Stark width of 4p'⁰[1/2]–4s[3/2] ArⅠtransition (696.543 nm)

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Received 9 October 1995, in final form 20 June 1996

Abstract. The full width at half maximum (FWHM) of the 696.5 nm ArⅠspectral line profiles was measured in the plasma temperature range from 13 500 K to 24 000 K and free electron density from 1.2 to 2×10²³ m⁻³. Results were obtained for this line emitted from the near-cathode region of an atmospheric pressure, 200 A arc burning in pure argon. Our results are compared with data existing up to now. In the electron density range of our experiment, the 696.543 nm ArⅠline Stark FWHM is linearly proportional to the electron density. The observed dependence of the FWHM on the plasma temperature and electron density is in qualitative agreement with Griem’s theory; however, the ratio of calculated and measured FWHM was equal to 1.55, for the dependence on electron density and temperature. The dependence of FWHM on electron density, obtained by weighted least squares fitting of all our data with the constraint that the curve passes through the origin, is well represented by the following equation:

\[ \lambda_n(\text{our data}) = (1 ± 0.067) \times 0.08297 \, \text{nm} \times \left( \frac{N_e}{10^{23} \, \text{m}^{-3}} \right) \],

for the temperature \( T = 13 \, 000 \, \text{K} \).

1. Introduction

The measured spectral line shape is the result of the interaction of different mechanisms causing broadening of spectral lines. In thermal plasmas, having temperatures around 20000 K, the dominant mechanism of the spectral line broadening is the Stark effect. This component of the observed line profile may be well approximated by a symmetric Lorentzian function. In many experimental conditions other broadening effects have to be taken into account. In particular, the Doppler effect and apparatus function contributes to the line profile and must be taken into account as the Gaussian component of the measured line profile. The effective line shape is a convolution of the Gaussian and Lorentzian components, and can be represented by the Voigt function. Very small asymmetry of the line profile, due to collisions of atoms and ions, was also detected in the ArⅠline shape [2]. In this work, this asymmetry is neglected.

The 696.543 nm ArⅠline (Mult. 13, transition 4p'[1/2]–4s[3/2]⁰), is of great interest because it is a strong and well isolated line of the neutral argon spectrum. For this reason, it is often used in the diagnostic of argon plasmas. This line corresponds to the transition from the upper energy level \( E_u = 13.324 \, \text{eV} \) (statistical weight: \( g_u = 3 \)) to the lower energy level \( E_l = 11.545 \, \text{eV} \) (\( g_l = 5 \)), and has the transition probability \( A_{656.543 \, \text{nm}} = (6.39 \pm 5\%) \times 10^6 \, \text{s}^{-1} \), as proposed by Wiese et al [3].

In earlier publications [4–6], we described results of our studies of the near-cathode region of the electric arc burning in pure argon. In this paper, we use the same arc and
plasma diagnostic procedures to calibrate the Stark FWHM of the 696.543 nm Ar I line, in the temperature range from 13,500 K to 24,000 K and electron density from $1.2 \times 10^{23} \text{ m}^{-3}$ to $2.0 \times 10^{23} \text{ m}^{-3}$.

2. The experimental set-up

Details of our apparatus (cf figure 1) and experimental procedures are described in previous publications [4–6]. The discharge was generated at the conical cathode tip (angle of 40°) made of 2% thoriated tungsten. The upper part of the arc consisted of three copper disks of 5 mm channel diameter. The first disk, with the hole shaped in a convergent nozzle, increased the arc stability. The upper disk worked as an anode. Such a three-disk system isolates the neighbourhood of the cathode from the influence of the anode region and reduces plasma fluctuations. The arc worked at atmospheric pressure with the arc current $I_{\text{arc}}$ of 200 A and argon flow maintained to $d_{\text{s}} = 4 \text{ l min}^{-1}$. The study of the arc column was performed side-on, for several plasma slices between the cathode and the first disk, at different distances ($0.25 < z < 5.5 \text{ mm}$) from the cathode tip. The spatial resolution of the optical system was determined by the width of the entrance slit (15 µm), the height of the photodetector (39 µm) and the aperture of the optical system (1:200).

The arc was mounted on a step-motor driven table which translated it horizontally (the $x$-direction in figure 1), so the image of the arc traversed the entrance slit of the Ebert-type spectrometer (resolution equal to 150,000), equipped with a CCD linear array of 1728 contiguous photodiodes ($13 \times 39 \mu \text{m pixel size}$). The effective spectrometer dispersion was 1.5 pm/pixel. The measured apparatus function, which could be very well approximated by the Gaussian profile, had a half width of about $\Delta \lambda_{\text{app}} \approx 4.4$ pixels (FWHM).
at $\lambda = 696.543$ nm.

