Study of Metastable Population Density in a Hollow Cathode Helium Discharge

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The population density of metastable helium atoms is experimentally investigated in a hollow cathode discharge. The metastable population density measured using laser absorption spectroscopy is proportional to the square root of electron density under conditions of constant electron temperature and a constant neutral density. Calculation based on a collisional-radiative model and diffusion loss indicates that metastable population density is linearly proportional to electron density.

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Understanding the behavior of metastable atoms in plasmas is a worthwhile subject in divertor plasmas of magnetically confined devices as well as in some plasma processing devices. In the divertor region of burning plasma, such understanding will be important in terms of the suppression of helium-ash recycling and the reduction of heat flux onto the divertor plates. Thus, diagnostic methods to estimate the population density of metastable helium atoms are required.

Laser diagnostics such as absorption spectroscopy and induced fluorescence spectroscopy are established methods to directly measure metastable atoms. However, it is sometimes difficult to apply laser measurement to divertor plasmas due to limited port accessibility. If fundamental plasma parameters are obtained, on the other hand, the population density can be calculated with the aid of a collisional-radiative (CR) model and taking transport into consideration. In the latter, proper treatment of neutral-transport and neutral-neutral collisional processes will be an issue in making this method more reliable. Hence, in order to develop a calculation method, experimental investigation using a simple device is important. We have constructed a hollow-cathode discharge device to study the behavior of metastable helium atoms, in which localization of the production region and transport loss dominated simply by radial diffusion are expected.

In this paper, the initial results of the population density of metastable helium atoms obtained in the hollow-cathode device are shown. The population density directly measured using laser absorption spectroscopy [1] is compared with that calculated by simple rate equations.

The experiments were performed in the hollow-cathode device for the production of metastable atoms (PROMESTA device) in Tohoku University. A schematic of the experimental setup is shown in Fig. 1. A cylindrical cathode made of aluminum with an inner diameter of 10 mm and an axial length of 40 mm is installed in a Pyrex glass tube. Two cylindrical anodes, which have the same diameter as that of the cathode, are positioned with 2 mm gaps at both ends of the cathode on the same axis. In this experiment, helium gas pressure was kept at about 200 Pa corresponding to a helium atom density of 4.8×10^{22} m^{-3} in a room temperature (300 K). The discharge current was varied from 10 mA to 50 mA. The discharge voltage was almost constant at approximately 200 V.

Electron temperature and density measured using a double probe at the center of the cathode are about 3.2 eV and 1.2×10^{14} m^{-3}, respectively, for the discharge current I_{dis} = 10 mA. While the electron density increases with the discharge current up to 2.0×10^{15} m^{-3}, the electron temperature is independent of the discharge current. The longitudinal distribution of the electron temperature and density are shown in Fig. 2, where position x is measured from the center of the cathode along the axis. While the electron temperature gradually decreases in the anode region

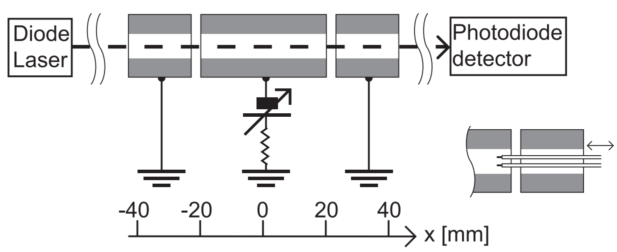

Fig. 1 Schematic of the experimental setup. The dashed line passing through the cylindrical electrodes shows the absorption path of a laser beam. A schematic of the double probe measurement is also shown.

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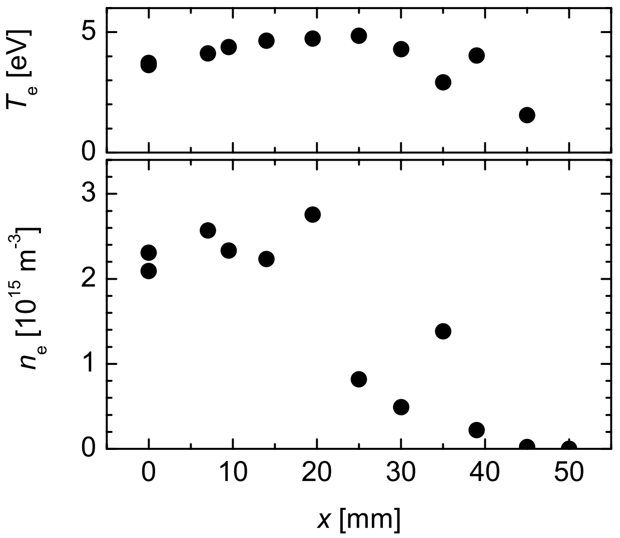

Fig. 2 Spatial distribution of electron temperature and density obtained at I_{dis} = 50 mA and p = 200 Pa.

