

$\text{SiCl}_4^+(\text{C}^2\text{T}_2\text{-X}^2\text{T}_1, \text{C}^2\text{T}_2\text{-A}^2\text{T}_2)$   
Emissions Produced from the  $\text{He}(2^3\text{S}),$   
 $\text{Ne}(^3\text{P}_{<2,0>})/\text{SiCl}_4$  Penning Ionization and  
 $\text{Ar}^+(\text{^}2\text{P}_{<3/2>})/\text{SiCl}_4$  Charge-Transfer Reaction  
at Thermal Energy

Tsuji, Masaharu  
Institute of Advanced Material Study, Kyushu University

Nakamura, Masafumi  
Department of Molecular Science and Technology, Graduate School of Engineering Sciences,  
Kyushu University

Mizuguchi, Toshinori  
(Present address)Nippon Steel Corp.

Kaneko, Nobuo  
(Present address) Sanken Electronic Co.

他

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# $\text{SiCl}_4^+(\tilde{\text{C}}^2\text{T}_2-\tilde{\text{X}}^2\text{T}_1, \tilde{\text{C}}^2\text{T}_2-\tilde{\text{A}}^2\text{T}_2)$ Emissions Produced from the $\text{He}(2^3\text{S}), \text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$ Penning Ionization and $\text{Ar}^+(^2\text{P}_{3/2})/\text{SiCl}_4$ Charge-Transfer Reaction at Thermal Energy

Masaharu TSUJI, Masafumi NAKAMURA,\* Toshinori MIZUGUCHI,\*\*

Nobuo KANEKO\*\*\*, and Yukio NISHIMURA

The bound-free  $\text{SiCl}_4^+(\tilde{\text{C}}^2\text{T}_2-\tilde{\text{X}}^2\text{T}_1, \tilde{\text{C}}^2\text{T}_2-\tilde{\text{A}}^2\text{T}_2)$  emissions resulting from the  $\text{He}(2^3\text{S}), \text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$  Penning ionization and  $\text{Ar}^+(^2\text{P}_{3/2})/\text{SiCl}_4$  charge-transfer reaction have been observed in the rare gas flowing afterglows. A comparison of the observed spectral features with those in a reported electron-impact spectrum suggested that  $\text{SiCl}_4^+(\tilde{\text{C}})$  is formed through a vertical Franck-Condon type process in the  $\text{He}(2^3\text{S}), \text{Ne}(^3\text{P}_{0,2})/\text{SiCl}_4$  Penning ionization, while the  $\text{Ar}^+(^2\text{P}_{3/2})/\text{SiCl}_4$  charge-transfer reaction preferentially populates near-resonant highly vibrationally excited levels with small Franck-Condon factors for ionization.

## 1. Introduction

In general, large molecular ions do not give fluorescence, because competitive non-radiative transitions become significant with increasing the number of atoms in a molecular ion. Therefore, little optical spectroscopic study has been carried out on Penning ionization and charge-transfer (CT) reactions of large polyatomic molecules. According to a recent systematic study of Tuckett and co-workers,<sup>1-3)</sup> the group IV tetrahalide cations are exceptional large molecular ions which decay by fluorescence in the ultraviolet and visible region. The fluorescence quantum yield of  $\text{SiCl}_4^+(\tilde{\text{C}}^2\text{T}_2)$  has been measured to be unity.<sup>3)</sup> In the present study, a comparative spectroscopic study was conducted on the  $\text{He}(2^3\text{S}), \text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$  Penning ionization and the  $\text{Ar}^+(^2\text{P}_{3/2})/\text{SiCl}_4$  CT reaction leading to the emitting  $\text{SiCl}_4^+(\tilde{\text{C}})$  state. The observed  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{X}}, \tilde{\text{C}}-\tilde{\text{A}})$  spectra are compared with the reported spectra obtained under fast electron impact<sup>1)</sup> in order to examine whether ionization takes place via a vertical Franck-Condon (FC) process or not.