The profile for each line was measured at 40–50 horizontal positions of the arc. The measured chordal intensity was converted to the radial distribution pixel by pixel, using the numerical Abel inversion procedure [7]. Then the Voigt functions on a linear continuous background were fitted to measured line profiles using the downhill simplex method [8].

3. Plasma diagnostic

To obtain reliable results of the plasma diagnostic, the following spectral lines were recorded: 397.936 nm, 396.836 nm, 480.602 nm (Ar II lines) and 696.543 nm (Ar I line). We determined the radial distribution of the plasma temperature $T$ using three independent methods:

(a) the Larentz–Fowler–Milne (LFM) method [9],
(b) the Olsen–Richter (OR) graph [10] applied to 696.543 nm Ar I and 480.602 nm Ar II lines,
(c) the relative intensity measurement of two Ar II lines (397.936 nm and 396.836 nm).

Details on the plasma diagnostic are described in [4–6]. We have shown that the temperature profiles determined with these methods agree very well. For $z < 2.5$ mm we observed that experimental points did not follow the 1 atm isobar in the OR diagram. This deviation depended on the distance from the cathode and symmetry axis of the plasma column. Nevertheless, our plasma was in the radiative–collisional equilibrium [6], and knowing the plasma temperature and position of each measurement point in the OR diagram, the free electron density could be calculated. It should be pointed out that for plasma layers close to the cathode, the radial distribution of free electron density had an off-axis maximum. For these layers, one $N_e$ value could correspond to two temperatures at different radial distances from the arc axis.

Finally, the temperature and electron density ranges, in the zone between the cathode tip and the first stabilizing disk, are [13 500 K, 24 000 K] and [1.21×10$^{23}$ m$^{-3}$, 1.97×10$^{23}$ m$^{-3}$], respectively.

Uncertainties of the temperature, determined from measurements of spectral line emission coefficients, arise from different sources including the Abel inversion procedure, corrections for the line wings, uncertainties of fitted parameters of the line profile and possible errors caused by treatment of self-absorption.

In our experiments, the total emission profile of each line was obtained with a few hundred pixels for the recorded profile and the Abel inversion was performed with about 50 points on the horizontal axis. The statistical errors of the fitted line profile parameters were small (about 1%). The plasma optical depth never exceeded 0.15, and the self-absorption correction for the total line intensity never exceeded 5%. In the applied numerical fitting procedure, wings of the line profile were automatically taken into account. Results obtained from the different diagnostic methods allowed us to estimate that the statistical errors of the temperature and electron density radial distributions stay below ±5%. An analysis of our experimental procedure uncertainties and results is described in [6].

4. Results and discussion

4.1. Theory of the Stark broadening

The Stark FWHM of a spectral line is related to the electron density by the well known semi-empirical formula proposed by Griem [1] and valid for $0.05 \leq \alpha \leq 0.5$ and $r \leq 0.8$:
\[ \Delta \lambda_S = 2 [1 + 1.75 \alpha (1 - c_0 r)] w \]

with

\[
\begin{align*}
    w &= (N_e/N_e^0) w_n(T) \\
    r &\approx 9 \times 10^{-3} N_e^{1/6} / \sqrt{T} \\
    \alpha &= (N_e/N_e^0)^{1/4} \alpha_n(T) \\
    N_e^0 &= 10^{22} \text{ m}^{-3} \quad \text{and} \quad N_e \text{ in m}^{-3} \\
    c_0 &= 0.75 \quad \text{for a neutral emitter.}
\end{align*}
\]

In this expression, \( r \) is the ratio of the mean distance between ions and the Debye length: it varies as a function of \( N_e^{1/6} \) and \( T^{-1/2} \), \( w \) is the half width at half maximum (HWHM) due to collisions with electrons (proportional to electron density \( N_e \) and weakly dependent on the temperature \( T \)); \( \alpha \) is characteristic of the quasi-static ion broadening (proportional to \( N_e^{1/4} \) and dependent on \( T \)). Parameters \( w_n(T) \) and \( \alpha_n(T) \), normalized to \( N_e = 10^{22} \text{ m}^{-3} \), were tabulated by Griem [1] for different temperatures (see table 1). These values have to be treated with caution, since they do not account for the perturbations due to excitations of the lower levels. However for our particular transition, this is a negligible effect since its lower level does not have a dipole transition to the ground state.

