Line Intensity Ratios of Helium Atom in an Ionizing Plasma

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Line intensity ratios of helium atom in an ionizing plasma

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Abstract

Effective emission rate coefficients $C_{em}^{eff}(\lambda)$, line intensity ratios, $C_{em}^{eff}(\lambda_1) / C_{em}^{eff}(\lambda_2)$, and $S_{em}^{eff} / C_{em}^{eff}(\lambda)$, with $S_{em}^{eff}$ the ionization rate coefficient, are obtained by the collisional radiative model for an ionizing plasma using new excitation and ionization rate coefficients. In the plasma with electron density $n_e > 10^4$ cm$^{-3}$, $C_{em}^{eff}(\lambda)$ for various lines are enlarged, since the normalized population densities for the metastable states, $n(2^{1}S)/n_{He^+}$, becomes large, and the excitation rate coefficients from $2^{1}S$, $2^{3}S$, $2^{1}P$, are large compared to that from the ground state $1^{S}$.$\Rightarrow$ In high $n_e$ plasma ($n_e > 10^{12}$ cm$^{-3}$), with frequent electron impacts on the excited heliums, $n(i)/n_{He^+}$ becomes constant to $n_e$, which results in the decrease of $C_{em}^{eff}(\lambda)$. Hot electrons and resonance scattering, which are often important for the experimental applications, are included in this model. A small amount of hot electrons (several percent) can enhance the line emission and ionization rates for low electron temperature plasma with $T_e$ ($T_e < 10$ eV). The resonance scattering reduces the emission of the resonance lines ($1^{S} - n^{1}P$) and enlarges $n^{1}P$ and $2^{1}S$ populations when the column density of helium gas $n_{He^+} \times L$ exceeds $2 \times 10^{13}$ cm$^{-2}$. 

Key words: helium atom, plasma diagnostics, line intensity ratio, collisional radiative model, hot electrons, resonance scattering

I. INTRODUCTION

Helium atom is an attractive atomic species for electron temperature ($T_e$) and density ($n_e$) measurements, since it has various advantages as a probe particle, i.e., well-known atomic data, strong visible lines, and an intrinsic species in the fusion burning plasma. So far, $T_e$ and $n_e$ measurements using He I line intensity ratios has been developed and improved [1-7]. Recently, $n_e$ and $T_e$ measurements based on the collisional radiative (C.R.) model for helium atom [8] have been applied to the TEXTOR tokamak [9], the PSI-1 linear device [10], and the NAGDIS-I linear device [11-13]. Helium is also important for the fusion plasma from the viewpoints of fuel dilution and energy balances [14]. The C.R. model, which involves excited heliums and various plasma particles such as electrons, ions, atoms, molecules, is indispensible for the investigations of the fusion plasmas with high $n_e$ ($> 10^{12}$ cm$^{-3}$). A numerical code of the C.R. model for helium atom is developed by Fujimoto [8], and various improvements were made [12]. In this work, the C.R. model was revised using recommended excitation and ionization rate coefficients [15-19].

Hot electron or superthermal electrons sometimes exist in the RF and DC glow discharge as well as the fusion edge, and play an important role on the plasma confinement and the sheath formations [20,21]. Hot electrons are also important for the spectroscopic diagnostics, since they have a large contribution on the excitation processes [12]. In the typical helium glow discharge plasma, with pressure above $10^{-4}$ Torr, the resonance scattering or imprisonment of resonance lines apparently reduces transition probabilities $A_{ij}$, which reduces the emission of resonance lines ($1^{S} - n^{1}P$) and enlarges $n^{1}P$ and $2^{1}S$ populations [22]. The reduction of $A_{ij}$ is included in this model using an optical escape factor $\Lambda(\lambda)$ [23,24]. It has been reported that the increase of $501.6$ nm line emission ($2^{3}S - 3^{1}P$) is consistent with the C.R. model in NAGDIS-I [12].

The ratio of the effective rate coefficient for ionization to that for emission, $S_{em}^{eff} / C_{em}^{eff}(\lambda)$, is often used for the density determination of the probe atomic beams in the plasma, and the measurement of impurity flux released from the wall. So far, the $n_e$ measurement using Li beam, and the $T_e$ measurement using Al, Ti, C, and He beams using $S_{em}^{eff} / C_{em}^{eff}(\lambda)$ have been developed [7,26].

II. COLLISIONAL RADIATIVE MODEL AND NORMALIZED POPULATION DENSITIES

The population densities $n(i)$ are derived from the numerical code by Fujimoto [8] revised by the recommended rate coefficients for ionization and excitations from the ground state $1^{S}$ and the two metastable states $2^{1,3}S$ [15-19]. The excited states with principal quantum number $n \leq 20$ are included in this work as shown in Fig. 1. Energy levels $E(i)$ for the excited states with $n \leq 7$ are
summarized in Table I [25]. Excited states with \( n = 8 \) - 20 are grouped by the same principal quantum numbers as shown in Fig. 1 and Table II. In the C.R. model for the ionizing plasma, rate equations for the population density \( n(i) \) are expressed as

\[
\frac{dn(i)}{dt} = \left( n_e \sum_{k \geq i} A_{kj} n(k) + \sum_{k < i} A_{ik} n(k) \right) \]

\[- \left( n_e \sum_{k \geq i} C_{ik} n(k) + \sum_{k < i} A_{ik} n(k) \right) - n_e S_i n(i) = 0, \tag{1}\]

where \( A_{ij} \) is the transition probability for \( i \rightarrow j \) transition [s\(^{-1}\)]. The wavelengths \( \lambda \) and \( A_{ij} \) for the lines presented in this article are summarized in Table III [25]. The \( C_{ij} \) and \( S_i \) are the excitation/de-excitation rate coefficients, and the ionization rate coefficient for electron impact, respectively. The population densities \( n(i) \) are obtained by solving the rate equations for all excited states with putting \( n(i)/dt = 0 \). The normalized population density is defined as \( n(i)/n_{He} \), with \( n_{He} \) the density of helium atom (\( n_{He} = \sum n(k) \)).

