Iterative calculation of helium atom radiation trapping
ヘリウム原子発光線の輻射輸送収束計算

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An iterative computational method for solving the radiative transfer equation coupled with the collisional-radiative rate equation (K. Sawada: J. Plasma Physics 72 (2006) 1025-1029.) is applied to neutral helium collisional-radiative model (M. Goto: JQSRT 76 (2003) 331.). Emission intensity of 3^1P- 2^1S and 4^1P- 2^1S are well reproduced by the model.

1. Introduction

Analysis of the intensity of neutral helium line radiation by the collisional-radiative model (CR model) [1] is a standard technique for determining the electron temperature T_e and density n_e. However, in general, evaluating the contribution of radiation trapping is a difficult task because emission or absorption in one location depends on the radiation flux coming from the rest of the plasma.

We have proposed a simple experimental method [2] to evaluate the effect of the radiation trapping on the excited state population distribution; photo-excitation events from the ground state 1^1S to the 2^1P, 3^1P, and 4^1P states per second per one atom are treated as fitting parameters in the CR model in addition to T_e, n_e, and the ground and meta-stable populations $n(1^1S)$, $n(2^1S)$, $n(2^3S)$ to reproduce measured population distribution [2,3].

This simple method was well tested [3]. However, for low temperature plasmas ($T_e < 10$ eV), because T_e dependence to the excited state population distribution is small, the ground state atom density, e.g., evaluated from the gas pressure, should be given to the model. [4]. In this case, T_e is determined from the absolute intensity of helium lines.

We have previously constructed an iterative computational code for atomic hydrogen which solves the radiative transfer equation coupled with the CR model rate equation [5]. In this study, we developed iterative helium CR model for the purpose of evaluating $n(1^1S)$ from populations of 3^1P, and 4^1P evaluated by visible spectroscopic measurement.

2. Model

Population of excited state p is given in the form

$$\begin{aligned} &n(p) \\ &= r_1(p)\, n(1^1S)\, n_e + r_2(p) n(2^1S)\, n_e + r_3(p) n(2^3S)\, n_e \\ &+ R_{2^1p}(p)\, n(1^1S) I_{2^1p} \\ &+ R_{3^1p}(p)\, n(1^1S) I_{3^1p} + R_{4^1p}(p)\, n(1^1S) I_{4^1p} + \dots , \end{aligned} \quad (1)$$

where $r_1(p)$, $r_2(p)$, $r_3(p)$, and $R_{2^1p}(p)$, $R_{3^1p}(p)$, $R_{4^1p}(p)$ are population coefficients calculated by the CR model. The parameters I_{2^1p}, I_{3^1p}, and I_{4^1p} are the photo-excitation rates from the ground state 1^1S to the 2^1P, 3^1P, and 4^1P states per one atom, respectively [2]. In the experiment in Ref. 2 the fitting parameters T_e, n_e, $n(1^1S)$, $n(2^1S)$, $n(2^3S)$, I_{3^1p}, I_{4^1p} are determined from the emission intensities of visible singlet and triplet 16 emission lines including 3^1P- 2^1S and 4^1P- 2^1S.

When T_e, n_e, $n(1^1S)$, $n(2^1S)$, and $n(2^3S)$ are given, the following iterative algorithm is applied to radiation trapping analysis [5]:

1. Divide the space into cubic cells of linear dimension Δl.
2. For each cells, give T_e, n_e, $n(1^1S)$, $n(2^1S)$, $n(2^3S)$ and the line profile function $g(\nu)$ for the transition from the 3^1P - 1^1S and 4^1P - 1^1S.
3. Compute the excited state population distribution for each cell using Eq.(1) without considering the photo-excitation.
4. Compute the I_{3^1p} and I_{4^1p} using the $n(p)$ obtained in step 3 considering emission and absorption for each cell.
5. Considering the photo-excitation, compute the population distribution for each cell using Eq.(1).