<table>
<thead>
<tr>
<th>( T ) (K)</th>
<th>( w_n ) (nm/10(^22) m(^{-3}))</th>
<th>( \alpha_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>0.00327</td>
<td>0.047</td>
</tr>
<tr>
<td>5000</td>
<td>0.00409</td>
<td>0.040</td>
</tr>
<tr>
<td>10000</td>
<td>0.00537</td>
<td>0.032</td>
</tr>
<tr>
<td>20000</td>
<td>0.00710</td>
<td>0.026</td>
</tr>
<tr>
<td>40000</td>
<td>0.00873</td>
<td>0.023</td>
</tr>
</tbody>
</table>

\( w_n \approx 1.796 \times 10^{-3} T^{0.3685} \)

In our experimental conditions, the term \( 1.75 \alpha (1 - c_0 r) \), which is proportional to ion broadening, is relatively small, and the term \( w_n(T) \), expressed in nm/10\(^22\) m\(^{-3}\), can be fitted by a temperature power, with an error below 2%:

\[ w_n(T) \approx 1.796 \times 10^{-3} T^{0.3685} \quad \text{(nm/10}\(^23\) \text{ m}^{-3}). \]

Finally one may say that variations of \( \Delta \lambda_S \) should be a linear function of electron density, and nearly independent of temperature.

### 4.2. Data treatment

The total FWHM \( \Delta \lambda \) of the Ar I line is a result of the convolution of the Lorentz profile (the Stark effect) and the Gaussian profile (the Doppler effect and instrumental broadening). The other broadening mechanisms appeared to be negligibly small in the pressure and temperature range of our experiment (\( P \approx 1 \text{ atm}, T \approx [13500 \text{ K}, 24000 \text{ K}] \)):

(a) the natural broadening was of the order \( 10^{-5} \) nm,

(b) the Van der Waals broadening, estimated using the formula proposed by Vallée [11], stayed below \( 10^{-6} \) nm,

(c) there was no resonant broadening since the lower level of the investigated transition has no dipole transition to the \( 3p^6 \) ground state,

(d) in this interval of temperatures, the Doppler FWHM \( \Delta \lambda_D \) is equal to

\[
\Delta \lambda_D = \frac{\lambda}{C} \sqrt{\frac{8 \log 2 k_B T}{m}} \approx 7.1626 \times 10^{-7} \lambda \sqrt{T/\mu}
\]
and varies from 9 to 11 pm for $T = 13\,500$ K and $T = 24\,000$ K, respectively. In this last expression, $k_B$ and $C$ are conventional physical constants, $T$ is the plasma temperature, $\lambda$ is the wavelength of the line, $m$ is the mass of the argon atom and $\mu = 40$ is its atomic weight in atomic units;

(e) the instrumental FWHM $\Delta \lambda_{\text{app}}$, for the 696.543 nm Ar I line, was equal to 6.4 pm.

In our experimental conditions, the Gaussian part $\Delta \lambda_G = (\Delta \lambda_D^2 + \Delta \lambda_{\text{app}}^2)^{1/2}$ of the line profile was formed of two approximately equal contributions $\Delta \lambda_D$ and $\Delta \lambda_{\text{app}}$, and must be taken into account.

The side-on measured intensity was inverted to the radial distribution of the emission coefficient pixel by pixel and the obtained profile was corrected for spectral sensitivity of the optical system. To the inverted spectrum, the Voigt $V(x, y)$ function superposed on a linear continuous background was fitted. The function was centred on $\lambda_0$ and its Gaussian part $\Delta \lambda_G$ (previously calculated) was fixed. The fitted function had the form

$$W(\lambda_i) = a_0 + a_1 \lambda_i + I_0 V \left( \frac{\Delta \lambda}{\Delta \lambda_G}, \frac{\lambda - \lambda_0}{\Delta \lambda_G} \right) / V \left( \frac{\Delta \lambda}{\Delta \lambda_G}, 0 \right)$$

where $\lambda_i$ was the wavelength at the $i$th pixel; $W(\lambda_i)$ was the measured emission coefficient at $\lambda_i$, $a_0$, $a_1$, $I_0$, $\lambda_0$ and $\Delta \lambda$ were adjustable parameters. The total emission coefficient

$$I = \pi I_0 \Delta \lambda_G / V \left( \frac{\Delta \lambda}{\Delta \lambda_G}, 0 \right)$$

was calculated using the fitted values of $I_0$, $\Delta \lambda$ and $\Delta \lambda_G$. With these values a new distribution of the temperature was calculated. Then the experimental line profile was fitted again with the new Gaussian contribution. This iterative procedure was repeated until the change of the Doppler broadening, obtained from two successive temperature distributions, was smaller than the chosen convergence parameter. The gradient expansion near the minimum of $\chi^2$ was used to calculate the standard deviation for the fitted parameters.

