Charge-Transfer Cross Sections of Ground State He^+ Ions in Collisions with He Atoms and Simple Molecules in the Energy Range below 4.0 keV*)

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Charge-transfer cross sections of the ground state He^+ ions in collisions with He atoms and simple molecules (H_2, D_2, N_2, CO and CO_2) have been measured in the energy range of 0.20 to 4.0 keV with the initial growth rate method. Since previously published experimental data are scattered in the low energy region, the present observations would provide reasonably reliable cross section data below 4 keV. The charge transfer accompanied by dissociation of product molecular ion can be dominant at low energies for molecular targets. In $He^+ + D_2$ collisions, any isotope effect was not observed over the present energy range, compared to H_2 molecule.

Keywords: charge-transfer cross section, slow He^+ ion, He atom, simple molecule, growth rate method, dissociative charge transfer, edge plasma

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1. Introduction

Helium is the second most abundant element in the universe. Indeed, helium ions were observed in the outer space of the Earth by an extreme ultraviolet scanner on Mars Orbiter Planet-B [1]. In 1990s, X-ray emissions from many comets were observed, and the origin of this emission has been interpreted as being due to charge transfer into solar-wind ions involving He ions from the cometary gases [2]. Helium will be also one of typical impurities in D-T fusion plasmas as ashes, if the D-T fusion reactions are achieved in controlled thermonuclear fusion devices. The accurate knowledge on charge-transfer collisions between He^+ ions as well as He^{2+} ions and common impurity molecules is critically important in better understanding of low temperature edge plasmas, and their plasma modeling in the fusion devices [3].

Total cross sections of these charge-transfer collisions have been extensively measured since the 1950s [4]. In the low collision energy region, however, discrepancy is seen among existing experimental data.

Therefore, we have systematically measured the charge-transfer cross sections for ground state He^+ (^1S) ions colliding with He atoms and simple molecules (H_2, D_2, N_2, CO and CO_2) in the energy range of 0.20 to 4.0 keV by applying an initial growth rate method.

2. Experiment

A detailed explanation of the experimental apparatus and methods used in the present investigation has been previously given [5, 6], and so some essential features and a few different points are briefly mentioned here.

A mass-analyzed $^4He^+$ ion beam extracted from an electron impact ion source was introduced into a 40 mm long collision cell. Target gas of high purity was fed into the cell which gas pressure was monitored with a calibrated Pirani gauge. The back pressure was less than about 6×10^{-6} Pa in the chambers which were evacuated by a 500 l/s turbo molecular pump and a 6″ cryogenic pump. The primary He^+ ions and product neutral He atoms emerging from the cell after charge-transfer collisions were charge-separated with an electrostatic deflector and were detected with a position sensitive micro-channel plate detector (MCP). The charge-transfer cross sections were derived based on the growth rate method. Namely, the cross sections were determined from the slope of the linear part of the observed fraction curve for neutral He atoms formed in charge-transfer collisions versus the target gas thickness.

Threshold electron energies in the ion source for producing the ground state He^+ ($1s\ ^2S$) ions and the metastable state He^{+*} ($2s\ ^2S$) ions from ground state He atoms are 24.6 and 38.2 eV, respectively [7]. In order to determine the charge-transfer cross sections of the ground state He^+ ($1s\ ^2S$) ions, the effective electron energy into the ion source was set to 30.3 eV.

The statistical uncertainties of the present cross sec-

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tions were ranged from 0.2 to 8.6%. Uncertainties due to those of the target thickness, temperature of target gas and so forth are estimated to range from 10.0% at high energies to 17.6% at low energies. Total experimental uncertainties of the absolute cross sections are given as the quadratic sum of these uncertainties involved.

3. Results and Discussion

3.1 He atoms

The present experimental cross sections for charge transfer of He^+ ions colliding with He atoms are listed in Table 1 and are shown in Fig. 1 together with the previous representative cross sections of experimental data [4,8–16] and theoretical calculations [17, 18].