## 2. Experimental

The flowing afterglow apparatus used in the present study was similar to that reported previously.<sup>4,5)</sup> In brief, the metastable  $\text{He}(2^3\text{S}), \text{Ne}(^3\text{P}_{2,0})$ , or  $\text{Ar}(^3\text{P}_{2,0})$  atom and  $\text{He}^+, \text{He}_2^+, \text{Ar}^+$ , or  $(\text{Ar}^+)^*$  ion were generated by a microwave discharge of the high purity He, Ne, or Ar gas. It was found that all of the  $\text{Ar}^+$  ion in the ground state was located in the lower  $^2\text{P}_{3/2}$

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Dedicated to Professor Hiroshi Kobayashi on the occasion of his retirement

\*Department of Molecular Science and Technology, Graduate School of Engineering Sciences, Kyushu University.

\*\*Present address: Nippon Steel Corp., Yahata-Higashi-ku, Kitakyushu 805.

\*\*\*Present address: Sanken Electronic Co., Niiza City, Saitama 352.

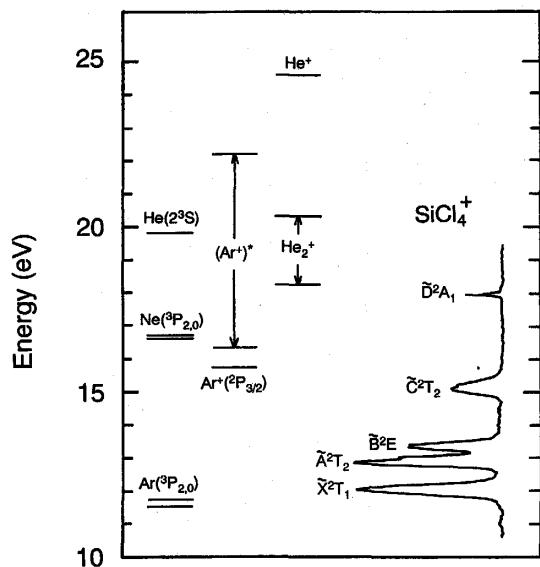
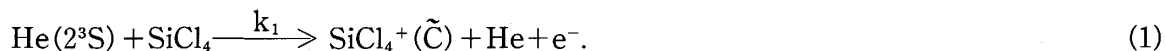


Fig. 1 Photoelectron spectrum of SiCl<sub>4</sub><sup>+</sup> reported by Green et al.<sup>7)</sup> and energies of rare gas active species involved in the He, Ne, and Ar afterglows.

SiCl<sub>4</sub><sup>+</sup> in the 11-18 eV region. Among them, the  $\tilde{C}^2T_2$  state with adiabatic and vertical ionization potentials of 15.09 and 15.27 eV, respectively,<sup>8)</sup> decays by fluorescence into the  $\tilde{X}^2T_1$  and  $\tilde{A}^2T_2$  states. The ionization energies of the  $\tilde{C}^2T_2$  state are lower than the available energies of He<sup>+</sup> (24.58 eV), He(2<sup>3</sup>S): 19.82 eV), Ne(3<sup>2</sup>P<sub>0</sub>): 16.72 eV), Ne(3<sup>2</sup>P<sub>2</sub>): 16.62 eV), Ar<sup>+</sup> (3<sup>2</sup>P<sub>3/2</sub>): 15.76 eV), and (Ar<sup>+</sup>)<sup>\*</sup> (16.41-22.19 eV),<sup>5)</sup> while it is higher than those of Ar(3<sup>2</sup>P<sub>2</sub>): 11.55 eV) and Ar(3<sup>2</sup>P<sub>0</sub>): 11.75 eV). The intensity distribution of the HeI PES spectrum reflects the relative magnitudes of the FC factors for the ionization of SiCl<sub>4</sub>. From an inspection of Fig. 1, it can be seen that the FC factor for SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) has a maximum at  $\sim$ 15.3 eV, and rapidly decreases with increasing the vibrational energy.

A typical emission spectrum resulting from the He(2<sup>3</sup>S)/SiCl<sub>4</sub> reaction is shown in Fig. 2(a). The spectrum consists of two broad continuous bands in the 350-500 nm region with a peak at  $\sim$ 410 nm and in the 510-650 nm region with a peak at  $\sim$ 560 nm. Since the observed spectral features are very similar to those measured by Lambert et al. under electron-impact at 200 eV,<sup>1)</sup> the shorter and longer wavelength bands are ascribed to the bound-free  $\tilde{C}^2T_2$  -  $\tilde{X}^2T_1$  and  $\tilde{C}^2T_2$  -  $\tilde{A}^2T_2$  transitions of SiCl<sub>4</sub><sup>+</sup>, respectively,



