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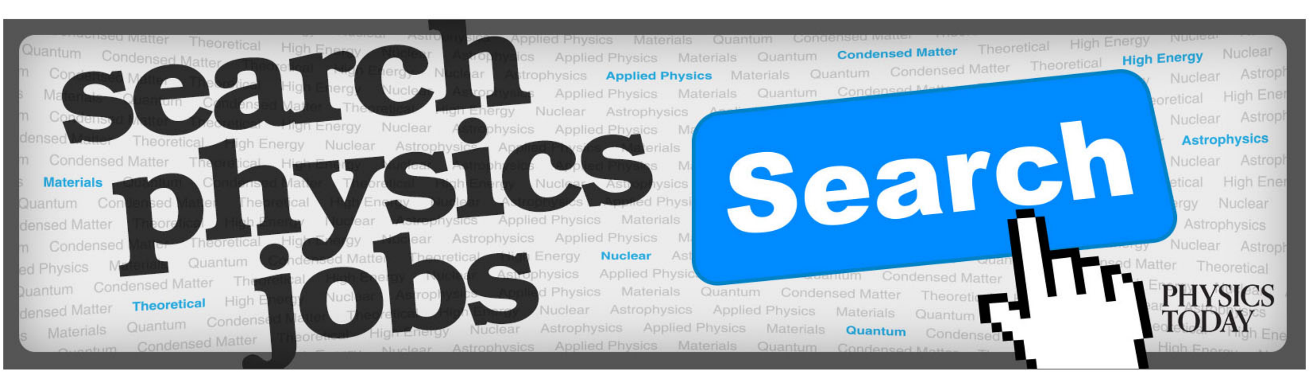

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Optical diagnostics with radiation trapping effect in low density and low temperature helium plasma

Wonwook Lee,[1,a)] Kyungdeuk Park,[2] Duck-Hee Kwon,[1] and Cha-Hwan Oh[2]
[1]Nuclear Data Center, Korea Atomic Energy Research Institute, Daejeon 34057, South Korea
[2]Department of Physics, Hanyang University, Seoul 04763, South Korea

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Low density ($n_e < 10^{11}\,\mathrm{cm}^{-3}$) and low temperature ($T_e < 10\,\mathrm{eV}$) helium plasma was generated by hot filament discharge. Electron temperature and density of neutral helium plasma were measured by Langmuir probe and were determined by line intensity ratio method using optical emission spectroscopy with population modelings. Simple corona model and collisional-radiative (CR) model without consideration for radiation trapping effect are applied. In addition, CR model taking into account the radiation trapping effect (RTE) is adopted. The change of single line intensity ratio as a function of electron temperature and density were investigated when the RTE is included and excluded. The changes of multi line intensity ratios as a function of electron temperature were scanned for various radiative-excitation rate coefficients from the ground state and the helium gas pressures related with the RTE. Our CR modeling with RTE results in fairly better agreement of the spectroscopic diagnostics for the plasma temperature or density with the Langmuir probe measurements for various helium gas pressures than corona modeling and CR modeling without RTE. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4954047]

I. INTRODUCTION

Optical emission spectroscopy (OES) is a widely used plasma diagnostics tool because OES is easy to measure, does not disturb plasmas during the measurement, and its measurement system is simple.[1] Plasma diagnostics using OES are based on comparison between theoretical and experimental transition line intensity ratios. The theoretical transition line intensities and their ratio can be expected by a population modeling.[2,3] Population densities of excited states are the functions of plasma parameters, such as electron temperature and density. Therefore, electron temperature (T_e) and density (n_e) can be determined from the matching of the theoretically modeled and the experimentally measured line intensity ratios.

Corona model has been normally adopted for low density plasma ($n_e < 10^{11}\,\mathrm{cm}^{-3}$) as a population model. Optical diagnostics using corona model have been applied to neon (Ne), argon (Ar), and their mixture plasmas and compared with another diagnostics method, such as Langmuir probe (LP). Based on the evaluation with another diagnostic method, OES synthesized with corona model has been successfully applied to determine the electron temperature for Ne[4] and Ar[5–7] in electron density ($n_e < 10^{11}\,\mathrm{cm}^{-3}$) and temperature range ($T_e < 5\,\mathrm{eV}$).

