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# Experimental Stark widths and shifts of uv and vuv carbon I lines (resonance transitions $2p3s\ ^3P^o_{0,1,2}$-$2p^2\ ^3P_{0,1,2}$ and transitions to low-lying quantum states)

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We have measured Stark broadening and shift parameters for spectral lines of the C I resonance multiplet $2p3s\ ^3P^o_{0,1,2}$-$2p^2\ ^3P_{0,1,2}$ as well as for lines corresponding to transitions to low-lying quantum states. The lines were emitted under approximately optically thin conditions from a dense equilibrium plasma (wall-stabilized arc; electron number density, $6.1\times10^{22}\ \mathrm{m}^{-3} \le n_e \le 2.1\times10^{23}\ m^{-3}$; temperature, $11700\ \mathrm{K} \le T \le 16000\ \mathrm{K}$). As predicted by the theory, the Stark widths and shifts for different lines of the resonance multiplet at $\approx 165$ nm were found to be equal within the experimental uncertainty. The experimental values for these lines agree well with recent calculations by Griem. For $n_e = 10^{23}\ \mathrm{m}^{-3}$ the experimental (full) half-width amounts to $(4.0\pm0.7)\times10^{-3}$ nm and the red shift $(1.9\pm0.3)\times10^{-3}$ nm. A significant deviation from Griem's calculation was only found for C I at 175.19 nm ($^1P^o$-$^1S$), for which the measured shift is larger by a factor of 2. For this line, the calculations by Wilson and Nicolet approximately agree with the results of this study.

## I. INTRODUCTION

The Stark broadening of spectral lines in the near uv and visible spectral range has been experimentally and theoretically investigated in the course of several decades.[1,2] In the vacuum uv, however, with a few exceptions, only calculated line broadening parameters exist, for which an experimental verification is still to be performed. To develop and to improve specific plasma models (e.g., equilibrium models), radiative transfer problems have to be solved, for which a reliable knowledge of the broadening parameters of vacuum uv lines is necessary, particularly for the strongest lines in the resonance series. To measure the broadening parameters of these lines, several experimental conditions must be fulfilled.

(a) Resonance lines with high oscillator strengths have to be generated in dense plasmas under approximately optically thin conditions.
(b) Reabsorption in the cooler boundary layers of the plasma has to be avoided.
(c) The Stark parameters for the resonance lines to be investigated are comparatively small. Therefore, high number densities of the electrons of the order of $10^{23}\ \mathrm{m}^{-3}$ are necessary to produce line profiles governed by Stark broadening rather than by Doppler broadening.
(d) Because of the comparatively small half-widths and shifts of the lines, a spectrometer with high resolving power and high linear dispersion has to be available, having widths of the instrumental functions equal to or smaller than the expected Doppler widths. In addition, the line-shift measurements require a good wavelength stability of the spectrometer.

The broadening and shift of C I spectral lines in the uv and vacuum uv have been measured, for which calculated broadening parameters are known.[3,4] Previous experimental investigations are only known for the C I line at 247.856 nm,[5,6] for which, however, the aforementioned conditions had not been fulfilled.

## II. EXPERIMENTAL SETUP AND METHOD

The C I line radiation was generated in a common wall-stabilized cylindrical arc (channel diameter, 4 mm; length, 100 mm) operated in argon with a trace of carbon dioxide (fractional concentration in argon $\leq 10^{-3}$). The arc plasma was observed in end-on direction (Fig. 1) and focused 1.2-fold enlarged onto the entrance slit of a highly resolving 5-m echelle Czerny-Turner spectrometer,[7] with a predisperser of the Wadsworth type. To measure the plasma parameters in the visible spectral range, the spectral radiance standard (low current carbon arc[8]) was focused onto the entrance slit under the same optical conditions. The wall-stabilized arc was connected to a pumping system of three stages, with which the plasma pressure of 1.11 bar was decreased to $1.01\times10^{-9}$ bar in the vacuum uv spectroscopic system. To characterize this system, it may be mentioned that it had been successfully used to measure the optically thin line profile of hydrogen Lyman-$\alpha$.[9]

