Optical emission intensity of molecular hydrogen in a recombining hydrogen plasma

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We observed optical emissions of molecular hydrogen in a recombining hydrogen plasma with an electron temperature of 0.1 eV and an electron density of 3×10^{12} cm^{-3}. The optical emission intensities of molecular hydrogen in the recombining plasma were roughly 10%–45% of those in an ionizing plasma with an electron temperature of 4 eV. Because of the low electron temperature of 0.1 eV, the optical emission intensities in the recombining plasma are not explained by electron impact excitation. We discussed possible recombination processes which can produce excited states of molecular hydrogen in the recombining plasma.

Recombining hydrogen plasmas attract much interest of many researchers, in conjunction with the reduction of heat flux to a divertor plate from a fusion plasma. A scenario for reducing the heat flux is the volume recombination between ions and electrons, which results in the isotropic dissipation of heat via optical radiation. The recombination processes studied intensively are three-body recombination ($H^+ + e + e \rightarrow H^* + e$), dissociative recombination ($H_2^+ + e \rightarrow H^* + H$), and mutual neutralization ($H^+ + H^- \rightarrow H^* + H$). The reaction products in all the above recombination processes are atomic hydrogen and its excited state. In this work, we examined the possibility of recombination processes which can produce excited states of molecular hydrogen, by observing optical emission spectra of a recombining hydrogen plasma.

We used a linear-type helicon-wave plasma source with a uniform magnetic field of 350 G along the cylindrical axis [1]. An rf power source at 13.56 MHz was connected to a helical antenna wound around a quartz glass tube with an inner diameter of 1.6 cm. The glass tube was attached to a stainless steel vacuum chamber. A plasma column with the diameter same as the glass tube was confined radially by the external magnetic field. We used pure hydrogen for discharge in this experiment. The plasma was produced in a pulsed mode with a repetition frequency of 10 Hz and a discharge duration of 5 ms to avoid over-heating of the machine. Conventional optical emission spectroscopy was performed in the downstream region at a distance of 22 cm from the helical antenna using a spectrograph with a focal length of 50 cm. The spectrum was recorded using a charge-coupled device camera with a gated image intensifier (ICCD camera). The gate of the ICCD camera was opened from 4.89 to 4.99 ms after the initiation of the pulsed discharge.

A typical density jump of helicon-wave discharge was observed at an rf power of ~ 1.5 kW, when the discharge pressure was higher than 30 mTorr. The high-density mode discharges at gas pressures less than 50 mTorr produced ionizing plasmas (pink plasmas) in the observation region, while we observed recombining plasmas (blue or purple plasmas) when the gas pressure was higher than 50 mTorr. We observed optical emissions of the Balmer series of atomic hydrogen at Rydberg states ($n \leq 18$) in the recombining plasma. We evaluated an electron temperature of 0.1 eV and an electron density of 3.2×10^{12} cm^{-3} from the Saha-Boltzmann plot of the population densities of the excited states, when the gas pressure was 65 mTorr and the rf power was 2.5 kW [2, 3]. On the other hand, according to a measurement using a Langmuir probe, the electron temperature and the electron density of an ionizing plasma, which was produced at an rf power of 2.5 kW and a gas pressure of 40 mTorr, were 4 eV and 8×10^{12} cm^{-3}, respectively.

Figure 1 shows an optical emission spectra in a wavelength range between 457 and 464 nm, which were observed in the ionizing and recombining plasmas. As indicated in the figure, the line emissions are

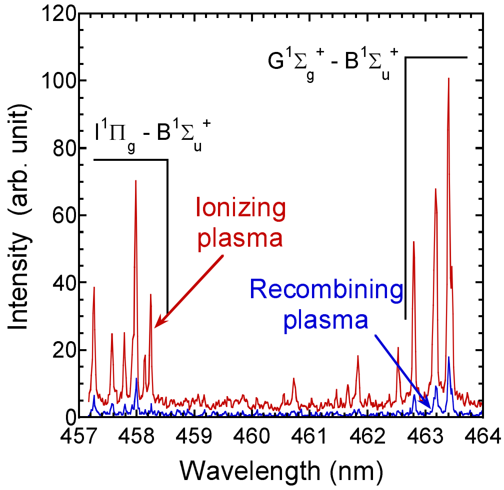

Fig. 1: Examples of optical emission spectra of molecular hydrogen observed in the ionizing and recombining plasmas.