Figure 2.1 (a) and (b) show the \( T_e \) and \( n_e \) dependences of \( n(1S)/n_{He} \) for \( 2^1S \) and \( 2^3S \), and the sum of \( n(i)/n_{He} \) for singlet and triplet, \( n_s = \sum n(s)/n_{He} \) (singlet), \( E(s) > E(2^1S) \) and \( \sum n(t)/n_{He} \) (triplet), \( E(t) > E(2^3S) \). Population balance involving \( 2^3S \) is shown as percentage contributions of electron in/out flows in Fig. 2.2. For low \( n_e \) \( (n_e \leq 10^5 \text{ cm}^{-3}) \), population balance can be described with neglecting radiative electron in flows (\( \leq 5 \% \)), described as,

\[
n_e \cdot C_{1S \rightarrow 2S} \frac{n(1S)}{n_{He}} = A_{2S \rightarrow 1S} \frac{n(2S)}{n_{He}}, \tag{2}\]

which gives the relation of \( n(2^1S)/n_{He} \) proportional to \( n_e \). For \( n_e > 10^8 \text{ cm}^{-3} \) (middle \( n_e \) region), excitations to the singlet states, and ionization becomes dominant processes as follows:

\[
n_e \cdot C_{1S \rightarrow 2S} \frac{n(1S)}{n_{He}} = \left( \sum_{s \text{singlet}} C_{2S \rightarrow s} + S_{2S} \right) \frac{n(2^1S)}{n_{He}}, \tag{3}\]

which gives constant \( n(2^1S)/n_{He} \). As \( n_e \) exceeds \( 10^{13} \text{ cm}^{-3} \), \( n(2^1S)/n_{He} \) increases with \( n_e \) due to the de-excitation from the singlet excited states down to \( 2^1S \). In very high \( n_e \) plasma \( (n_e > 10^{16} \text{ cm}^{-3}) \), the population balances are determined by the collisional processes between \( 2^1S \) and all singlet states:

\[
n_e \cdot \sum_{s \text{singlet}} C_{s \rightarrow 2S} \frac{n(s)}{n_{He}} = n_e \left( \sum_{s \text{singlet}} C_{2S \rightarrow s} + S_{2S} \right) \frac{n(2^1S)}{n_{He}}. \tag{4}\]

Figure 2.3 shows the percentage contributions of the electron in/out flows to/from \( 2^3S \). In the low \( n_e \) plasma \( (n_e \leq 10^6 \text{ cm}^{-3}) \), the population balance involving \( 2^3S \) can be approximated as,

\[
\left( \sum n \cdot A_{n \rightarrow 2S} \frac{n(n^2P)}{n_{He}} \right) \approx \sum n \cdot C_{1S \rightarrow n^2P} \frac{n(n^1S)}{n_{He}} = A_{2S \rightarrow 1S} \frac{n(2^3S)}{n_{He}}. \tag{5}\]

Since the radiative de-excitation can be replaced by the \( 1^1S - n^2P \) excitations, \( n(2^3S)/n_{He} \) is proportional to \( n_e \). For \( n_e > 10^6 \text{ cm}^{-3} \), excitation to the triplets and ionization become the dominant out-flows as follows:

\[
\left( \sum n \cdot A_{n \rightarrow 2S} \frac{n(n^2P)}{n_{He}} \right) \approx \sum n \cdot C_{1S \rightarrow n^2P} \frac{n(n^1S)}{n_{He}} = n_e \left( \sum_{\text{triplet}} C_{2S \rightarrow 1S} + S_{2S} \right) \frac{n(2^3S)}{n_{He}}, \tag{6}\]

which gives constant \( n(2^1S)/n_{He} \) independent to \( n_e \) \( (\approx 5 \times 10^{-3} \text{ at } T_e = 20 \text{ eV}) \). For high \( n_e \) plasma \( (n_e \geq 10^{12} \text{ cm}^{-3}) \), the radiative electron in-flows to \( 2^3S \) becomes small, and the population balance is described as,

\[
n_e \sum_{\text{triplet}} C_{1S \rightarrow 2S} \frac{n(1S)}{n_{He}} = n_e \left( \sum_{\text{triplet}} C_{2S \rightarrow 1S} + S_{2S} \right) \frac{n(2^3S)}{n_{He}}, \tag{7}\]

where \( n(2^3S)/n_{He} \) is smaller compared to that in the middle \( n_e \) region \( (\approx 3 \times 10^{-4} \text{ at } T_e = 20 \text{ eV}) \).

Figures 2.4 and 2.5 show \( T_e \) and \( n_e \) dependences of \( n(i)/n_{He} \) for several singlet \( (2^3P, 3^3S, 3^1P, 4^1D) \) and triplets \( (2^3P, 3^3S, 3^3P) \) excited states. The \( T_e \) dependences of \( n(i)/n_{He} \) are similar to those for \( C_{1S \rightarrow 1S} \). The \( T_e \) dependences of \( n(1S)/n_{He} \) for the triplet have a peak around \( T_e \approx 20 \text{ eV} \) and gradually decrease with \( T_e \) for \( T_e > 20 \text{ eV} \), while those for the singlet monotonously increase with \( T_e \) for \( T_e < 1000 \text{ eV} \). Figure 2.6 shows the population balance involving \( 4^1D \), for example. The radiative electron in-flows, which is often called as "cascade", \( \sum A_{s \rightarrow 1S} \frac{n(s)}{n_{He}} \) is larger than \( 10 \% \) of the total electron in-flows for \( n_e < 10^5 \text{ cm}^{-3} \). As \( n_e \) exceeds \( 10^{13} \text{ cm}^{-3} \), the population balance is determined by the collisional processes between \( 4^1D \) and the singlet states with \( n \geq 3 \).