To avoid reabsorption in the cooler boundary layers, the first diaphragm of the pumping system was located close to the plasma column. In addition, the carbon atoms had to be kept away from the anode region. This was achieved by a continuous stream of argon through the arc channel to the

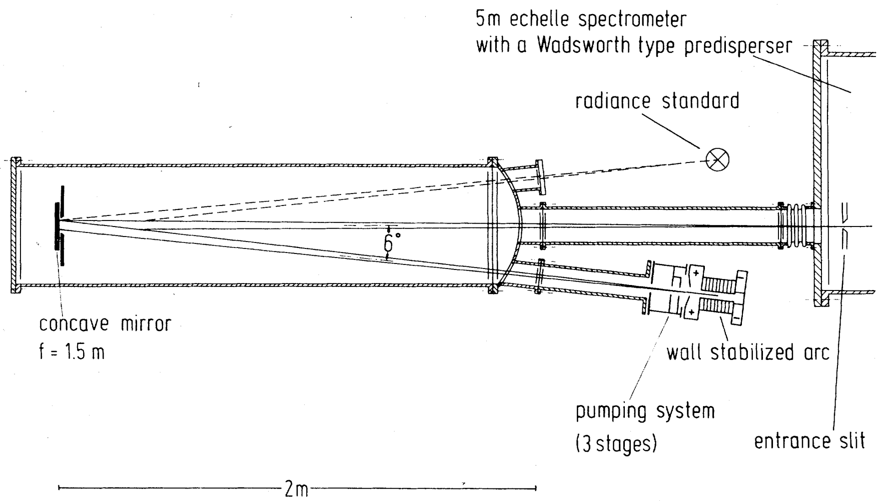


FIG. 1. Vacuum uv spectroscopic setup; for details of the 5-m echelle spectrometer see Ref. 7.

cathode side. The carbon dioxide was fed into the arc channel at a distance of approximately 1 cm from the anode side of the plasma column, using a gas mixture of argon (95%) and carbon dioxide (5%).

## III. RESULTS

### A. Plasma parameters

The C I line profiles were measured as a function of the electron number density $n_e$ and the temperature $T$. The temperature was determined from the measured emission coefficient of Ar II at $\lambda = 480.6$ nm using the value of the transition probability published in Ref. 10. Deviations from local thermodynamic equilibrium (LTE) were found[10] to be negligibly small in the investigated interval of $n_e$. The calculated electron number density is based on the measured temperature $T$ applying the equilibrium relations. Varying the arc current between 40 and 150 A at a plasma pressure of $p = 1.11$ bar, electron number densities $n_e$ between $6.1 \times 10^{22}$ and $2.1 \times 10^{23}$ m$^{-3}$ were achieved at temperatures between 11 700 and 16 000 K (uncertainties: $\Delta n_e/n_e = \pm 0.1$, $\Delta T/T = \pm 0.02$).

### B. Stark widths

The three best isolated lines in the C I resonance multiplet $2p3s\ {}^3P^0_{0,1,2} - 2p^2\ {}^3P_{0,1,2}$ at 165 nm as well as transitions to low-lying energy levels were investigated. Figure 2 shows a simplified energy level diagram only including these transitions. The measured profiles were determined by Stark broadening, Doppler broadening, and broadening influences due to residual optical depths and due to the widths of the instrumental functions. Estimations according to Unsöld[11] show that van der Waals broadening and resonance broadening were negligible (e.g., $\Delta\lambda_{1/2}^{\text{v.d.Waals}} \leq 3 \times 10^{-4}$ nm and $\Delta\lambda_{1/2}(\text{resonance}) \leq 6 \times 10^{-8}$ nm for C I at $\lambda = 165.626$ nm). This conclusion is confirmed by the experimental (full) half-widths $\Delta\lambda_{1/2}$ and red shifts $\Delta\lambda_{\text{red}}$ plotted in Figs. 4 and 5, which were found to be proportional to $n_e$.

#### 1. Optical depth

The C I lines were excited under the optical depth $\tau(\lambda)$, which was measured according to Eq. (1).

