Charge-Transfer Cross Sections of H^+ Ions in Collisions with Noble Gas Atoms in the Energy Range below 4.0 keV*)

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(Received 20 December 2010 / Accepted 8 February 2011)

Charge-transfer cross sections in collisions of H^+ ions with the ground state He, Ar, Kr, and Xe atoms have been measured in the energy range below 4.0 keV with the initial growth rate method. These observed cross sections are also compared with previously published experimental data and theoretical predictions. In the He and Ar targets, it is found that some previous experimental data deviate significantly from the present observed cross sections as the collision energy decreases. It has been found that in the Kr and Xe targets, the energy dependence of the present observed cross sections behaves as "near-resonant" charge transfer.

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Keywords: charge-transfer cross section, slow H^+ ion, noble gas atom, growth rate method, energy defect, edge plasma, gas puff

DOI: 10.1585/pfr.6.2401102

1. Introduction

Because charge-transfer collisions of slow H^+ ions (protons) with noble gas atoms are the most fundamental atomic collision processes cross-section data for these processes are important in a number of various applications and must be accurate. In the current controlled thermonuclear fusion devices with a gas puffing system, for example, these collisions play a key role in cooling and diagnostics of low-temperature edge plasmas [1, 2].

Earlier experimental cross section data presented before 1958 involving hydrogen atoms at collision energies above 0.2 keV were compiled and assessed in a review article by Allison [3]. Other review articles which added the data after this were issued by Tawara and Russek [4] and Tawara [5]. Experimental data for these collisions at collision energies below 10 keV are given by Stedeford and Hasted [6], Stier and Barnett [7], Koopman [8], Williams and Dunbar [9], Rudd *et al.* [10], and Johnson *et al.* [11, 12]. Since these data sets were found to be almost consistent with each other, it was believed so far that the cross-section data for charge transfer in these collision systems were well established and understood.

In our previous study for H^+ + Ne collisions [13], however, observed cross sections increase steeply as the collision energy increases. This behavior is expected to occur at low collision energies for the present collision system that has a large energy defect between the initial and charge-transferred channels for the ground state. The previous data measured by Stedeford and Hasted [6] are found to be significantly larger than our observed cross sections by a factor of about five at 0.6 keV and about three at 0.8 keV. Our experimental results are also supported by theoretical calculations with a molecular-orbital close-coupling method (MOCC).

In a previous theoretical study by Kimura and Lin on H^+ + He collisions, a similar situation is found [14]. However, no experimental verification has been performed.

To obtain precise and reliable cross-section data, therefore, we have measured the charge-transfer cross sections of H^+ ions colliding with He, Ar, Kr, and Xe atoms at collision energies below 4.0 keV. The observed cross sections are compared with other previously published experimental data and theoretical predictions.

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2. Experiment

A detailed explanation of the present experimental apparatus and methods has been provided previously [15, 16], and so only some essential features will be briefly mentioned here.

A hydrogen ion beam was generated in an electron impact ion source by 50 eV electron impact on H_2 molecules. Then, the ion beam was mass-separated with a Wien filter and passed through a collision cell filled with target noble gases of high purity (He and Ar 99.999%, Kr 99.95%, Xe 99.9%). The primary H^+ ions and product neutral H atoms emerging from the cell after charge-transfer collisions were charge-separated with an electrostatic deflector and detected with a position sensitive micro-channel plate detector (MCP-PSD). From the integrated counts of each peak corresponding to H^+ ions and H atoms recorded on a pulse height analyzer as a position-charge spectrum, the fraction F_0 of neutral hydrogen atoms was derived as a function of the target gas pressure (or target thickness).

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*) This article is based on the presentation at the 20th International Toki Conference (ITC20).

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The charge-transfer cross sections were determined from the slope of the linear part of the observed fraction curve F_0 (growth rate method), after confirming that the detection efficiencies of the present MCP-PSD for H^+ and H particles were identical within the experimental uncertainties over the present collision energy range [17].

