20PB-115

# Measurements of Helium $2^3S$ Metastable Atom Density in Low-Pressure Glow Discharge Plasmas by Observation of Helium Atom $2^3S$-$2^3P$ Emission Line Shape Affected by Radiation Re-absorption

# ふく射再吸収によるヘリウム原子$2^3S$-$2^3P$発光線形状の変化を利用した低圧グロー放電プラズマ中のヘリウム$2^3S$準安定原子密度計測

Taiichi Shikama[1], Shuhei Ogane[1], Hidekazu Ishii[2], Yohei Iida[3] and Masahiro Hasuo[1]
四竈泰一[1], 大金修平[1], 石井秀和[2], 飯田洋平[3], 蓮尾昌裕[1]

1) *Graduate School of Engineering, Kyoto University, Kyoto 615-8540, Japan*
1) 京都大学大学院工学研究科，京都市 〒615-8540
2) *Faculty of Engineering, Kyoto University, Kyoto 615-8540, Japan*
2) 京都大学工学部，京都市 〒615-8540
3) *Bunkokeiki Co. Ltd., Hachioji, Tokyo 192-0033, Japan*
3) 分光計器株式会社，東京都八王子市 〒192-0033

The helium $2^3S$ metastable atom densities are experimentally evaluated by self-absorption spectroscopy of the HeI $2^3S$-$2^3P$ transition spectra in two kinds of cylindrical glow discharge plasmas, which have different radii and are operated under different pressures of 300 and 20 Pa. The spectra are measured by using an interference spectroscopy system with a wavelength resolution of about 60 pm, and from the observed relative intensities of the fine structure transitions, the $2^3S$ metastable atom densities are determined under assumptions on the spatial profiles of the upper and lower state densities and temperatures. The validity of the measurements is confirmed from the fact that the evaluated density increases with the discharge current.

## 1. Introduction

In plasmas containing helium atoms, the $2^1S$ and $2^3S$ metastable atoms are known to affect the plasma parameters through the Penning ionization and secondary electron emission on the surface. In order to understand and control the effect of the metastable atoms on the plasma, diagnostic techniques for the metastable atom densities have been investigated. In this paper, we present a self-absorption spectroscopy technique for the evaluation of the metastable atom density. The self-absorption spectroscopy utilizing the re-absorption of emission from the plasma itself usually requires reflection of the emission back into the plasma to observe re-absorption, but a simpler method, which is feasible only by observation of the emission spectral line shape, has been proposed [1]. The method evaluates the relative intensities of the $2^3S$-$2^3P$ fine structure transitions by using a high resolution spectroscopy system. The $2^3S$ state density can then be estimated from the difference in absorption coefficients among the fine structure transitions. Compared with the laser-aided spectroscopy techniques, this method has a potential advantage in that it could be applicable to plasmas in which the transmission of laser light is difficult such as the ones compiled in devices for applications. We measure the $2^3S$ state densities in two kinds of low-pressure glow discharge plasma tubes by using this method.

## 2. Methods

The HeI $2^3S$-$2^3P$ transition consists of three fine structures, as listed in Table I. The fine structure transitions have a unique lower state and an identical spontaneous emission coefficient, so that if we neglect the difference in the transition frequency and assume that the upper state population densities follow the statistical distribution, the observed emission intensity ratio among the fine structure transitions can be written as $I_{01} : I_{11} : I_{21} = \eta_{01} : 3\eta_{11} : 5\eta_{21}$, where $I_{J'J}$ is the emission intensity and $\eta_{J'J}$ is the probability that the emitted photons will escape from a given plasma geometry. Here, $J$ denotes the total angular momentum quantum number, and the prime represents the upper state. For a given plasma geometry, $\eta_{J'J}$ can be calculated as a function of the spatial profiles of the upper and lower state densities and temperatures [2]. The $2^3S$ state density can then be evaluated from the observed intensity ratio under certain assumptions on the

Table I. Wavelength ($\lambda$), A-coefficient ($A$), and absorption oscillator strength ($f$) for the HeI $2^3S$-$2^3P$ transition.

| Transition | $\lambda$ (nm) | $A$ (x$10^7$ s$^{-1}$) | $f$ (x$10^{-1}$) |
|---|---|---|---|
| $2^3S_1$-$2^3P_0$ | 1082.909 | 1.0216 | 0.59902 |
| $2^3S_1$-$2^3P_1$ | 1083.025 | 1.0216 | 1.7974 |
| $2^3S_1$-$2^3P_2$ | 1083.034 | 1.0216 | 2.9958 |

spatial profiles of the densities and temperatures.

## 3. Experiments

Experiments were carried out using two kinds of glow discharge tubes with different diameters and operation pressures. The first one, which we denote as (A), is made of quartz glass with an inner diameter of 5 mm and a length of 190 mm. The tube was filled with pure helium, and the pressure measured by a capacitance manometer was 300 Pa. The second one, which we denote as (B), is a commercial helium discharge lamp (Electro-Technic Products). The inner diameter and length of the glass tube are about 3 and 260 mm, respectively, and the pressure is 20 Pa. For both the discharge tubes, dc glow discharges were sustained with a discharge current of up to 3 mA.

