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Plasma shift of the He II P_α line

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We have measured the shift of the He II 4685.7-Å line at electron density ranging from 2.5×10^{17} to 18.8×10^{17} cm^{-3} and electron temperature between 8 and 10.5 eV. The plasma was produced in a Z-pinch discharge. Systematic red shifts linear in density are observed. The experimental results are in agreement with the best-fit curve of earlier results by Pittman and Fleurier obtained at lower electron densities and temperatures.

I. INTRODUCTION

Several measurements of the Stark shifts of the Paschen-α (P_α) ($\lambda=4685.7$ Å) He II line in low-temperature, medium electron density plasmas have been reported recently.[1-7] These experiments have been motivated by the potential use of the shift for nonperturbing-plasma diagnostics while the experimental measurements and their interpretation have been a matter of controversy. Here we shall confine our further discussion to the experimental results, while one can find detailed analysis of various theoretical approaches in Refs. 5 and 7 and the references therein.

It is common for recent experiments[1-7] that they all report for P_α of He II a red shift. However, there are considerable differences in the magnitude of the shift. For example, the shifts of Hashimoto[3] and Murakawa[4] are almost four times smaller than those in Refs. 5 and 7. The results of Ackermann *et al.*[6] agree better, within a factor of 2, with Refs. 5 and 7. Finally, the discrepancy between data in Refs. 5 and 7 is around 40%, the shifts of Ref. 5 being systematically larger. This discrepancy is curious since both experiments were performed with almost identical discharges with very similar spectroscopic and plasma-diagnostic techniques.

In this paper we report the results of an attempt to resolve this discrepancy. Furthermore, reported Stark shifts are measured in an extended range of electron densities, which is of practical importance for plasma diagnostics.

II. EXPERIMENT

A. Apparatus and procedure

The plasma source is a linear Z-pinch designed similarly to the recently developed discharge for CO$_2$-laser–pellet simulation experiments.[8] It consists of a rapid discharge capacitor having a peak voltage rating of 25 kV, capacitance 10 μF, and inductance 60 nH. The Z pinch is fired by an ignitron and the ringing frequency of the whole circuit including discharge vessel is 12 μs. The discharge tube is made of Pyrex glass with a 31-mm internal diameter. The distance between copper electrodes is 28 cm, and 1.8-mm holes are located at the center of both electrodes to facilitate optical alignment and to allow end-on plasma observations. During the experiment a continuous flow of helium is maintained at a pressure of 133 Pa (1 torr).

The light from the Z pinch is observed end-on on a shot-to-shot basis with a 1-m monochromator (inverse linear dispersion in the first order 8.4 Å/mm) equipped with photomultiplier tube. This instrument has, with 12-μm slits, a measured instrumental half width of 0.13 Å. Spectroscopic observations are made along the Z-pinch axis through the hole in the electrode. The discharge is imaged onto the entrance slit of the monochromator by means of a focusing lens. A system of diaphragms placed in front of the lens ensures that light comes only from a central part, 1.5 mm in diameter, about the discharge axis.

For line-shift measurements we use plasma radiation at the late times of plasma decay as a source of less-shifted line profiles.[9] Thus, to measure the line shift it is necessary to analyze oscilloscopic traces obtained from the photomultiplier-monochromator system at various wavelengths and at various times of the decay. An example of these measurements is given in Fig. 1 where two experimental profiles of He II 4686 Å at electron density $N=16.9\times10^{17}$ cm^{-3} and 16 μs later at $N=2.0\times10^{17}$ cm^{-3} are presented. From Fig. 1 it is possible to determine the line shift, and in a similar way all reported measurements are performed. Here one should notice that the reported shifts are measured at the half width of both line profiles, but it should be pointed out that there is no difference, within the limits of experimental error, if shifts are measured anywhere between 0.25 to 0.75 of the maximum of line profiles.

B. Plasma diagnostics

For electron-density measurements we use the width of He II 4686-Å line. The full width at half maximum $\Delta\lambda_{\text{FWHM}}$ of this line is related to the electron density N_e using the following relationship:[2,5,7]

$$N_e=2.04\times10^{16}(\Delta\lambda_{\text{FWHM}})^{1.21}\ \text{cm}^{-3} \tag{1}$$

where $\Delta\lambda$ is in Å units. This equation is based on the fitting of the experimental data, and in fact closely