### III. EFFECTIVE EMISSION RATE COEFFICIENTS

The effective emission rate coefficient in the C.R. model \( C_{em}^{eff}(\lambda) \) [cm\(^3\)/s] is defined as,
Photon production rate per unit volume is given as $n_c^{eff}(\lambda)n_{He} [cm^{-3} s^{-1}]$. The $C_{em}^{eff}(\lambda)$ for various lines, $1^1S_n^1P, 2^1P - n^1S, 2^3S - n^1P, 2^3P - n^1D, 2^3P - n^3S, 2^3S - n^3P, and 2^3P - n^3D$ are shown as $T_e$ and $n_e$ dependences in Figs. 3.1 - 3.7.

The $C_{em}^{eff}(68.4 nm, 1^1S - 2^1P)$, for the resonance line, is almost constant for a wide $n_e$ range ($n_e \leq 10^{14} cm^{-3}$) because of large value of $A_{2^1P - n^1S}$. It is slightly enlarged by the excitation from $2^1S$ for $n_e = 10^7 - 10^{14} cm^{-3}$. As $n_e$ exceed $10^{14} cm^{-3}$, where the rate for collisional de-excitation becomes large compared to those for radiations, $C_{em}^{eff}(68.4 nm)$ gradually decreases because $n(i)/n_{He}$ becomes almost constant. The $C_{em}^{eff}(\lambda)$ for the other lines with small $S_k A_k$ have small critical densities ($n_e = 10^{11} - 10^{13} cm^{-3}$). The $2^3S$ metastable state slightly influences on the $n = 3 or 1^3D$ lines, e.g. $58.4 nm (2^3S - 3^1P), 728.1 nm (2^3P - 3^1S), 667.8 nm (2^3P - 3^1D), and 492.2 nm (2^3P - 4^1D)$. For the triplet lines, $2^3S$ has a big influences on $n_e$ dependence of $C_{em}^{eff}(\lambda)$, since $y_{2^3S - 1}^{eff}$ is much larger than $y_{1^1S - 1}^{eff}$ (from the ground state).

IV. LINE INTENSITY RATIOS

The line intensity ratios, $C_{em}^{eff}(\lambda)/C_{em}^{eff}(\lambda_n)$, for the use of $n_e$ and $T_e$ measurements are shown in Figs. 4.1 - 4.6. Figure 4.1 shows $T_e$ and $n_e$ dependences of the line intensity ratios for singlet - triplet line pairs, $504.8 nm (2^3P - 4^1S) / 471.3 nm (2^3P - 4^3S), 501.6 nm (2^3S - 3^1P) / 471.3 nm, and $492.2 nm (2^3P - 4^1D) / 471.3 nm$, whose wavelengths are long compared to $500 nm$. Since $C_{em}^{eff}(\lambda)$ for the singlet and triplet lines have different $T_e$ dependences each other, the line intensity ratios have strong $T_e$ dependences, which are suitable for $T_e$ measurement. As $n_e$ exceeds $10^{14} cm^{-3}$, these line intensity ratios are slightly decreased by the increase of $C_{em}^{eff}(471.3 nm)$ due to the enhanced excitation from $2^3S$. The $504.8 nm / 471.3 nm$ line intensity ratio has an advantage of relatively weak $n_e$ dependence compared to the other ones in high $n_e$ plasma ($n_e \geq 10^{11} cm^{-3}$). Figure 4.2 shows the $T_e$ dependences of these line intensity ratios for $T_e = 5 - 50 eV$ for the experimental applications. Figure 4.3 shows $T_e$ and $n_e$ dependences of the singlet - singlet intensity ratios of $501.6 nm / 504.8 nm, 501.6 nm / 492.2 nm,$ and $492.2 nm / 504.8 nm$. The strong $n_e$ dependences for $n_e > 10^{11} cm^{-3}$ and weak $T_e$ dependence due to the similar $T_e$ dependence of $C_{em}^{eff}(\lambda)$ is suitable for $n_e$ measurement. Figure 4.4 shows $n_e$ dependences of these line intensity ratios for $n_e = 10^9 - 10^{16} cm^{-3}$.

Figure 4.5 shows $T_e$ and $n_e$ dependences of the line intensity ratios of $728.1 nm (2^3P - 3^1P) / 706.5 nm (2^3P - 3^3S), 667.8 nm (2^3P - 3^1D) / 706.5 nm, and 667.8 nm / 728.1 nm$, whose wavelengths are around $700 nm$. Since $C_{em}^{eff}(706.5 nm)$ is enlarged due to the large $n(2^3S)/n_{He}$, the line intensity ratios of $728.1 nm / 706.5 nm$ and $667.8 nm / 706.5 nm$ are slightly reduced for $n_e = 10^9 - 10^{12} cm^{-3}$. The $728.1 nm / 706.5 nm$ line intensity ratio is suitable for the $T_e$ measurement in high $n_e$ plasma due to the small $n_e$ dependence. The $T_e$ dependences of $728.8 nm / 706.5 nm$ and $667.8 nm / 706.5 nm$ for $T_e = 5 - 50 eV$ and the $n_e$ dependence of the $667.8 nm / 728.1 nm$ line intensity ratio for $n_e = 10^9 - 10^{14} cm^{-3}$ are shown in Fig. 4.6.

Simultaneous $T_e$ and $n_e$ measurements are available by using singlet - singlet and singlet - triplet line pairs. Firstly, $n_e$ is obtained from the singlet - singlet intensity ratio with assuming $T_e$. Secondly, $T_e$ is obtained from the singlet - triplet line pairs with using $n_e$ obtained from the singlet - singlet ratios. It is recommend to use the $492.2 nm / 504.8 nm$ intensity ratio for $n_e$ measurement and $492.2 nm / 471.3 nm$ for $T_e$ measurement. Detailed data of the intensity ratios are shown in Appendix A as contour plots and $n_e$ and $T_e$ dependences.