4.3. Results

To ensure consistency and reproducibility of the results, and to cover large temperature and electron density ranges, we have performed a series of measurements at different distances $z$ from the cathode tip. For each experiment, all selected lines were recorded during the same measurement session and the symmetry axis $r = 0$ mm of the plasma column was determined from the integrated intensity of the lines. To be able to compare the different quantities at the same radial distances $r_j = j \times 0.05$ mm ($j = 0–30$) from the symmetry axis, Abel-inverted values at $r_j$ were interpolated from measurement points using cubic splines.

It was possible, in general, to record the ‘thermometer’ Ar II lines up to a distance of about 1.10 mm from the axis. However, the profiles were relatively uncertain in the peripheral zones of the column and the consecutive numerical procedures increased this inaccuracy. We have thus decided not to use results obtained beyond the radial distance of 1.00 mm. Similarly, beyond the axial distance of 1.50 mm, the line shape procedure applied to the 480.602 nm Ar II line was considered unreliable due to the sharpness of the lines, and the attendant small number of points defining its shape.

Our results are plotted in figure 2(a) (measured FWHM $\Delta \lambda_S$ against electron density) and (b) (FWHM $\Delta \lambda_S^0 = \Delta \lambda_S \times (N_0^0 / N_e)$ normalized at $N_0^0 = 10^{23}$ m$^{-3}$ against temperature). In figure 2(a), one may notice the temperature dependence of the FWHM: for similar electron density there are points with different FWHM values, depending from which temperature region the line was emitted. As was stated before, for plasma layers close to the cathode, the radial distribution of electron density had the off-axis maximum. In
Figure 2. (a) Our 696.543 nm Ar I line FWHM data: $\Delta \lambda_S$ as a function of electron density $N_e$. □, $z = 0.26$ mm; △, $z = 0.88$ mm; ○, $z = 1.00$ mm; ◆, $z = 1.50$ mm; ■, $z = 2.21$ mm; ▲, $z = 2.50$ mm; ●, $z = 3.83$ mm; ♦, $z = 5.00$ mm; *, $z = 5.48$ mm. (b) Our 696.543 nm Ar I line FWHM data: $\Delta \lambda_S^*$ as a function of temperature $T$. □, $z = 0.26$ mm; △, $z = 0.88$ mm; ○, $z = 1.00$ mm; ◆, $z = 1.50$ mm; ■, $z = 2.21$ mm; ▲, $z = 2.50$ mm; ●, $z = 3.83$ mm; ♦, $z = 5.00$ mm; *, $z = 5.48$ mm.
these layers, one $N_e$ value could correspond to two temperatures at two different radial distances from the arc axis. This temperature dependence is quite pronounced in our experimental conditions. Thus, in order to establish a dependence between FWHM and electron density, we first normalized our results to the temperature value $T^n = 13,000$ K.

For this normalization, we used the theoretical temperature dependence calculated by Griem [1]. We applied the following formula for normalization of the temperature dependence (see equation (2)):

$$
\Delta \lambda^n_S = \Delta \lambda_S \times \left( \frac{n}{T} \right)^{0.3685}
$$

(6a)

and, for the temperature and electron density normalization together, the expression

$$
\Delta \lambda^{on}_S = \Delta \lambda^0_S \times \left( \frac{T^n}{T} \right)^{0.3685} = \Delta \lambda_S \times \frac{N_e}{N_e^0} \times \left( \frac{T^n}{T} \right)^{0.3685}.
$$

(6b)

Our data show the temperature dependence which is in good agreement with theory if calculated values are divided by 1.55 (see section 4.5 and figure 4). The proportionality constant between FWHM and $N_e$, obtained by weighted least squares fitting of all our data, is equal to

$$
\Delta \lambda^n_S^{(\text{our data})} = (1 \pm 0.067) \times 0.08297 \text{ nm} \times \frac{N_e}{10^{23} \text{ m}^{-3}},
$$

(7)

where $\Delta \lambda^n_S$ is in nm and $N_e$ in m$^{-3}$, and $T^n = 13,000$ K. This dependence is shown in figure 3(a) (full line) with its error range (broken lines).