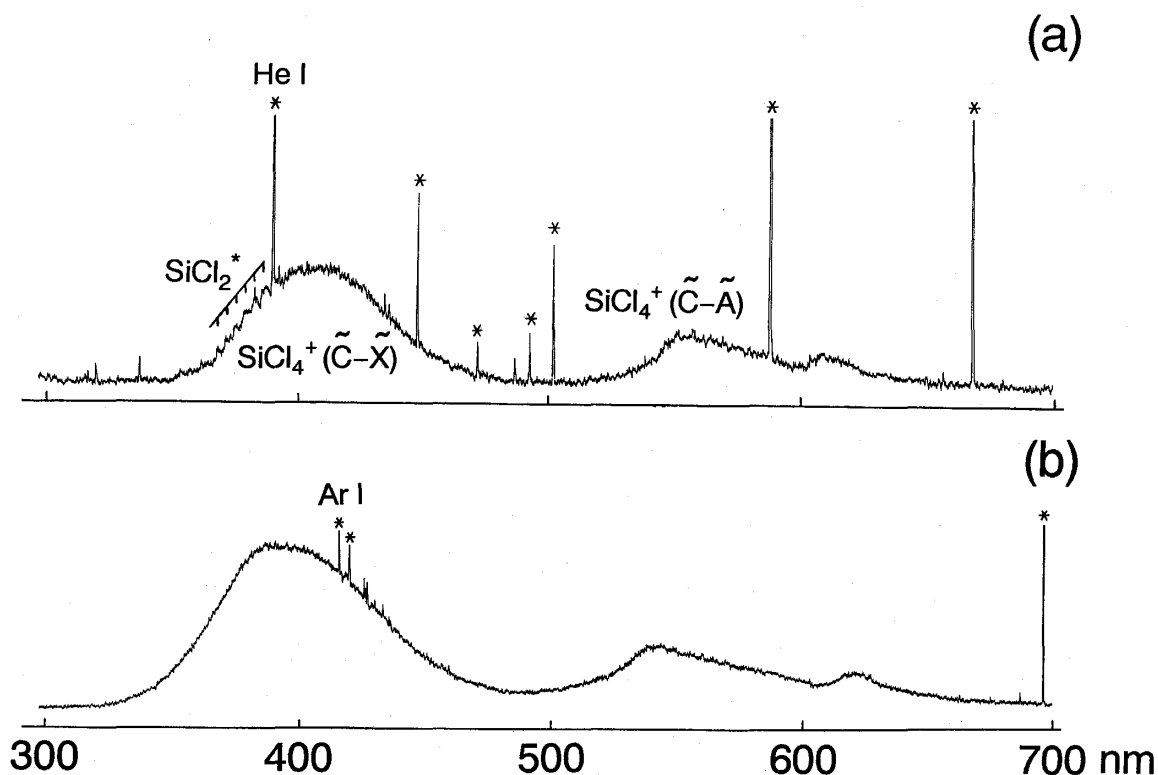
A weak band with a peak at  $\sim$ 620 nm must not be associated with SiCl<sub>4</sub><sup>+</sup> because the same peak has been found in the He(2<sup>3</sup>S)/GeCl<sub>4</sub> reaction.<sup>9)</sup> The measurements of the relative sensitivity of the optical detection system by using a standard halogen lamp suggested that it arises from a rapid change in the optical sensitivity. Partially overlapping with the SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ) transition, weak discrete bands, which have been ascribed to SiCl<sub>2</sub><sup>\*</sup> by Sameith et al.,<sup>10)</sup> are found in the 360-390 nm region.

When emission spectrum resulting from the He(2<sup>3</sup>S), He<sup>+</sup>, He<sub>2</sub><sup>+</sup>/SiCl<sub>4</sub> reactions was observed without applying a retarding potential to the ion-collector grids, no appreciable change in emission intensities was found for the SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) bands. The absence of the SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) emissions due to the He<sup>+</sup>/SiCl<sub>4</sub> and He<sub>2</sub><sup>+</sup>/SiCl<sub>4</sub> reactions is attributed to the fact that the formation of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) by these CT reactions are highly exoergic,

