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Stark parameters of neutral helium 318.8 nm line

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ABSTRACT

Aims. Our aims is to measure with good accuracy the Stark parameters (width and shift) of the He I 318.8 nm (2s ^{3}S−4p ^{3}P^o) line and to calibrate Stark width and shift dependencies of this line as a function of the electron density. In this way, it is possible to obtain an alternative method of diagnosing the plasmas of astrophysical origin and to check the quality of theoretical models that predict these parameters.

Methods. We made a spectroscopic and interferometric analysis of a pulsed plasma. The electron temperature was obtained with an intensity ratio of He II lines and ranges from 19 000 to 23 000 K. Electron density was determined by interferometry ranging from 1.25×10^{22} m^{-3} to 6.22×10^{22} m^{-3}.

Results. These experimental results are new for these plasma conditions. When joined with previous bibliographic data, they allowed us to obtain an empirical calibration expression for the Stark width and the shift of this line in a broad range of electron densities. Comparisons with different theoretical models are also included.

Key words. plasmas – atomic data – line: profiles

1. Introduction

Helium plasmas are used in industrial applications like welding, but are also found in astrophysics, particularly in the He-atmosphere evaluation of hot stars of types O and B (Leone & Lanzafame 1998). The HeI line 318.8 nm is particulary interesting in a number of astrophysical fields. For instance, most helium was created in the first few minutes of the universe's existence, and measurements of the helium abundance in astrophysical objects can be used to constrain the parameters of primordial nucleosynthesis (Walker et al. 1991). One of the methods used to obtain this helium abundance is to analyse the optical thickness of the He I triplet lines from the 2s ^{3}S level, at which point, the role played by the HeI line 318.8 nm is relevant (Peimbert et al. 2003a; Benjamin et al. 1999, 2002). This method has been used recently in regions of 30 Doradus nebula (Peimbert 2003b) and NGC 2467 (García-Rojas et al. 2005). The HeI 318.8 nm line was also identified in various nebulae of strong astrophysical interest (Osterbrock et al. 1992; Hyung et al. 2000; Garnett et al. 2000; Ruiz et al. 2003), spiral galaxies (Garnett et al. 1999), and quasars (Hall et al. 2002). Furthermore, its width has been measured in some blue compact dwarf galaxies (Thuan et al. 2005).

This work, which complements previous experimental studies of neutral helium developed in this laboratory (Pérez et al. 1991, 1995, 1996, 2003), reports Stark linewidths and shifts for the HeI 318.8 nm line in a broad electron density range ($1.25–6.22 \times 10^{22}$ m^{-3}) where there were no previous data. Results are compared with previous experiments and with the predictions of semiclassical perturbation models (Griem 1974; Bassalo et al. 1982; and Dimitrijević & Sahal-Bréchot 1990), where electron contribution is treated in the impact approximation and where the resulting Lorentzian profiles are usually acceptable, as long as the lines can be considered are isolated. Quantum mechanical models like close coupling theory (Schöning 1994) are not considered since there are no data available. These comparisons may be useful in future theoretical modelling. Additionally, these results, joined to previous experimental data, have allowed us to calculate an accurate empirical calibration expression for the Stark width and shift of HeI 318.8 nm line, which may then be used in plasma diagnostics.

2. Experimental arrangement and plasma diagnostics

All the measurements were carried out in a pulsed plasma, generated by discharging a capacitor bank of 20 μF charged up to 8000 V on the electrodes of a lamp filled with a continuous flow of pure helium at a rate of 2 cm^3/min and a pressure of 1.16 KPa. The experimental arrangement appears in Fig. 1 and has been described in detail in previous works (Gigosos et al. 1994; del Val et al. 1998). With these experimental conditions, He I emission lasts around 300 μs. Spectroscopic and interferometric end-on measurements were made on the lamp at two different plasma columns 3 mm in diameter and placed 2 mm off the lamp axis in the symmetrical positions relative to it. The validity of this method has already been proved (del Val et al. 1998; Peláez et al. 2005).

