Measurement of Stark Broadening and Shift of the Helium I Line $\lambda = 4471.5$ Å and its Forbidden Component $\lambda = 4470$ Å for Electron Densities $7 \cdot 10^{14} \lesssim N_e \,[\mathrm{cm}^{-3}] \lesssim 3 \cdot 10^{16}$

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The profiles of the HeI line $\lambda = 4471.5$ Å ($4^3\mathrm{D} - 2^3\mathrm{P}$) and its forbidden component $\lambda = 4470$ Å ($4^3\mathrm{F} - 2^3\mathrm{P}$) have been measured for electron densities N_e ranging from $7 \cdot 10^{14}$ cm^{-3} to $3 \cdot 10^{16}$ cm^{-3}. The line was emitted from a continuous afterglow plasma emerging from a plasmatron device. The working pressure ranged from 100 Torr to 2 atmospheres. Our measurements agree with those of Bekefi et al. (1971), Bretagne et al. (1971/1973) and Drawin and Ramette (1974). Relatively by large discrepancies are found with some theoretical calculations. Our measurements include the very interesting density region from $N_e = 2 \cdot 10^{15}$ cm^{-3} to $N_e = 1 \cdot 10^{16}$ cm^{-3} for which only a very few experimental data are available.

Experimental

A helium plasma was created in a welding type plasmatron device already used for other spectroscopic measurements in our laboratory [1,2]. The plasmatron consists of an electron arc burning between a central tungsten cathode and a circular copper anode, both water-cooled. The arc plasma diffuses out of a hole (diameter 4.8 mm) in the anode. The emitted radiation is observed in the afterglow region. At atmopheric pressure, the helium gas flow was approximately 12 liters/minute, the electric power 10 kW in continuous operation. When working in the laminar regime, the plasma jet is of high stability and therefore particularly well adapted for spectroscopic precision measurements. The temporal evolution of the emission was continuously monitored with the help of a glass fiber connected to a photomultiplier the output voltage of which was continuously recorded. The observed fluctuations were less than $\pm 5\%$.

The gas circulated in a closed device at various absolute pressures, ($p = 100$ Torr to $p = 2$ atmospheres). The cylindrical plasma jet was observed through a quartz window perpendicular to the axis of the plasma flow. The line intensities were measured with an Ebert-Fastie grating type spectrometer (focal distance 2 m, grating 1200 lines/mm) working in second order with an effective resolving power $\lambda/\varDelta\lambda$ of 100.000. The line intensities and the line profiles were recorded at different lateral positions of the line of sight relative to the axis of the plasma. Measurements were performed at a position 5 mm distant from the orifice through which the plasma diffused into the observation chamber.

In order to determine the electron density, we added 0.5% hydrogen to helium. This quantity was sufficient to observe simultaneously both the helium lines and the H_β line.

The absolute line intensities were obtained by comparing the measured line intensities with the emission of a tungsten ribbon lamp calibrated by the N.B.S. Washington.

The exact wavelength position was determined by measuring simultaneously the He lines emitted from a low pressure spectral lamp.

Procedure

Several helium lines and the H_β line were recorded for different lateral positions of the "line of sight" with an entrance slit width of 30 μ and a height of 1 mm. In order to obtain the radial emission coefficients $\varepsilon(r, \lambda)$ and wavelength λ, the measured data were submitted to a "Abel inversion". Prior to the inversion procedure, the measured line intensities and their derivatives were smoothed out by the method of Gram's polynomials [2,3].

We have verified that the $\lambda = 4471$ Å line was emitted from an optically thin layer. This was not the case for the $\lambda = 5876$ Å line which showed self-absorption. All other lines were optically thin.

