Experimental Confirmation of the Validity of the Branching Ratio Method for Calibrating Vacuum Ultraviolet Monochromators Using TPD-1 Plasma Source

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Measurements of the branching pair of neutral and ionized helium were carried out and it was shown experimentally that the heliuin plasma produced in the TPD-1, a linear plasma confinement machine, satisfies the coiiditions required for the application of the branching ratio method for calibrating a vacuum ultraviolet monochromator, such as the absorption free condition and equipartition between unresolved sublevels.

I. Introduction

The radiation loss in a fusion oriented high temperature plasma apparatus is mainly due to the presente of highly ionized impurity ions[1]. It is well known that the radiations due to tliese impurities are emitted mainly in the vacuum ultraviolet (VUV) region. Hence, the quantitative nieasurement of radiation intensities in this region come to be of great interest in high temperature plasmas. However, the absolute calibration techniques available presently in the VUV region are still complicated or of low confiability because of the lack of a suitable primary standard as the one that exists in the visible region[2].

Among the various inethods of calibration in VUV region, the branching ratio method is the most popular one because of its relatively simple procedures and the possibility of calibrating the instrument in situ, i.e., using the source to be studied also as the radiation standard[3,4]. However, it should be noted that there are still unclear points on whether the conditions required for the applicability of this method are satisfied or not for the plasmas usually used as light sources (for example, hollow cathode, RFP or Tokamaks devices). The conditioris in question are:

1. No reahsorption of the lines in considerations should occur inside the plasma.

2. The occupancies of the unresolved fine structure levels are proportional to their statistical weight.

The TPD-1 (Test Plasma by Direct-Current Discharge) apparatus used for the VUV monochromator calibratioii experinients, is a linear machine which produces a stationary, quiescent, high density plasma[5]. In the helium plasma produced in this machine, we can cliange the plasma parameters in a wide range ($N_e \approx 10^{12} - 10^{15} cm^{-3}$ and $T_e \approx 0.1 - 50$ eV), by varying the discharge current from 1 A to 100 A, discharge pressure from 0.5 Torr to 10 Torr and neutral helium gas pressure in plasma region from 10^{-5} Torr to 10^{-1} Torr. These characteristics allowed us to confirm the validity of the branching ratio method in the VUV region, in this light source.

II. Experimental Procedure and Results

The schematic drawing of the set-up used in this experiment is shown in Fig. 1. To measure the visible line of the branching pair, a SPEX 1400 double monochromator was used. For the line in the vacuum ultraviolet a grazing incidence VUV spectrometer was used.

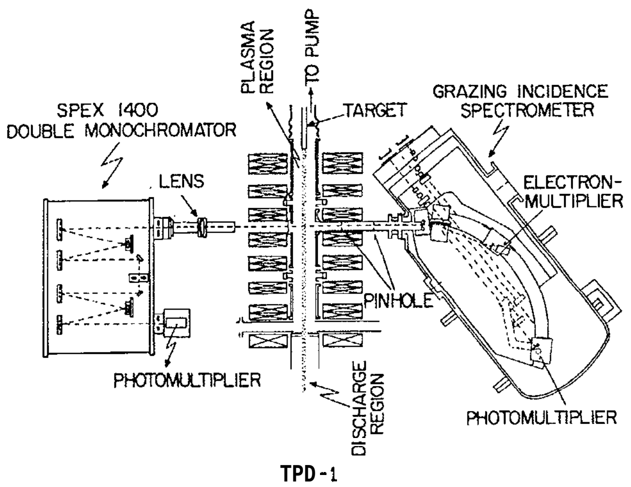

Figure 1: Schematic drawing of the experimental set-up for the absolute calibration of the VUV spectrometer, using the TPD-1 light source.

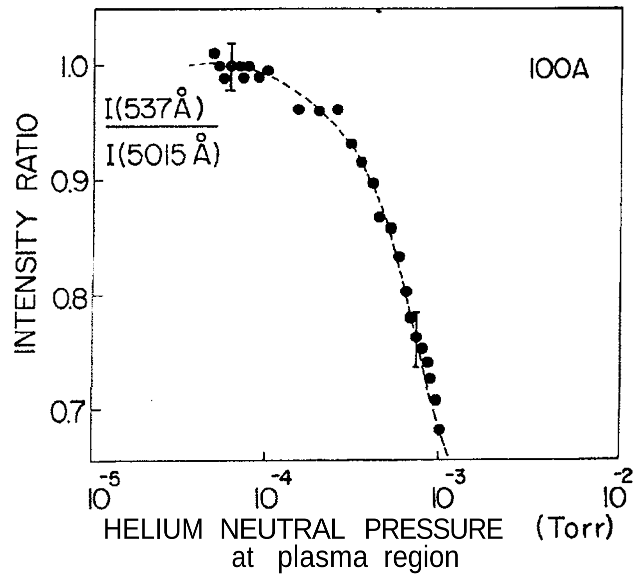

Figure 2: Intensity ratio of HeI (537 Å), $1s^2 \rightarrow 1s^3p$, to He I (5015 Å), $1s^2 \rightarrow 1s^3p$), vs. neutral helium pressure in the plasma region. The ratio is normalized at the pressure of 5 x 10^{-5} Torr.