The spectroscopic beam is directed by two diaphragms (D1, D2) with a 3 mm diameter and is focused by a concave mirror (M 6) of 150 mm focal length into the entrance slit of a Jobin-Yvon monochromator (1500 mm focal length, 2400 lines/mm holographic grating) equipped with an optical multichannel analyzer (OMA) and a detector divided into 512 channels (EG&G 1455R-512-HQ), with a dispersion of 6.16 pm/channel at 318.8 nm in the first order of diffraction. As entrance slit at the spectrometer was selected to be 70 μm. In these conditions, the instrumental function was 3 OMA channels. The exposure

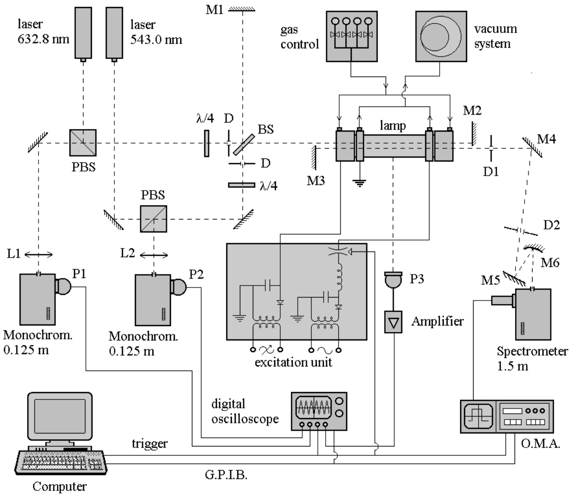

Fig. 1. Schematic diagram of the experimental setup.

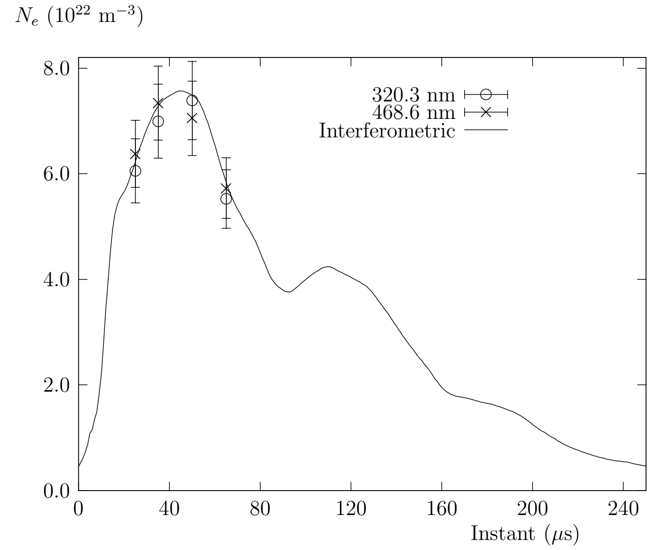

Fig. 2. Electron density obtained by two-wavelength interferometry and from He II 320.3 nm and 468.6 nm Stark widths by using the theoretical Griem model (Griem 1974) in all instants where these lines are intense enough.

time of the OMA detector was always 5 μs, in order to assure the temporal plasma homogeneity. Spectra were taken in 9 different instants of the plasma life, between 25 μs and 200 μs after the beginning of the discharge.

Concerning possible inhomogeneities due to the end regions of the plasma column, it is important to notice that, after comparisons of axial and radial measurements (del Val et al. 1998), it was concluded that boundary layers, if they exist as all, do not have any detectable influence on the experimental line shapes. In spite of this, possible self-absorption was checked in this experiment with the mirror M 3 in the figure for all profiles in all instants of the plasma life where measurements were performed. This mirror allows comparisons between the spectra taken with and without it. From them, it was concluded that self-absorption is negligible in these plasma conditions.

The electron density is measured with a Twyman-Green interferometer by using two lasers of 543.0 nm and 632.8 nm that cross the lamp in the axial direction. This arrangement allows those refractivity changes that are due only to free electrons to be obtained. Interferograms for both wavelengths have been processed according to algorithms developed and described in previous works (de la Rosa et al. 1990; Aparicio et al. 1998), and the resulting electron density ranges from 1.25×10^{22} m^{-3} to 6.22×10^{22} m^{-3} in this work. Electron density was also obtained from the Stark width of He II 320.3 nm and 468.6 nm spectral lines for all instants where these lines were rather intense. Griem's model (Griem 1974) was used. Figure 2 shows very good agreement between interferometric and spectroscopic electron density determinations, as happened in previous works (Mar et al. 2000; del Val et al. 2000a,b). This is another point that reinforces the negligible or undetectable influence of boundary layers in this experiment. These considerations allow us to conclude that a good determination of the electron density may come from the interferometric measurements with a total error around 10%.

Concerning temperature, the relevant one for the Stark effect is the kinetic electron temperature. This has often been assumed to be very similar to the excitation temperature, as usually happens in collision-dominated plasmas like this. The excitation temperature was obtained from the Boltzmann-plot of He II P_α and P_β lines, and it ranges in this experiment from 19 000 to 23 000 K. Griem's conditions (Griem 1963) for equilibrium indicate that, for He II, partial local thermodynamic equilibrium is achieved for ions whose principal quantum number is equal or greater than 2. The temperature was also calculated from the intensity ratio of He II P_β and He I 318.8 nm lines. The resulting values differed less than 15% from those obtained by He II Boltzman-plot. This is the uncertainty assumed for this parameter in this work.