V. RATIO OF EFFECTIVE RATE COEFFICIENT FOR IONIZATION TO THAT OF LINE EMISSION

The quantity of $S^{eff}/C_{em}^{eff}(\lambda)$, with $S^{eff}$ the effective ionization rate coefficient, is often used for the density determination of the atomic beam in a plasma [7]. The effective ionization rate coefficient $S^{eff}$ is defined as,

$$S^{eff} = \frac{\sum_i S_i n(i)}{\sum_k n(k)} = \frac{\sum_i S_i n(i)}{n_{He}}.$$  (9)

Since $S_i$ (from the excited state) are larger than $S_{1S}$ (from the ground state), $S^{eff}$ is greater than $S_{1S}$. The $T_e$ and $n_e$ dependences of $S^{eff}$ are shown in Fig. 5.1. In the plasma with $T_e > 20 eV$, $S^{eff}$ has small $n_e$ dependence. For low $T_e$ plasmas ($T_e \leq 20 eV$), however, $n_e$ dependence is strong due to small value of $S_{1S}$, while $S_i$ from the excited states. For low $T_e$ plasmas ($T_e \leq 20 eV$), however, $n_e$ dependence is strong due to small value of $S_{1S}$, while $S_i$ from the excited states. $S^{eff}$ increases with $n_e$ due to the ionizations from various excited states. In this technique, the density of the helium atomic beam $n_{He}$ is obtained from the line intensity $I_{He}(z)$, which is expressed by,

$$I_{He}(z) = n_c C_{em}^{eff}(\lambda)n_{He}$$  (10)

where $z$ and $\eta$ are the position along the beam and the sensitivity of the optical detector, respectively. For the monochromatic helium atomic beam with velocity of $v_{He}$, beam attenuation due to the ionization is described as,

$$\frac{dn_{He}}{dt} = -n_c S^{eff} n_{He}.$$  (11)

Helium atoms injected into the plasma are ionized and removed away from the beam with trapped by the magnetic field, usually perpendicular to the beam. By using eqs. (10) and (11), $n_{He}(z)$ is given by,
\[ n_{He}(z) = \sqrt{\frac{S_{eff}}{C_{em}^\ddagger}} \frac{I_{He}(z) d\zeta}{\nu_{He}}. \]  

(12)

Figures 5.2 - 5.7 show \( T_{e} \) and \( n_e \) dependences of \( S_{eff}/C_{em}^\ddagger(\lambda) \) for various visible lines. The line of 501.6 nm (\( 2^1S - 2^1P \)) is attractive because of its small \( n_e \) and \( T_{e} \) dependences for \( n_e \leq 10^{13} \text{ cm}^{-3} \) and \( T_{e} \geq 5 \text{ eV} \).

VI. EFFECT OF HOT ELECTRON IN A PLASMA

For the investigation of hot electrons in a plasma, we consider two temperature plasma with electron temperature of \( T_{e} \) and \( T_{eh} \) for cold and hot components. The electron velocity distribution function \( f(v_e) \) is expressed as a superposition of two Maxwellians, \( f_{c}(v_e) \) and \( f_{h}(v_e) \) with electron temperature of \( T_{ec} \) and \( T_{eh} \).

\[ f(v_e) = (1 - \alpha) f_{c}(v_e) + \alpha f_{h}(v_e), \]  

(13)

where \( \alpha \) is the abundance of the hot component given by \( \alpha = n_{eh}/n_{e} \) with \( n_{eh} \) the density of the hot electron component. Then, \( C_{ij} \) is expressed as,

\[ C_{ij} = \int_{0}^{\infty} \sigma_{ij} v_{e} f(v_{e}) \mu v_{e}^{2} d\mu, \]

(14)

where \( C_{ij}(T_{ec}) \) and \( C_{ij}(T_{eh}) \) are \( C_{ij} \) at \( T_{ec} \) and \( T_{eh} \), respectively. In the similar way, the ionization rate coefficient \( S_{i} \) can be obtained as \( S_{i} = (1 - \alpha) S_{i}(T_{ec}) + \alpha S_{i}(T_{eh}) \).

Examples of \( C_{em}^\ddagger(\lambda) \) for 54.8 nm and 667.8 nm, \( C_{em}^\ddagger(\lambda) / C_{em}^\ddagger(\lambda_{0}) \) for 504.8 nm / 471.3 nm and 492.2 nm / 471.3 nm, and \( S_{eff} \) in the presence of hot electrons with \( T_{eh} = 20 \text{ eV} \) and 40 eV at \( \alpha = 10 \% \) are shown in Figs. 6.1 - 6.3. Since \( C_{11}(T_{ec}) \) and \( S_{11} \) (from the ground state) are very small for \( T_{e} \leq 3 \text{ eV} \), \( C_{em}(\lambda) \) and \( S_{eff} \) at \( \alpha = 10 \% \) are rather similar to 0.1 \( C_{em}(\lambda) \) and 0.1 \( S_{eff} \) at \( T_{ec} = T_{eh} \), respectively. The hot electrons are very important for the \( T_{e} \) measurement in a low \( T_{ec} \) plasma (\( T_{ec} < 10 \text{ eV} \)), since the experimental result seems like a monochromatic temperature plasma with \( T_{e} = T_{eh} \).

VII. EFFECT OF RESONANCE SCATTERING BY THE HELIUM GAS

In the typical helium discharge plasma, with pressure above 10^{-4} Torr, helium gas has large optical depths \( \tau(\lambda) \) for the resonance lines (\( 1^1S - n^1P \)). Figure 7.1 shows \( \tau(\lambda) \) for 58.4 nm (\( 1^1S - 2^1P \)), 53.7 nm (\( 1^1S - 3^1P \)), and 52.2 nm (\( 1^1S - 4^1P \)) in the helium gas with 300 K (room temperature). This figure suggests we must consider the resonance scattering when the column density \( n_{He} \times L \) exceeds \( 10^{13} \text{ cm}^{-2} \), since \( \tau(58.4 \text{ nm}) \) exceeds unity. It corresponds to the helium gas pressure of \( 2.8 \times 10^{-5} \text{ Torr} \) in the vacuum vessel with radius of \( L = 10 \text{ cm} \). The effects of resonance scattering are included in this model using an optical escape factor \( \Lambda(\lambda) \), which is obtained by the following formula for large \( \tau(\lambda) \) [22–24,28]:

\[ \Lambda(\lambda) = \frac{1}{\tau(\lambda) \sqrt{\pi \ln(\tau(\lambda))}}. \]  

(15)

The optical escape factor \( \Lambda(\lambda) \) has a value of \( \Lambda(\lambda) < 1 \), and \( \Lambda(\lambda) = 1 \) corresponds \( \tau(\lambda) = 0 \). The resonance scattering is included in the model using \( \Lambda(\lambda) \times A_{ij} \) instead of \( A_{ij} \). The \( \Lambda(\lambda) \) for 58.4 nm, 53.7 nm and 52.2 nm included in this model are shown in Fig. 7.1. Photon absorptions by the metastable states \( 2^3S \) and the other excited states are neglected because the population densities and the absorption coefficients are small.