Using the empirical Hill formula [4] (which is based on Griem's theoretical calculations [5])

$$N_e = 10^{13} (\Delta\lambda)^{3/2} [C_0(T) + \sum_{n=1}^{m} C_n(T) (\ln\Delta\lambda)^n] \text{ cm}^{-3}$$

in the form

$$N_e = 10^{13} (\Delta\lambda)^{3/2} [C_0(T) + C_1(T) \ln\Delta\lambda] \text{ cm}^{-3} \text{ for } H_\beta$$

which relates the half width $\Delta\lambda$ of the H_β line to the electron density N_e, the latter could be determined with a precision of $\pm 10\%$. [The coefficients $C_0(T)$ and $C_1(T)$ are two coefficients tabulated by Hill; $\Delta\lambda$ is in Anstrom units, N_e in cm^{-3}.] Once the electron density is known, the plasma (electron) temperature T_e can be determined from the absolute population densities of the excited levels and/or from a Boltzmann plot, since partial L.T.E. exists under the present experimental conditions [6-8]. The T_e values ranged from 3700 K at $N_e \cong 7 \cdot 10^{14}$ cm^{-3} to 15000 K at $N_e \cong 3 \cdot 10^{16}$ cm^{-3}.

A measurement of the apparatus function showed that it could completely be neglected besides Stark broadening. The Doppler profile could also be neglected in the explored electron density range since the lines are emitted from a recombining afterglow plasma at elevated central particle density which ensures rapid cooling of the gas [9]. Thus, unfolding of the profiles were not necessary.

Results

The results of our measurements are displayed in Figs. 1 a to 3 b together with those of other authors. In order to show both the T_e and N_e dependence of our results, the latter have been put into six different temperature regions characterized by six different symbols:

This experiment

▲	$9700 \leqq T[K] \leqq 10\,000$	
●	$7000 \leqq T[K] \leqq 12\,000$	
■	$9000 \leqq T[K] \leqq 13\,000$	experimental.
▼	$9000 \leqq T[K] \leqq 15\,000$	
○	$5900 \leqq T[K] \leqq\ \ 7\,600$	
⊙	$3700 \leqq T[K] \leqq\ \ 5\,000$	

The results of other authors are indicated by the following symbols:

other authors ✕	Barnard et al. [18]	
▣	Bekefi et al. [17]	
✶	Bretagne et al. [10]	experimental;
✱	Drawin et al. [9]	
+	Nelson et al. [11]	
⊕▽	Barnard et al. [15, 19]	
⊖	Deutsch et al. [16]	theoretical.
✡	Griem [14]	

All experimental and theoretical values are given as a function of electron density N_e

- Figs. 1 a, b show the wavelength distance $\delta\lambda$ [Å] between the intensity maxima of the allowed and forbidden components at $\lambda = 4471.5$ Å and $\lambda = 4470$ Å respectively.

- Figs. 2 a, b show the ratio I/p of the intensity maxima I of the forbidden component to that of the allowed line (P).
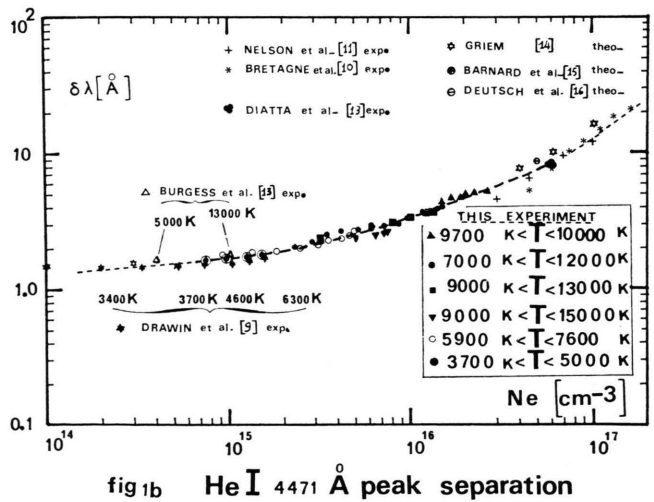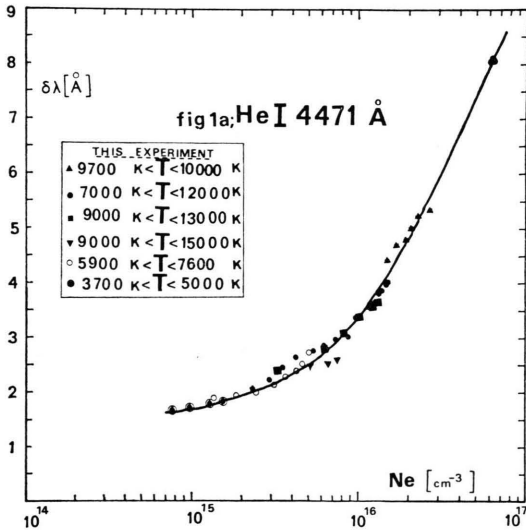