6. Iterate steps 4 and 5 until the above values converge.

We applied this iterative method to helium atom CR model.

3. Results and Discussion

In order to test the iterative helium CR model developed in this study, we applied it to a cylindrical RF plasma. Plasma radius is 2.5×10^{-2} m.

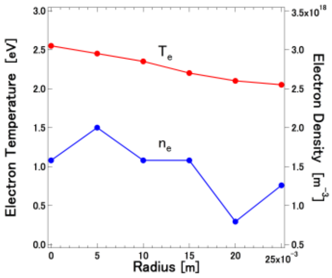

Fig.1. Radial profiles of T_e and n_e.

First, as the analysis in Ref. 2, we determined parameters T_e, n_e, $n(1^1S)$, $n(2^1S)$, $n(2^3S)$, and $I_{3\ p}^{1}$, $I_{4\ p}^{1}$. Figure 1 shows T_e and n_e. The density of the ground state atom is 1.16×10^{21} m^{-3}.

Next, we calculated $I_{3\ p}^{1}$ and $I_{4\ p}^{1}$ using the iterative CR model with the values of T_e, n_e, $n(1^1S)$, $n(2^1S)$, $n(2^3S)$. Gas temperature is 300 K. In the calculation, cubic cell with the edge length Δl of one-fifth of the absorption length at the center wavelength is used: 1.7×10^{-4} m for 3^1P-1^1S and 4.2×10^{-4} m for 4^1P- 1^1S, respectively. We assume uniform plasma in the direction of the cylinder axis.

Figures 2 and 3 shows $n(3^1P)$ and $n(4^1P)$ calculated by the iterative model. Experimental data are well reproduced. This result indicates that we can determine $n(1^1S)$ using the iterative model.

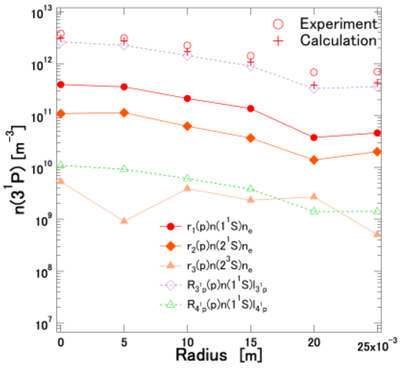

Fig.2. Radial profile of the population of excited state $n(3^1P)$.

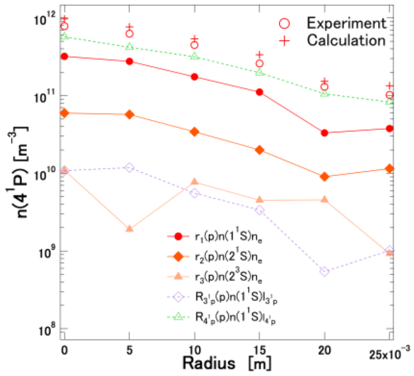

Fig.3. Radial profile of the population of excited state $n(4^1P)$.

In applying this technique to the experiment, fast calculation is desirable. In the present model, iterative step is different between the upper state population for the photo-emission and that produced by the photo-absorption. We have constructed a new code in which both populations in each cell are equal. Figure 4 compares the results of the previous and new model. It is found that the number of the iterative time is shortened drastically in the new code.

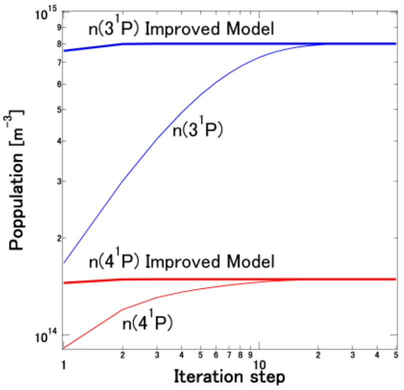

Fig.4. Populations of $n(3^1P)$ and $n(4^1P)$ in the iteration process. "Improved" denotes the result of the new code.

References

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