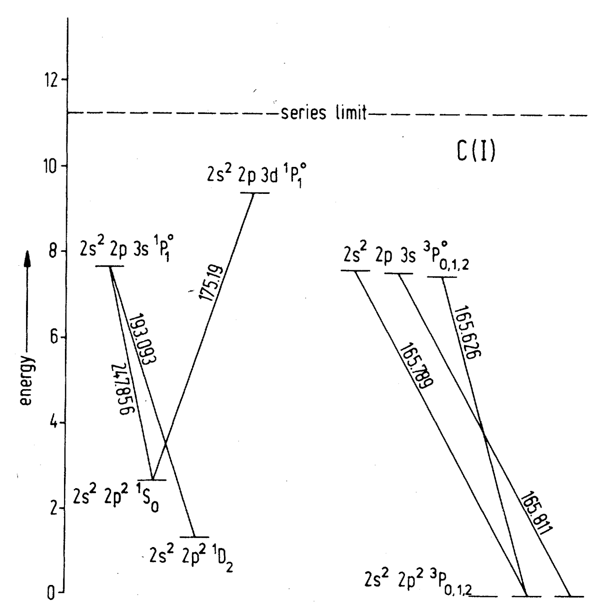


FIG. 2. Simplified energy level diagram of C I; only those transitions were inserted, which were investigated in this study.

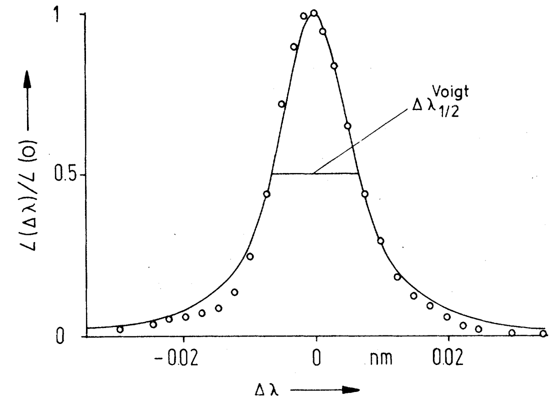


FIG. 3. Experimental, optically thin line profile of C I at 193.093 nm (circles), fitted by a Voigt function with a Gauss component $\Delta\lambda_{1/2}^{\text{Gauss}} = 0.0052$ nm, which is composed of the Doppler width $\Delta\lambda_{1/2}^{\text{Doppler}} = 0.0050$ nm and the instrumental width $\Delta\lambda_{1/2}$ (instrumental) $= 0.0015$ nm ($n_e = 2.1 \times 10^{23}$ m$^{-3}$, $T = 16\,000$ K).

$$\tau(\lambda) = -\ln(1 - L_\lambda/S_\lambda). \quad (1)$$

$L_\lambda$ is the measured spectral radiance at the wavelength $\lambda$, and $S_\lambda$ the measured source function.[12] Table I contains the optical depths $\tau(\lambda_c)$ in the center of the C I lines. An optical depth up to approximately 0.6 was chosen in order to facilitate an accurate separation of the line radiation from the continuous background. Using the measured optical depth, the optically thin line profiles were calculated from the measured profiles. The broadening influence of the absorption can be characterized by the ratios of the corresponding half-widths $\Delta\lambda_{1/2}$(optically thin)/$\Delta\lambda_{1/2}$(measured), which are presented in Table I.

TABLE I. Optical depths $\tau(\lambda_c)$ in the centers of C I lines and corresponding ratios $\Delta\lambda_{1/2}$ (optically thin)/ $\Delta\lambda_{1/2}$ (measured), describing the broadening influence of absorption. The values of $\Delta\lambda_{1/2}$ (optically thin)/$\Delta\lambda_{1/2}$ (measured) are only listed for the highest values of $n_e$ and $T$ in this experiment ($n_e = 2.1 \times 10^{23}$ m$^{-3}$ and $T = 16\,000$ K).