The previous experimental data are found to be somewhat scattered at energies below 5 keV. The present data are found to lie in the middle position of the previous data, especially two absolute observations by Hayden and Utterback [10] and by Kadota and Kaneko [13]. The present data can be connected with the data of Belyaev *et al.* [11] at energies below 0.1 keV and the data of Shelton and Stoycheff [12] at energies above 2 keV. We also measured the cross sections in this collision below to 0.1 keV. These cross sections are found to steeply decrease at energies below 0.18 keV as the collision energy decreases. Therefore we concluded that the detection efficiencies for He^+ ions and for energetic neutral He atoms in the present MCP are practically the same within the experimental uncertainties in the energy range above 0.2 keV. It is noted that previous study on the charge-transfer cross section of H^+ ions colliding with H_2 molecules showed an agreement with absolute measurement of Gealy and Van Zyl at energies above 0.2 keV [19].

The He^+ + He collision system is so called as the "*symmetric resonant charge transfer*" and the energy defect ΔE of this reaction is exactly equal to zero,

$$He^+(^2S) + He(^1S) \rightarrow He(^1S) + He^+(^2S) + \Delta E, \quad (1)$$

and it is, therefore, expected to have a simple decreasing curve as the collision energy increases. Some theoretical calculations support this energy dependence [17, 18].

Table 1 Charge-transfer cross sections of He^+ ions colliding with He atoms.

Energy (keV)	Cross section (10^{-16} cm^2)
0.20	10.2 ± 1.0
0.25	10.6 ± 1.1
0.30	10.3 ± 1.0
0.50	10.4 ± 1.1
0.55	9.69 ± 0.93
1.0	9.18 ± 0.88
1.5	8.67 ± 0.98
3.0	7.61 ± 0.77

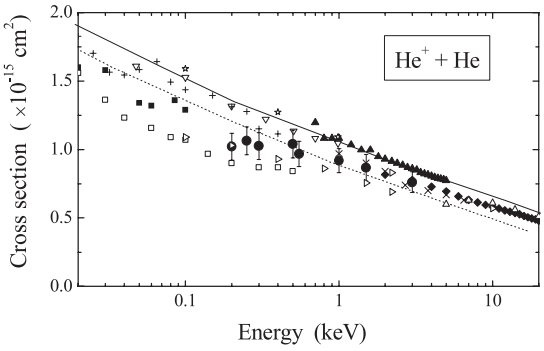

Fig. 1 Charge-transfer cross sections of He^+ ions colliding with He atoms. Experiment: ● - present data, ▷ - [4], ☆ - [8], + - [9], ▽ - [10], ■ - [11], ◆ - [12], □ - [13], ▲ - [14], × - [15], △ - [16]. Theory: broken curve - [17], solid curve - [18].

3.2 H_2 and D_2 molecules

The present experimental cross sections for charge transfer of He^+ ions colliding with H_2 and D_2 molecules are summarized in Table 2 and are shown in Fig. 2 together with the previous experimental data [4, 16, 20–26]. The present data for D_2 molecules are found to be almost the same as the data of H_2 molecules, indicating that there is no isotope effect in the present energy region.

The charge-transfer cross sections for H_2 molecules

Table 2 Charge-transfer cross sections of He^+ ions colliding with H_2 and D_2 molecules.

H_2		D_2	
Energy (keV)	Cross section (10^{-16} cm^2)	Energy (keV)	Cross section (10^{-16} cm^2)
0.20	0.513 ± 0.097	0.25	0.54 ± 0.11
0.36	0.75 ± 0.14	0.50	0.87 ± 0.13
0.66	0.84 ± 0.12	1.0	0.79 ± 0.13
1.2	0.95 ± 0.14	2.0	0.795 ± 0.088
2.2	0.90 ± 0.11	3.5	0.855 ± 0.091
4.0	0.765 ± 0.084		

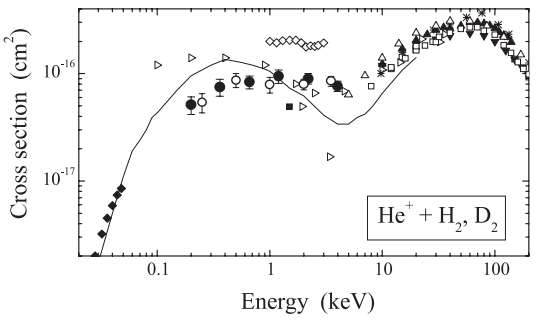

Fig. 2 Charge-transfer cross sections of He^+ ions colliding with H_2 and D_2 molecules. Experiment: ● - present data for H_2, ○ - present data for D_2, ▷ - [4], □ - [20], ▲ - [21], ◆ - [22], ▼ - [23], ◇ - [24], ∗ - [25], △ - [16], ■ - [26], solid curve - the recommended value by Janev *et al.* [27].

