Diagnostics of helium plasma by collisional-radiative modeling and optical emission spectroscopy

Wonwook Lee[*] and Duck-Hee Kwon
Nuclear Data Center, Korea Atomic Energy Research Institute, Daejeon, 305-353, Korea
[*]Corresponding author: wwlee@kaeri.re.kr

1. Introduction

Optical diagnostics for the electron temperature (T_e) and the electron density (n_e) of fusion plasma is important for understanding and controlling the edge and the divertor plasmas in tokamak. Since the line intensity ratio method using the collisional-radiative modeling and OES (optical emission spectroscopy) is simple and does not disturb the plasma, many fusion devices with TEXTOR, JET, JT-60U, LHD, and so on, have employed the line intensity ratio method as a basic diagnostic tool for neutral helium (He I) [1].

The accuracy of the line intensity ratio method depends on the reliability of the cross sections and rate coefficients. Especially, the reaction cross sections by the electron impact are important factor affecting the results of the collisional-radiative modeling.

We performed state-of-the-art R-matrix calculations including couplings up to n=7 states and the distorted wave (DW) calculations for the electron-impact excitation (EIE) cross sections of He I using the flexible atomic code (FAC) [2]. The collisional-radiative model for He I was constructed using the calculated the cross sections.

2. Collisional-Radiative Model

The population densities of the energy states of He I were calculated by the collision-radiative model and expressed as

$$\begin{aligned}\frac{d}{dt}n(p) &= \sum_{q<p} C(q,p)n_e n(q) \\ &\quad - \left[\sum_{q<p} F(p,q) + \sum_{q>p} C(p,q) + S(p) + \frac{1}{n_e}\sum_{q<p} A(p,q)\right] n_e n(p) \\ &\quad + \sum_{q>p}\left[F(q,p)n_e + A(q,p)\right] n(q) \\ &\quad + \left[\alpha(p)n_e + \beta(p) + \beta_d(p)\right] n_e n^+ \quad , \qquad (1)\end{aligned}$$

where the excitation by photon was neglected, p and q represent any energy states of helium except for the ground state. $n(p)$ and n_e indicate the densities of p-state and the electron density, respectively. n^+ is the density of the singly ionized helium. $C(p,q)$, $F(q,p)$, and $S(p)$ are the rate coefficients of the electron impact excitation, de-excitation, and ionization, respectively. $A(p,q)$ is the Einstein A coefficient from p-state to q-state. $\alpha(p)$, $\beta(p)$, and $\beta_d(p)$ represent the rate coefficients of the three-body recombination, the radiative recombination, and the dielectronic recombination, respectively.

From the quasi-steady-state condition, Eq. (1) is approximated to zero for all helium energy states except for the ground state. [3,4]

$$\frac{d}{dt}n(p) = 0 \quad \text{for } p > 2 \qquad (2)$$

Thus, $n(p)$ is expressed by the linear coupled equation as

$$n(p) = r_0 n_e n^+ + r_1 n_e n(1) \quad , \qquad (3)$$

where $n(1)$ is the density of the ground state. The r_0 and r_1 are the population coefficient as a function of n_e and T_e. The first term in the right side indicates the recombining plasma component and the second term denotes the ionizing plasma component.

The rate coefficients of the electron-impact excitation, de-excitation, and ionization were derived from the cross sections. The cross sections for the electron-impact excitation were calculated by the state-of-the-art R-matrix method at near threshold energy and the distorted wave method in the range far from the threshold energy. The cross section by the distorted wave method was extrapolated to the Bethe limit. All calculations were performed with the FAC code modified to enable parallel computation by us.