| Transition $\lambda$ in nm | $\tau(\lambda_c)$ | $\Delta\lambda_{1/2}^{\text{opt. thin}}/\Delta\lambda_{1/2}^{\text{meas.}}$ |
|---|---|---|
| 165.626 | 0.55 | $0.87 \pm 0.02$ |
| 165.789 | 0.55 | $0.87 \pm 0.02$ |
| 165.811 | 0.55 | $0.87 \pm 0.02$ |
| 175.19 | 0.33 | $0.92 \pm 0.01$ |
| 193.093 | 0.33 | $0.92 \pm 0.01$ |
| 247.856 | 0.16 | $0.96 \pm 0.01$ |

*2. Deconvolution*

Figure 3 shows for a typical line (C I at 193.093 nm; $n_e = 2.1 \times 10^{23}$ m$^{-3}$, $T = 16\,000$ K), that the optically thin profile can be fitted by a Voigt function (half-width $\Delta\lambda_{1/2}^{\text{Voigt}} = 1.33 \times 10^{-2}$ nm). The Gauss

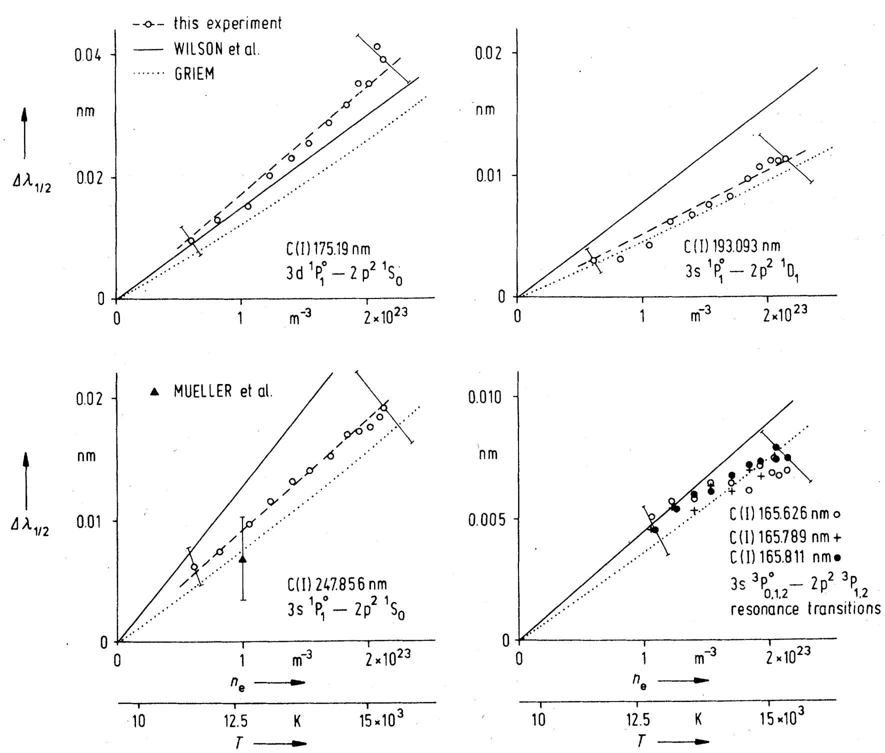


FIG. 4. Experimental (full) Stark half-widths $\Delta\lambda_{1/2}$ of C I lines, plotted vs the electron number density $n_e$ and the temperature $T$. For comparison the theoretical results of Griem (Ref. 3) (dotted lines), and Wilson and Nicolet (Ref. 4) (solid lines), as well as the half-width for C I at 247.856 nm measured by Müller *et al.* (Ref. 6) (black triangle) are inserted.

TABLE II. Experimental and theoretical (full) Stark width parameters $\Delta\lambda_{1/2}/n_e$ for uv and vacuum uv C I lines ($n_e$ in $10^{23}$ $m^{-3}$, $\Delta\lambda_{1/2}$ in $10^{-3}$ nm). The estimated systematic uncertainties include an uncertainty of the number density of the electrons $\Delta n_e/n_e = \pm 0.1$. The measurements were performed at electron number densities between $6.1\times10^{22}$ and $2.1\times10^{23}$ $m^{-3}$, corresponding to temperatures between 11 700 and 16 000 K.

