Numerical Study on Radiation Trapping of He I Resonance Lines in Arc Plasma Under High-Gas Pressures*)

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In high-gas pressure helium arc plasmas, a forbidden line (1s ^{1}S-2p ^{3}P : 59.1 nm) as well as the resonance lines 1s ^{1}S - np ^{1}P lines of He I have been observed. The intensity ratio of the 1s ^{1}S - 2p ^{1}P line of He I to forbidden line calculated from the Einstein A coefficients (NIST database) is $\sim 10^{-7}$, whereas the value obtained experimentally was as small as ~20. The reason for the discrepancy between the experiment and database can be interpreted from that the photoabsorption (self-absorption) of the resonance lines 1s ^{1}S - np ^{1}P lines can cause the drastic change in radiative processes in high-pressure plasmas. In order to validate our interpretation on this mismatch, we investigated the influence of self-absorption of the resonance lines 1s ^{1}S - np ^{1}P lines by numerical simulations. The simulation code calculated the photoabsorption process by He atom along a line-of-sight by using coupled rate equations incorporated with the radiation trapping effect. As a result, the simulation yielded the line intensity ratio of 25 because of the strong self-absorption.

Keywords: radiation trapping, helium arc plasma, spectral line shape

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1. Introduction

For plasma diagnostics, line intensity ratio method is one of useful methods to determine plasma parameters without disturbing plasma itself. Generally, a self-absorption process (radiation trapping) is not taken into account for a low-density plasma. For high-density plasma, such as, atmospheric thermal plasmas and divertor plasmas of a nuclear fusion device, however, the radiation trapping becomes important for population dynamics and energy transport [1]. In particular, for resonance transitions terminating into the ground state, the radiation trapping alters its population kinetics drastically. Thus, we cannot apply the intensity ratio method for determination of the electron temperature and density at all.

In order to evaluate the optical thickness in high-density helium plasmas, we measured He I resonance lines in a helium arc plasma (T_e : > 1 eV, n_e : > 10^{13} cm^{-3}, pressure of the discharge region : < 4 kPa, pressure of the expansion chamber : < 45 Pa). Interestingly, a forbidden line (1s ^{1}S - 2p ^{3}P : 59.1 nm) as well as the 1s ^{1}S - 2p ^{1}P line of He I have clearly been observed by using a vacuum UV (VUV) spectrometer [2]. Although for typical He discharge, such as, cascade arc discharges the emissions from the resonance lines 1s ^{1}S - np ^{1}P lines are very intense, the CCD exposure time for 5 min. was needed to measure the the resonance lines 1s ^{1}S - np ^{1}P lines with good signal to noise ratio. The experimental results showed that an intensity ratio of the 1s ^{1}S - 2p ^{1}P line to forbidden line was around 20, whereas the spontaneous emission coefficients for two transitions indicated that the ratio is $\sim 10^7$. In order to elucidate the reason for this, we examined the influence of radiation trapping to line shape of the 1s ^{1}S - 2p ^{1}P line in high-density helium plasmas [3]. As a result, the radiation trapping caused the line intensity slightly being changed by 0.5. Thus, we have concluded that the self-absorption of the resonance lines 1s ^{1}S - np ^{1}P lines due to ambient He atoms in the expanding chamber could be the main reason for the above mismatch.

In this study, therefore, in order to justify our assumption, the spectral line shapes of resonance lines 1s ^{1}S - np ^{1}P lines of He I traveling in dense helium gases have been calculated. We consider the He I resonance lines of 1^1S-2^1P (58.4 nm), 1^1S-3^1P (53.7 nm), 1^1S-4^1P (52.2 nm), 1^1S-5^1P (51.6 nm), 1^1S-6^1P (51.2 nm), and 1^1S-7^1P (51.0 nm) are optically thick. The condition under the numerical calculation is set to be the same as those of the experiment. In Sec. 2, we describe the simulation code, which consists of the coupled rate equations corresponding to the ground and various He I excited levels and the equation of radiative transfer. The simulation results and their comparison with experimental results are presented in Sec. 3. The final section provides our summary.