3. Line intensity ratio method

Assuming a uniform distribution of the plasma at the area seen by the spectrometer, the measured intensity of radiation is expressed by

$$I(\lambda_{ki}) = \frac{1}{4\pi} N_k A_{ki} V \Omega T(\lambda_{ki}) \eta(\lambda_{ki}) \qquad (4)$$

where V is the plasma volume seen by the spectrometer, Ω is the solid angle of the optics collecting the radiation, $T(\lambda_{ki})$ is the transmission factor of the measuring system, and $\eta(\lambda_{ki})$ is the quantum efficiency of the detector at wavelength λ_{ki}. From Eq. (4), the line intensity ratio is described by

$$\frac{I(\lambda_{ki})}{I(\lambda_{qp})} = \frac{1}{F_R}\frac{N_k A_{ki}}{N_q A_{qp}} \qquad (5)$$

where F_R is the relative calibration factor of the detection system. The ratio of the population density is simply determined by the transition line intensity ratio.

In order to diagnose the electron temperature and density of the plasma, we selected the transition line sets of 667.8nm (3^1D-2^1P), 706.5nm (3^3S-2^3P), and 728.1nm (3^1S-2^1P). The dependencies of the line ratio for the electron density and the electron temperature were calculated by the collisional-radiative model, as shown in Fig. 1. The line intensity ratio of $I_{667.8}$ / $I_{728.1}$ was sensitive to the electron density, and the line intensity ratio of $I_{706.5}$ / $I_{728.1}$ changed significantly as functions of both the electron density and the electron temperature.

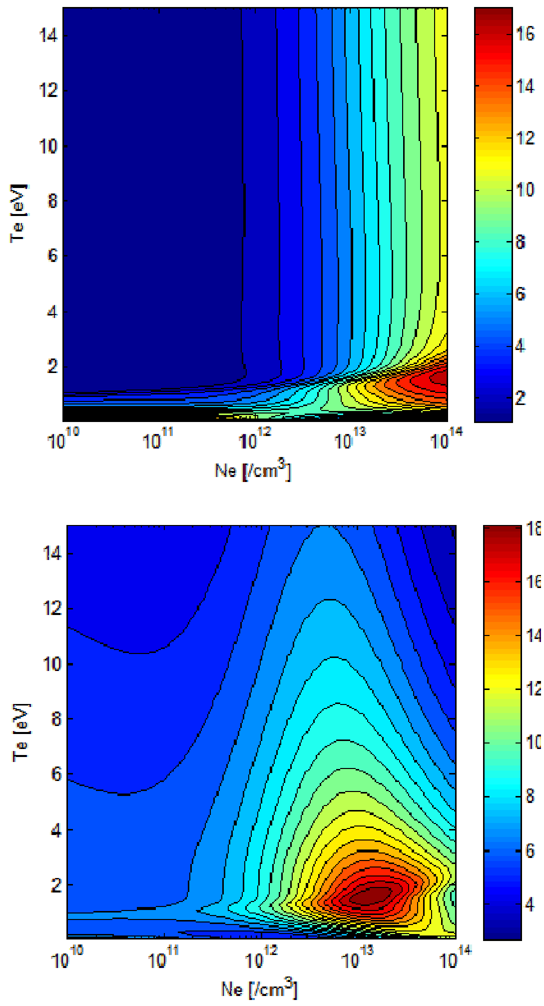

Fig. 1. Contour plot of the line intensity ratios of (a) $I_{667.8}$ / $I_{728.1}$ and (b) $I_{706.5}$ / $I_{728.1}$.

The electron density and electron temperature of plasma were determined by minimizing the test function.

$$f(T_e,n_e)=\sum_i\left(\frac{R_i^{exp}-R_i^{cal}(T_e,n_e)}{R_i^{exp}}\right)^2 \qquad (6)$$

where R^{exp} is the line intensity ratio which is measured by experiment, R^{cal} is the calculated line intensity ratio from the helium collisional-radiative model. The summation was performed for the selected transition line set.

3. Conclusions

The helium collisional-radiative model for He I was constructed to diagnose the electron temperature and the electron density of the plasma. The electron impact excitation cross sections in the collisional-radiative model were calculated by the R-matrix method and the distorted wave method. The electron temperature and density were determined by using the line intensity ratio method.

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