The target gas pressures for Ar, Kr, and Xe gases were measured with a Pirani gauge calibrated with an MKS Baratron capacitance manometer. This gauge is highly sensitive, but its reproducibility and stability are less reliable for light gas particles such as He, H_2, and D_2 [18]. In the measurement of cross sections in H^+ + He collisions, the target He gas pressure was relatively high and set to range from 10^{-2} to 1 Pa because of small cross sections. To minimize the experimental uncertainties, in the present study, the He gas pressure was directly measured with the Baratron.

The front and main chambers were evacuated down to the back pressure of less than about 5×10^{-6} Pa by 500 l/s and 50 l/s turbo-molecular pumps (TMP) and a 6″ cryopump. In the measurement of cross sections in H^+ + He collisions, a 300 l/s TMP was used instead of the cryopump.

The statistical uncertainties of the cross sections were almost within 5% for most of the present study, except in the He target, where it ranged from 2% at 4.0 keV to 18% at 1.6 keV. Uncertainties due to those of the target thickness, temperature of target gas, and so forth were estimated to be from 10.5% 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 numerical cross sections for charge transfer in H^+ + He collisions are listed in Table 1 and are shown in Fig. 1 together with the previous data and theoretical calculations. The present cross sections increase steeply as the collision energy increases and are found to smoothly connect with the data of Stier and Barnett [7], Williams and Dunbar [9], Rudd *et al.* [10], and Johnson *et al.* [11] at higher energies. The previous data of Stedeford and Hasted [3,6] are found to be larger by a factor of about two at 1.6 keV.

In the H^+ + He collision system, the charge-transfer process is largely endothermic with a large energy defect,

$$H^+ + He(^1S) \rightarrow H(^2S) + He^+(^2S) - 11.0\,\text{eV}, \qquad (1)$$

and it is, therefore, expected to have a simple increasing curve in the low collision energies. In the previous theoretical study by Kimura and Lin [14], the atomic orbital (AO) and molecular orbital (MO) matching method has been proposed. This result is successful in the energy range above 4 keV. In a joint study with a group of Rice University, Kimura presented new MOCC calculations [11]. The present data are found to be in excellent agreement with his MOCC results.

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

H^+ energy (keV)	Cross section (10^{-16} cm^2)
1.6	0.0314 ± 0.0067
1.9	0.0440 ± 0.0060
2.2	0.0522 ± 0.0081
2.6	0.0705 ± 0.0099
3.0	0.111 ± 0.014
4.0	0.188 ± 0.021

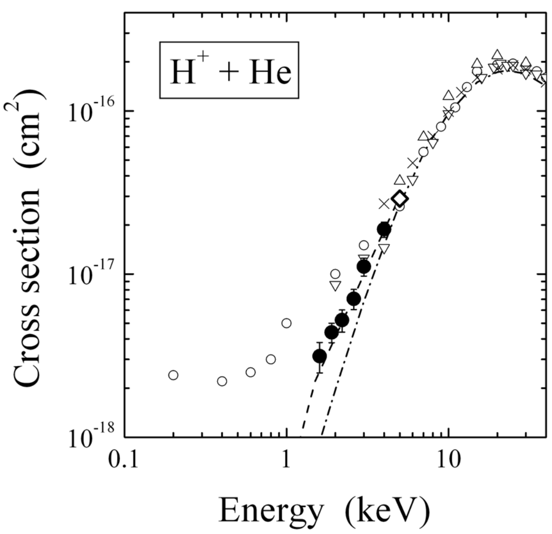

Fig. 1 Charge-transfer cross sections of H^+ ions colliding with He atoms. Experimental data: ●, present data; ○, the evaluated value from Allison [3] (primarily based on Stedeford and Hasted [6]); ×, Stier and Barnett [7]; ∇, Williams and Dunbar [9]; △, Rudd *et al.* [10]; ◇, Johnson *et al.* [11]. Theoretical calculation: dot–dash line, Kimura and Lin [14]; broken line, Johnson *et al.* [11] (MOCC results).