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2. Simulation for Radiative Transfer in Dense Helium Gases

In this study, since we simulate the spectra of the resonance lines 1s ^{1}S - np ^{1}P lines of He I observed, the corresponding experimental situation should be modeled. Figure 1 shows a schematic drawing of the experimental setup of the cascade arc plasma source and VUV emission spectroscopy. The He I spectra radiated from the observation region propagated along the line-of-sight with a length of $\sim$1 m and then reached the entrance slit of the spectrometer, which was installed in the direction of 45 degrees with respect to the plasma jet axis. A VUV spectrometer with a focal length of 1.0 m and grating of 1200 grooves/mm was used. A reciprocal linear dispersion on a CCD detector was 0.01 nm/pixel at the wavelength of 58 nm. Analysis of H-β Stark broadening and recombination continuum emission determined the electron density and temperature in the plasma jet, respectively [2]. The plasma parameters were controlled by He gas flow rate and arc discharge current. In the expansion chamber, the gas pressure was measured by an absolute pressure gauge. By assuming the He gas temperature according to $p_{He} = n_{He}k_B T_{He}$, we can evaluate the He gas density. In the simulation, we assumed that the arc jet was a homogeneous plasma with a cylindrical shape. Likewise, the absorption volume along the VUV line-of-sight was assumed to be a cylinder (distance between the radiation source and the slit was l cm and its diameter was 200 μm).

As the computational scheme, the first step is to calculate the spectra of resonance lines 1s ^{1}S - np ^{1}P lines of He I radiated from the plasma jet by solving the coupled rate equations. For the population density in the energy level p [4], which is given by

$$\frac{\mathrm{d}n_p}{\mathrm{d}t} = -\left\{\sum_{q\neq p} C_{pq}n_e + S_p n_e + \sum_{q<p} A_{pq}\right\} n_p + \left\{\sum_{q\neq p} C_{qp}n_e + \sum_{q>p} A_{qp}\right\} n_q + \left(\alpha_p n_e + \beta_p + \beta_p^d\right) n_i n_e, \quad (1)$$

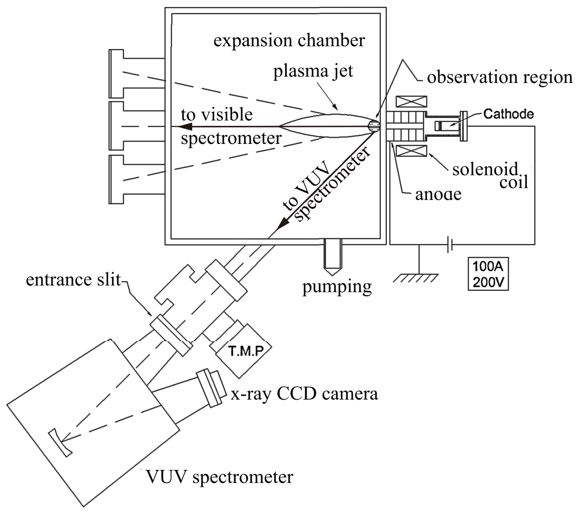

Fig. 1 A schematic drawing of the experimental setup of the VUV spectrometer in the high-gas pressure cascade arc discharge plasmas [2].

where, C_{qp} is the electron impact transition rate coefficient; S_p is the ionization rate coefficient; A_{pq} is the Einstein A coefficient from level p to q; α_p, β_p, and β_p^d are the rate coefficients for three-body, radiative, and dielectronic recombination, respectively. n_e and n_i are electron and ion densities, respectively. In a plasma condition under our experiment, typical time to hold an assumption of quasi-steady state is the orders of 10^{-6} s. In the arc plasma, the degree of ionization is a few percent of atomic density, and thus the self-absorption occurs very frequently. In the initial stage, we calculate the spectra of the resonance lines 1s ^{1}S - np ^{1}P lines without the self-absorption. Subsequently, the radiative transfer equation is solved to evaluate how extent the ambient gas absorbs the resonance lines 1s ^{1}S - np ^{1}P lines and deform the spectral line shape, as will be described. For the population density of He atom in the energy level p, the coupled rate equation including radiation trapping is given by

$$\frac{\mathrm{d}n_p}{\mathrm{d}t} = -\left\{\sum_{q<p} A_{pq}n_p + \sum_{q>p}\int_{line} B_{pq}I(\nu)n_p P'(\nu)d\nu + \sum_{q<p}\int_{line} B_{pq}I(\nu)n_p P(\nu)d\nu\right\} + \left\{\sum_{q>p} A_{qp}n_q + \sum_{q<p}\int_{line} B_{qp}I(\nu)n_q P'(\nu)d\nu + \sum_{q>p}\int_{line} B_{qp}I(\nu)n_q P(\nu)d\nu\right\} - \frac{n_p}{\tau_p}, \quad (2)$$

