

[a]The classical model (Ref. 1) predicts $n=3$.

Transfer ionization process producing a $(q-1)$—charge-state ion of the projectile via two-electron capture into autoionizing levels was observed in some cases; for example, the O^{7+} + He and N^{7+} + He collisions.[4] The two-electron—capture process was found to be much more dominant than one-electron—capture process in the C^{4+} + He collision. In the cases of one- and two-electron—capture processes by C^{4+} not only the principal quantum number n but also the orbital quantum number l could be determined because the energy separation of the sublevels becomes larger in low-n shells.

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[11]As mentioned in Sec. III A, the R_c value is slightly different from the R_n value which is evaluated in Ref. 1. If the R_n is used instead of the R_c, the classical theory correctly predicts the experimentally determined principal quantum numbers n of the capturing levels with the sole exception in $N^{7+} + He$ collisions.