Figure 7.2 shows the modifications of \( n(\lambda)/n_{He} \) for \( 2^1S, 2^3S, 2^1P, 3^1P, \) and \( 4^1P \) by the resonance scattering at \( n_{e} = 10^{12} \text{ cm}^{-3} \) and \( T_{e} = 20 \text{ eV} \). The \( n(\lambda)/n_{He} \) are enhanced by the reduction of \( \Lambda(\lambda; 1^1S - 1^1P) \), resulting in the increase of \( C_{em}^\ddagger(\lambda; 2^1S - n^1P) \) and \( n(\lambda)/n_{He} \). The \( C_{em}^\ddagger(\lambda) \) for the resonance lines, 53.7 nm and 52.2 nm, decrease with \( n_{He} \times L \) because of the reduction of \( \Lambda(\lambda) \) as shown in Fig. 7.3. The \( C_{em}^\ddagger(\lambda) \) for the \( 2^1P - n^1D \) and \( 2^1P - n^1S \) lines are enhanced by the excitations from the \( n(\lambda)/n_{He} \). Line intensity ratios are shown in Fig. 7.4 as a function of \( n_{He} \times L \). The \( C_{em}^\ddagger(501.6 \text{ nm}) \) is very sensitive to the resonance scattering for \( n_{He} \times L > 2 \times 10^{13} \text{ cm}^{-2} \). Figure 7.5 shows the increase of \( S_{eff} \) because of the enlargement of \( n(\lambda)/n_{He} \) for \( 2^1S \) and the other excited states.

VIII. DISCUSSION

A. Accuracy of data

The accuracy of \( C_{em}^\ddagger(\lambda) \), \( C_{em}^\ddagger(\lambda)/C_{em}^\ddagger(\lambda_{0}), S_{eff}, \) and \( S_{eff}/C_{em}^\ddagger(\lambda) \) primarily depends on the reliability of atomic data. The transition probability \( A_{ij} \) has a good accuracy within 5%. The accuracy of \( C_{ij} \) and \( S_{ij} \) from the ground state can be estimated within 10 - 20 % for \( n_{e} \leq 50 \text{ eV} \) by including the analytical fitting error [15–18]. For \( n_{e} \geq 50 \text{ eV} \), \( C_{ij} \) has a better accuracy because of less uncertainty of excitation cross sections \( \sigma_{ij} \) for high electron impact energy, especially for the allowed excitations. So, we can estimate the accuracy of \( C_{em}^\ddagger(\lambda) \) and \( S_{eff} \) in the range of 10 - 20 % for low \( n_{e} \) plasma \( (n_{e} < 10^{4} \text{ cm}^{-3}) \), where excitation and ionization from the ground state are the dominant process to determine these quantities.

As \( n_{e} \) exceeds \( 10^{4} \text{ cm}^{-3} \), the reliability of atomic data for the atomic processes involving the excited states becomes important. Shevelko has compared his model calculations with various theoretical and experimental data of \( \sigma_{ij} \) from the excited states including \( 2^1S \) and \( 2^3S \) [19]. The accuracy for the excitation data involving metastable and excited states will be within 20 - 50%, and \( C_{em}^\ddagger(\lambda) \) will have accuracy of the same values. The number of
excited states included in the calculation (n ≤ 20) is sufficient for the investigation of the lines with n ≤ 4.

B. Comparison of line intensity ratios to the other works

The line intensity ratios presented by Schweer [9], and Behrendt [10], including the excited states with principal quantum number n ≤ 4, are compared to this work (including n ≤ 20). Figure 8.1(a) compares the 667.8 nm / 728.1 nm intensity ratios to Schweer’s. The line intensity ratios obtained including and removing n > 4 excited states in this work have small discrepancy each other, within ± 10% at ne = 10^{13} cm^{-3}. Discrepancy between this work and Schweer’s at ne = 10^{11} cm^{-3} is as large as factor of two, which may come from the difference in C_{1S} (from the ground state) and n(2^{1}S)/n_{He}. Figure 8.1(b) compares the 501.6 nm / 504.8 nm intensity ratio to Behrendt’s work. The contribution of n > 4 excited states is small for ne ≤ 10^{13} cm^{-3}, but rapidly increases for ne > 10^{13} cm^{-3}. Behrendt’s result is in good agreement to this work within 5 - 10% for ne = 10^{11} - 10^{13} cm^{-3} [10]. Figure 8.1(c) compares the 728.1 nm / 706.5 nm intensity ratio to Schweer’s at ne = 10^{12} cm^{-3}. The discrepancy may come from the difference in the Te dependence of C_{1S}.

These results show the accuracy of line intensity ratio is very important for the Te and ne measurements. Only several percent difference in the line intensity ratio results in several factor and one order of deviations in Te and ne determination respectively. The accuracy of atomic data especially for C_{ij} from the excited states including 2^{1}S is important as well as the contribution of excited states with n > 4.

C. Recombination of helium ions

This work considers pure ionizing plasma and neglect recombinantion of the helium ions. In the low Te or high ne plasma, however, the recombination of helium ions is not negligible on the population balance. By including recombinations, the population density n(i) is expressed as n(i) = n(i)_{ion} + n(i)_{rec}, the sum of pure ionizing and recombining components n(i)_{ion} and n(i)_{rec}. Figure 8.2 shows n(i)_{rec}/n(i) for 4^{1}D and 4^{3}S in the plasma with n_{He}/n_{He} = 0.1, where n_{He} is the density of He\textsuperscript{+} ions. The ratio of n_{He}/n_{He} = 0.1 is an example in the NAGDIS-I helium discharge plasma with Te = 8 - 20 eV and ne = 10^{11} - 4 × 10^{12} cm^{-3}. For low Te (≤ 5 eV) or very high ne (≥ 10^{17} cm^{-3}), recombination cannot be neglected. Figure 8.3 shows the influence of recombination on the several line intensity ratios at: ne = 10^{14} cm^{-3}, which shows the recombination can be neglected for Te ≥ 3 - 5 eV.