The optical diagnostics with corona model has been applied to low density helium (He) plasma as well. Boivin *et al.*[8] calculated the line intensity ratio of 504.8 nm/471.3 nm by corona model against various T_e and measured electron temperature and density with LP. Electron temperature by corona model agreed with $T_e \sim 10\,\mathrm{eV}$ by LP in $n_e < 10^{11}\,\mathrm{cm}^{-3}$ with reasonable accuracy. However, Podder *et al.*[9] reported that their calculated line intensity ratios by corona model show large difference with the measured line intensity ratio at $T_e < 5\,\mathrm{eV}$ even for similar electron density with Boivin's experiment. They suggested that collisional-radiative (CR) model with radiation trapping effect (RTE) in He plasma has to be taken into account in the population model.

RTE has been called as the induced absorption effect of atoms, stimulated absorption effect, self-absorption effect of photon, photo-excitation effect, and so on. The effect has been usually neglected in optically thin plasma. Since He CR modeling with radiative-excitation rate coefficient has been suggested by Sawada *et al.*,[10] various He plasmas have been diagnosed by CR model with RTE.[10–13] Especially, Kajita and Ohno[13] compared optically diagnosed electron temperature and density by CR model with RTE with the LP measurement for high density ($n_e > 10^{11}\,\mathrm{cm}^{-3}$) He plasma. However, in low density He plasma, the optically diagnosed plasma parameters by CR model with RTE have not been tested with another diagnostic method.

In this paper, we determined electron temperature and density by using CR model with RTE for low density ($n_e < 10^{11}\,\mathrm{cm}^{-3}$) He plasma. The optically diagnosed parameters were compared with the measured parameters with LP. Also, our CR modeling with RTE for line intensity ratios was extended to plasma density and temperature regions beyond the low density and the low temperature to verify in which density and temperature regions in RTE are significant.

This paper is organized as follows. In Section II, line intensity ratio method for optical diagnostics will be described in detail. In Section III, experimental apparatus and conditions for hot filament discharge will be stated. In Section IV, the RTE on the line intensity ratios will be discussed in detail

a)Electronic mail: wwlee@kaeri.re.kr

for CR modeling with RTE. The optically diagnosed electron temperatures and densities by various population models will be compared with the LP measurement, temperature by simple corona model, and temperature and density by CR modeling without RTE. Finally, our results will be briefly concluded in Section V.

II. LINE INTENSITY RATIO METHOD

The radiation intensity from plasma I_{ki} is given by $I_{ki} = E_{ki} N_k A_{ki}$ (W/cm^3) where E_{ki} is the energy difference between energy states E_i and E_k ($E_k > E_i$), A_{ki} is the transition probability, and N_k is the population density of upper energy state k. The line intensity ratio L can be expressed by

$$L = \frac{I_{ki}}{I_{pq}} = \frac{\lambda_{pq} N_k A_{ki}}{\lambda_{ki} N_p A_{pq}}, \tag{1}$$

where λ_{ki} is the transition wavelength from energy states k to i.

Population densities of state N_k and N_p in Eq. (1) can be determined by kinetics modelings depending on electron temperature and density of plasma.[2,3]

A. Population density models

Simple model for low density plasma is corona model which assumes that electron impact excitation and de-excitation between excited atoms and ions are neglected and spontaneous transition is only allowed by the depopulation process.[1–3,8,9] In this assumption, population density of k state is governed by the balance between the electron impact excitation from ground state to the state k and the spontaneous emission from k state, i.e.,

$$N_g n_e C_{gk}(T_e) = N_k \sum_{i<k} A_{ki}, \tag{2}$$

where N_g is the population density of ground state, n_e is the electron density, C_{gk} is the electron impact excitation rate coefficient from ground state to k state, and $\sum_{i<k} A_{ki}$ is the total transition probability from k state to lower state i. From Eqs. (1) and (2), the line intensity ratio L with corona model can be written as

$$L = \frac{\lambda_{pq} R_{ki} C_{gk}}{\lambda_{ki} R_{pq} C_{gp}}, \tag{3}$$

where R_{ki} is the branch ratio given by $A_{ki}/\sum_{i<k} A_{ki}$. In this corona model, the line intensity ratio is given as a function of only electron temperature. In our corona model calculation, the electron impact excitation cross sections given by Ralchenko *et al.*[15] and transition wavelengths and probabilities given by Wiese and Fuhr[16] were used.