Fig. 1. Wavelength distance $\varepsilon\lambda$ [Å] between allowed and forbidden component: (a): our measurements only, (b): comparison with experimental and theoretical results of other authors.
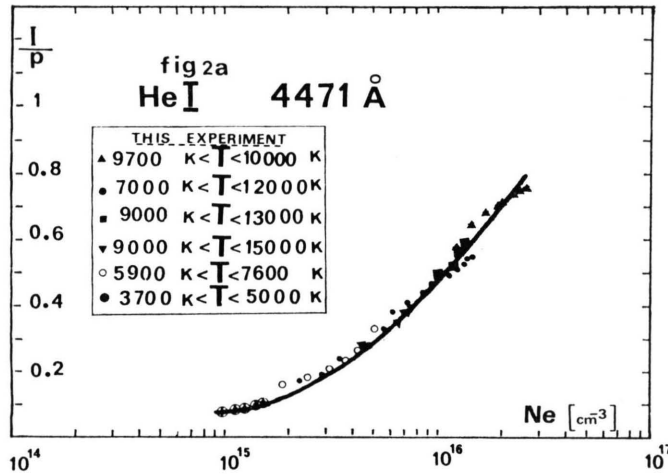
Fig. 2. Intensity ratio I/P of the maxima of the forbidden (I) and the allowed component (P): (a): our measurements only, (b): comparison with other authors.
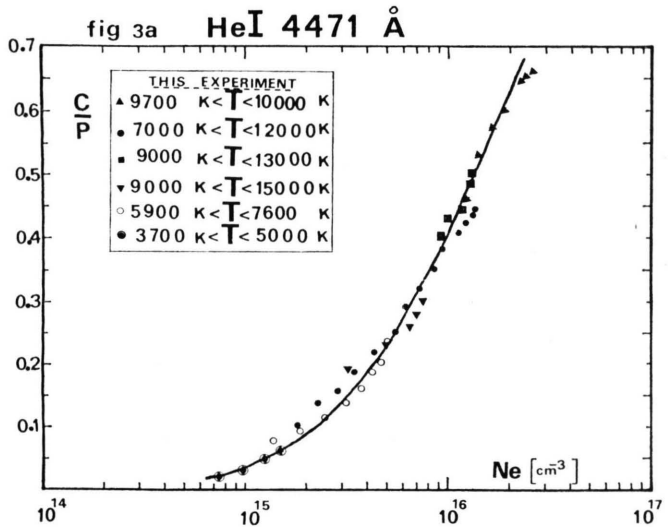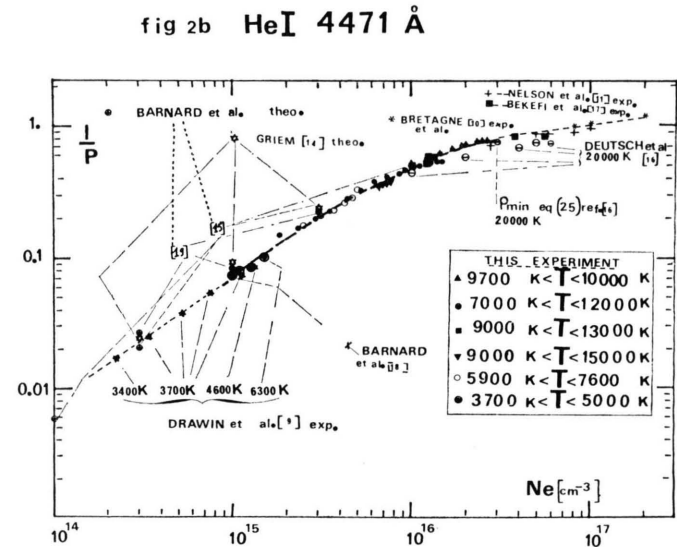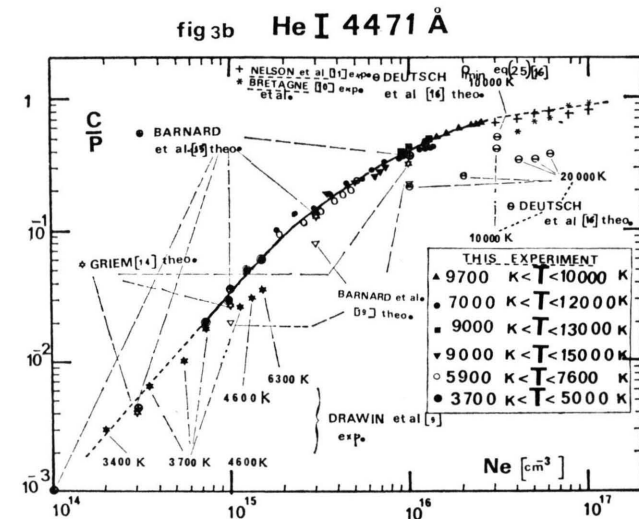