have been measured by many research groups in the energy range above 5 keV and these values are almost consistent each other. However, at low energies below 5 keV, the previously reported experimental data are a few and scattered. The present cross sections have a maximum and can be connected with the data of many research groups at high collision energy [16, 20, 21, 23, 25], and also be connected with the data of Rozett and Koski [22] at low energies below 50 eV. The data of Moran and Conrads [24] are larger than ours, while the data of Gao *et al.* [26] are smaller. The first measurements of this collision partner by Stedeford and Hasted [4] is heavily overestimated at energies below 1 keV. In 1987, Janev *et al*. presented the recommended values from the previously reported data [27]. Therefore, it seems that their recommended values need to be reexamined.

In all of the present collision partners for molecules, the energy defect ΔE is very large for both the processes of charge transfer into ground ^{1}S and excited ^{3}S states of He atoms. However the charge transfer into ground ^{1}S state of He atoms is exothermic reaction channel, and the produced target molecular ions can be electronically and/or vibrationally excited, and sometimes followed by dissociation. The following processes are possible in $He^+ + H_2$ collisions which lead to simple charge transfer, and dissociative charge transfer:

$$He^+(^2S) + H_2(X^1\Sigma_g^+, v = 0) \rightarrow He(^1S) + H_2^+(X^2\Sigma_g^+, v') + \Delta E, \quad (2)$$

$$\rightarrow He(^1S) + H^+ + H(^2S) + 6.5\,[eV], \quad (3)$$

where v and v' are the vibrational quantum numbers of target molecules and product molecular ions. Since the ΔE value for $v' = 0$ in the process (2) is large and 9.2 eV, dissociative charge transfer (3) can be a major process in the present energy region.

3.3 N_2, CO and CO_2 molecules

The present experimental cross sections for charge transfer in $He^+ + N_2$, CO and CO_2 collisions are listed in Table 3 and are shown in Figs. 3 (a), (b) and (c) together with the previous data [16, 20, 21, 26, 28–35].

As shown in Fig. 3 (a), the charge-transfer cross sections for N_2 collision system have been also measured by many research groups and their values are almost consistent each other in the energy range above 10 keV. The present cross sections have a maximum at 1 keV similar to H_2 target and can be connected with these data [16, 20, 21, 32] at high collision energy, and also be connected with the data of Smith and Kevan [33] at 50 eV. While the data of Stebbings *et al*. [28], Koopman [29], Mahadevan and Magnuson [30], and Schlumbohm [31] are larger than the present observations and behave the near-resonant feature. The data of Gao *et al*. [26] are smaller than ours.

As shown in Fig. 3 (b), the present experimental cross section curve for CO molecules has a maximum at about 1 keV in energy and can be connected with the data of Rudd *et al*. [16] in higher energy region and the data of Smith and Kevan [33] at 50 eV, but in disagreement with those of Coplan and Ogilvie [34]. The data of Moran and Conrads [24] are larger, and the data of Gao *et al*. [26] are smaller than the present observations, respectively.

As shown in Fig. 3 (c), the energy dependence of the present experimental cross sections is weak for CO_2 molecules, but this cross section curve has a maximum at about 0.5 keV and can be connected with the data of Rudd *et al*. [16] in higher energy region and the data of Smith and Kevan [33] at 50 eV, but in disagreement with those of Koopman [29], Moran and Conrads [24], and Greenwood *et al*. [35]. These data behave similar to the near-resonant feature.

In 1963, Stebbings *et al*. [28] were interpreted in terms of the accidental near-resonant charge-transfer processes

Table 3 Charge-transfer cross sections of He^+ ions colliding with N_2, CO and CO_2 molecules.