When electron density increased, electron impact excitation and de-excitation between excited atoms are not neglected. Thus, corona model is no longer applied and the population model taking into account the various processes for atoms in ground state as well as in excited states is required. The CR model is the population model which includes electron impact excitation and de-excitation processes for all of the energy states, recombination processes from ionization stage, and spontaneous emission. Population density is obtained by solving a set of rate equations for a CR model. In CR modeling for neutral He,[3,17,18] the rate equation is expressed by

$$\begin{aligned} \frac{d}{dt} N_p = & \sum_{q<p} C_{qp} n_e N_q \\ & - \left[\sum_{q<p} F_{pq} + \sum_{q>p} C_{pq} + S_p + \frac{1}{n_e} \sum_{q<p} A_{pq} \right] n_e N_p \\ & + \sum_{q>p} [F_{qp} n_e + A_{qp}] N_q + \left[\alpha_p n_e + \beta_p + \beta_p^d \right] n_e N^+, \end{aligned} \tag{4}$$

where N_p and N^+ are population densities of an excited state and an ionization stage, respectively. C_{pq} and F_{pq} are the electron impact excitation and de-excitation rate coefficients from p state to q state, respectively. S_p is the electron impact ionization rate coefficient of p state, and α_p, β_p, and β_p^d are three body, radiative, and dielectronic recombination rate coefficients from an ionization state to p state, respectively. When quasi steady state (QSS) approximation of $dN_p/dt = 0$ is valid for all excited states, Eq. (4) can be simply expressed by[3,17,18]

$$N_p = R_0 n_e N^+ + R_1 n_e N_g, \tag{5}$$

where R_0 and R_1 are the population coefficients in Eq. (5). The first term is the recombining plasma component and the second term is the ionizing plasma component.

He I energy structures are shown in Fig. 1.[17] The spin singlet states and triplet states are shown in left and right sides, respectively. He I has two metastable states of 2^1S and 2^3S. When QSS approximation is not applied to the metastable

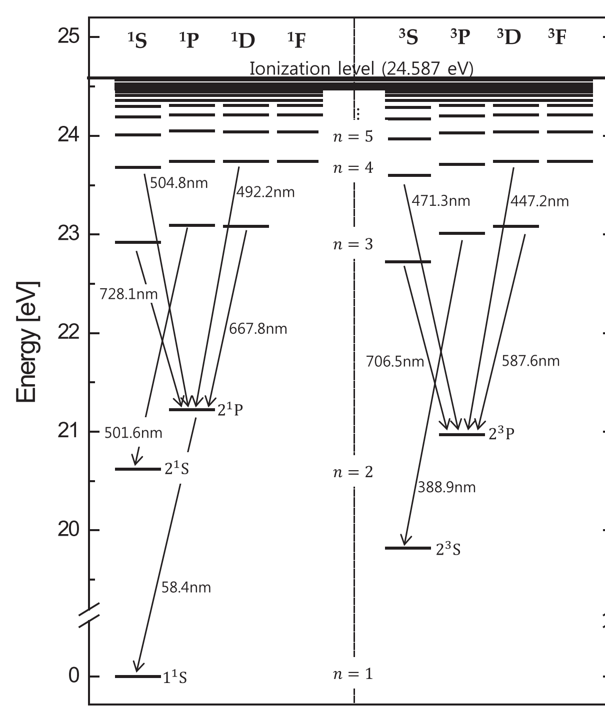

FIG. 1. Partial Grotrian diagram of neutral He.

states as well as the ground state, the population density of excited states except that of metastable states is given by[10,11,17]

$$N_p = r_0 n_e N^+ + r_1 n_e N_g + r_2 n_e N(2^1\mathrm{S}) + r_3 n_e N(2^3\mathrm{S}), \quad (6)$$

where $N(2^1\mathrm{S})$ and $N(2^3\mathrm{S})$ are the population densities of metastable states 2^1S and 2^3S, respectively. r_0, r_1, r_2, and r_3 are population coefficients in Eq. (6). The first term represents the recombining plasma component and the other terms correspond to the ionizing plasma components in Eq. (6).[3,17,18] In our CR model calculation, the source for excitation/de-excitation rate coefficients, wavelengths, and transition probabilities is same as that in our corona model calculation stated above. Other atomic data for the rate equation are same as those used in the CR modeling by Goto.[17–24] The population density obtained in this manner is used to determine the line intensity ratio of Eq. (1).