where B_{qp} and B_{pq} are the Einstein B coefficients for photoabsorption and induced emission; $I(\nu)$ is the radiance; $P(\nu)$ and $P'(\nu)$ are the normalized line profiles for emission and absorption, respectively; τ_p is the particle confinement time. In Eq. (2), we do not consider the electron impact, recombination, and ionization processes, because the light propagates in the He gas without collisional interactions. Because He atoms move randomly due to thermal motion, they remain on the line-of-sight for a finite period. The confinement time is evaluated by the period, at which He atoms cross the line-of-sight vertically. In the simulation, we use the thermal velocity, $v_{th} = \sqrt{3k_B T_{He}/m_{He}}$, to determine the particle confinement time. For example, in the case of the gas temperature of 1000 K and the thermal velocity of 2.5×10^3 m/s, the confinement time is 8×10^{-8} s.

In a homogeneous medium, an analytical solution of the radiative transfer equation for the transition $q \leftarrow p$ at a frequency ν is given by

$$I_\nu(x) = I_\nu(0)\exp(-k_\nu x) + \frac{\eta_\nu}{k_\nu}\left[1 - \exp(-k_\nu x)\right]. \quad (3)$$

Here, k_ν and η_ν are the absorption and emission coefficients, respectively. x is the coordinate along the optical path. The absorption and emission coefficients are given by

$$k_\nu = \frac{h\nu}{4\pi}\left\{n_q B_{qp} P'(\nu) - n_p B_{pq} P(\nu)\right\}, \tag{4}$$

and

$$\eta_\nu = \frac{h\nu}{4\pi} n_p A_{pq} P(\nu), \tag{5}$$

respectively. Actually, because the radiance decrease during light propagation according to Eq. (3), absorption and emission rate coefficients in Eq. (2) have spatial distribution along the line-of-sight. Thus we divide the line-of-sight into N regions from the observation area to the entrance slit. The cell of number 1 is located in the side of the observed region. In the calculation, N is set to satisfy $l/N = 0.1$ cm.

In this study, we assume that line profiles of $P(\nu)$ and $P'(\nu)$ have the Gaussian shape. The profile of the induced emission is the same as that of the emission. Each process, i.e., photoabsorption, emission, and induced emission, occur via neutral helium atoms being in the line-of-sight. The temperature of the ground state atom is equivalent to that of the excited state. Thus, the line widths of various processes are the same each other. Figure 2 shows the normalized profiles of the emission attributed to the $1\,s^1S$ - $2p^1P$ line of He I from the plasma jet, of absorption, and of emission (induced emission). The absorption profile is shown as negative value to distinguish it from the emission profile. He atom temperature at plasma jet and of ambient neutral gas are 0.1 eV and 0.086 eV, respectively. Because the the $1\,s^1S$ - $2p^1P$ line of He I emitted from the plasma jet plays the role of injection light into ambient helium gas region, it has line width of temperature of 0.1 eV. On the other hand, because photoabsorption and emission (induced emission) occur via ambient helium gas, these profiles have line width of temperature of 0.08 eV.

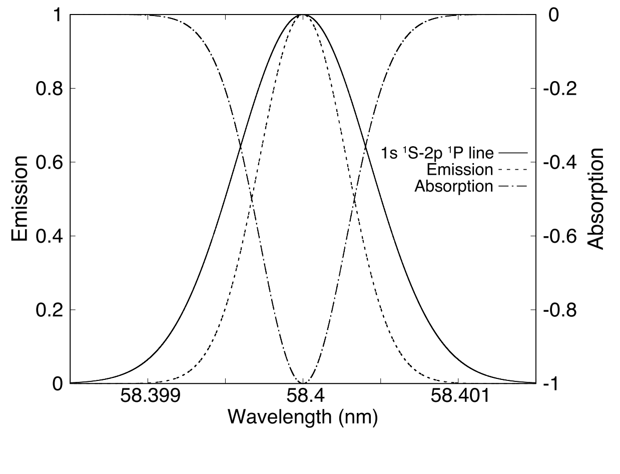

Fig. 2 Profiles of the $1\,s^1S$ - $2p^1P$ line of He I emission from the plasma jet, of emission, and of absorption. These profiles are normalized for clarity. The absorption profile is shown as negative value.