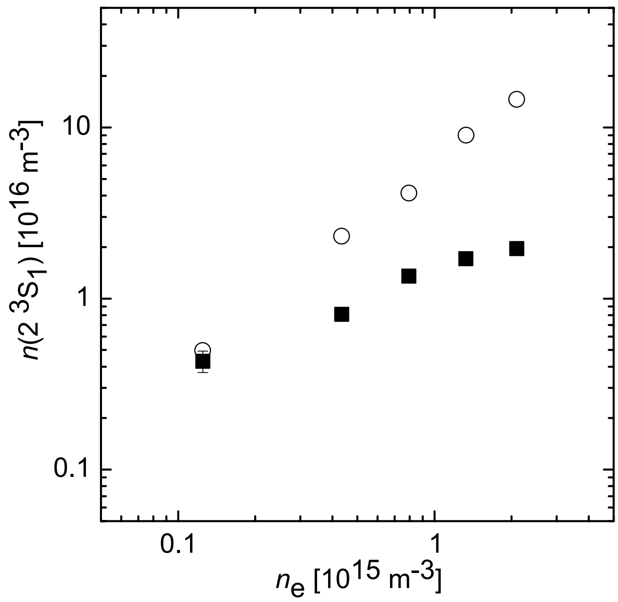

Fig. 3 Electron density dependence of metastable population density. Plots with a closed square (■) are obtained using laser absorption spectroscopy, while those with an open circle (○) are calculated from the measured electron temperature and density.

(x = 22-42 mm), the electron density rapidly decreases in the gap between the cathode and the anode (x = 20-22 mm). This localized distribution of the electron density suggests that a region producing metastable helium atoms is also localized in the cathode, because the production is dominated by the electron impact excitation of ground state atoms. We assume, for simplicity, that the metastable population density is localized and is constant within the cathode. It is then obtained from the line-integrated density of the metastable atoms measured by laser absorption spectroscopy.

The line density of the metastable (2^3S_1) helium atoms was measured by laser absorption spectroscopy using an external cavity-stabilized diode laser. The center of the laser wavelength was tuned to 1082.909 nm, which corresponds to a 2^3S_1-2^3P_0 transition. The laser power was attenuated ($\sim$ 50 μW) in order to avoid saturation. Thus, the influence of the photoexcitation processes induced by the laser light on the metastable population is also negligible. The laser light passing through the plasma along the cathode axis is detected by a silicon photodiode. When the laser light is absorbed in a length Δx of a swarm of metastable atoms, the population density $n(2^3S_1)$ of metastable atoms is obtained by $n(2^3S_1)\,\Delta x\,\sigma(\nu) = -\ln(I(\nu)/I_0)$, where ν is the laser frequency , and $I(\nu)$ and I_0 are the laser power after and before the absorption, respectively. The absorption cross section $\sigma(\nu)$ is deduced from a Doppler-broadened spectrum. Taking the absorption length as the cathode length, Δx = 40 mm, the population density is obtained. The population density increases with the discharge current up to $2.0 \times 10^{16}\,\mathrm{m}^{-3}$ at I_{dis} = 50 mA, while in the case of the lowest discharge current (I_{dis} = 10 mA) a density of $4.3 \times 10^{15}\,\mathrm{m}^{-3}$ is obtained.

In order to calculate the population density of the metastable helium atoms, simple rate equations are considered. The population densities of the two metastable states, $n_2 \equiv n(2^1S_0)$ and $n_3 \equiv n(2^3S_1)$, in a steady state are described by the following non-linear equations:

$$k_{32}n_en_3 + k_{02}n_in_e + k_{12}n_1n_e = h_2{n_2}^2 + h_2n_2n_3 + (k_2n_e + \Phi_2 + h_{21}n_1)n_2 \quad (1)$$

$$k_{23}n_en_2 + k_{03}n_in_e + k_{13}n_1n_e = h_3{n_3}^2 + h_3n_2n_3 + (k_3n_e + \Phi_3 + h_{31}{n_1}^2)n_3, \quad (2)$$

where n_e, n_i, and n_1 are the electron, ion, and ground state atom density, respectively. The left hand sides represent the production of the metastable atoms, where k's are the CR coupling coefficients defined in Refs. [2, 3]. The right hand sides represent losses, where h_2 and h_3 are the ionization rate due to metastable-metastable collisions [4]; h_{21} and h_{31} are the destruction rate due to the collision with the ground state [5]. The diffusion rates of the metastable atoms Φ_2 and Φ_3 are deduced from the diffusion coefficient [5] under the assumption that the diffusion scale length is the same as the cathode radius.

The population densities deduced from Eqs. (1)-(2) using electron temperature T_e and density n_e are compared with that obtained by means of the laser absorption spectroscopy as shown in Fig. 3. The same order of the population densities using both methods is obtained in a wide range of electron density, $n_e \simeq 10^{14} - 10^{15}\,\mathrm{m}^{-3}$. Note that taking the limit of $\Phi, h \rightarrow 0$ reduces to a result in which the metastable population in the calculation is two or three orders higher than that obtained in the laser absorption experiment and is unchanged even if the electron density is changed. Thus, including the diffusion loss and atom-atom collisional processes is important to obtain a reasonable population density in the present experiment.

On the other hand, different dependences of the metastable population densities on the electron density are depicted in Fig. 3. According to the calculation, the metastable atom density is almost proportional to the electron density, while experimental data show a square-root dependence. Further investigation of the electron density dependence of metastable population density, including detailed consideration of the spatial distributions of the diffusion coefficient, remains a subject of our future study.

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[1] A. Okamoto, K. Shinto, S. Kitajima and M. Sasao, Plasma Fusion Res. (2007) *in press*.
[2] M. Goto, J. Quant. Spectrosc. Radiat. Transf. **76**, 331 (2003).
[3] T. Fujimoto, J. Quant. Spectrosc. Radiat. Transf. **21**, 439 (1979).
[4] A.W. Johnson and J.B. Gerardo, Phys. Rev. A **7**, 925 (1973).
[5] A.V. Phelps, Phys. Rev. **99**, 1307 (1955).