4.4. Variation of the Stark FWHM against electron density

We have performed a systematic search of the literature on Ar I data published from 1965 to 1995 (except maybe for the material presented in meetings, theses and internal reports, which have not been published elsewhere). Over the last 30 years, at least 13 spectroscopy experiments have been carried out for Stark broadening of this line ([12–23], by chronological order—cf table 2). In figure 3(a) ($0 < N_e \leq 2 \times 10^{23} \text{ m}^{-3}$) and (b) ($N_e \leq 16 \times 10^{23} \text{ m}^{-3}$), the linear variation of the 696.543 nm Ar I line FWHM $\Delta \lambda^n_S$ with electron density as obtained from our measurements is compared with results from these references:

(a) Results of Popenoe and Shumacker [12] were obtained in a wall-stabilized arc of 10 cm length and 5 mm diameter of the channel, observed side-on. Experimental data were Abel-inverted, fitted to the Lorentzian profile on a linear continuous background and corrected for the Gaussian broadening contribution. The measured FWHM of the hydrogen H$\beta$ line was used for electron density determination ($0.12–0.77 \times 10^{23} \text{ m}^{-3}$). The temperature was deduced from the LTE plasma composition data (9700–12,250 K). The graph, where 696.543 nm Ar I line experimental data ($\sim 60$ points) are plotted against electron density, seems to show a weak quadrature dependence. Nevertheless, authors propose $\Delta \lambda^0_S = 0.096 \text{ nm}$ as the normalized Stark FWHM at $1 \times 10^{23} \text{ m}^{-3}$ ($T = 12,850$ K). Some of their results are plotted in figure 3(a) and (b).

(b) Evans and Tankin’s [13] data were obtained with a low-voltage high-current free burning arc. The temperature (10,000–20,000 K) was determined via the LFM method and from absolute Ar I line intensity. Electron density $N_e$ ($0.48–1.96 \times 10^{23} \text{ m}^{-3}$) was calculated from the plasma composition data with the LTE assumption. Experimental line profiles were Abel-inverted, fitted to the Lorentzian function with a linear continuous background. Some data were corrected by the authors for the Doppler and instrumental broadening; only these data are stated in figure 3(a), the corrections are marked by arrows.

(c) Results of Chapelle et al [14, 15] were obtained from observation of the axial part of an atmospheric pressure plasma jet (without the Abel inversion). The temperature
Table 2. 696.543 nm Ar I line ($\Delta \lambda_{\text{w}}^{\text{on}}$) values (in nm/10^{24} m^{-3} – T_n = 13 000 K) found by different authors.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Plasma source</th>
<th>Method of measurement</th>
<th>$N_e$ (m^{-1})</th>
<th>$T$ (K)</th>
<th>Stark FWHM $\Delta \lambda_{\text{w}}(10^{-1} \text{ nm})$</th>
<th>Mean value $\langle \Delta \lambda_{\text{w}}^{\text{on}} \rangle$</th>
<th>Acc. $\langle w_n/w_{\text{on}}^{\text{on}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12]</td>
<td>Wall-stabilized arc</td>
<td>H\beta Stark width (0.12–0.77) × 10^{23}</td>
<td>9700–12 265</td>
<td>0.17–0.69</td>
<td>≈60</td>
<td>0.964</td>
<td>20%</td>
</tr>
<tr>
<td>[13]</td>
<td>High current, free-burning arc</td>
<td>LTE equations set</td>
<td>11 900–14 700</td>
<td>0.58–1.17</td>
<td>11</td>
<td>0.691</td>
<td>20%</td>
</tr>
<tr>
<td>[14]</td>
<td>Plasma jet (without Abel inversion)</td>
<td>LTE equations set</td>
<td>13 800</td>
<td>0.55</td>
<td>1</td>
<td>0.540</td>
<td>35%</td>
</tr>
<tr>
<td>[15]</td>
<td>Wall-stabilized arc</td>
<td>H\beta Stark width (0.13–0.77) × 10^{23}</td>
<td>9900–12 200</td>
<td>0.07–0.79</td>
<td>13</td>
<td>0.831</td>
<td>22%</td>
</tr>
<tr>
<td>[16]</td>
<td>Wall-stabilized arc</td>
<td>H\beta Stark width (0.19–1.47) × 10^{23}</td>
<td>10 200–13 900</td>
<td>0.08–1.07</td>
<td>6</td>
<td>0.708</td>
<td>22%</td>
</tr>
<tr>
<td>[17]</td>
<td>Wall-stabilized arc</td>
<td>H\beta Stark width 1.0 × 10^{23}</td>
<td>13 000</td>
<td>0.81</td>
<td>1</td>
<td>0.810</td>
<td>15%</td>
</tr>
<tr>
<td>[18]</td>
<td>Wall-stabilized arc</td>
<td>H\beta Stark width 1.0 × 10^{23}</td>
<td>12 750</td>
<td>0.80</td>
<td>1</td>
<td>0.806</td>
<td>30%</td>
</tr>
<tr>
<td>[19]</td>
<td>Linear flash tube</td>
<td>H\beta Stark width (6.0–10.0) × 10^{23}</td>
<td>16 500–18 700</td>
<td>4.40–6.50</td>
<td>6</td>
<td>0.626</td>
<td>20%</td>
</tr>
<tr>
<td>[20]</td>
<td>Linear flash tube</td>
<td>H\beta Stark width (5.8–9.1) × 10^{23}</td>
<td>13 600–14 600</td>
<td>0.28–0.43</td>
<td>5</td>
<td>0.697</td>
<td>15%</td>
</tr>
<tr>
<td>[21]</td>
<td>Plasma jet</td>
<td>H\beta Stark width (5.7–15.7) × 10^{23}</td>
<td>15 700–19 000</td>
<td>3.90–7.10</td>
<td>13</td>
<td>0.543</td>
<td>36%</td>
</tr>
<tr>
<td>[22]</td>
<td>Linear flash tube</td>
<td>LTE equations set 2 lines intensities ratio</td>
<td>13 500–24 000</td>
<td>1.18–1.85</td>
<td>189</td>
<td>0.8297</td>
<td>6.7%</td>
</tr>
<tr>
<td>Our work</td>
<td>High current, near cathode arc</td>
<td>LTE equations set, OR diagram, 2 lines intensities ratio</td>
<td>(1.21–1.97) × 10^{23}</td>
<td>(N_e ≤ 2 × 10^{23} m^{-3} – T_n = 13 000 K)</td>
<td>1.814</td>
<td>5.0%</td>
<td>1.55(±16%)</td>
</tr>
</tbody>
</table>