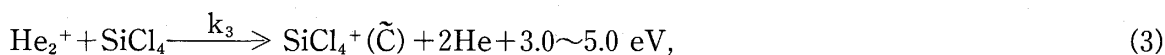
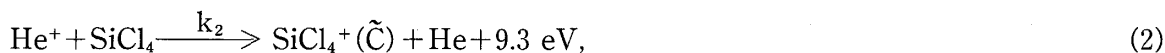
spin-orbit state by observing the ArF<sup>\*</sup> excimer resulting from the Ar<sup>+</sup>(<sup>2</sup>P<sub>1/2,3/2</sub>)/SF<sub>6</sub><sup>-</sup> ionic-recombination reaction.<sup>6)</sup> The contribution of ionic active species to the observed emissions was examined by using a pair of ion-collector grids placed between the discharge section and the reaction zone. The sample SiCl<sub>4</sub> gas was admixed with the rare gas discharge flow operated at a buffer gas pressure range of 0.03-0.5 Torr for Ar, 0.04-0.07 Torr for Ne, and 0.5-1.5 Torr for He (1 Torr = 133.3 Pa). The emission spectra were dispersed in the 200-700 nm region with a Jarrell Ash 1 m monochromator.

### 3. Results and discussion

Figure 1 shows the photoelectron spectrum (PES) of SiCl<sub>4</sub> measured by Green et al.<sup>7)</sup> along with the available energies of rare gas active species involved in the He, Ne, and Ar afterglows. There are five electronic states of



**Fig. 2**  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{X}}, \tilde{\text{C}}-\tilde{\text{A}})$  emissions produced from (a) the  $\text{He}(2^3\text{S})/\text{SiCl}_4$  Penning ionization and (b)  $\text{Ar}^+(^2\text{P}_{3/2})/\text{SiCl}_4$  charge-transfer reaction at thermal energy (uncorrected for relative sensitivity). A weak peak at  $\sim 620$  nm is not a real peak but it arises from a rapid change in the relative sensitivity.



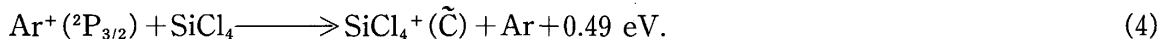
where the  $\Delta H$  values are calculated by using a vertical ionization potential of  $\text{SiCl}_4^+(\tilde{\text{C}})$ . Thus, significant energy transfer from the internal energy of the reactant ion to the relative translational energy of the products is required. Such an energy transfer process is generally unfavorable. The relative concentrations of  $\text{He}(2^3\text{S})$ ,  $\text{He}^+$ , and  $\text{He}_2^+$  at a He pressure of 1 Torr were estimated to be 1, 1.5, and 0.25, respectively, by comparing the total intensities of the  $\text{N}_2^+(\text{B}^2\Sigma_u^+ - \text{X}^2\Sigma_g^+)$  emissions resulting from the reactions of  $\text{He}(2^3\text{S})$ ,  $\text{He}^+$ , and  $\text{He}_2^+$  with  $\text{N}_2$ .<sup>5)</sup> Taking account of these ratios, the  $k_2/k_1$  and  $k_3/k_1$  ratios were evaluated to be less than 0.002 and 0.07, respectively. The lack of the  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{X}}, \tilde{\text{C}}-\tilde{\text{A}})$  emissions due to the  $\text{He}^+/\text{SiCl}_4$  reaction is consistent with a small formation rate of  $\text{SiCl}_4^+$  in the  $\text{He}^+/\text{SiCl}_4$  reaction [ $(4 \pm 2) \times 10^{-11} \text{ cm}^3\text{s}^{-1}$ ].<sup>11)</sup>

The  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{X}}, \tilde{\text{C}}-\tilde{\text{A}})$  emissions due to the  $\text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$  reaction were also found in the Ne afterglow reaction of  $\text{SiCl}_4$ . The observed spectral features were the same as those in the  $\text{He}(2^3\text{S})/\text{SiCl}_4$  reaction, indicating that the  $\text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$  Penning ionization proceeds through a similar mechanism. The  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{X}})$  emission starts from  $\sim 350$  nm and gives a peak at  $\sim 410$  nm. On the other hand, the  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{A}})$  emission starts from  $\sim 510$  nm and the main peak is observed at  $\sim 560$  nm. These spectral features in the  $\text{He}(2^3\text{S})/\text{SiCl}_4$  and  $\text{Ne}(^3\text{P}_{2,0})/\text{SiCl}_4$  Penning ionization are very similar to those obtained under fast electron-impact ionization,<sup>1)</sup> where ionization is expected to proceed through a vertical FC mecha-

nism. It is therefore concluded that the He(<sup>2</sup>S)/SiCl<sub>4</sub> and Ne(<sup>3</sup>P<sub>2,0</sub>)/SiCl<sub>4</sub> Penning ionization leading to SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) takes place through a vertical FC mechanism.