B. Radiation trapping effect

When plasma is optically thick, the radiation measured by detector becomes smaller than the radiation produced in plasma due to RTE. RTE is based on the induced absorption process of atoms where radiation spontaneously emitted by an atom is absorbed by another atoms in plasma. The attenuated radiation intensity through plasma is a function of the absorption coefficient $k_{pq} = h\nu_{pq} n_p B_{pq} I_\nu / c$[3,25] where n_p is the population density of lower state p in the RTE process, h is the Planck's constant, $h\nu_{pq}$ is the energy difference between p state and the higher q state, B_{pq} is the Einstein B-coefficient, I_ν is the line shape function, and c is the speed of light. Thus, RTE is a function of population density of lower state.

For low density plasma, optical depth is normally thin and is negligible. Corona model successfully determines the electron temperature for low density Ne and Ar plasma without considering RTE.[4–6] However, for low density He plasma, RTE from ground state to excited states is not negligible,[10,13,26] while RTE between the excited states is negligible since most of the population is in the ground state. CR model including dominant RTEs from ground state to excited states for He is given by

$$N_p = r_0 n_e N^+ + r_1 n_e N_g + r_2 n_e N(2^1\mathrm{S}) + r_3 n_e N(2^3\mathrm{S}) + r_4 K_{3^1\mathrm{P}} N_g + r_5 K_{4^1\mathrm{P}} N_g, \quad (7)$$

where $K_{3^1\mathrm{P}}$ and $K_{4^1\mathrm{P}}$ are radiative-excitation rate coefficients from the ground state to excited states 3^1P and 4^1P, respectively.[10,13] r_4 and r_5 are the population coefficients. In our CR-model calculation, RTEs for 3^1P and 4^1P are taken into account.

III. EXPERIMENTAL SETUP

Low density plasma was generated with hot filament discharge in a vacuum vessel as shown in Fig. 2(a). The details of vacuum vessel and hot filament configuration are described in Ref. 14. The He plasma was produced by the discharging power of about 150 V/7.8 A and was maintained through adjusting the heating power for the hot filament. The

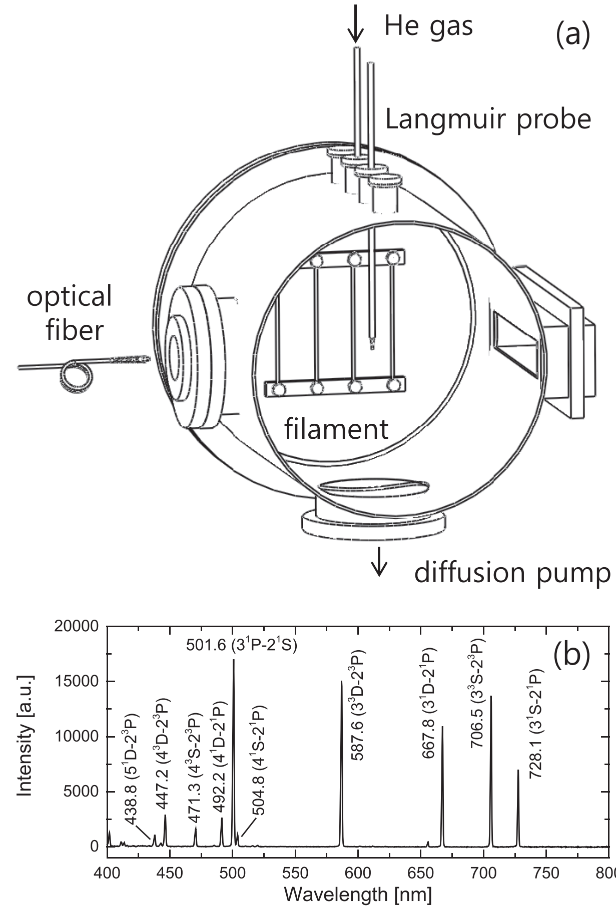

FIG. 2. (a) Schematic diagram for hot filament discharge and (b) spectrum of He plasma by hot filament discharge.

