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Effect of Radiation Trapping on an He I CR Model for a Divertor Simulator MAP-II

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Abstract

An He I collisional-radiative (CR) model with radiation trapping was applied to spectroscopic data obtained in a divertor simulator MAP-II. We first applied the model to ionizing plasmas and examined the correction mode by taking into consideration the effect of radiation trapping. In the recombining plasmas, the electron density obtained from the best-fit of the model to measured n^3D populations decreased by several tens percent when the radiation trapping was included. This result shows that the effect of radiation trapping for resonant transition must be taken into consideration even for the measurement using triplet series.

Keywords:

radiation trapping, collisional-radiative model, He I, optical escape factor, recombining plasma, divertor simulator, MAP-II

1. Introduction

Measurement of electron temperature (T_e) and electron density (n_e) is important to understand plasma dynamics in the divertor region of nuclear fusion devices. The Langmuir probe method is widely used for parameter measurement in various plasmas. In the application to divertor plasmas, however, large heat flux can result in the erosion of the probe tip in high density ionizing plasmas, while in recombining plasmas, an anomaly in the probe current (I)-voltage (V) characteristics disturbs the measurement of T_e and n_e [1]. Thus, passive spectroscopies are thought to be alternatives for the measurement of the parameters of divertor plasmas.

For the spectroscopic measurement of T_e and n_e based on the intensity ratio of He I series, we need a proper model of the excitation and de-excitation processes. A collisional-radiative (CR) model for He I was first developed by Fujimoto in 1979 [2], and updated by Goto in 2003 [3]. Because neutral density is high (10^{11}-10^{15} cm^{-3}) in the divertor region, the effect of the radiation trapping of the resonance lines must be taken into consideration. The optical escape factor, which is used for describing the effective radiative decay rate, was first formulated by Holstein in terms of optical depth [4,5], and modified by Otsuka *et al.* [6] and Fujimoto [2] to yield more accurate values over a wider range of optical depth. Fujimoto developed a CR model for He I with radiation trapping by including the optical escape factor [2].

In the present study, we applied the CR model for He I with Otsuka's optical escape factor to ionizing and recombining plasmas in a divertor simulator MAP-II [7, 8]. The former application was aiming at confirming the effect of radiation trapping for known T_e and n_e, while the latter was aiming at determining them only from the spectroscopic results.

2. Effect of radiation trapping on an He I CR model

2.1 Optical escape factor

Under the condition of considerable gas density, the spatial distribution of the resonant state is modified due to the optical trapping as if the corresponding spontaneous emission coefficient A decreases to $\Lambda(\boldsymbol{r}_0)A$. Here, the optical escape factor $\Lambda(\boldsymbol{r}_0)$ for the position $\boldsymbol{r}_0$ is dependent on the parameter profiles of the plasmas. Otsuka [6] and Fujimoto [2] formulated the optical escape factor in the infinite cylindrical plasma for which the line profile of the emission/absorption spectra with respect to the resonant state can be described by Gaussian. Let $n_k(\boldsymbol{r}_0)$ and $n_i(\boldsymbol{r}_0)$ be the population densities at the position $\boldsymbol{r}_0$ in the media, where k and i denote the upper and lower state for the transition $k \rightarrow i$, respec-

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tively. Otsuka analytically deduced the optical escape factor on the axis of a cylinder ($r_0 = 0$) based on the assumption that $n_k(r_0) = \beta n_i(r_0)$, where β is a constant, as

$$\Lambda_{ik}(0) = \frac{2}{\pi}\int_0^\infty \mathrm{d}x \int_0^1 \mathrm{d}t \exp\left[-x^2 - \frac{\hat{\tau}}{\sqrt{1-t^2}}\exp(-x^2)\right]. \tag{1}$$

The optical depth $\hat{\tau}$ for the transition $k \to i$ at the center of the line profile is described as

$$\hat{\tau} = \frac{e^2}{4m_e c\epsilon_0} f_{ik}\left(1 - \beta\frac{g_i}{g_k}\right)\lambda_{ki}\sqrt{\frac{M}{2\pi\kappa_B T_g}}\int_0^l n_i(\rho)\mathrm{d}\rho, \tag{2}$$

where f_{ik} is the absorption oscillator strength ($i \to k$), λ_{ki} is the wavelength for the transition $k \to i$, m_e is the mass of the electron, M is the mass of the He atom and T_g is the gas temperature. l is the effective radius of the plasma and needs to be left as a free parameter.