The TPD-1 machine is a linear device that produces a stationary, quiescent, high density plasma in operation at the National Institute for Fusion Science, Nagoya, Japan. A plasma produced in the "arc discharge region" flows into the "plasma region" passing through a hole (diameter: 8mm). The plasma diameter at the observation point is about 1--2 cm. The TPD-1 apparatus can be operated at gas pressures from 0.5 Torr up to 10 Torr in the "discharge region", maintaining pressures of 1 x 10^{-4} to 10^{-1} Torr in the "plasma region". Discharge currents of up to 100 A, discharge voltages of 130-200 V and confinement magnetic fields of up to several kG can he realized in this machine. At a discharge current of 100 A and pressure of several Torr in the "discharge region", the electron density can reach 10^{15} cm^{-3}, which has been confirmed previously by an HCN and CO_2 interferometry[6,7].

In order to reduce the experimental error in the intensities measurements of the branching line pairs, the visible and VUV spectrometers were accurately positioned so that they observed the same spatial region of the TPD-1 plasma.

To confirm the absorption-free condition for the resonance lines of neutral atom of working helium gas, the branching ratio was determined under the operating condition with low concentration of neutral helium gas (corresponding to a pressure of $\sim 10^{-5}$ Torr in the plasma region). The dependence of the intensity ratio HeI (537 Å) / HeI (5015 Å) on neutral helium pressure is shown in Fig. 2. From the experimental result shown in this figure, we can see that the intensity ratio I(537 Å)/I(5015 Å) for pressures helow 10^{-4} Torr is constant, indicating that the plasma region becomes optically thin at 537 Å. This conclusion is based on the fact that for the visible line HeI (5015 Å) the plasma is certainly optically thin for pressures less than 10^{-2} Torr. The calculation of the HeI (537 Å) absorption, based on a radiative transfer equation, also agrees with this experimental result.

The condition of statistical equilibrium at the n-th state is given by[2]

$$\frac{6 \times 10^6 (kT_e)^{1/2}}{(n^4 N_e)} < \tau_R(nP),$$

where n is the principal quantum number and $\tau_R(nP)$ is the radiative lifetime of the nP state. This means that the statistical equilibrium between sublevels is established at high electron density and low electron temperature (for example at electron densities larger than

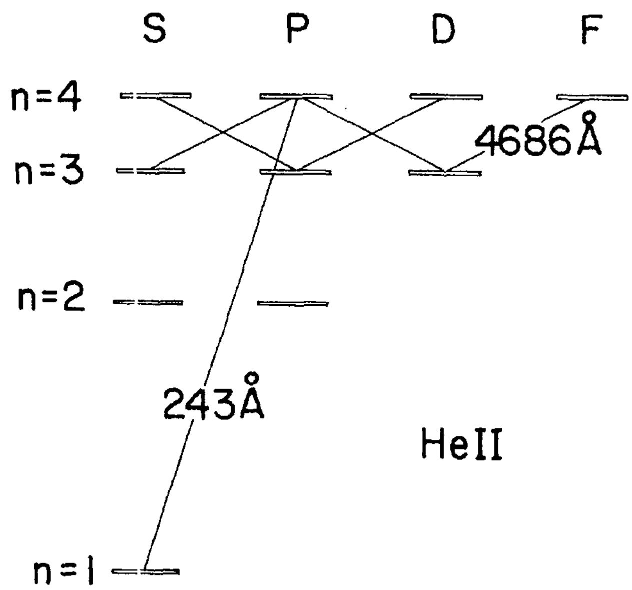

Figure 3: Simplified grotorian diagram of He II lower energy states with tlie transitions corresponding to lines **243** Å and 4684 Å.

1.2 x 10^{14} cm^{-3}, and electron temperature of 20 eV in the case of ionized helium with n = 4). A simple grotorian diagram of He II lower energy states is shown in Fig. 3 which can be helpful to understand the equipartition process. The transitions corresponding to the branching line pairs He II(243 Å) and He II(4684 Å) are also shown here.