D. Relaxation time of the population densities

The population densities of the metastable states, 2^{1}S and 2^{3}S, have large relaxation times, since A_{21,2S-1S} (to the ground state) are very small, e.g. A_{21,2S-1S} = 1.7 \times 10^{-4} s^{-1} [27]. Then, the relaxation times of the 2^{1}S metastable states can be estimated as ≈ 1/neS_{21,2S} in the middle or high density plasma, where n_{e}S_{21,2S} > A_{21,2S-1S}. Here, the ionization is considered to have a largest contribution on the population balance because of the large values of S_{21,2S} (e.g. S_{21,2S} ≈ 10^{-7} cm^{3}/s at Te = 20 eV). As suggested by the ne dependence of C_{en}(λ), the contributions of 2^{1}S on the singlet populations are small. The relaxation times for the singlets can be estimated as ≈ 1/A_{ij} (≈ several tens of nanoseconds), while those for the triplets depend on the relaxation time of n(2^{3}S)/n_{He}.

IX. EXPERIMENTAL APPLICATIONS OF Te AND n_{e} MEASUREMENTS

A. Limitations for the experimental applications

Te and ne measurement technique using He I line intensity ratios neglects several factors which can deteriorate the accuracy of measurements such as,

a) hot electrons in a plasma,

b) recombinations of helium ions,

c) atomic or molecular processes modifying population balance of helium atoms not include in the model,

d) resonance scattering by ambient helium gas,

e) movement of helium atoms in the plasma.

Here, the limitations of this technique due to these factors are discussed.

(a) Since the rate coefficient C_{ij} is obtained for Maxwellian velocity distribution function, it is inherently impossible to discriminate hot electron component from the thermalized one. This method is rather sensitive to hot electrons especially for Te < 10 eV, compared to standard Te measurement methods such as Langmuir probe and Thomson scattering. However, it can be a good indication of existence of hot electrons if we can measure Te of cold or thermalized component by the other method [12]. It also may be useful for the investigation of hot electrons in the R.F. heated plasma where hot electrons are often produced.

(b) Population balances for the recombinating plasma is quite different from those for the ionizing plasma. Empirically, the contribution of recombination can be neglected for Te > 1/3 × E_{i} (E_{i} = 24.6 eV) for volume recombination. For the beam probe application, where a small amount of helium atom is injected into the plasma, the recombination can be neglected since the helium ions are quickly removed away with the magnetic
fields [9,10]. Surface recombination should be also considered for the wall facing regions in relation to the movement of recombined helium atoms.

(c) Complicated atomic processes such as charge transfer from/to various atoms and molecules or ion impact excitation and ionization can modify the population balance [29]. Proton impact must be included for high-temperature hydrogen plasma (> several hundreds eV) and for the fast helium atomic beam experiment [18].

(d) The resonance scattering influences the populations balance as a column density of the helium gas $n_{He} L > 2 \times 10^{13}$ cm$^{-2}$, which corresponds partial pressure of helium gas of $10^{-5}$ Torr for $L = 10$ cm. For the cylindrical plasma, $L$ corresponds to the radius of vacuum vessel. Reducing partial pressure of helium gas or using helium beam probe technique will solve this problem, although we should note various atomic processes involving atoms and ions in the target plasma.

(e) Movement of helium atom must be considered for low $n_e$ plasma with large relaxation time $\tau_{relax}$ or fast beam application with high helium velocity $v_{He}$, where $v_{He} \times \tau_{relax}$ is comparable or larger than the spatial length we concerned. For the plasma with low $n_e$ or small vacuum vessel, where $v_{He} \times \tau_{relax}$ is comparable to the dimensions of the vacuum vessel, population balances involving $2^3S$ metastable states will be modified. The spatial resolution of this method concerns with $v_{He} \times \tau_{relax}$, which is important for the fast beam application. Line intensity ratio data with the parameter of $n(2^1S)/n(3^3S)$ are necessary to obtain high spatial resolution. So far, the time dependent population behavior has been considered for the fast He beam probe spectroscopy in TEXTOR [9].

B. Experimental error of $T_e$ and $n_e$ measurements

Here, the experimental error of $T_e$ and $n_e$ measurement with assuming the limitations discussed above are solved. For example, errors in the $T_e$ measurement using the 492.2 nm / 471.3 nm line intensity ratio, Fig. 4.2(c), is considered for a target plasma with $T_e = 20$ eV and $n_e = 10^{12}$ cm$^{-3}$. The theoretical error due to the reliability of $C^{2^3S}_e (\lambda_1)$ is estimated within 20 %, giving the resultant $T_e$ error of $\pm 4$ eV. Adding 10 % of the experimental error on the reliability of atomic data results in $\pm 7$ eV error. The uncertainty of $n_e$ as much as a factor of two, for example $5 \times 10^{11} - 2 \times 10^{12}$ cm$^{-3}$, gives a deviation in the 492.2 nm / 471.3 nm line intensity ratio of $\pm 25$ %. Then, the resultant $T_e$ error can be estimated as $\pm 8$ eV. The error in $n_e$ measurements is considered with the 492.2 nm / 504.8 nm line intensity ratio. The reliability of $C^{2^3S}_e (\lambda_1)/C^{2^3S}_e (\lambda_2)$ is within 20 - 50 % for $n_e > 10^{10}$ cm$^{-3}$. Then, the resultant $n_e$ error reaches up to a factor of 1.5 - 2 by adding the experimental error of $\pm 10$ %. The uncertainty of $T_e$ gives small variation of the 492.2 nm / 504.8 nm intensity ratio as shown in Fig. 4.4(c). For example, $\pm 5$ eV uncertainty of $T_e$ corresponds a variation of the line intensity ratio smaller than $\pm 10$ %.