In the present study we assumed the uniformity of the ground and upper state density profiles. The term $\beta(g_i/g_k)$ in eq. (2), which came from an induced emission process, was neglected in the calculation becausethe upper state density is smaller than that of the ground state by a few orders of magnitude in the present conditions.

It should be noted that Fujimoto's formula in ref. [2] assumed that $n_k(r_0)$ is a parabolic function while $n_i(r_0)$ is a constant. If we apply Fujimoto's model for the same $n_k(0)$ and l, the difference in the resulting $\Lambda_{ik}(0)$ becomes 2.5 times larger for the optically thick ($\hat{\tau} > 10$) region, which is practically within the ambiguity in the choice of l.

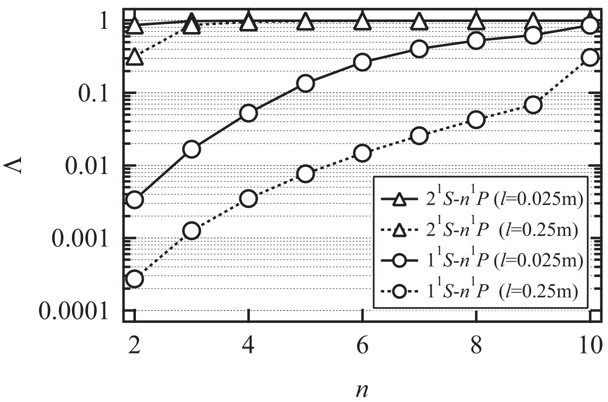

Fig. 1 Optical escape factor for 1^1S – n^1P and 2^1S – n^1P transitions for two different lengths of the system l.

The optical escape factors Λ for the resonance transition $1^1\mathrm{S} - n^1\mathrm{P}$ and for the non-resonance transition $2^1\mathrm{S} - n^1\mathrm{P}$ as a function of the principal quantum number n of the upper states are shown in Fig. 1. Based on our experimental conditions, T_g, n_{1^1S} and n_{2^1S} of 300 K, 1.1×10^{14} cm^{-3} and 5.3×10^9 cm^{-3}, respectively, are used in the calculation. Because the position of the plasma boundary cannot be determined clearly, two extreme cases for l were chosen. One is the radius of the plasma column, 0.025 m, while the other is that of the vacuum chamber, 0.25 m. As shown in Fig. 1, Λ for $2^1\mathrm{S} - n^1\mathrm{P}$ are almost equal to unity, whereas those for $1^1\mathrm{S} - n^1\mathrm{P}$ are smaller than that by a few orders of magnitude. Therefore, Λ of the radiative transition to the 1^1S state needs to be taken into account in the analysis of our spectroscopic results.

2.2 CR model with radiation trapping

The outflow rates of the population from 2^1P and 7^1P states due to the electron impact excitation and de-excitation are compared with that due to the spontaneous emission in Table 1. In the case of 2^1P, the outflow rate due to spontaneous emission is larger than that due to the electron impact, whereas for 7^1P, the outflow rate due to electron impact is larger than that due to spontaneous emission by two orders of magnitude. Thus, for determining the population of the excited state atoms in our conditions, the radiation trapping from the states of small principal quantum number is important.