| | | $\Delta\lambda_{1/2}(10^{-3}$ nm$)/n_e(10^{23}$ $m^{-3})$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Experimental | | | Theoretical | | |
| C I multiplet | λ nm | This study | Müller *et al.*[6] | Kusch[5] | Griem[3] | Wilson and Nicolet[4] | Ratio of this study/Griem[3] |
| Resonance transitions | | | | | | | |
| $^3P^0$–$^3P$ | 165.626 | 4.0 ± 0.7 | ··· | ··· | 3.7 | 4.5 | 1.08 ± 0.19 |
| | 165.789 | 4.0 ± 0.7 | ··· | ··· | 3.7 | 4.5 | 1.08 ± 0.19 |
| | 165.811 | 4.0 ± 0.7 | ··· | ··· | 3.7 | 4.5 | 1.08 ± 0.19 |
| Transitions to low-lying levels | | | | | | | |
| $^1P^0$–$^1S$ | 175.19 | 17.0 ± 2.0 | ··· | ··· | 12.4 | 15.0 | 1.37 ± 0.16 |
| $^1P^0$–$^1D$ | 193.093 | 5.2 ± 0.9 | ··· | ··· | 4.6 | 7.8 | 1.13 ± 0.20 |
| $^1P^0$–$^1S$ | 247.856 | 9.0 ± 1.6 | 6.8 ± 3.4 | 54 | 7.6 | 12.8 | 1.18 ± 0.21 |

component of this profile (full half-width $\Delta\lambda_{1/2}^{\rm Gauss} = 5.2\times10^{-3}$ nm), caused by Doppler effect and by the width of the instrumental function, was eliminated by deconvolution according to Elste.[13] For $T = 16\,000$ K the half-width of the Doppler component is $\Delta\lambda_{1/2}^{\rm Doppler} = 5.0\times10^{-3}$ nm. Using an extension of the study of van Cittert,[14] the instrumental function was computed for the applied slit widths (typically 150 μm) of the spectrometer and could fairly well be approximated by a Gauss profile of the half-width $\Delta\lambda_{1/2}$(instrumental) $= 1.5\times10^{-3}$ nm.[15] A decrease of the width of the instrumental function to a value significantly smaller than $\frac{1}{3}$ of the Doppler width does not increase the accuracy of the deconvolution procedure. Under the experimental conditions used, the influence of the width of the