3. Data treatment, results, and discussion

For our plasma conditions, He I 318.8 nm and He II 320.3 nm lines overlap for electron densities greater than 5×10^{22} m^{-3}. The algorithm used to obtain isolated profiles for these lines has been extensively explained in previous works (Rodríguez et al. 2003; Peláez et al. 2005). In our work, differences between experimental profiles and best fits are lower than 10%. The good agreement between electron density obtained from the He II P_β Stark width and the interferometric two-wavelength method determination also shows the quality of this algorithm (see Fig. 2).

Doppler broadening and instrumental function have been considered for the Stark width of He I 318.8 nm. Kinetic heavy-particles temperatures, which are not known in this plasma, was assumed to be 20 000 K. Although a two-temperature model might be considered for this kind of plasma, differences in the final Stark width, when considering 10 000 or 20 000 K for this temperature, are lower than 2% in the most unfavourable situation. Therefore, these broadening mechanisms are shown to be negligible for this spectral line and these plasma conditions. To estimate shift, as in previous works (Peláez et al. 2005), it was assumed that the centre of the line is the average of the middle points at heights between 25% and 75% of the maximum intensity. In order to obtain the relative shift, centres of He I 318.8 nm lines for different instants along the plasma life were fitted to a straight line, which takes null value when the electron density is zero.

In Fig. 3, our final experimental Stark FWHM values are plotted as a function of the electron density. Shifts in the line are also plotted versus N_e in Fig. 4. In both graphs other experimental results, as well as different theoretical predictions [G] (Griem et al. 1962, 1974), [BCW] (Bassalo et al. 1982), and [DSB] (Dimitrijević & Sahal-Bréchot 1990), have been

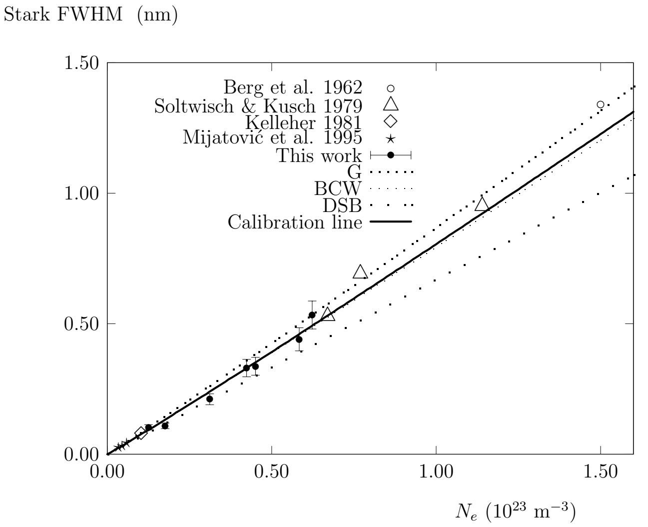

Fig. 3. Experimental Stark FWHM values with an uncertainty of 10% and theoretical estimations at 20 000 K for the He I 318.8 nm line. The calibration curve was obtained from a fit of experimental data with a similar temperature to Griem's model (Griem 1974).

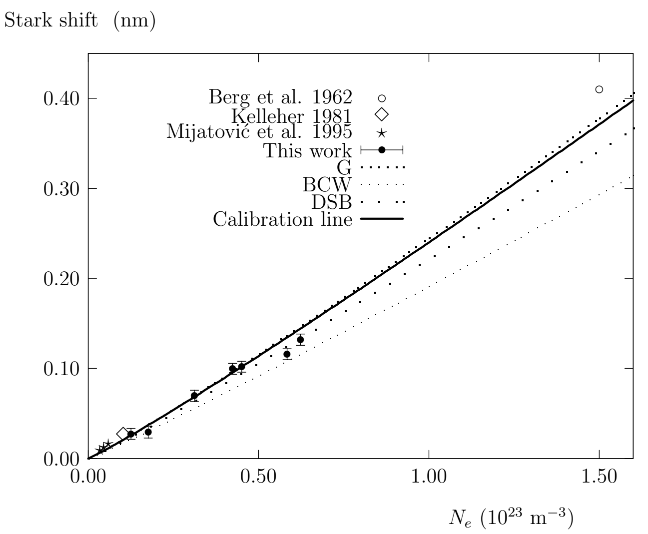

Fig. 4. Experimental Stark He I 318.8 nm shifts with uncertainties around the one OMA channel (6.2 pm). Comparisons with theoretical calculations at 20 000 K are included, as well as a calibration curve obtained from a fit of experimental data to Griem's model (Griem 1974).