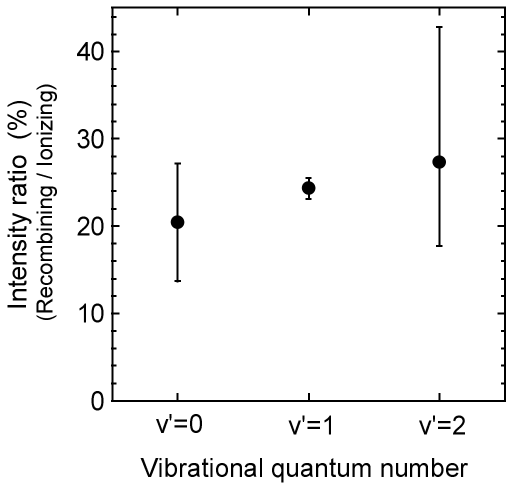

Fig. 2: Ratio between the optical emission intensities of molecular hydrogen in ionizing and recombining plasmas as a function of the vibrational quantum number of the $d^3\Pi_u$ state.

assigned as the transitions of $I^1\Pi_g \rightarrow B^1\Sigma_u^+$ and $G^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$ of molecular hydrogen. As shown in the figure, even though the optical emission intensities of the recombining plasma were weaker than those of the ionizing plasma, the optical emission intensities were observable levels even in the recombining plasma.

We classified the optical emission lines according to the electronic and vibrational states of upper energy levels, and examined the ratio between the optical emission intensities in the ionizing and recombining plasmas. The ratio ranged between 10% and 45%. We observed no remarkable difference in the ratio of the optical emission intensities when we compared it with respect to the energy of the upper electronic state ($d^3\Pi_u$, $i^3\Pi_g$, $I^1\Pi_g$, $G^1\Sigma_g^+$, $j^3\Delta_g$, $r^3\Pi_g$ in order of the energy). Figure 2 shows the intensity ratio of the lines emitted from the $d^3\Pi_u$ state with different vibrational quantum numbers. As shown in the figure, the optical emission intensity of molecular hydrogen in the recombining plasma was relatively stronger when it was emitted from a higher vibrational quantum state. This means that the vibrational temperature of the $d^3\Pi_u$ state is higher in the recombining plasma than the ionizing plasma. Similar results were observed for optical emissions from the $I^1\Pi_g$, $G^1\Sigma_g^+$, $j^3\Delta_g$, and $r^3\Pi_g$ states. A slight decrease in the intensity ratio with the vibrational quantum number was observed only for the $i^3\Pi_g$ state.

It should be emphasized that the optical emission intensities of molecular hydrogen observed in the recombining plasma are not explained by electron impact excitation from the ground state because of the low electron temperature of 0.1 eV. The experimental result shown in Fig. 2 suggests the production of the $d^3\Pi_u$ state via recombination processes, since the vibrational temperature of molecular ion is expected to be higher than that of neutral molecule. Considering the energy of the $d^3\Pi_u$ state, possible recombination processes are $\mathrm{H_2^+ + e + M(e) \rightarrow H_2^* + M(e)}$, $\mathrm{H_2^+ + H^- \rightarrow H_2^* + H}$, and $\mathrm{H^+ + H^- + Me \rightarrow H_2^* + M(e)}$, while the corresponding recombination processes in usual understanding are $\mathrm{H_2^+ + e \rightarrow H^* + H}$, $\mathrm{H_2^+ + H^- \rightarrow H^* + H + H}$, and $\mathrm{H^+ + H^- \rightarrow H^* + H}$, respectively. We will discuss the possibilities of recombination processes which can produce molecular hydrogen at electronic excited states at the conference.

References

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