Fig. 3. Intensity ratio C/P of "valley intensity (C)" to the intensity of the maximum of the allowed line (P): (a): our measurements only, (b): comparison with other authors.

— The ratio C/P of the intensity C of the valley between the two components to the maximum intensity I of the allowed line is shown in Figures 3 a, b.

The whole line profiles will be given in a more detailed paper.

The figures exhibit the following essential results.

1°) The wavelength distance $\delta\lambda$ is an non linear function of the electron density. For $10^{16} < N_e$ $[\text{cm}^{-3}] < 2 \cdot 10^{17}$ one has approximately the dependence $\delta\lambda \propto \log N_e$; for $N_e < 10^{16} \, \text{cm}^{-3}$, the N_e dependence of $\delta\lambda$ becomes weaker than $\log N_e$ with decreasing electron density. Our results agree generally well with the experimental ones of other authors [9] to [13]. At low electron densities, the values of Burgess and Cairns [12] lie slightly above our ones. The same trend was found by Drawin and Ramette [9]. At high electron densities, two values of Nelson and Barnard [11] lie definitely below our measured values. All theoretical values of Refs. [14] to [16] lie slightly above the measured data.

2°) The intensity ratio I/P increases linearly with N_e for N_e values smaller than $5 \cdot 10^{15} \, \text{cm}^{-3}$. For higher N_e values, the N_e dependence becomes more complexe. In the region about $2 \cdot 10^{16} \, \text{cm}^{-3}$ I/P varies like $N_e^{2/9}$. For large N_e the ratio $I/P \rightarrow 1$. There is general agreement between our results and those given in [9, 11, 17, 18]. Comparison of theory with experiment leads to the following conclusion: at high electron densities agreement with the results of Deutsch al. [15, 19] lie slightly above the experimental cut-off value given by Eq. (25) of Reference [16]. If not, the theoretical values of Deutsch et al. lie definitely below the experimental ones. At medium and low electron densities, all theoretical values of Griem [14] and of Banard et al, [15, 19] lie slightly above the experimental curve, with the exception of one value.

3°) The intensity ratio C/P shown in Figs. 3 a, b is in rather good agreement with the theoretical calculations of Barnard et al. [19] and the more recent calculations of Deutsch et al. [16] yield values which lie definitely below the experimental ones. In the density N_e range $1.10^{15} \ldots$ $1.5 \cdot 10^{15} \, \text{cm}^{-3}$ our measured values are approximately 1.6 times larger than the values measured by Drawin and Ramette [9] whereas extrapolation to lower electron densities yields quantitative agreement with their results.

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