3.2 Ar atoms

The present cross sections for charge transfer in H^+ + Ar collisions are listed in Table 2 and are shown in Fig. 2 together with the previous data and theoretical calculations. The present cross sections increase steeply as the collision energy increases and are found to smoothly connect with the data of Stier and Barnett [7], Williams and Dunbar [9], and Rudd *et al.* [10] at higher energies. The data of Koopman [8] and Johnson *et al.* [12] are also in good agreement with the present data. The previous data of Stedeford and Hasted [3,6] are found to be near the present cross sections. But their data are larger than the present data at 0.2 keV by a factor of about three. The energy dependence of the theoretical calculations by Kirchner [19]

Table 2 Charge-transfer cross sections of H^+ ions colliding with Ar atoms.

H^+ energy (keV)	Cross section (10^{-16} cm^2)
0.20	0.68 ± 0.11
0.25	1.18 ± 0.19
0.30	1.73 ± 0.25
0.36	2.42 ± 0.35
0.48	4.01 ± 0.49
0.66	5.96 ± 0.73
0.90	8.42 ± 0.94
1.2	10.2 ± 1.2
2.2	12.7 ± 1.4
4.0	13.7 ± 1.6

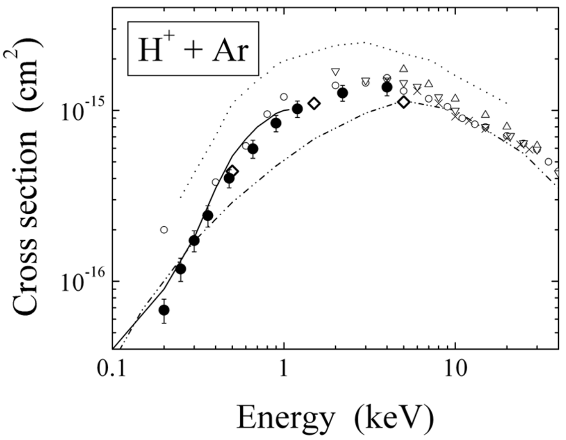

Fig. 2 Charge-transfer cross sections of H^+ ions colliding with Ar atoms. Experimental data: ●, present data; ○, the evaluated value by Allison [3] (primarily based on Stedeford and Hasted [6]); ×, Stier and Barnett [7]; —, Koopman [8]; ▽, Williams and Dunbar [9]; △, Rudd *et al.* [10]; ◇, Johnson *et al.* [12]. Theoretical calculation: dotted line, Kirchner [19]; dot–dot–dash line, Cabrera-Trujillo *et al.* [20].

is in general reproduced in the present experimental cross sections, but those calculations are found to be larger by a factor of about two. Recent calculations by Cabrera-Trujillo *et al.* [20] do not coincide with the experimental data at energies below 5 keV.

In the H^+ + Ar collision system, the charge-transfer process is also endothermic,

$$H^+ + Ar(^1S) \rightarrow H(^2S) + Ar^+(^2P) - 2.16\,\text{eV}, \qquad (2)$$

and it is, therefore, expected to have a simple increasing curve in the low collision energies.

3.3 Kr and Xe atoms

The present cross sections for charge transfer in H^+ + Kr and Xe collisions are listed in Table 3 and are shown in Figs. 3 and 4 together with the previous data.

Table 3 Charge-transfer cross sections of H^+ ions colliding with Kr and Xe atoms.

H^+ energy (keV)	Cross section (10^{-16} cm^2) Kr	Xe
0.20	29.4 ± 4.6	38.1 ± 6.7
0.36	25.3 ± 3.6	29.7 ± 4.7
0.66	23.1 ± 2.8	28.8 ± 4.1
1.2	22.3 ± 2.7	27.9 ± 3.7
2.2	19.7 ± 2.4	25.8 ± 3.4
4.0	17.5 ± 1.9	23.9 ± 3.2