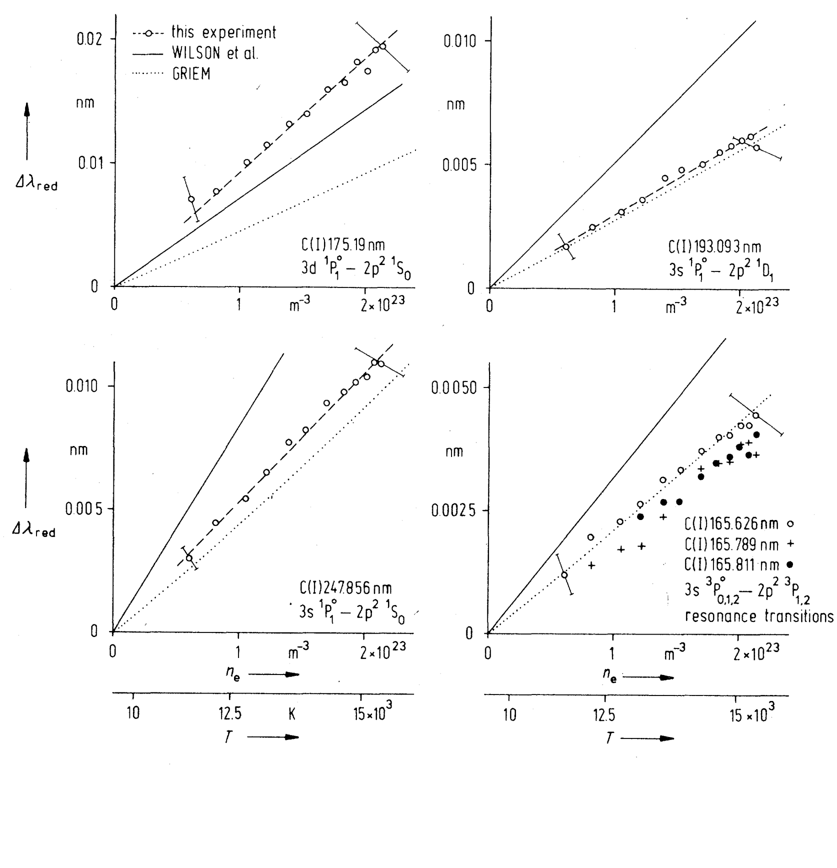


FIG. 5. Experimental Stark red shifts $\Delta\lambda_{red}$ of C I lines, plotted vs the electron number density $n_e$ and the temperature $T$. For comparison, the theoretical results of Griem (Ref. 3) (dotted lines), and Wilson and Nicolet (Ref. 4) (solid lines) were inserted.

TABLE III. Experimental and theoretical Stark shift parameters $\Delta\lambda_{red}/n_e$ for uv and vacuum uv C I lines ($n_e$ in $10^{23}$ m$^{-3}$, $\Delta\lambda_{red}$ in $10^{-3}$ nm). The estimated systematic uncertainties include an uncertainty of the number density of the electrons $\Delta n_e/n_e = \pm 0.1$. The measurements were performed at electron number densities between $6.1\times10^{22}$ and $2.1\times10^{23}$ m$^{-3}$, corresponding to temperatures between 11 700 and 16 000 K.

| | | $\Delta\lambda_{red}(10^{-3}$ nm$)/n_e(10^{23}$ m$^{-3})$ | | | |
|---|---|---|---|---|---|
| | | Experimental | Theoretical | | |
| C I multiplet | λ nm | this study | Griem[3] | Wilson and Nicolet[4] | Ratio of this study/Griem[3] |
| Resonance transitions | | | | | |
| $^3P^0$–$^3P$ | 165.626 | 1.9 ± 0.3 | 2.1 | 3.2 | 0.90 ± 0.14 |
| | 165.789 | 1.9 ± 0.3 | 2.1 | 3.2 | 0.90 ± 0.14 |
| | 165.811 | 1.9 ± 0.3 | 2.1 | 3.2 | 0.90 ± 0.14 |
| Transitions to low lying levels | | | | | |
| $^1P^0$–$^1S$ | 175.19 | 9.1 ± 1.3 | 4.6 | 7.3 | 1.98 ± 0.28 |
| $^1P^0$–$^1D$ | 193.093 | 2.9 ± 0.4 | 2.8 | 5.1 | 1.04 ± 0.14 |
| $^1P^0$–$^1S$ | 247.856 | 5.5 ± 0.6 | 4.5 | 8.5 | 1.22 ± 0.13 |

instrumental function on the total Gauss component only amounts to 4%, which is almost negligible.

### 3. Stark widths

The deconvoluted experimental half-widths $\Delta\lambda_{1/2}$ in Fig. 4 (full Stark half-widths) are plotted versus $n_e$ and $T$ and are compared with values calculated by Griem[3] (dotted lines) and by Wilson and Nicolet[4] (solid lines), respectively. The Stark width parameters $\Delta\lambda_{1/2}/n_e$ taken from Fig. 4 are given in Table II. For all listed lines the values by Griem[3] are smaller than the values by Wilson and Nicolet[4] (maximum deviation 40%). The agreement between both calculations and the results of this study is striking mainly for the resonance transitions. The maximum deviation from Griem's[3] calculations was found to be 37% for C I at 175.19 nm, whereas the calculations of Wilson and Nicolet[4] show a maximum deviation of 50% for C I at 193.093 nm.