base pressure was $\sim 3 \times 10^{-5}$ Torr. He gas was injected and the gas pressure was controlled and maintained by mass-flow-rate controller (MFC) during the measurement. The plasma parameters were measured at the pressure of 0.005–0.045 Torr. The gas pressure was adapted so that He transition lines clearly distinguished and plasma was maintained stably. He particle density was calculated from He gas pressure by ideal gas law at room temperature and we assumed that He particle density was same to the population density of ground state.

LP was installed on top of the vacuum vessel to measure electron temperature and density, and located at the center of the vacuum vessel as shown in Fig. 2(a). An optical fiber with a core diameter of 400 μm collected radiation from plasma and transferred the radiation to a spectrometer. The optical fiber was placed toward the end of the LP as shown in Fig. 2(a). The spectrum of radiation was analyzed with a portable spectrometer (HR4000, Oceanoptics). Wavelength range of the spectrometer was 200 nm–1100 nm with resolution of $\sim$1 nm. All optical systems of viewport, optical fiber, and spectrometer were relatively calibrated with a quartz tungsten halogen lamp (63976, ORIEL). Exposure time of the spectrometer was 50 ms and the spectra of plasma were averaged for 10 times the measurements. Fig. 2(b) shows the spectrum of He plasma whose background spectrum without discharge was measured for every spectrum of He plasma and eliminated.

IV. RESULTS AND DISCUSSION

In order to discuss the line intensity ratio variation depending on RTE, contour plots for line intensity ratio of 504.8 nm (4^1S – 2^1P)/471.3 nm (4^3S – 2^3P) are displayed as a function of (T_e, n_e) for chosen population densities of metastable states and radiative-excitation rate coefficient in Fig. 3. Line intensity ratio not considering RTE is almost independent of electron density in $n_e < 10^{10}\,\text{cm}^{-3}$ while the line intensity ratio changes as a function of not only electron temperature but also electron density in $n_e > 10^{10}\,\text{cm}^{-3}$, as shown in Fig. 3(a). When electron temperature decreases the line intensity ratio in Fig. 3(a) decreases monotonically. Thus, the line intensity ratio of 504.8 nm/471.3 nm can be used to determine the electron temperature by corona model depending only on the electron temperature without RTE in the low electron density region of $n_e < 10^{10}\,\text{cm}^{-3}$. When RTE is considered, the line intensity ratio changes as shown in Fig. 3(b).