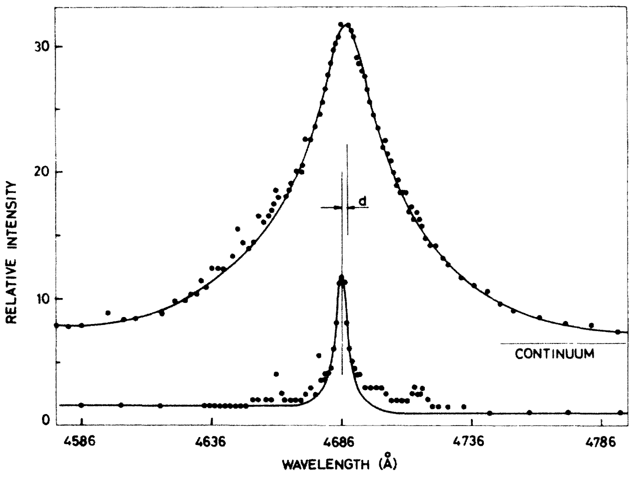

FIG. 1. Two experimental profiles of the He II 4686-Å line obtained at maximum electron density 16.9×10^{17} cm^{-3} and at 2.0×10^{17} cm^{-3}; d denotes shift of the line.

agrees with calculations by Griem and Shen.[10] Our main concern in electron-density measurements is a possible presence of self-absorption of the 4686-Å line which may distort the line profiles. This would result in erroneous reading of the line half width which, after the use of Eq. (1), introduces an error in electron-density measurements. There are several experimental methods which can be used for self-absorption check (see, e.g., Ref. 11) but unfortunately none of them is convenient for the He II 4686-Å line or for our long, pulsed plasma source. The only possibility left is the comparison with theoretical profiles. For this purpose we present in Table I results of the measurements of the width at different heights of the He II 4686-Å line, together with corresponding results of theoretical calculations.[12,13] In this table experimental results for the red wing of the line are given. The blue wing of this line is enhanced and this asymmetry is usually attributed to the quadrupole effect[14,15] which is not taken into account in Refs. 12 and 13. In order to illustrate weak dependence of the P_α line shape upon electron temperature, theoretical results at various electron temperatures are also given in Table I.

Comparison of our experiment with theoretical data in Table I shows that experimental profiles of the 4686-Å line are not distorted to a measurable extent by self-absorption. Unfortunately, this conclusion is of limited value since the applied method is very rough and it can be used with confidence only to detect the presence of large self-absorption.[16]

The axial electron temperatures in the range 8–10.5 eV are determined from the Boltzmann plot of the relative intensities of O III 3754.21-, 3707.24-, 3702.75-, and 3455.12-Å impurity lines with transition probabilities being taken from Wiese *et al.*[17] To determine electron temperature thermal equilibrium in an optically thin medium is assumed. The spectral response of photomultiplier monochromator system is calibrated against a standard coiled-coil quartz iodine lamp.

III. RESULTS AND DISCUSSION

Results of experimental measurements of the red shift of the He II P_α line are given in Fig. 2 together with some other recent experimental data and calculated shifts. Earlier experimental work is discussed in detail in Refs. 5 and 7. The estimated errors of our experimental data in Fig. 2 are as follows: shifts, ±15; electron density, ±10%, while electron temperatures measured in the range 8–10.5 eV are accurate within ±10%. Here we draw attention to the fact that in this experiment the position of unshifted line profile is not measured; our reference profiles are taken at $N_e=(1.1-2.0)\times10^{17}$ cm^{-3}. Therefore, in this experiment we determine the dependence of shift d upon electron density N_e without knowing where the d versus N_e line intercepts the d axis at $N_e=0$. Here, we assumed that at the $N_e=0$ Stark shift of the P_α line $d=0$. This assumption allows us to make sensible comparison with all other results in Fig. 2. However, it should be stressed here that this procedure does not influence the accuracy of our shift measurements; it may induce an error only in the determination of d at $N_e=0$ which is measured in Refs. 5, 7, and 18 where they are found to be exceedingly small (<0.015 Å) which justifies our assumption.

Straight lines 1 and 3 in Fig. 2 represent the least-squares fit of experimental points from Refs. 5 and 7, respectively. Solid lines represent the regions of measure-

TABLE I. Comparison of measured and theoretical data along the He II 4686-Å line profiles.