3. Numerical Results and Discussion

We have simulated spectral line profiles of the resonance lines 1s ^{1}S - np ^{1}P lines of He I and forbidden line, propagating in high He gas pressure. The calculation condition is as follows. The arc plasma at the anode exit has an electron and He ion densities of 10^{13} cm^{-3}. The electron, He ion, and He atom temperature at the anode exit are 0.1 eV. The He atom density is assumed to be very low, because the plasma is classified into a recombination one. On the VUV line-of-sight axis, the He atom density and He atomic temperature are 3.26×10^{13} cm^{-3} and 0.086 eV, respectively. Figure 3 shows the simulated line intensities (a) with and (b) without the photoabsorption process due to the ambient gas. The length of the line-of-sight is 100 cm. In both cases, the intensities of forbidden line almost remain constant. On the other hand, by taking into account the self-absorption effect due to ambient gas, the intensities of the resonance lines 1s ^{1}S - np ^{1}P lines decrease drastically. Here, we focus on the intensities of the 1s ^{1}S - 2p ^{1}P line and forbidden line. The Einstein A coefficients for the 1s ^{1}S - 2p ^{1}P line and the forbidden transition are 1.8×10^9 s^{-1} and 1.8×10^2 s^{-1}, respectively [5]. The Einstein B coefficients corresponding photoabsorption for the above transitions are 2.7×10^{12} J^{-1} cm^2 sr Hz and 7.5×10^5 J^{-1} cm^2 sr Hz, respectively. Therefore, the absorption by He atom has little effect on the reduction of forbidden line intensity.

The dependence of line intensities on the absorption length is shown in Fig. 4. The absorption length corresponds to the VUV line-of-sight length. The 1s ^{1}S - 2p

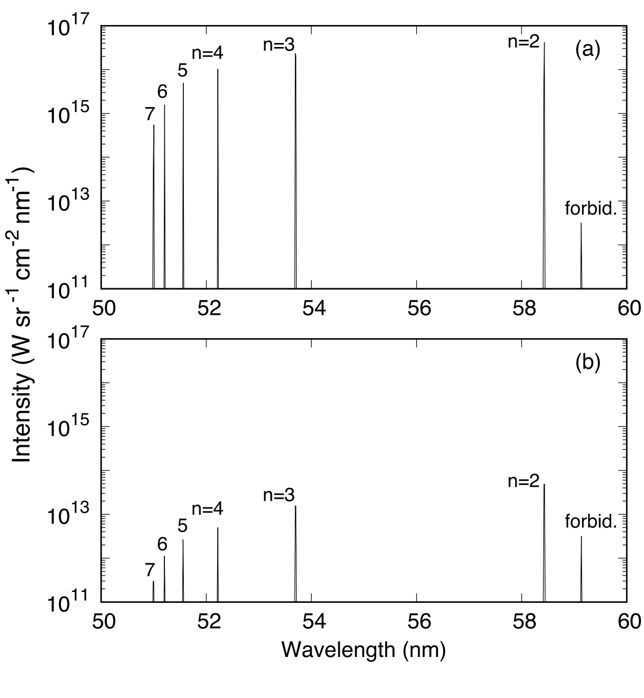

Fig. 3 Simulated spectra of the resonance lines 1s ^{1}S - np ^{1}P lines and forbidden transition, (a) and (b) show VUV spectra without and with photabsorption process, respectively.

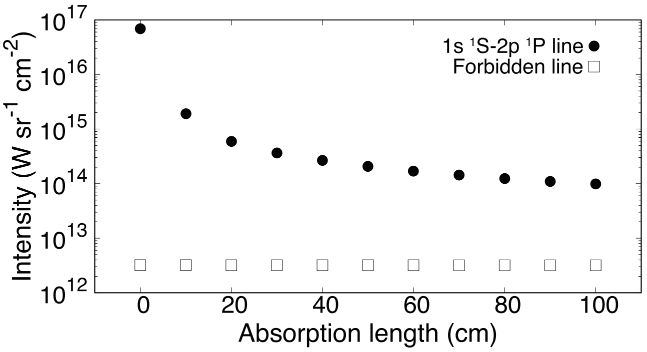

Fig. 4 Dependence of spectral line intensities of the 1s ^{1}S - 2p ^{1}P line and forbidden line on the absorption length. The absorption length corresponds to the line-of-sight length.

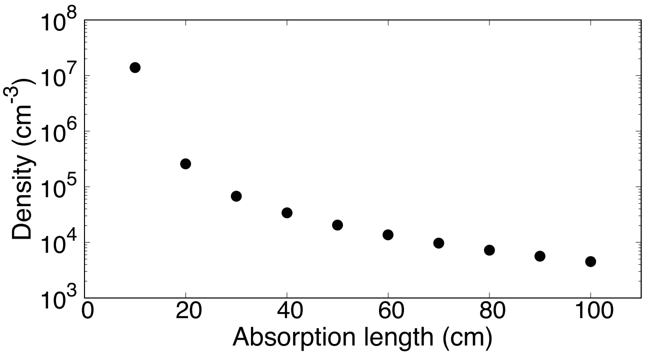

Fig. 5 Population density of He I 2^1P excited state along the line-of-sight.