Obase et al.<sup>12)</sup> have found that vibrational distributions of HCl<sup>+</sup>(A<sup>2</sup>Σ<sup>+</sup>) and HBr<sup>+</sup>(A<sup>2</sup>Σ<sup>+</sup>) in the He(<sup>2</sup>S)/HCl,HBr Penning ionization were different from those predicted from FC factors for ionization. The deviations from FC like distributions have been explained as due to a He(<sup>2</sup>S)-HX (X=Cl or Br) interaction in the incoming half collision and/or a HX<sup>+</sup>(A)-He(<sup>1</sup>S) interaction in the outgoing half collision. The present study demonstrates that such interactions are insignificant in the He(<sup>2</sup>S)/SiCl<sub>4</sub> and Ne(<sup>3</sup>P<sub>2,0</sub>)/SiCl<sub>4</sub> reactions leading to SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ).

When SiCl<sub>4</sub> was introduced into the Ar afterglow operated at Ar gas pressures above 0.25 Torr, where Ar(<sup>3</sup>P<sub>2,0</sub>), Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>), and (Ar<sup>+</sup>)<sup>\*</sup> were present as active species,<sup>5)</sup> the SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) transitions are found in the 310-650 nm region, as shown in Fig. 2(b). The SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) emissions disappeared completely when ionic active species were removed from the discharge flow. This implies that Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) and/or (Ar<sup>+</sup>)<sup>\*</sup> are the responsible excitation source of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ). The dependence of the emission intensity of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) on the Ar buffer gas pressure was different from that of the Kr<sup>\*</sup> lines from the (Ar<sup>+</sup>)<sup>\*</sup>/Kr reaction.<sup>13)</sup> However, it was identical to that of the OCS<sup>+</sup>( $\tilde{A}$ <sup>2</sup>Π- $\tilde{X}$ <sup>2</sup>Π) emission due to the Ar<sup>+</sup>/OCS CT reaction,<sup>14)</sup> indicating that the same active species participates in the excitation of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ). Thus, it is concluded that Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) is the responsible active species for the excitation of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ),