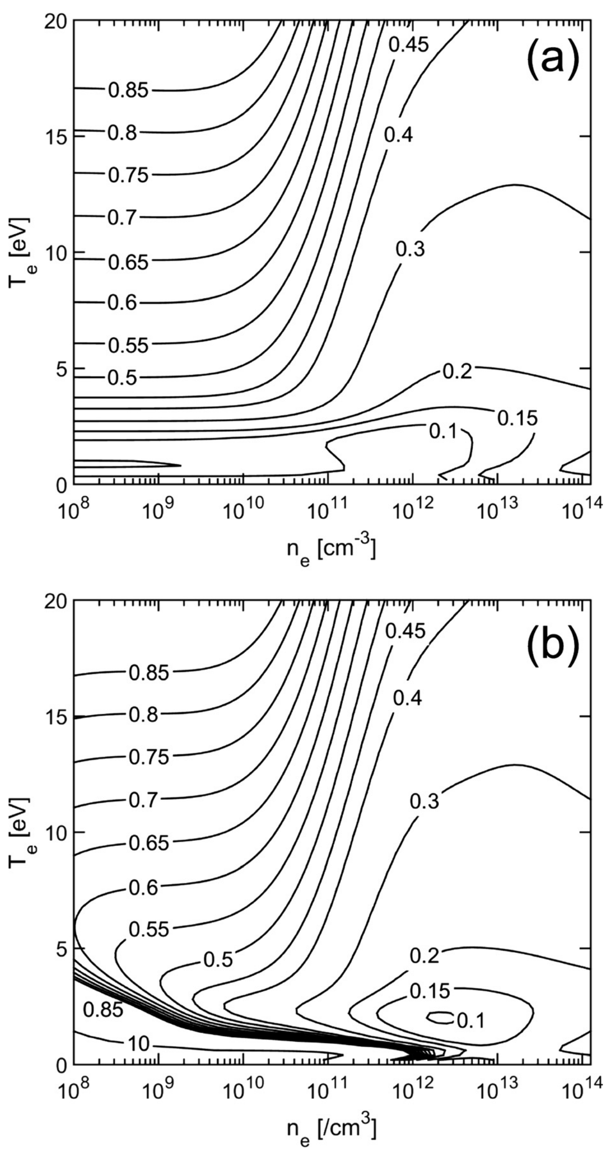

FIG. 3. Line intensity ratios of (a) 504.8 nm/471.3 nm without RTE and (b) with RTE as a function of electron density and electron temperature where $N(2^1\text{S}) = 5 \times 10^3\,\text{cm}^{-3}$, $N(2^3\text{S}) = 5 \times 10^9\,\text{cm}^{-3}$, $K_{4^1\text{P}} = 0.1$, and $N_g = 1.93 \times 10^{14}\,\text{cm}^{-3}$.

In the low electron density region $n_e < 10^{10}\,\text{cm}^{-3}$, the line intensity ratio for $T_e < 10\,\text{eV}$ changes as functions of not only the electron temperature but also the electron density. However, in the low electron density region the line intensity ratio for $T_e > 10\,\text{eV}$ is insensitive to the electron density as similar as in Fig. 3(a). Therefore, the RTE becomes significant in the low density and low temperature He plasma.

Fig. 4 shows the line intensity ratios for various transitions as a function of electron temperature when the radiative-excitation rate coefficient increased from 10^{-1} to 10^3 and the gas pressure is increased from 0.006 Torr to 0.06 Torr where $N(2^1\text{S}) = 5 \times 10^3\,\text{cm}^{-3}$, $N(2^3\text{S}) = 5 \times 10^9\,\text{cm}^{-3}$, and $n_e = 5 \times 10^9\,\text{cm}^{-3}$. Line intensity ratio as a function of electron temperature for the radiative-excitation rate coefficients and the ground state density according to the gas pressure are different for various transition lines as shown in Figs. 4(a)–4(d). The line intensity ratios change largely in $T_e < 10\,\text{eV}$ and have the same value in $T_e > 10\,\text{eV}$ when radiative-excitation rate coefficient $K_{3^1\text{P}}$ increases to 10^1. As well line intensity ratios change more sensitively in $T_e < 5\,\text{eV}$ when the gas pressure is high. The line intensity ratio of 501.6 nm (3^1P – 2^1S)/728.1 nm is about 75 and is almost constant in $T_e < 2\,\text{eV}$ when RTE is considered. The population density of 3^1P state is the most effective on the RTE and the population density in $T_e < 2\,\text{eV}$ is mainly determined by RTE. As electron temperature increases and the electron-impact excitation and de-excitation processes become large in $T_e > 2\,\text{eV}$, the line intensity ratio of 501.6 nm/728.1 nm changes rapidly and meets the line intensity ratio not considering RTE. Therefore, RTE is the dominant process in low temperature ($T_e < 10\,\text{eV}$) and low density ($n_e < 10^{11}\,\text{cm}^{-3}$) He plasma.

In corona model, line intensity ratio is given as a function of only electron temperature, because C_{gk} in Eq. (3) is a function of electron temperature. The electron temperature of the discharged plasma can be simply determined by comparing the measured line intensity ratio with the line intensity ratio calculated by corona model. However, in CR model, line intensity ratio is given as a function of more plasma parameters. Electron temperature and electron density in CR model are determined as the values minimizing the error function

$$f_{err}\left(T_e, n_e, N(2^1\text{S}), N(2^3\text{S}), K_{3^1\text{P}}, K_{4^1\text{P}}\right) = \sum \left(\frac{L_{exp} - L_{CR}}{L_{CR}}\right)^2, \quad (8)$$

where L_{exp} and L_{CR} are the line intensity ratios determined by experiment and CR model, respectively.