^{1}P line intensity is significantly decreased with increasing absorption length. Figure 5 shows the He excited population density of 2 ^{1}P state along the line-of-sight. The He ground state atom is excited into the upper states due to photoabsorption process with a large cross section. This phenomenon indicates that the VUV light propagates with repeating the photoabsorption and emission. The light re-emitted after photoabsorption is emitted into 4π solid angle. The solid angle of the VUV line-of-sight is very small, so that the initial light radiated from the plasma jet axis does not reach the entrance slit. This causes the decrease in the resonance line intensities, as shown in Fig. 4.

In addition, in Fig. 4, the decay of intensity of the 1s ^{1}S - 2p ^{1}P line seems to be saturation state at the absorption length over ~80 cm. As shown in Fig. 2, because the line width of the 1s ^{1}S - 2p ^{1}P line is broader than that of the absorption, the calculated spectral line profile including photoabsorption has a central dip. The increase in depth of the central dip, i.e., the decrease in intensity of the central dip region, causes the decrease in spectral line intensity. The depth of the central dip increases with absorption length according to Eq. (3) and, eventually the intensity of the central dip region reaches zero. And thus, intensity of the 1s ^{1}S - 2p ^{1}P line approaches to a convergence value.

Figure 6 shows dependence of intensity ratio of the

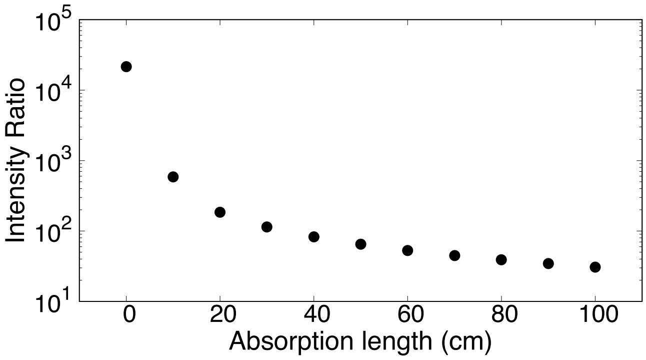

Fig. 6 Dependence of intensity ratio of the 1s ^{1}S - 2p ^{1}P line to the forbidden line on the absorption length. At the absorption length at 0 cm, the ratio corresponds to value without the photoabsorption process.

1s ^{1}S - 2p ^{1}P line to the forbidden line on the absorption length. The intensity ratio at the absorption length at 0 cm is a condition without the photoabsorption. The ratio of 25 is obtained at the absorption length of 100 cm, and this value is in a good agreement with the experimental result of 20. Thus, we conclude that the experimental findings on lowl VUV resonance intensity can be explained by the self-absorption process based on our physical model and numerical simulation.

4. Summary

In order to reproduce the experimental result, in which He I forbidden line as well as the resonance lines 1s ^{1}S - np ^{1}P lines were measured, we have developed the simulation code for the radiative transport of VUV resonance lines. The code considered self-absorption process due to ambient helium atom. The intensities of resonance lines 1s ^{1}S - np ^{1}P lines were decreased with increasing the absorption length. On the other hand, the line intensity of forbidden line did not change, because the absorption coefficient was very small. The simulation result showed the intensity ratio of the 1s ^{1}S - 2p ^{1}P line to forbidden line was as low as 25, which was in good agreement with the value of 20 obtained in the experiment. This result showed that under the high-ambient He pressure the self-absorption of He I resonance transitions plays an important role for population dynamics. For future work, we are preparing new experimental setup to reveal the dependence of intensity ratio on the absorption length and other experimental conditions.

[1] S. Kado, M. Goto *et al.*, J. Plasma Fusion Res. **86**, 631 (2010) (in Japanease).

[2] Md. Anwarul Islam, T. Yamaguchi, K. Fukuyama, H. Kawazome, N. Tamura and S. Namba, IEEE Transactions on Plasma Science (accepted).

[3] H. Kawazome and S. Namba, Plasma Fusion Res. **11**, 2401124 (2016).

[4] M. Goto, JQSRT **76**, 331 (2003).

[5] https://www.nist.gov/pml/atomic-spectra-database