Recently the half-width of C I at 247.856 nm was measured by Müller *et al.*[6] under optically thick conditions in a wall-stabilized arc plasma, using the curve of growth method. Although this method leads to comparatively high uncertainties, the agreement with the results of this study is satisfactory. An experimental half-width for the same line determined at a pulsed discharge by Kusch[5] is, however, larger by a factor of 6 than the result of this study ($\Delta\lambda_{1/2}^{\rm Kusch} = 0.054$ nm for $n_e = 10^{23}$ m$^{-3}$, $T = 12\,800$ K), which may indicate that the line was measured under unknown optical depth.[16]

## C. Line shifts

The shift of the line center of the investigated C I lines was measured relative to the unshifted absorption peak. Its wavelength position was determined in advance by enforced reabsorption of the C I line radiation in cold boundary layers. The positions of line center and absorption peak were measured using a length measuring device in the focal plane of the spectrometer with a length resolution of 0.5 μm (corresponding to $3.9\times10^{-6}$ nm in wavelength units at $\lambda = 165$ nm). This particularly high resolution for the measurement of wavelength differences and the overall stability of the spectrometer used facilitated the determination of the comparatively small values of the line shifts. The measured red shifts $\Delta\lambda_{red}$ of the investigated C I lines are presented in Fig. 5 as functions of $n_e$ and $T$. Corresponding Stark shift parameters $\Delta\lambda_{red}/n_e$ are given in Table III. Stark shifts calculated by Griem[3] (dotted lines in Fig. 5) are in agreement with the results of this study for the resonance lines and for C I at 193.093 nm. A significant deviation from Griem's[3] calculations was only found for C I at 175.19 nm ($^1P^0$ – $^1S$), for which the measured shift is larger by a factor of two. For this line, the calculations by Wilson and Nicolet[4] approximately agree with the results of this study, whereas their results deviate significantly for all other lines (maximum deviation up to a factor of 1.8 for C I at 193.093 nm).

[1]N. Konjevic and J. R. Roberts, J. Phys. Chem. Ref. Data 5, 209 (1976).

[2]N. Konjevic and W. L. Wiese, J. Phys. Chem. Ref. Data 5, 259 (1976).

[3]H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic, New York, 1974), p. 329.

[4]K. H. Wilson and W. E. Nicolet, J. Quant. Spectros. Radiat. Transfer 7, 891 (1967).

[5]H. J. Kusch, Z. Phys. 67, 64 (1967).

[6]D. Müller, G. Pichler, and Č. Vadla, Phys. Lett. 46, 247 (1973).

[7]H. Nubbemeyer and B. Wende, Appl. Opt. (to be published).

[8]H. Magdeburg and U. Schley, Z. Angew. Phys. 20, 465 (1966).

[9]K. Grützmacher and B. Wende, Phys. Rev. A 16, 243 (1977).

[10]H. Nubbemeyer, J. Quant. Spectros. Radiat. Transfer 16, 395 (1976).

[11]A. Unsöld, *Physik der Sternatmosphären* (Springer-Verlag, Berlin, 1968), p. 331.

[12]The fractional concentration of carbon atoms was increased (by a factor of approximately 3), until the source function limit $S_\lambda$ was achieved in the center of the C I lines investigated. Applying this method for the measurement of $S_\lambda$ the population of the C I levels involved may deviate from the Boltzmann population, determined by the temperature of a LTE argon plasma. However, the thus determined source function might, in principle, slightly deviate from the source function entering in Eq. (1) (corresponding to the approximately optically thin C I radiation). Because of the small correction due to the measured optical depths, a significant influence of this deviation on the determination of C I Stark parameters cannot be expected. Particularly for hydrogen Ly-$\alpha$, this has experimentally been proved in Ref. 9.

[13]G. Elste, Z. Astrophys. 33, 157 (1953).

[14]P. van Cittert, Z. Phys. 65, 547 (1930).

[15]It can be expected that the computation yields a sufficiently accurate instrumental function, because $\Delta\lambda_{1/2}$ (instrumental) $= 1.5\times10^{-3}$ nm corresponds to only $\approx 10\%$ of the diffraction-limited (theoretical) value of the resolving power at 193 nm. In the visible spectral range ($\lambda = 514$ nm) a diffraction-limited resolving power of 838 000 has been experimentally confirmed (Ref. 7).

[16]H. J. Kusch and H. P. Pritschow [Astron. Astrophys. 4, 31 (1970)] used this Stark width measured in Ref. 5 to determine the electron number densities $n_e$ in a line-broadening experiment on calcium. The Stark widths parameters of several Ca I and Ca II lines, given in Ref. 14 (compiled in Refs. 1 and 2), therefore cannot be considered as reliable data.