included. In these figures, there are some important facts worth mentioning here. First, in comparisons with other experimental widths, the only previous data that were available were in the extremes of the electron density interval where our measurements were performed. In fact, there is very good agreement with both Soltwisch & Kusch (1979) and Kelleher (1981). Concerning shifts, comparisons with other experimental data (Kelleher 1981) are not far wrong, especially if experimental errors for both measurements are considered. Second, our results are new in the electron density range of 1.25×10^{22} m^{-3} to 6.22×10^{22} m^{-3}. In both cases (widths and shifts), our results, together with all those obtained at electron densities higher than 10^{22} m^{-3} show, as a whole, apparently good linear dependence on N_e. In the case of width, our data, along with previous measurements taken from the literature, cover a broad interval of electron density values (0.34×10^{22} to 1.5×10^{23} m^{-3}).

Table 1. Calculated parameters used in calibration expressions 1 and 2, as well as their statistical associated uncertainty.

	Value	Error
A	6.17×10^{-1}	2.7×10^{-2}
B	4.95×10^{-7}	2.2×10^{-8}
C	1.33×10^{-1}	9.7×10^{-3}
D	2.83×10^{-7}	2.1×10^{-8}

Table 2. Average ratios of the measured 318.8 nm HeI line Stark width (w_m) and shift (d_m) to the theoretical results (w_{th} and d_{th}).

	ω_m/ω_{th}	d_m/d_{th}
G	0.89	0.95
BCW	0.97	1.17
DSB	1.12	1.03

All experiments have beend developed at temperatures around 20 000 K, except for Berg's (Berg et al. 1962), which was performed at 29 000 K. This is the reason the temperature normalization has not be considered in these figures. In order to obtain an empirical calibration expression for width and shift as a function of N_e, experimental data were fitted to a mathematical expression that follows Griem's model (Griem et al. 1962, 1974) functional dependence. This model includes the ion contributions to the Stark effect in a static approximation. All previous experimental data were considered, except Berg's data for width and shift (obtained, as cited previously, at a higher electron temperature than the others), as well as Mijatović shift measurements (Mijatović et al. 1995). This author considers that ion-dynamics effects are significant for his shift measurements at low electron densities, but not particularly for widths. The mathematical expressions that fit the data better are the following:

$$w = N_e \left[A + B N_e^{1/4} \left(1 - 4.81 \times 10^{-5} N_e^{1/6}\right)\right] \times 10^{-23} \qquad (1)$$

$$d = N_e \left[C + D N_e^{1/4} \left(1 - 4.81 \times 10^{-5} N_e^{1/6}\right)\right] \times 10^{-23} \qquad (2)$$

where width w and shift d are expressed in nanometers and N_e in m^{-3}. The parameters of these equations are shown in Table 1. These calibration expressions are particularly valid for Stark data obtained at temperatures around 20 000 K and electron densities in the interval 1.25×10^{22} to 6.22×10^{22}. The interval of electron densities where these expressions may be valid might be extended with caution, especially for lower electron-density values where the ion-dynamic contribution to the Stark effect must be considered, particulary for shift.

In Table 2, the mean values of the ratios of our experimental data to predicted width and shift by different theoretical models (G, BCW, and DSB) are shown. Since our plasma conditions do not allow us to reach the maximum electron density for which this helium line can be treated as an isolated line in the core (Dimitrijević & Sahal-Bréchot 1990), the DSB model was also considered for comparisons. As seen in this table, BCW calculations agree better with linewidth measurements than do the DSB or G estimations, as was already observed in previous works when comparing experimental data with theoretical calculations (Dimitrijević & Sahal-Bréchot 1985). However, these improvements are barely significant in view of the combined errors of ~15% in widths and electron densities. All theoretical predictions for shifts agree well with our experimental data, particularly those from G and DSB, as is also shown in Table 2.

4. Conclusions

This work reports new Stark widths and shifts for the He I 318.8 nm line at temperatures around 20 000 K in a broad range of electron densities where previous experimental data did not exist. These data, obtained with a pulsed plasma source with very controlled features concerning its reproducibility between discharges and non-detectable boundary layers effects, agree very well with theoretical predictions (BCW model for widths and G and DSB models for shifts) and previous experimental results. They have allowed us to calculate calibration expressions for these Stark parameters, which may be very accurately used for plasma diagnostics of astronomical objects in the UV range.

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