Mean value (see text)
$T = 13\,800\, K$ was determined from measured absolute intensities of the 415.86 nm Ar I line and continuum. The electron density $N_e = 1.45 \times 10^{23} \, \text{m}^{-3}$ was calculated via the LTE equations set.

(d) Tonejc et al [16] used a 7.7 cm wall-stabilized arc of 5 mm canal diameter. The FWHM of the hydrogen H$\beta$ was applied in order to determine the electron density, which was in the range from 0.19 to 0.88 $\times 10^{23} \, \text{m}^{-3}$. The temperature ($10\,100 \, \text{K}$–$12\,500 \, \text{K}$) was deduced via the LTE equations set and from the absolute intensity of the 430.0 nm Ar I line. The 696.543 nm Ar I line experimental data, corrected for self-absorption, were given for $N_e$ in the range from $0.13 \times 10^{23} \, \text{m}^{-3}$ to $0.77 \times 10^{23} \, \text{m}^{-3}$ ($9900 \leq T \leq 12\,200 \, \text{K}$).

(e) The data of Nick [17] were taken in a wall-stabilized arc, at electron density from $0.19 \times 10^{23} \, \text{m}^{-3}$ to $1.47 \times 10^{23} \, \text{m}^{-3}$ and temperatures ranging from 10 200 K to 13 900 K. The FWHM of the hydrogen H$\beta$ line gave the electron density. The plasma temperature was deducted from the calculated LTE plasma composition.

(f) The data of Jones et al [18] were taken end-on in a wall-stabilized arc of 10 cm length and 3 mm channel diameter, at electron density from $0.7 \times 10^{23} \, \text{m}^{-3}$ to $1.1 \times 10^{23} \, \text{m}^{-3}$ and temperatures ranging from 12 100 K to 13 100 K. Data were corrected for self-absorption. The FWHM of the hydrogen H$\beta$ line measurements gave the electron density. The plasma temperature was deducted from the calculated LTE plasma composition. Recorded line profiles were fitted to the Lorentzian line shape on a smooth continuum background, and
corrected for the Doppler and instrumental broadening. In their paper, the authors give the normalized Stark FWHM at $N_e = 10^{23} \text{ m}^{-3}$: $\Delta \lambda^{0}_{S} = 0.081 \text{ nm} \ (T = 13\,000 \text{ K})$.