The experimental errors of $T_e$ and $n_e$ measurements depend on the plasma parameters and employed line pairs. Cross check using several line pairs will improve the reliability of the measurements. Empirically, $T_e$ and $n_e$ errors in this technique are considered within 50 % and a factor of two for the plasma with $T_e = 5 - 50$ eV and $n_e < 10^{13}$ cm$^{-3}$, respectively.

C. Conclusion

Helium I line intensity ratios have been obtained with the revised C.R. model, and summarized as a database for the $T_e$ and $n_e$ measurements. Although this technique has several limitations for experimental applications, depending on atomic and molecular species in the plasma, energy distributions of the plasma electrons and the other various particles, pressure of helium gas, and the dimensions and configurations of the device, it is still attractive for the investigations or indications of hot electrons, resonance scattering, and change in $T_e$ and $n_e$. The reliability of the line intensity ratios will be improved by including various experimental conditions in the C.R. model.

X. APPENDIX

The line intensity ratios for the experimental use are summarized as contour plots and $n_e$ and $T_e$ dependences in Figs. A1-A9. Rate coefficients for excitation and ionization $C_{ij}$ and $S_i$ from the ground state and the two metastable states $2^1S$ included in this work are shown in Figs. B1 - B4 [15-18].

ACKNOWLEDGMENTS

The authors are grateful to Prof. T. Fujimoto for the valuable discussions and for the original numerical code of the collisional radiative model.
## Tables

### TABLE I. Energy level $E(i)$ of helium atom with principal quantum number $n \leq 7$ [25].

<table>
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<tr>
<th>Term</th>
<th>$E(i)$ [eV]</th>
<th>Term</th>
<th>$E(i)$ [eV]</th>
<th>Term</th>
<th>$E(i)$ [eV]</th>
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### TABLE II. Energy level $E(i)$ of helium atom with principal quantum number $n = 8 - 30$ employed in this work.

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### TABLE III. Wavelength $\lambda$ [nm] and transition probability $A_{ij}$ [1/s] of helium atom for $i \rightarrow j$ transition helium atom [25].

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<th>Transition probability $A_{ij}$ [1/s]</th>
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<th>Transition probability $A_{ij}$ [1/s]</th>
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Figure Captions

Fig. 1 Energy level $E(i)$ of helium atom.

Fig. 2.1 Normalized population densities, $n(i)/n_{He}$, for $2^1S$ and $2^3S$, and the sums of $n(i)/n_{He}$ for singlet ($s$) and triplet ($t$) are shown as (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 2.2 Percentage contributions of (a) in-flows and (b) out-flows of electrons involving $2^1S$ at $T_e = 20$ eV.

Fig. 2.3 Percentage contributions of (a) in-flows and (b) out-flows of electrons involving $2^3S$ at $T_e = 20$ eV.

Fig. 2.4 Normalized population densities, $n(i)/n_{He}$, for $2^1P$, $3^1P$, $3^3S$, and $4^1D$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 2.5 Normalized population densities, $n(i)/n_{He}$, for $2^1P$, $3^1P$, and $3^3S$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 2.6 Percentage contributions of (a) in-flows and (b) out-flows of electrons involving $4^1D$ at $T_e = 20$ eV.

Fig. 3.1 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the resonance lines $(1^1S - n^1P)$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.2 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the singlet S lines $(2^1P - n^1S)$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.3 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the singlet P $(2^1S - n^1P)$ lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.4 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the singlet D $(2^1P - n^1D)$ lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.5 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the triplet S lines $(2^3P - n^3S)$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.6 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the triplet P lines $(2^3S - n^3P)$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 3.7 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ for the triplet D lines $(2^3P - n^3D)$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 4.1 Line intensity ratios for singlet - triplet line pairs with $\lambda \approx 500$ nm for $T_e$ measurement are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 4.2 The $T_e$ dependence of the singlet - triplet line intensity ratios with $\lambda \approx 500$ nm, (a) 504.8 nm / 471.3 nm, (b) 501.6 nm / 471.3 nm, (c) 492.2 nm / 471.3 nm.

Fig. 4.3 Line intensity ratios for singlet - singlet line pairs with $\lambda \approx 500$ nm for $n_e$ measurement are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 4.4 The $n_e$ dependence of singlet - singlet line intensity ratios with $\lambda \approx 500$ nm, (a) 501.6 nm / 504.8 nm, (b) 501.6 nm / 492.2 nm, (c) 492.2 nm / 504.8 nm.

Fig. 4.5 Line intensity ratios for the line pairs with $\lambda \approx 700$ nm are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 4.6 Line intensity ratios with $\lambda \approx 700$ nm for experimental applications; (a) $T_e$ dependence of 728.1 nm / 706.5 nm at $n_e = 10^{12}$ cm$^{-3}$, (b) $T_e$ dependence of 697.8 nm / 706.5 nm at $n_e = 10^{12}$ cm$^{-3}$, (c) $n_e$ dependence of 678.8 nm / 728.1 nm at $T_e = 20$ eV.

Fig. 5.1 Effective ionization rate coefficient $S^{eff}$ are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.2 $S^{eff}/C_{em}^{eff}(\lambda)$ for singlet S lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.3 $S^{eff}/C_{em}^{eff}(\lambda)$ for singlet P lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.4 $S^{eff}/C_{em}^{eff}(\lambda)$ for singlet D lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.5 $S^{eff}/C_{em}^{eff}(\lambda)$ for triplet S lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.6 $S^{eff}/C_{em}^{eff}(\lambda)$ for triplet P lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 5.7 $S^{eff}/C_{em}^{eff}(\lambda)$ for triplet D lines are shown in (a) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (b) $n_e$ dependence at $T_e = 20$ eV.

Fig. 6.1 Effective emission rate coefficient $C_{em}^{eff}(\lambda)$ for (a) 54.8 nm and (b) 667.8 nm in the presence of hot electrons with $T_{eh} = 20$ eV and 40 eV, $\alpha = 10\%$ at $n_e = 10^{12}$ cm$^{-3}$.

