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A double electron capture by alpha particles in collisions with hydrogen molecules in low temperature plasma

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Abstract

Spectroscopic study has been made of double electron capture process by alpha particles, He^{2+}, when helium plasmas contact with cold hydrogen molecules. Fast enhancements of He I $n = 2$, 4 and 5 as well as of He I $n = 3$ level populations due to the selective double electron capture have been found at the early period of hydrogen gas injection into the helium plasmas. Large population inversion resulting from these enhancements has been also observed between $n = 2$ and 3 levels. Numerical calculation based on a collisional-radiative model has revealed the enhancement mechanism.

Keywords: TPD-II; Divertor plasma; Atomic physics

1. Introduction

One of the most important atomic processes in the divertor plasmas is the hydrogen molecular ones [1]. As a basic study of the processes, experimental and theoretical studies of interaction of a plasma with cold neutral gases will make useful contributions to elucidate the important atomic processes in divertor plasmas.

We have been spectroscopically studying He plasma contact with cold gasses at the TPD-I and -II plasma machines at the National Institute for Fusion Science [2]. Spectroscopic observations have been made mostly on recombining plasmas resulting from rapid cooling of the electron temperature due to the contact with cold neutral helium or hydrogen gases. Population inversions have been found between the He II low-lying levels [3]. Numerical studies have been also made to understand production mechanism of the population inversion [4,5].

We have recently observed anomalously intense photon emission from He I lines ($n = 3$–$n = 2$) at the early period of cold hydrogen gas injection. This phenomenon is understood to be due to the following selective double electron capture process [6,7]:

$$He^{2+} + H_2(v = 0) \rightarrow He^*(1s3l) + H^+ + H^+ \qquad (1)$$

whose cross section is very large at low energy [8,9].

A numerical study based on a collisional-radiative model was also made to analyze the effect of this process on the temporal evolution of the He I and II level populations [10]. The numerical result explained fairly well the observed temporal evolution of the enhanced He I line intensity ($n = 3$–$n = 2$), and gave us further predictions that other level populations of $n = 2$ and 4 are also enhanced, though much smaller than the $n = 3$ level populations. Though preliminary observations to confirm this prediction were also made [6,7], more detailed experimental and theoretical studies would be desirable.

In this paper, we report further investigations on the above interesting phenomena in experiment and theory. Experimental effort has been focused on the VUV observation to measure the He I 2^1P level population in the plasma. A numerical study based on a collisional-radiative model is also developed to analyze dominant atomic processes in the plasmas.

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2. Experimental

2.1. Experimental setup

The experimental setup was already described in Ref. [7]. The present experiment has been carried out at the TPD-II machine which is similar to the TPD-I. The schematics is shown in Fig. 1. The produced He plasma with an electron density of 10^{14} cm^{-3} and an electron temperature of several eV, diffused out through an orifice with 14 mm diameter, flows 2 m with a speed of about 10^5 cm/s along the axial magnetic field of 5 kG before reaching a target. The He pressure was 7×10^{-2} Pa in the observation region without cooling H_2 gas. A piezoelectric valve was used to introduce hydrogen gas with a pressure of about 10 Pa into the He plasma for the duration of 12.5 ms, as shown in Fig. 2(a). The spectroscopic observation was made mostly by using a 2 m VUV monochromator (Fig. 2(b)). Calibration of relative intensity was performed. The effect of the resonance scattering of He atom was estimated to be less than 10% for the He I 58.4 nm resonance line observed in the TPD-II plasma.

2.2. Experimental results

The experiments were carded out under various He gas flow rates (120–270 cc/min) into the discharge region. Other conditions were kept unchanged. The produced He plasma column had a diameter of 14 mm and a lower gas flow rate of less than 200 cc/min. At a flow rate of higher than 200 cc/min, the plasma column had double coaxial layers: the core plasma column, which was almost the same as produced at the gas flow rate of 190 cc/min, and the outer layer with a radius of larger than 3 cm, whose plasma density and temperature seemed to be quite lower than the core ones.