In the following CR model calculation, we replaced A with ΛA for $1^1\mathrm{S} - n^1\mathrm{P}$ ($n = 2 \sim 7$) transitions. We refer to this as a modified CR model hereafter to distinguish it from the CR model without radiation trapping. We assumed a quasi-steady-state (QSS) approximation even for meta-stable levels. This assumption is valid in the present condition because the decay time due to the electron collision (~ 0.41 ms for 2^1S and ~ 0.87 ms for 2^3S) is much shorter than the residence time of neutrals (~ 16 ms). Therefore, the population of each excited level can be expressed as the sum of the ionizing component and the recombining component. In this paper, only the ionizing component was used for ionizing plasma while only the recombining component was

Table 1 Comparison of the decay rate of 2^1P and 7^1P populations due to the electron impact with that due to the spontaneous emission. ΛA is also evaluated. $n_e = 1.0 \times 10^{12}$ cm^{-3} and $T_e = 6.1$ eV were used.

state	decay rate by electron impact		decay rate by spontaneous emission		
	$n_e \sum C_{p\to q}$ [s^{-1}]		$\sum A$ [s^{-1}]		$\sum \Lambda A$ [s^{-1}]
2^1P	1.34×10^6	$<$	1.80×10^9	$\to$	8.02×10^6
7^1P	1.52×10^9	$\gg$	4.85×10^7	$\to$	2.10×10^7

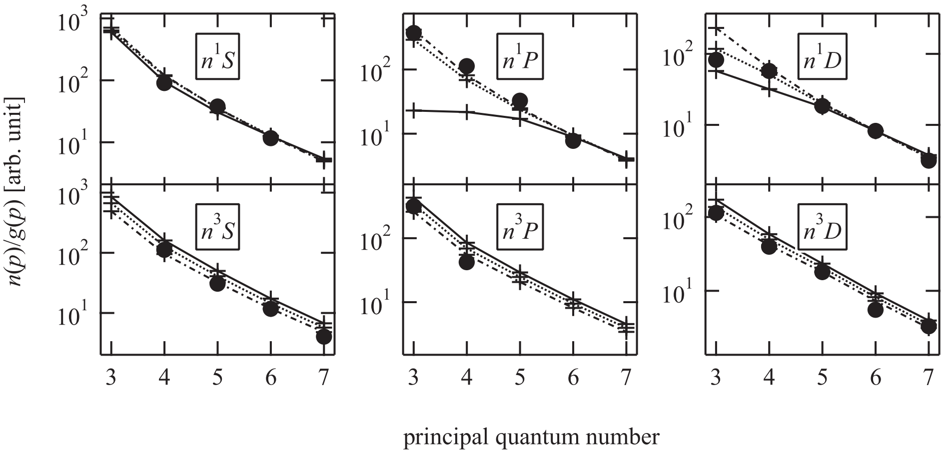

Fig. 2 Relative population per degeneracy (*g*) of excited levels of He I is shown as a function of principal quantum number. Filled circles show the measured population distribution, solid lines the calculations based on the unmodified CR model, and dashed and dotted lines the calculations based on the modified CR model with $l = 0.025$ m and 0.25 m, respectively.

used for recombining plasma, because the other component was negligible.

3. Experiment

3.1 Applicability of the modified CR model

The population distribution for six sublevels of He I in the ionizing plasmas was obtained from the spectroscopic measurement and was compared with that deduced from the CR model calculation as shown in Fig. 2. The three conditions for the calculation were an unmodified CR model, a modified CR model with an absorption length l of 0.025 m, and a modified CR model with an absorption length of 0.25 m. The T_e and n_e values used for the model calculation were obtained by the Langmuir probe measurement, and were 6.1 eV and 1.0×10^{12} cm^{-3}, respectively. It should be noted that the calculated populations were normalized to an average value of $n = 6$ levels over the whole terms obtained experimentally.

As shown in Fig. 2, the large deviation from the experimental data observed in the case of the unmodified CR model in n^1P and n^1D was compensated for in the case of the modified CR model. On the other hand, these differences were not clear in the n^1S and the three triplet terms in this logarithmic scale. This is because the redistribution of the population from n^1P to these states was rather small. These results confirm the validity of the modified CR model used in our experiment. The effect of the small difference found in the linear scale on the n_e measurement is important for the study of recombining plasmas as shown in the next section.