To observe the effect of nonstatistical population of hydrogenic line structure levels on the He II line intensity ratio, we use the appropriate characteristics of the TPD-1 plasma, i.e., plasma parameters can be varied in a wide range by changing the discharge current or discharge pressure. It is confirmed by several measurements that as the discharge pressure increases, the electron density increases and the electron temperature decreases in this device. We confine our attention to the intensity between the lines of He II (243 Å) = 4 → 1, and line He II (4686 Å), n = 4 → 3. Figure 4 and 5 shows the dependence of the intensity ratio He II (243 Å) He II (4684 Å) on the discharge pressure.

At a discliarge current of 10A, the ratio of line pair varies with the discharge pressure (i.e., it is a func-

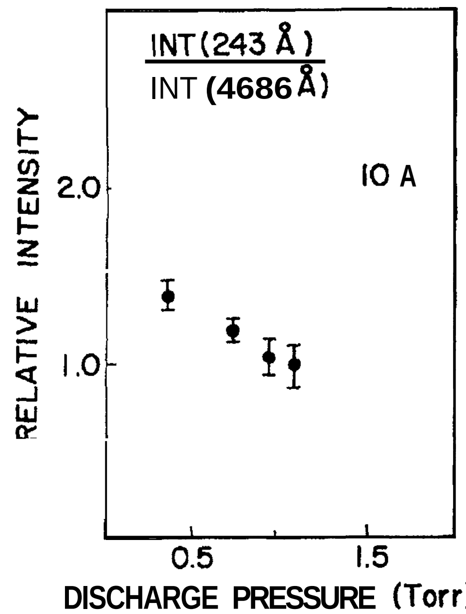

Figure **4**: Intensity ratio of He II (243 Å) $4p \rightarrow 1s$, to He II (4686 Å), $4p \rightarrow 3s$, measured as a function of the He neutral gas pressure in the discharge region. This is the case for discharge current of 10 A, $N_e \approx 5 \times 10^{12}$ cm^{-3} and $T_e \approx$ 5eV at 1.5 Torr. As neutral pressure decreases, the electron density decreases and the electron temperature increases.

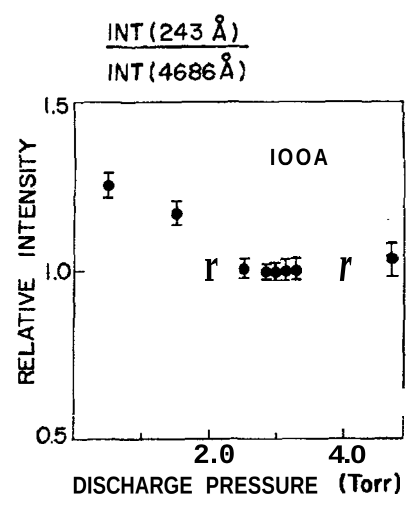

Figure 5: Intensity ratio of He II (243 Å) to He II (4686 Å). This is the case for discharge current of 100 A, $N_e \approx 3 \times 10^{14}$ cm^{-3}, $T_e \approx$ 20 eV at 3 Torr. The plasma parameters depend on the discharge pressure in the same way as of Fig. 4. For example, $N_e \approx$ 2 x 10^{14} cm^{-3} and $T_e \approx$ 30 eV at 2 Torr. The ratio is normalized at the pressure of 3 Torr.

tion of the electron density and the temperature) as shown in Fig.4. In the range of operation which corresponds to a 10A discharge current, the TPD-1 device produces heliuin plasmas with low electron density ($\sim 10^{12}$ cm^{-3}) which show no statistical equilibrium between fine structure sublevels of He *II ions*. This case would result in a constant line ratio for varying plasma density. However, at a discharge current of 100A, it is found that the intensity ratio He I (243 Å)/He II (4686 Å) stays constant for pressure higher than 2 Torr as shown in Fig. 5. For such conditions the electron density increases while the electron temperature decreases as a function of pressure. This result indicates that the statistical population of fine structure levels on He^+, n = 4, can be obtained under the condition of electron density above $\sim 2 \times 10^{14}$ cm^{-3} and electron temperature less than $\sim$ 30 eV, attained in the TPD-1 plasma. This conclusion is in agreement with the prediction.

III. Conclusions

In conclusion, we have shown that the TDP-1 plasma is appropriate to be used as a standard light source for the calibration of VUV spectrometers by the method of branching ratio if proper operating conditions are used.

Our experimental results also open perspectives for more detailed studies regarding the anomalies of population distributions between sublevels against the variations of plasma paraineters.

Another interesting study suggested from this calibration experiment is to clarify the mechanism of radiation transfer including scattering in the region of VUV.

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