Fig. 3 shows the temporal evolutions of the measured He I level relative populations of n^1P ($n = 2$–5) at the He gas flow rate of (a) 190 cc/min and (b) 230 cc/min. The valve opens at $t = 60$ ms. The 3^1P level population sharply increases and then decreases within about 2 ms after H_2 gas injection at the He gas flow rate of 190 cc/min (Fig. 3(a)). This peak is sharper than that observed previously under lower H_2 gas pressure of about 1 Pa [6]. A corresponding small enhancement appears also in the 2^1P level population as well as weakly in the 4^1P level one. It is noted that the population inversion takes place between the 2^1P and 3^1P levels. At a He gas flow rate of 230 cc/min, as shown in Fig. 3(b), more significant enhancements have been seen, and appear even in the 5^1P level. It is also noted that the maxima for $n = 4$, 5 level population show up later than those in a small He flow rate. A plausible explanation about these enhancements will be given in a later section.

3. Collisional-radiative model

3.1. Basic equations

The basic equations of a collisional-radiative model used for investigation of plasmas contacting with cold

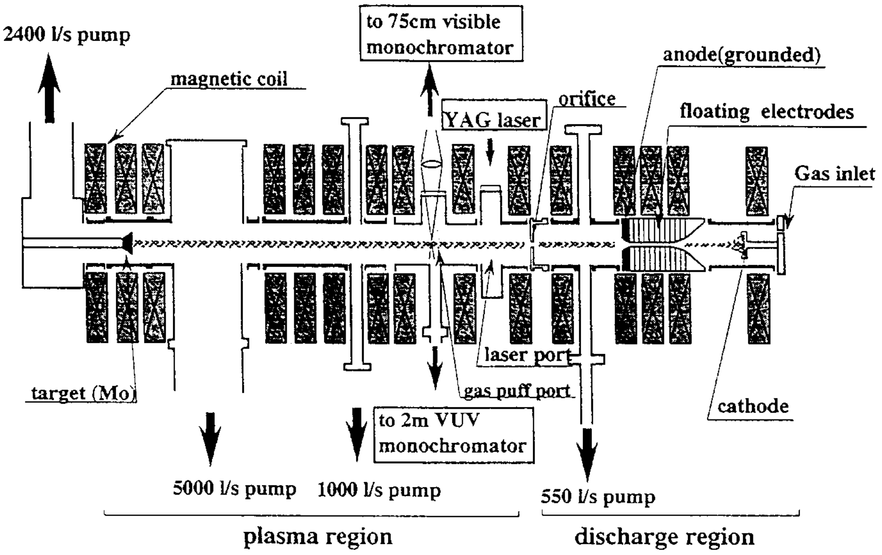

Fig. 1. Schematic diagram of the TPD-II plasma machine.

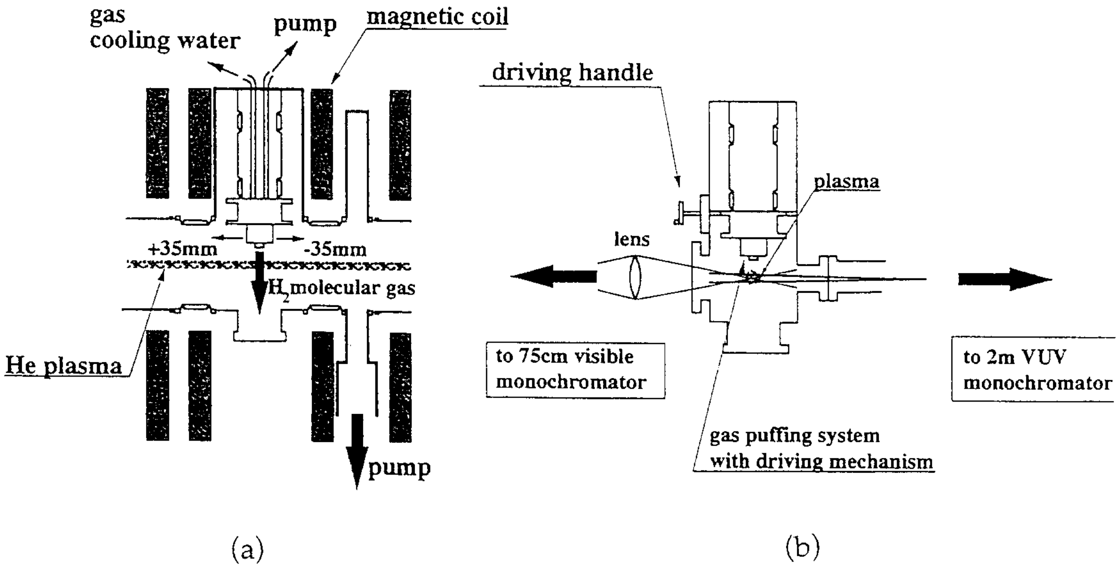

Fig. 2. (a) Gas puffing system. (b) Spectroscopic observation setup.