3.2 Application to recombining plasmas

We observed the spectra from Electron-Ion Recombination (EIR) phase plasmas at the periphery of the plasma column. In this case, a Boltzmann-plot of the measured population in the Rydberg state yields T_e [7]. The deduced value depends on the lowest principal quantum number usable for the fitting procedure. In our plasmas, the obtained T_e from n^3D for $n = 9 - 15$ was 0.070 ± 0.003 eV. Note that this value may be slightly overestimated, since, in partial local thermal equilibrium plasmas, the slope of the Boltzmann plot in the finite n is smaller than that in the ionization limit.

For the application of the CR model to recombining plasmas, the 2^3P – n^3D series was used because it is the brightest among the six He-Balmer series. Comparing the measured population ratio of n^3D with the CR model calculation for $l = 0.025$ m, we obtained T_e and n_e as 0.06 eV and 1.22×10^{12} cm^{-3}, respectively. On the other hand, these values were 0.06 eV and 1.16×10^{12} cm^{-3}, respectively, for $l = 0.25$ m. The result for $l = 0.025$ m is shown in Fig. 3. It should be noted that the measured population for $n = 6$ happened to be irregular in this shot, and thus this point was removed from the analysis. The sensitivity of the population of n^3D series to n_e is so high that n_e can be determined to a considerable accuracy by using this small difference observed in the linear scale of Fig. 3. In comparison, the results obtained based on the unmodified model were 0.06 eV and 1.62×10^{12} cm^{-3}. One can see that the obtained T_e is not largely dependent on the optical escape factor in the recombining plasmas, while the obtained n_e decreases by several tens percent by using the modified CR model. This result shows that the effect of radiation trapping must be included for the n_e measurement even when we make use of the n^3D series which are not optically coupled with the singlet states. As seen in the

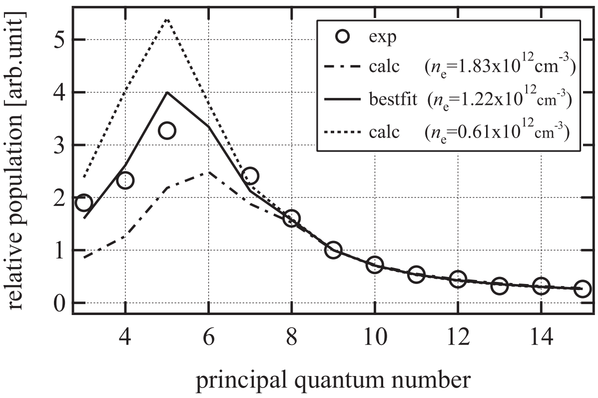

Fig. 3 Best-fit of the n^3D population to experimental data to determine n_e and T_e. Populations for $n_e = 0.61 \times 10^{12}$ cm^{-3} and 1.83×10^{12} cm^{-3} for the same T_e are calculated as a comparison.

dependence of deduced n_e on l, ambiguity of l leads to an error of about ten percent in the measurement of n_e. This is because the increased population in the n^1P state due to the radiation trapping is redistributed through the collisional processes.

4. Summary

The effect of radiation trapping on an He I CR model was investigated. In the divertor plasma simulator MAP-II, the effective spontaneous transition probability for 1^1S – n^1P was decreased by the order of magnitude due to the self-absorption process. In the ionizing plasmas, using the modified CR model, which adopts an the optical escape factor and the effective A values, the calculated population distribution of He I almost reproduced the experimental result. In the recombining plasmas, T_e and n_e can be obtained by the best-fit of the n^3D population. By applying the modified CR model, the best-fitted n_e was decreased by several tens percent compared with that from the unmodified CR model. The ambiguity of the best-fitted n_e value caused by the ambiguity of l was estimated to be about ten percent.

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