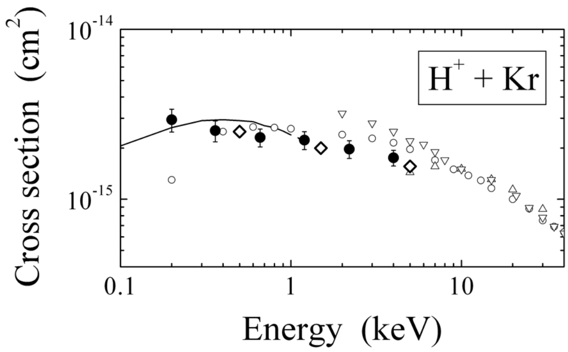

Fig. 3 Charge-transfer cross sections of H^+ ions colliding with Kr atoms. Experimental data: ●, present data; ○, the evaluated value from Allison [3] (primarily based on Stedeford and Hasted [6]); —, Koopman [8]; ▽, Williams and Dunbar [9]; △, Rudd *et al.* [10]; ◇, Johnson *et al.* [12].

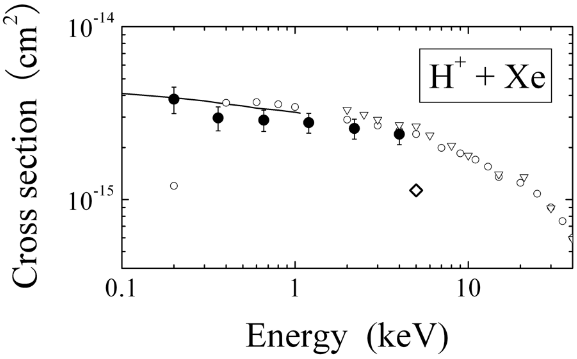

Fig. 4 Charge-transfer cross sections of H^+ ions colliding with Xr atoms. Experimental data: ●, present data; ○, the evaluated value from Allison [3] (primarily based on Stedeford and Hasted [6]); —, Koopman [8]; ▽, Williams and Dunbar [9]; ◇, Johnson *et al.* [12].

3.3.1 Kr

The present cross sections decrease gently as the collision energy increases and are found to smoothly connect with the data of Williams and Dunbar [9], and Rudd *et al.* [10] at higher energies above 10 keV. The previous data of Stedeford and Hasted [3,6] and Koopman [8] are found to be close to the present cross sections, but the former data are much smaller than the present data at 0.2 keV. The present data and the data of Johnson *et al*. [12] agree very well.

In the H^+ + Kr collision system, the charge-transfer process is also endothermic,

$$H^+ + Kr(^1S) \rightarrow H(^2S) + Kr^+(^2P) - 0.401\,\text{eV}, \quad (3)$$

but the energy defect of this process is small. Therefore, this collision is “near-resonant” charge transfer, and it is expected to have a simple decreasing curve as the collision energy increases.

3.3.2 Xe

The present cross sections decrease gently as the collision energy increases and are found to smoothly connect with the data of Williams and Dunbar [9] at higher energies above 4 keV. The previous data of Stedeford and Hasted [3, 6] and Koopman [8] are found to be close to the present cross sections, but the former data at 0.2 keV and the data of Johnson *et al*. [12] at 5 keV are both much smaller than the present data.

In the H^+ + Xe collision system, the charge-transfer process is exothermic,

$$H^+ + Xe(^1S) \rightarrow H(^2S) + Xe^+(^2P_{3/2}) + 1.47\,\text{eV}. \quad (4)$$

Therefore, the following charge transfer with the excitation of the target Xe ions can be realized,

$$H^+ + Xe(^1S) \rightarrow H(^2S) + Xe^+(^2P_{1/2}) + 0.164\,\text{eV}. \quad (5)$$

The energy defect of this process (5) is very small, therefore this collision process is also “near-resonant” charge transfer. It is expected to have a simple decreasing curve as the collision energy increases.

In conclusion, the present observations have provided reasonably reliable cross-section data for the charge transfer of H^+ ions in collisions with He, Ar, Kr, and Xe atoms in the energy range below 4.0 keV. 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.

Soon we plan to measure them for tungsten ions which are critically important for the divertor of the present ITER (International Thermonuclear Experimental Reactor).

Acknowledgments

The authors would like to express their sincere appreciation to the late Professor Mineo Kimura for his valuable discussions. The present study was performed as a collaboration research program of the National Institute for Fusion Science in Japan (NIFS07KQHM005).

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