Fig. 6.2 Line intensity ratios in the presence of hot electrons, (a) 504.8 nm / 471.3 nm, (b) 492.2 nm / 471.3 nm, (c) 728.1 nm / 706.5 nm, (d) 678.8 nm / 706.5 nm.

Fig. 6.3 Effective ionization rate coefficient $S^{eff}$ in the presence of hot electrons.

Fig. 7.1 Optical depth $\tau(\lambda)$ and optical escape factor $\Lambda(\lambda)$ for 58.2 nm $(1^1S - 2^1P)$, 53.7 nm $(1^1S - 3^1P)$, and 52.2 nm $(1^1S - 4^1P)$ lines.
Fig. 7.2 Normalized population densities $n(t)/n_{He}$ as a function of helium column density $n_{He} \times L$ at $n_e = 10^{12}$ cm$^{-3}$ and $T_e = 20$ eV.

Fig. 7.3 Effective emission rate coefficients $C_{em}^{eff}(\lambda)$ as functions of helium column density $n_{He} \times L$ at $n_e = 10^{12}$ cm$^{-3}$ and $T_e = 20$ eV; (a) $1^1S - n^1P$, (b) $2^1P - n^1S$, (c) $2^3S - n^3P$, (d) $2^3P - n^3D$.

Fig. 7.4 Line intensity ratios $C_{em}^{eff}(\lambda_1)/C_{em}^{eff}(\lambda_2)$ as functions of helium column density $n_{He} \times L$. (a) Singlet - triplet pairs with $\lambda \approx 500$ nm. (b) Singlet - triplet pairs with $\lambda \approx 500$ nm. (c) Line intensity ratios with $\lambda \approx 700$ nm.

Fig. 7.5 Effective ionization rate coefficient $S^{eff}$ as a function of helium column density $n_{He} \times L$.

Fig. 8.1 Line intensity ratios in this work are compared to the results by Schweer and Behrendt; (a) 667.8 nm / 728.2 nm, (b) 501.6 nm / 504.8 nm, (c) 728.1 nm / 706.5 nm.

Fig. 8.2 Contribution of the recombining component on the population density, $n(i)_{rec} / n(i)$ at ion / atom density ratio $n_{He}^i/n_{He} = 0.1$: (a) $n(4^1D)^{rec}/n(4^1D)$, (b) $n(4^3S)^{rec}/n(4^3S)$.

Fig. 8.3 Modification of the line intensity ratios for singlet - triplet pair, 492.2 nm / 471.3 nm, 501.6 nm / 471.3 nm, 504.8 nm / 471.3 nm due to the recombining components of the excited state at ion / atom density ratio $n_{He}^i/n_{He} = 0.1$ and $n_e = 10^{12}$ cm$^{-3}$.

Appendix

Fig. A1 The 504.8 nm / 471.3 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A2 The 501.6 nm / 471.3 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A3 The 492.2 nm / 471.3 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A4 The 501.6 nm / 504.8 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A5 The 501.6 nm / 492.2 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A6 The 492.2 nm / 504.8 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A7 The 728.1 nm / 706.5 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A8 The 667.8 nm / 706.5 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. A9 The 728.1 nm / 667.8 nm line intensity ratio is shown as (a) contour plot, (b) $T_e$ dependence at $n_e = 10^{12}$ cm$^{-3}$, and (c) $n_e$ dependence at $T_e = 20$ eV.

Fig. B1 Excitation rate coefficients from the ground state $1^1S$: (a) $1^1S - n^1S$, (b) $1^1S - n^1P$, (c) $1^1S - n^1D$, (d) $1^1S - n^3S$, (e) $1^1S - n^3P$, (f) $1^1S - n^3D$.

Fig. B2 Excitation rate coefficients from the metastable state $2^1S$: (a) $2^1S - n^1S$, (b) $2^1S - n^1P$, (c) $2^1S - n^1D$, (d) $2^1S - n^3S$, (e) $2^1S - n^3P$, (f) $2^1S - n^3D$.

Fig. B3 Excitation rate coefficients from the metastable state $2^3S$: (a) $2^3S - n^1S$, (b) $2^3S - n^1P$, (c) $2^3S - n^1D$, (d) $2^3S - n^3S$, (e) $2^3S - n^3P$, (f) $2^3S - n^3D$.

Fig. B4 Ionization rate coefficients from the ground state $1^1S$ and the metastable states $2^1S$ and $2^3S$. 

- 10 -
Effective emission rate coefficient

(a) $n_e = 10^{12} \text{cm}^{-3}$

- $1^1S-\text{n}^1P$
- 51.6nm(5$^1P$)
- 52.2nm(4$^1P$)
- 53.7nm(3$^1P$)
- 58.4nm(2$^1P$)

Electron temperature $T_e$ [eV]

Fig. 3.1(a)

(b) $T_e = 20$eV

- $1^1S-\text{n}^1P$
- 51.6nm(5$^1P$)
- 52.2nm(4$^1P$)
- 53.7nm(3$^1P$)
- 58.4nm(2$^1P$)

Electron density $n_e$ [cm$^{-3}$]

Fig. 3.1(b)

Percentage contribution of electron flows [%]

(a) In-flow to $4^1D$

- Singlet $E(s) > E(2^1S)$
- Ground
- Radiative $2^1S$
- Triplet

Electron density $n_e$ [cm$^{-3}$]

Fig. 2.6(a)

(b) Out-flow from $4^1D$

- Singlet $E(s) > E(2^1S)$
- Radiative
- Ionization

Electron density $n_e$ [cm$^{-3}$]

Fig. 2.6(b)
Fig. A1(a)
Fig. A3(a)
Fig. A7(a)
Fig. A7(b)

Fig. A7(c)
Electron temperature $T_e$ [eV]

667.8nm/706.5nm

Electron density $n_e$ [cm$^{-3}$]

Fig. A8(a)
Fig. A9(a)
Fig. A9(b)

Fig. A9(c)
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