neutral gases have been already described in detail [4,5]. In the present study these equations are used with additional terms for the double electron capture process (Eq. (1)). Here, only the outline of the basic equations used is given: (1) the rate equations for He^+ ions, helium (He) and hydrogen (H) atoms and hydrogen molecules (H_2) under the conditions of both the charge neutrality and the particle conservation for the helium plasma, and (2) the energy balance equations for electron, He^+ and He^{2+} ions (alpha particles), and H^+ and H_2^+ ions. The double electron capture process into alpha particles is assumed to take place only into the He I excited (1s3l) levels. For Eq. (1), the l distribution of each sublevel population for $n = 3$ is assumed to be proportional to its statistical weight. For the hydrogen molecule, six dissociation processes are taken into consideration. Numerical integration of the equations was performed using the high-speed Runge–Kutta method [11].

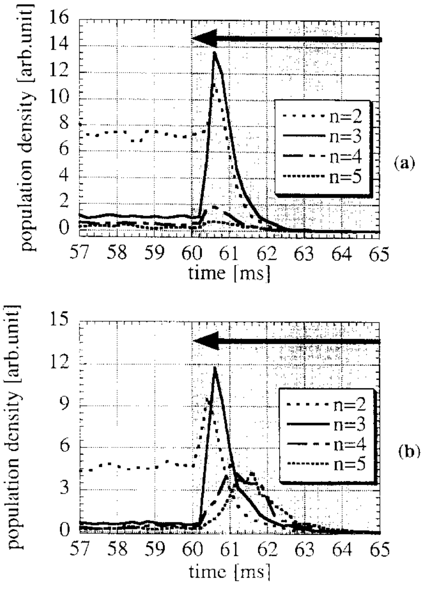

Fig. 3. Observed temporal evolution of the He I singlet level populations when H_2 gas is introduced into the He plasma column at He gas flow rate of (a) 190 cc/min and (b) 230 cc/min.

3.2. Numerical results and discussion

The initial conditions of the TPD-II plasma for the present calculation were the same as those chosen in Ref. [7]: an electron temperature T_e of 3 eV, all the ion temperatures (H^+, He^+, and He^{2+}) of 2.5 eV, an electron density n_e of 5×10^{13} cm^{-3}, and a hydrogen molecule density $n(H_2)$ of 1×10^{11} cm^{-3} in the plasma.

Fig. 4 shows the calculated temporal evolution of T_e, T_{a1} of helium ions, and T_{a2} of the hydrogen ion. The origin of the time axis is set at the onset of H_2 gas injection. The electron temperature decreases sharply by about 0.5 eV immediately after the gas injection, becoming close to equilibrium with T_{a1} and T_{a2}, and the temperatures of these particles are kept almost constant until about 6 ms. This nearly constant temperature is due to slow cooling of the ions through elastic collisions with the hydrogen molecules of low density. After that, the temperatures again decrease down below 1 eV.

The calculated temporal evolution of the He I singlet level populations, corresponding to that of the temperatures in Fig. 4, is shown in Fig. 5 [10], where a dotted curve depicts the corresponding evolution of the 2^1P level

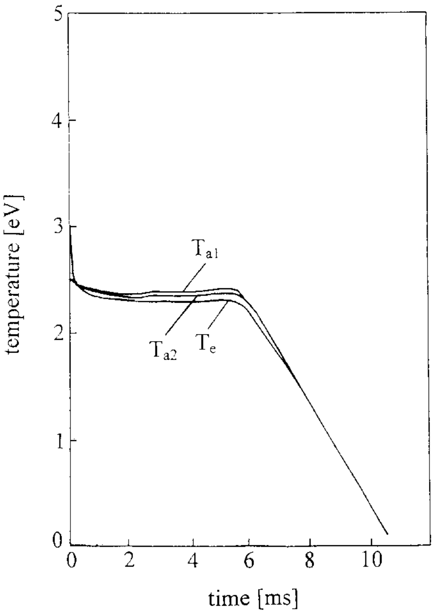

Fig. 4. Calculated temporal evolution of T_e, T_{a1} (of helium ions) and T_{a2} (of hydrogen ions). The origin of the time axis is chosen at the onset of H_2 gas injection.