Energy (keV)	Cross section (10^{-16} cm^2)		
	N_2	CO	CO_2
0.20	3.67 ± 0.47	3.07 ± 0.45	4.07 ± 0.59
0.36	4.58 ± 0.57	3.51 ± 0.53	5.27 ± 0.69
0.66	5.10 ± 0.63	4.46 ± 0.57	5.16 ± 0.64
1.2	5.06 ± 0.54	4.92 ± 0.55	5.03 ± 0.57
2.2	4.60 ± 0.49	4.38 ± 0.47	5.22 ± 0.57
4.0	4.43 ± 0.47	4.59 ± 0.60	5.74 ± 0.61

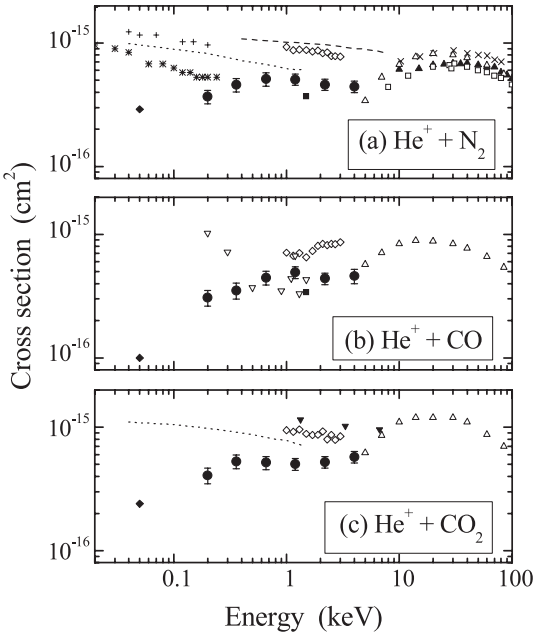

Fig. 3 Charge-transfer cross sections of He^+ ions colliding with N_2, CO and CO_2 molecules. Experiment: ● - present data, □ - [20], broken curve - [28], ▲ - [21], dotted curve - [29], + - [30], ∗ - [31], × - [32], ◆ - [33], ◇ - [24], ▽ - [34], △ - [16], ■ - [26], ▼ - [35].

for N_2 molecules

$$\mathrm{He}^+(^2\mathrm{S}) + \mathrm{N}_2(\mathrm{X}^1\Sigma_g^+, v = 0)$$
$$\rightarrow \mathrm{He}(^1\mathrm{S}) + \mathrm{N}_2^+(\mathrm{C}^2\Sigma_u^+, v' = 3) + 0.23\,[\mathrm{eV}], \quad (4)$$
$$\rightarrow \mathrm{He}(^1\mathrm{S}) + \mathrm{N}(^4\mathrm{S}) + \mathrm{N}^+(^3\mathrm{P}) + 0.29\,[\mathrm{eV}]. \quad (5)$$

We apply the Rapp-Francis theory [17] to the processes (4) and (5). The calculated curve for these reaction channels have the energy dependence different from previous experimental data in low energy range, namely the theoretical curves have a maximum at about 0.3 keV. Therefore, the energy defect of 0.23 eV is not so "fully-resonance", and the energy dependence of the present data is qualitatively supported by this calculation.

In the He^+ + CO collision system, the following dissociation channel

$$\mathrm{He}^+(^2\mathrm{S}) + \mathrm{CO}(\mathrm{X}^1\Sigma^+, v = 0)$$
$$\rightarrow \mathrm{He}(^1\mathrm{S}) + \mathrm{C}^+(^2\mathrm{P}) + \mathrm{O}(^1\mathrm{D}) + 0.23\,[\mathrm{eV}], \quad (6)$$

can be dominant. Calculated curve has also a maximum at about 0.4 keV. Similar interpretation may be valid for the collision system of $He^+ + CO_2$, namely it is expected to be dominant the reaction channel with dissociation of product molecular ions.

In conclusion, the present observations have provided reasonably reliable cross section data for the charge transfer of He^+ ions in collisions with He atoms and simple molecules (H_2, D_2, N_2, CO and CO_2) in the energy range below 4.0 keV. The charge transfer accompanied by dissociation of product molecular ion can be dominant at low energies in these collisions presently studied. It should be pointed out that it would also be important to determine the cross sections at still much lower energies which may be critical in the edge plasma region.

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