(g) In the work of Bakshi and Kearney [21], an atmospheric argon plasma jet was used. Spectral line data were Abel-inverted and fitted to the Voigt function. Electron density was determined from FWHM of the H$\beta$ line ($0.39 - 0.61 \times 10^{23} \text{ m}^{-3}$). No correction was made for self-absorption, which was regarded as negligible. We have estimated the plasma temperature (11 000–11 900 K) from the LTE equations set.

(h) Iglesias et al [19], Vitel and Skowronek [20] and Siyacoun [23] used flash tubes with different pressures (50 to 400 Torr) to obtain high electron density ($5.7 \times 10^{23} \text{ m}^{-3}$). Electron density was obtained via FWHM of the H$\beta$ line measurements. To measure $N_e$, Vitel and Skowronek [20] also used the intensity of the continuum for $\lambda$ between 360.0 nm and 385.0 nm and the laser interferometry for $\lambda = 3.39 \mu\text{m}$. Temperature (12 000 K to 30 000 K) was deduced from the Saha equation or from the intensity of optically thick Ar I infrared lines. Data were recorded side-on, corrected for self-absorption and fitted to the Lorentzian line shape after subtraction of the continuum. The radiation transport effect was taken into account using a simplified solution of the radiative transfer equation [24].

(i) Uzelac [22] used a similar experimental set-up, but realized in end-on geometry. Temperature (from 13 600 K to 14 600 K) was deduced from the intensity ratio of two lines. The plasma was assumed to be in the LTE state, and the electron density was in the range from 5.8 to 9.1 $\times 10^{23} \text{ m}^{-3}$. The deconvolution procedure was applied to separate the Stark profile and the Gaussian instrumental profile. The effects of self-absorption were corrected using the method proposed by Wiese [25].

In figure 3(a) one can see that the data of Evans and Tankin [13] and Chapelle et al [14, 15] seem to be too small. It is quite possible that the data of Evans and Tankin [13] are
affected by a systematic error. Their experiment was performed with the side-on geometry for the high current argon arc and the LFM method and Ar I line intensity measurements were applied for the temperature determination. As we know now (e.g. from [6]), the LFM method applied to the Ar I line may give overestimated values of the plasma temperature and thus free electron density (calculated via the LTE equation set). The results of Chapelle et al [14, 15] were obtained with the side-on geometry but without the Abel inversion, thus this result may also be affected by a systematic error, difficult to estimate.

At low electron density ($N_e \lesssim 2 \times 10^{23} \text{ m}^{-3}$), the 696.543 nm Ar I line Stark FWHM seems to be linearly proportional to the electron density in agreement with the theory [1]. For our results, the proportionality constant, obtained by a weighted least squares fit, with the constraint that the curve passes through the origin, is given by equation (7) and is shown in figure 3(a) as the broken line.

At higher electron density, the dependence of the measured Stark FWHM on electron density shows a significant departure from linear dependence (cf figure 3(b)). According to Vitek and Skowronek [20, 26] and Siyacoun [23], who observed similar phenomena for Ar II, Kr I, Kr II, Xe I and Xe II lines, the correlation between charged particles tends to decrease the influence of weak collisions in the Stark broadening. Uzelac [22] has not observed such a nonlinear variation of the Stark FWHM for krypton and xenon lines against electron density. To our knowledge, his results for argon were not published and can be found only in his thesis [22]. In spite of the fact that these values are apparently smaller than those proposed in this paper FWHM (see equation (7)), they agree with the linear dependence within the limits of estimated errors, thus it is impossible to make a final conclusion related to nonlinear dense plasma effects. Furthermore, Uzelac and Konjevic [27] explain observations of Vitek and Skowronek [20, 26] and Siyacoun [23] by an artefact in data evaluation, particularly in assumptions concerning the transport of radiation through the observed plasma layers.

4.5. Variation of normalized Stark FWHM against temperature

We normalized the Stark FWHM available in the literature and presented before in figure 3(a) and (b), to $N_e = 10^{23} \text{ m}^{-3}$. Although such a normalization can only be justified for points which show linear dependence on $N_e$ in figure 3, we also enclosed points from the nonlinear part of this figure ($N_e \geq 5 \times 10^{23} \text{ m}^{-3}$) to show their positions relative to the first group of data. Figure 4 shows the variations of those normalized Stark FWHM $\lambda S$ against the plasma temperature. We can remark that:

(a) The results of Iglesias et al [19] for $T = 12\ 800 \text{ K}$ and Jones et al [18] for $T = 13\ 000 \text{ K}$ are in good coincidence with our mean value, not only for the normalized FWHM as a function of $T$ but also for $\lambda S$ against electron density.

(b) Except for one value, the data presented by Tonejc et al [16] are well distributed around the mean value.