population calculated neglecting the double electron capture process. Enhancement of the 2^1P and 3^1P level populations clearly appears at the early period of H_2 gas injection. The enhancement of the 2^1P level population is quite natural because electron impact transfer between the 3^1P and 2^1P levels takes place dominantly. A very weak enhancement appears also on the 4^1P level population. These results are qualitatively compared to the observed results shown in Fig. 3(a). The calculated population inversion also shown in Fig. 5 indicates that the observed population inversion in Fig. 3(a) is mainly due to the double electron capture process (Eq. (1)). As pointed out in the previous paper [6], the measured radial distribution of the He I 587.6 nm (3^3D–2^3P) line suggests that the enhancement of the He I level population measured above is induced mainly at the plasma edge region where the injected H_2 gas comes into contact with the helium plasma, that is, the double electron capture process takes place mainly at the edge region. The initial conditions chosen for our calculation corresponds qualitatively to the plasma in the edge region.

The enhancement of the $n = 4$ and 5 level populations of helium during hydrogen injection and its delay observed at high He flow rates shown in Fig. 3(b) cannot be explained to be due to simple electron impact excitation processes from the $n = 3$ level. The most likely explanation involves the following two processes: (1) First, hydrogen molecules injected are excited to a vibrationally excited level (probably $\nu = 1$) through collisions with He plasma in the outer layer. (2) Then, these vibrationally excited hydrogen molecules collide with alpha particles in the core plasma and the following double electron capture into alpha particles from the vibrationally excited hydrogen molecules takes place:

$$He^{2+} + H_2^*(v = 1) \rightarrow He^*(1snl\colon n = 4, 5) \qquad (2)$$

which populates the He I $n = 4$ and 5 levels. In fact the energy difference in the vibrational excitation from $v = 0 \rightarrow v = 1$ (about 0.5 eV) of hydrogen molecules is roughly the same as that between He I ($1s3l$) and He I($1s4l$), suggesting that the electron capture collision process (2) can be accidental resonance and therefore can have the large cross sections, though no data are available up to now. If the vibrationally excited hydrogen molecules are first produced in the outer plasma layer, they need some time to reach the observation point and thus the process of Eq. (2) occurs at the core plasma with some delay after gas injection.

In summary, the present experimental and theoretical investigations have shown that, when helium plasmas contact with cold hydrogen molecules, fast enhancement takes place of the He I $n = 3$ level population, which is due to double electron capture into alpha particles in collisions with the vibrationally ground state hydrogen molecules. Thus, large population inversion has been also observed between He I $n = 2$ and 3 levels. Also we observed those of He I $n = 4$, 5, which are supposed to be due to the double electron capture in collisions with the vibrationally excited H_2^* ($v = 1$) molecules.

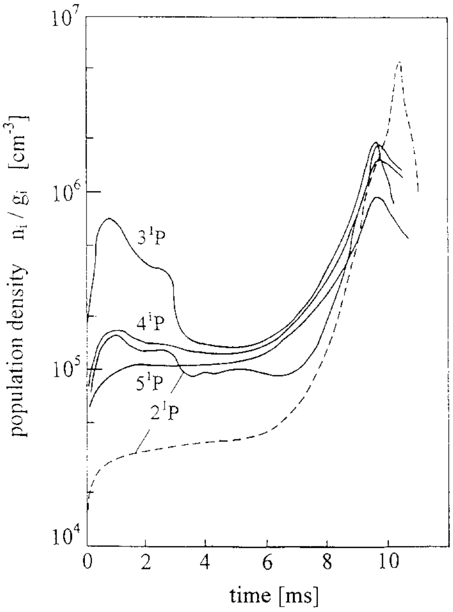

Fig. 5. Calculated temporal evolution of the He I singlet level populations, corresponding to that of the temperatures shown in Fig. 4. A dotted curve depicts the corresponding evolution of the 2^1P level population without the contribution of the double electron capture process.

The present study could make useful contributions to analysis of important atomic processes in divertor region in burning fusion plasmas as well as in development of soft X-ray lasers.

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