Emission from the discharge tubes was directly collected by a quartz optical fiber at the center of the discharge tubes. The viewing chord was directed perpendicular to the discharge tube axis, and the whole cross sections of the discharge tubes were observed at once; we assume uniformity of the plasmas in the axial direction within the viewing spot. The light transferred via the optical fiber was dispersed by an interference spectrometer [2, 3] and the He $2^3S$-$2^3P$ spectra were recorded. The instrumental function of the spectrometer was Gaussian with a FWHM of about 60 pm.

## 4. Results and Discussions

The measured HeI $2^3S$-$2^3P$ spectra at a discharge current of 3 mA are shown in Figure 1 by the markers. The measured intensity ratios of the large to small peaks are found to be smaller than that estimated from the statistical weight as a result of the radiation re-absorption. Since the plasma extinguishes on the discharge tube surface by recombination, we represent the spatial profile of the $2^3P$ state density by the zeroth-order Bessel function. Meanwhile, the spatial profile of the $2^3S$ state density is affected by diffusion determined by the mean free path of the inter-atomic collisions. In discharge tube (A), the mean free path is about 0.1 mm and sufficiently smaller than the discharge tube radius, while in discharge tube (B), it is about 1.4 mm and comparable to the discharge tube radius. We therefore assume that the spatial profile is represented by the Bessel function for the discharge tube (A) and by the uniform function for (B). We also assume that the temperatures of the upper and lower states are spatially uniform and equal to the room temperature of 300 K.

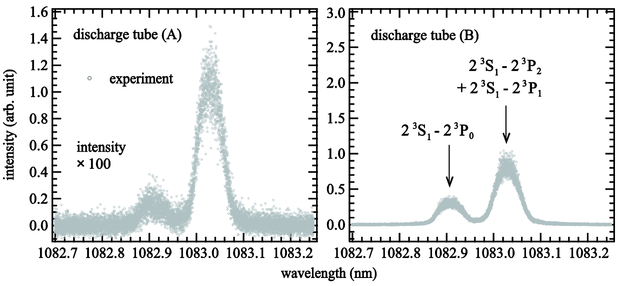


Figure 1. HeI $2^3S$-$2^3P$ spectra observed in the discharge tubes (A) and (B) at a discharge current of 3 mA.

Under the above assumptions, $\eta_{J'J}$ becomes a function of the optical depth $\tau_{100}$ at the line center of the $2^3S_1$-$2^3P_0$ transition, where $\tau_{100}$ is proportional to the $2^3S$ state density on the discharge tube axis [2]. The values of $\tau_{100}$ are obtained as 0.15 and 0.71 for discharge tubes (A) and (B), respectively. The corresponding $2^3S$ state densities on the discharge tube axes are 6.9 x $10^{17}$ and 5.4 x $10^{18}$ $m^{-3}$, respectively, and the values are comparable to those obtained in discharge plasmas produced under similar pressure conditions. Figure 2 shows the discharge current dependence of the observed total emission intensity and $\tau_{100}$. The intensity and $\tau_{100}$ monotonically increase with the current. This result suggests that accompanying the current, the electron density and consequently the excitation flux to the $2^3S$ state are increased.

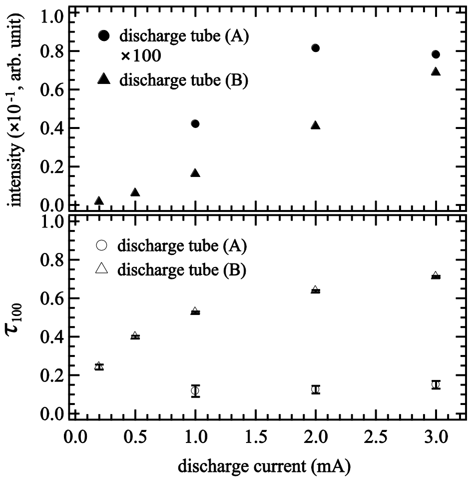


Figure 2. Observed variations in the total emission intensity and $\tau_{100}$ as a function of the discharge current.


## Acknowledgments

This work was partly supported by Kurata Grant from Kurata Memorial Hitachi Science and Technology Foundation.


## References


[1] S. Daviaud, G. Gousset, J. Marec, and E. Bloyet: J. Phys. D **23** (1990) 856.

[2] T. Shikama, S. Ogane, H. Ishii, Y. Iida and M. Hasuo: Jpn. J. Appl. Phys. **53** (2014) 086101.

[3] S. Ogane, T. Shikama, H. Zushi and M. Hasuo: Plasma Conference 2014, 19PB-085.