Fig. 5 shows the diagnosed electron temperatures and densities against He pressure and these plasma parameters are measured by LP and determined by OES combined with population modeling. The gray triangles represent electron temperature determined by corona model. Single line intensity ratio of 504.8 nm (4^1S – 2^1P)/471.3 nm (4^3S – 2^3P) is selected to compare with the previous results.[8,9] The blue diamonds and red circles represent electron temperature and densities which are determined by CR-model with RTE and without RTE, respectively. Five intensity ratios of 667.8 nm

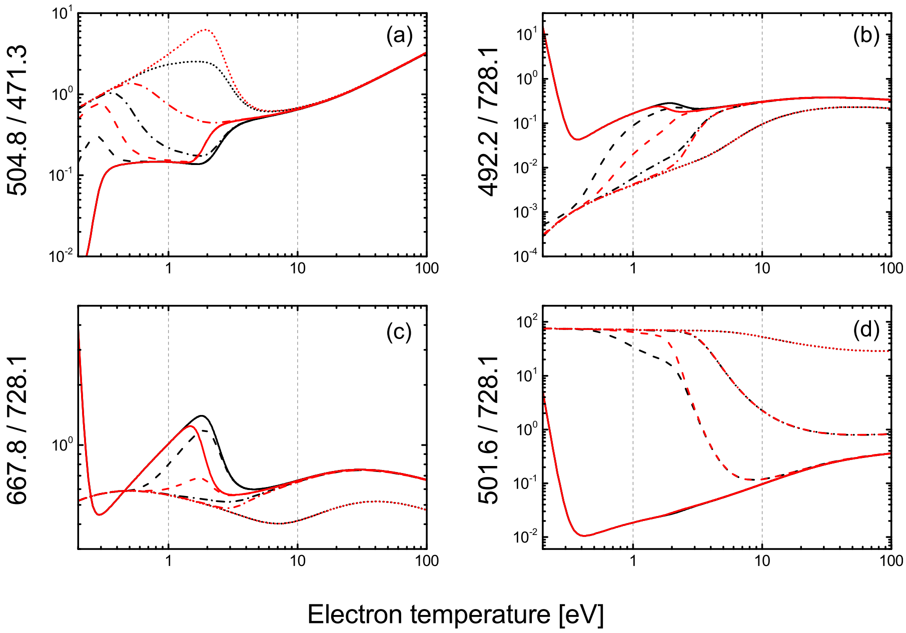

FIG. 4. Line intensity ratios for (a) 504.8 nm/471.3 nm, (b) 492.2 nm/728.1 nm, (c) 667.8 nm/728.1 nm, and (d) 501.6 nm/728.1 nm as a function of electron temperature at electron density of $n_e = 5 \times 10^9\,\mathrm{cm}^{-3}$ for various radiative-excitation rate coefficients. Black and red lines represent the line intensity ratios where He gas pressure are 0.006 Torr ($N_g = 1.93 \times 10^{14}\,\mathrm{cm}^{-3}$) and 0.06 Torr ($N_g = 1.93 \times 10^{15}\,\mathrm{cm}^{-3}$), respectively. Solid lines represent the line intensity ratios without RTE and dashed, dashed-dotted, and dotted lines represent the line intensity ratios by considering RTE with the coefficients $K_{3^1\mathrm{P}} = 10^{-1}$, 10^1, and 10^3, respectively, where $N(2^1\mathrm{S}) = 5 \times 10^3\,\mathrm{cm}^{-3}$ and $N(2^3\mathrm{S}) = 5 \times 10^9\,\mathrm{cm}^{-3}$.