(c) Although the results of Popenoe and Shumacker [12] and Nick [17] show a good dependence toward electron density, the normalized FWHM shows significant departures from the mean value, when the temperature decreases.

(d) Both groups of values obtained by Siyacoun [23] are smaller than the mean value, but one is distinctly smaller than the other. This group, which already gives the Stark FWHM too weak, corresponds to the experiments with 200 Torr pressure.

(e) Our data show a dependence on the temperature, which is in qualitative agreement with Griem’s theory.

(f) The data of Uzelac [22] as above have been taken from [23], and we do not know
what the plasma temperature was. So we have no conclusions concerning the normalized Stark FWHM of Uzelac’s results [22].

4.6. Comparison with Griem’s theoretical data

The term $\alpha_n$ in equation (1) contributes only for a small fraction $\Delta \lambda_S$ (up to 5%), and, generally, the uncertainties in the data preclude a determination of $\alpha_n$. Then we can use the theoretical value of the ion-broadening parameter $\alpha_n$ (cf table 1, according to Griem [1]) and the experimental value of $T$ and $N_e$ to determine $\Delta \lambda_S^{0b}$ from equation (1). The experimental values of $\Delta \lambda_S^0$ are compared with the theoretically calculated $\Delta \lambda_S^{0b}$ in figure 4. Although our results show similar dependence as Griem’s theoretical data, $\Delta \lambda_S^{0b}$ are always much higher than the experimental one with a mean factor $\langle \Delta \lambda_S^{0b} / \Delta \lambda_S^0 \rangle \approx 1.56 \pm 15\%$.

In the same way, we used the theoretical value of the ion-broadening parameter $\alpha_n$ [1] and the experimental values of $\Delta \lambda_S$, $T$ and $N_e$ to determine $w_n^{exp}$ from the equation (1). This value $w_n^{exp}$ is always much lower than Griem’s theoretical one $w_n$ with the same mean factor $\langle w_n / w_n^{exp} \rangle \approx 1.55 \pm 16\%$. The last column in table 2 shows the same factor for the different referenced works.

5. Conclusion

The mean values $\langle \Delta \lambda_S^{0n} \rangle$ for all referenced works are shown in table 2. Our study of the 969.543 nm Ar I line is in reasonable agreement with other works for this line in the low
electron density range \((N_e \leq 2 \times 10^{23} \, \text{m}^{-3})\). We calculated a global mean weighted value \(\langle \Delta \lambda_{S}^{\text{on}} \rangle^G\), using \(\langle \Delta \lambda_{S}^{\text{on}} \rangle\) from table 2 for results which were obtained in the low electron density range, except results by Chapelle et al. [14, 15] and Evans and Tankin [13], which were not included (see section 4.4):

\[
\langle \Delta \lambda_{S}^{\text{on}} \rangle^G = (0.0814 \pm 5.0\%) \, \text{nm} \quad \text{(normalized to } N_e = 10^{23} \, \text{m}^{-3}, T^o = 13000 \, \text{K}).
\]

(8)

In our opinion \(\langle \Delta \lambda_{S}^{\text{on}} \rangle^G\) may be used in plasma diagnostics for electron density measurements up to \(N_e \approx 3 \times 10^{23} \, \text{m}^{-3}\).

In figure 5 we give a history of the 696.543 nm Ar I normalized Stark FWHM \(\langle \Delta \lambda_{S}^{\text{on}} \rangle\) data. To the x-axis, we transferred the reference work in chronological order. In the ordinate axis, we draw the departure of the mean value of the considered work from the global mean value \(\langle \Delta \lambda_{S}^{\text{on}} \rangle^G\) proposed in table 2. The broken lines show the relative uncertainty of \(\langle \Delta \lambda_{S}^{\text{on}} \rangle^G\). Except for the value proposed by Chapelle et al. [14, 15], all the data agree within the limits of estimated errors with this mean value. Nevertheless, the data obtained for high electron density \((N_e \geq 2 \times 10^{23} \, \text{m}^{-3})\) must be considered with particular attention, and more work on this transition will be required in the future, especially in the high density regime to resolve the discrepancy between the data of the different workers.

**Figure 5.** History of mean normalized Stark FWHM \(\langle \Delta \lambda_{S}^{\text{on}} \rangle\) for the 696.543 nm Ar I line. Data rejected for mean value calculation (see text): □, probably systematic error; ○, data for \(N_e > 5 \times 10^{23} \, \text{m}^{-3}\).
References

[22] Uzelac N I 1989 Thesis Yugoslavia