N_e (10^{17} cm^{-3})	T_e (K)	$\Delta\lambda_2/\Delta\lambda_4$	$\Delta\lambda_2/\Delta\lambda_8$	$\Delta\lambda_2/\Delta\lambda_{16}$	$\Delta\lambda_2/\Delta\lambda_{32}$	Reference
10.0	20 000	0.524	0.332	0.226	0.164	13
	40 000	0.521	0.333	0.224	0.158	13
	80 000	0.512	0.328	0.222	0.164	13
	160 000	0.508	0.326	0.220	0.164	13
	80 000	0.477	0.290	0.198	0.142	12
18.8	115 000	0.500	0.336	0.224	0.168	This experiment
18.0	115 000	0.500	0.323	0.229	0.163	This experiment
16.9	115 000	0.500	0.336	0.227	0.161	This experiment
12.5	111 000	0.500	0.336	0.224	0.165	This experiment
11.5	111 000	0.483	0.319	0.224	0.161	This experiment
9.1	111 000	0.483	0.326	0.229	0.163	This experiment

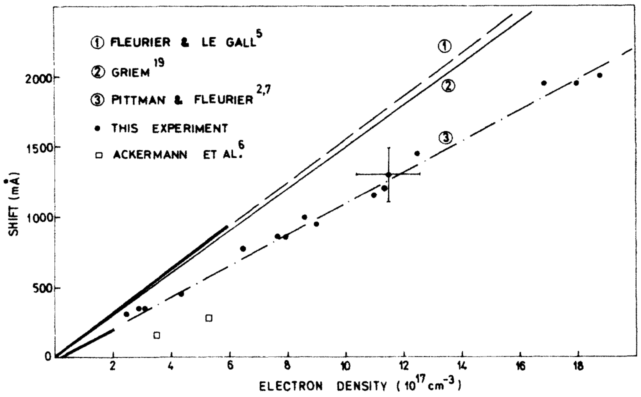

FIG. 2. Experimental red shift of the He II Paschen-α (P_α) line vs electron density. Computed shifts include electron-impact and ion quadrupole shifts at electron temperature 4×10^4 K (Ref. 19).

ments, while broken parts of the lines are extrapolations which are made to facilitate comparison with our data. Straight line 2 in Fig. 2 represents the calculated sum of shifts caused by electron collisions and quadrupole interactions at electron temperature 4×10^4 K.[19] Straight lines in Fig. 2 can be represented by the following equations: for Ref. 5,

$$d=-0.03+155N \ , \tag{2}$$

for Ref. 19,

$$d=150N \ , \tag{3}$$

and for Refs. 7 and 18,

$$d=-14.8+117.7N \ , \tag{4}$$

while best fit of our data gives the straight line

$$d=110.2N \ . \tag{5}$$

In the above equations d is in mÅ and $N=N_e\times 10^{-17}$ cm^{-3}.

Comparison of experimental results in Fig. 2 shows excellent agreement between our data and extrapolation of the best-fit curve from the work by Pittman and Fleurier.[7] Here, one should bear in mind that our shift measurements were performed at different, higher electron temperatures than in Ref. 7, while electron densities were determined from the width of the P_α line which itself depended upon electron temperature. These dependences are difference for both shift and width, this introducing a certain amount of uncertainty into our comparison. Nevertheless, the agreement is so good that the discrepancy does not exceed 1% at $N_e=1\times 10^{18}$ cm^{-3}, and therefore our best-fit curve is not drawn in Fig. 2. Data from Ref. 5 are systematically, about 40%, above our experiment and Ref. 7, while the results of Ackermann *et al.*[6] are far below all other data in Fig. 2. Since the results from our experiment and from Ref. 7 are obtained from different plasma sources using a different experimental procedure of shift measurement and plasma diagnostics, we give preference to Ref. 7 and to our experiment, and for plasma-diagnostic purposes we recommend Eq. (4) at the low-temperature region (2–4 eV) and Eq. (5) at higher electron temperatures (8–11 eV).

Although theoretical calculations in Ref. 19 are performed for lower electron temperatures and allowance should be made for the shift dependence upon electron temperature, systematic disagreement with Eq. (3) (see Fig. 2) indicates that the theory may require further refinement.

IV. CONCLUSIONS

We have measured the shift of the He II P_α line over an electron-density range 2.5×10^{17} to 18.8×10^{17} cm^{-3}. For these measurements we used Z-pinch plasma as a light source. The electron density is determined from the Stark width of the He II P_α line, while electron temperatures in the range 8–10.5 eV are determined from the Boltzmann plot of relative intensities of O III impurity lines. Measured shifts agree within a few percent with the best-fit curve of the results obtained by Pittman and Fleurier[7,18] at the low-electron-density region $(0.2\text{–}2.0)\times 10^{17}$ cm^{-3}. On the basis of experimental data (see also Fig. 2) for plasma-diagnostic purposes Eq. (5) is recommended. This equation disagrees by about 35% with theoretical calculations by Griem.[19]

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