(3^1D – 2^1P)/728.1 nm (3^1S – 2^1P), 728.1 nm/706.5 nm (3^3S – 2^3P), 501.6 nm (3^1P – 2^1S)/728.1 nm, 447.2 nm (4^3D – 2^3P)/706.5 nm, and 492.2 nm (4^1D – 2^1P)/728.1 nm are selected in the determination of the electron temperature and the electron density by minimizing the error function of Eq. (8). The set of plasma parameters which minimized the error function f_{err} are displayed with the averaged value for ten sets and the error bars which denote the maximum difference. f_{err} for CR-model without RTE are minimized at over than 0.96, while f_{err} for CR-model with RTE are minimized at less than 0.045. The value of $f_{err} > 0.96$ means it is impossible for CR model without RTE to obtain the value which simultaneously satisfies five line intensity ratios. Especially, the measured intensity of 501.6 nm (3^1P – 2^1S) is larger than that of 728.1 nm and the measured line intensity ratios of 501.6 nm/728.1 nm are 2–2.5 while the determined intensity by the CR-model without RTE is smaller than that of 728.1 nm and the ratio is less than 0.1. Thus, the CR-model not considering RTE cannot exactly expect the measured line intensity ratios of low density and low temperature He plasma.

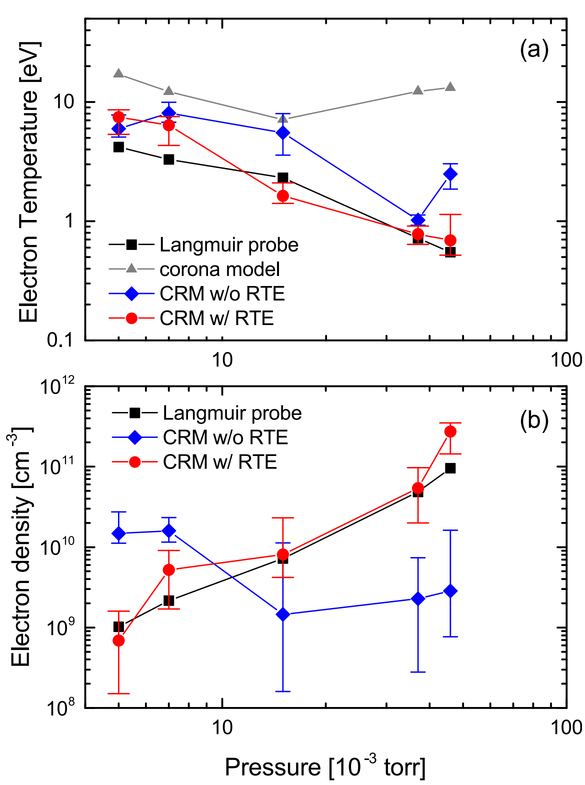

FIG. 5. (a) Electron temperatures by the LP measurement and by OES combined with corona model and CR model and (b) electron densities by the LP measurement and by OES combined with CR model as a function of He gas pressure. Five line intensity ratios (see the text of Sec. IV) were selected to determine the electron temperature and the density by the OES with the CR models.

As He pressure increases, the electron temperature decreases and electron density increases in the case of LP measurement as shown in Figs. 5(a) and 5(b). The electron temperatures by corona model are much higher than the LP measurement and show different values for the LP measurement when the gas pressure increases. Also, the electron temperatures and densities determined by CR-model without RTE have large different values from the LP measurement when gas pressure changes. The discrepancy for electron temperature and density as well as their change against gas pressure is greatly resolved by CR model with RTE. The electron temperatures and densities by CR model with RTE are in good agreement with the LP measurement as shown in Fig. 5.

V. CONCLUSION

We have calculated the population densities of He I excited states by corona, CR model with RTE, and CR model without RTE and performed various parametric studies for the line intensity ratio by the CR model with RTE. When RTE was considered, the line intensity ratios have changed in low electron density ($n_e < 10^{11}\,\mathrm{cm}^{-3}$) region. Line intensity ratios are sensitive to RTE in $T_e < 10$ eV and RTE can be negligible in $T_e > 10\,\text{eV}$. RTE is the most dominant processes in low density ($n_e < 10^{11}\,\text{cm}^{-3}$) and low temperature ($T_e < 10\,\text{eV}$) He plasma. In order to determine electron temperature and density of He plasma, we have generated low density ($n_e < 10^{11}\,\text{cm}^{-3}$) and low temperature ($T_e < 10\,\text{eV}$) He plasma and measured electron temperature and density with LP and by OES with various population modelings for different gas pressures. When RTE is neglected, the optically diagnosed electron temperatures with the corona and the CR modeling show large difference with those by the LP measurement. When RTE is taken into account for CR modeling, the electron density and temperature are in good agreement with those by the LP measurement.

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