The observation of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ,  $\tilde{C}$ - $\tilde{A}$ ) emissions due to the above CT reaction is consistent with a large formation rate constant of SiCl<sub>4</sub><sup>+</sup> [(8.5±2.6)×10<sup>-10</sup> cm<sup>3</sup>s<sup>-1</sup>].<sup>11)</sup> Since the radiative lifetime of the  $\tilde{C}$  state is short (τ=38 ns),<sup>2)</sup> vibrational and rotational relaxation by collisions with a buffer rare gas is expected to be negligible under the operating pressures. It should be noted that the  $\tilde{C}$ - $\tilde{X}$  and  $\tilde{C}$ - $\tilde{A}$  transitions due to the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>)/SiCl<sub>4</sub> reaction appear from ~320 and ~490 nm, respectively. These values are shorter than those due to the He(<sup>2</sup>S)/SiCl<sub>4</sub> and Ne(<sup>3</sup>P<sub>2,0</sub>)/SiCl<sub>4</sub> reactions by ~20 nm. The peak positions of the  $\tilde{C}$ - $\tilde{X}$  and  $\tilde{C}$ - $\tilde{A}$  transitions in the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>)/SiCl<sub>4</sub> reaction also shift to blue by ~20 nm in comparison with those in the He(<sup>2</sup>S)/SiCl<sub>4</sub> and Ne(<sup>3</sup>P<sub>2,0</sub>)/SiCl<sub>4</sub> reactions. These spectral shifts suggest that much higher rovibrational levels in SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) are populated in the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) reaction than those in the He(<sup>2</sup>S) and Ne(<sup>3</sup>P<sub>2,0</sub>) Penning ionization. It is highly likely that SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) around 15.3 eV with favorable FC factors is dominantly formed in the He(<sup>2</sup>S)/SiCl<sub>4</sub> and Ne(<sup>3</sup>P<sub>2,0</sub>)/SiCl<sub>4</sub> Penning ionization. On the other hand, Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>)/SiCl<sub>4</sub> CT reaction preferentially populates SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) around 15.5 eV with small FC factors based upon the observed spectral shifts. The maximum excitation energies of the  $\tilde{X} \rightarrow \tilde{C}$  transition were estimated from the observed shortest wavelength of the SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ - $\tilde{X}$ ) transition to be 3.9 eV for the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) CT reaction and 3.5 eV for the He(<sup>2</sup>S) and Ne(<sup>3</sup>P<sub>2,0</sub>) Penning ionization. Adding these energies to an adiabatic ionization potential of SiCl<sub>4</sub><sup>+</sup>( $\tilde{X}$ ), 11.79 eV,<sup>8)</sup> the highest excitation level of the  $\tilde{C}$  state is evaluated to be 15.7 eV for the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) reaction, whereas 15.3 eV for the He(<sup>2</sup>S) and Ne(<sup>3</sup>P<sub>2,0</sub>) reactions. A good agreement of the former value with the recombination energy of Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>): 15.76 eV suggests that the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>)/SiCl<sub>4</sub> populates the  $\tilde{C}$  state up to near-resonant levels with a high probability. Based upon the HeI PES shown in Fig. 1, FC factors for ionization of SiCl<sub>4</sub><sup>+</sup>( $\tilde{C}$ ) at ~15.7 eV are very small. The population of such near-resonant levels in the Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>)/SiCl<sub>4</sub> reaction may be interpreted by the distortion of the nuclear geometry of SiCl<sub>4</sub> due to a slowly approaching Ar<sup>+</sup>(<sup>2</sup>P<sub>3/2</sub>) ion field during the reaction.<sup>15)</sup>

The ionization mechanism of molecules by thermal CT reactions has been discussed in terms of energy-resonance and FC factors for ionization.<sup>16)</sup> According to our recent mass spectroscopic studies on thermal ion-molecule reactions, energy-resonant requirement takes precedence over FC factors for the CT reactions of  $\text{Ar}^+(^2P_{3/2})$  with polyatomic molecules such as  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$ .<sup>17)</sup> The present finding led us to conclude that the  $\text{Ar}^+(^2P_{3/2})/\text{SiCl}_4$  CT reaction also takes place through a near-resonant process where FC factors do not play a significant role.

Radiationless transitions of polyatomic ions have been classified into three cases: (a) resonance limit, (b) statistical limit, and (c) intermediate case, which are characterized by the structure of the vibronic levels of a lower electronic state which are coupled to isoenergetic vibronic levels of a higher electronic state.<sup>18)</sup> In case (a) for small cations, the density of vibrationally excited levels of a lower state is small, so that an initially excited level decays only radiatively and the fluorescence quantum yield is equal to unity. On the other hand, the density of vibrationally excited levels of a lower state is large in case (b) for large cations, so that non-radiative decay occurs to a quasi-continuum of isoenergetic lower levels and the fluorescence quantum yield becomes small. Since the fluorescence quantum yield of  $\text{SiCl}_4^+(\tilde{\text{C}})$  is close to unity,<sup>2)</sup> the relaxation process of low vibrational levels of  $\text{SiCl}_4^+(\tilde{\text{C}})$  in the FC region can be classified into case (a). In general, not only internal conversion described above, but also intramolecular vibrational redistribution and predissociation become significant for large cations with increasing the excess vibrational energy. The observation of  $\text{SiCl}_4^+(\tilde{\text{C}}-\tilde{\text{A}}, \tilde{\text{C}}-\tilde{\text{X}})$  emissions from the near-resonant levels suggests that case (a) probably holds for  $\text{SiCl}_4^+(\tilde{\text{C}})$  up to high vibrationally excited levels near  $\sim 15.76$  eV. The slow non-radiative decay rate of the large  $\text{SiCl}_4^+$  ion can be attributed to the high symmetry of  $\text{SiCl}_4^+$  which reduces the density of vibrational levels and a large energy gap between the  $\tilde{\text{C}}$  state and the lower  $\tilde{\text{B}}$  state which reduces the internal conversion rate from  $\tilde{\text{C}}$  to  $\tilde{\text{B}}$ .

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