Stark Broadening of A III and A IV Lines *

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The half-widths of five A III and two A IV lines have been measured in a pulsed arc operated in an argon-nitrogen mixture. Electron densities of 3.8 to 8.0×10^{16} cm^{-3} were determined by laser interferometry at a single wavelength while electron temperatures from 20750° to 23100 °K were measured from the relative intensities of A II lines. The experimental A III and A IV Stark profile halfwidths were compared with calculated values using various theoretical approximations.

Introduction

A number of experiments has been devoted to the investigation of the Stark broadening of neutral, singly, and multiply ionized atomic lines [1]. Therefore, it should be possible to find reliable experimental information on the line broadening parameters for a variety of atomic species. Unfortunately, only a limited number of papers which are dealing mainly with neutral and singly ionized atomic lines gives a complete set of informations, i. e. Stark width and shift, and electron density and temperature. In the case of multiply ionized atoms the situation is even worse since most of the experiments were performed in highly inhomogeneous plasmas (vacuum sparks and laser produced plasmas) without reliable independent determination of the plasma parameters. Thus, an almost complete lack of experimental data exist on the broadening of multiply ionized atom lines.

The aim of this work is to provide Stark widths of A III and A IV lines and to compare them with calculated theoretical results. The plasma source was a low pressure pulsed arc in an argon-nitrogen mixture. The electron density was determined by laser interferometry at 6328 Å and the electron temperature from relative intensities of A II lines.

Calculation of the Line Widths

Most of the details of the theoretical calculations can be found elsewhere [2–4], therefore only a few details will be given here for completeness.

Three different theoretical approaches were used for the calculations of the Stark line widths: the classical straight and hyperbolic path approximations and their combination for various perturber velocities. The line half-halfwidth W in a semi-classical straight-line path approximation with all sophistications used by Cooper and Oertel [4] (lower level broadening, symmetrization with respect to initial and final perturber states and corrections of the broadening functions A, B, a and b originally defined by Griem et al. [3]) is given by the following expression:

$$W = N_e \int_0^\infty f(v)\, v\, \mathrm{d}v \left| \pi \tilde{\varrho}^2 + \frac{4}{3} \pi \lambda\!\!^{-}{}^2 \sum_{j'} \frac{|\langle j | \mathbf{R} | j \rangle|^2}{2 J_j + 1} \left[a(|\tilde{Z}_{jj'}^{\min}|) - a(|\tilde{Z}_{jj'}^{\max}|) \right] \right| \tag{1}$$

where $\tilde{\varrho}_{\min} = \min(\varrho_{\min}, \varrho_{\max})$; $|\langle j | \mathbf{R} | j' \rangle|^2$ is the square of the matrix element of the electron position vector taken from Bates and Damgaard [5, 6] and calculated for each particular line;

$$Z_{jj'} = \varrho\, v\, \omega_{jj'} / [v^2 - (\hbar\, \omega_{jj'}/m_e)]$$

with $\hbar\, \omega_{jj'}$ the energy difference between perturbed level j and perturbing level j'. N_e, $f(v)$, $\lambda\!\!^{-}$, ϱ, J and m_e have the usual meaning. $\varrho_{\min}$ and $\varrho_{\max}$ are defined elsewhere [3, 4].

For the hyperbolic perturber-path trajectories approximation Baranger [7] gives the expression for the half-halfwidth of an isolated ion line as

$$W = \frac{3}{8\pi} N_e \lambda\!\!^{-}{}^2 \int_0^\infty f(v)\, \mathrm{d}v \sum_{j'} \frac{|\langle j | \mathbf{R} | j' \rangle|^2}{2 J_j + 1} f_{E_1}(\xi_{jj'}) \exp\{2\pi |\xi_{jj'}|\} \tag{2}$$

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where

$$\xi_{jj'} = \frac{e^2}{\hbar}\left(\frac{1}{v'} - \frac{1}{v}\right); \quad \frac{1}{2}\, m\, v^2 = \frac{1}{2}\, m\, v'^2 + \hbar\, \omega_{jj'} .$$

v' is the velocity of the perturbing electron after the interaction. The function f_{E_1} is tabulated by Alder et al. [8].

Cooper and Oertel [2] combined these two theoretical approaches [3,7] taking the advantages of the both methods. They used straight perturber path trajectories for large perturber velocities and hyperbolic trajectories for small ones. The limiting velocity between these two approximations is the one at which $\varrho_{\min}$ is equal to the "Coulomb cutoff" $e^2/m\, v^2$.

Experiment

The plasma source was a low pressure, pulsed arc driven by a 150 μF condensor bank charged from 1.0 to 1.4 kV as previously described [9]. The discharge vessel was a Pyrex tube (24 mm ID) with a distance of 20 cm between the electrodes. At the centre of both electrodes holes of 1 mm diameter were located for laser interferometric measurements and for end-on plasma observations. During the experiment a continuous flow of the argon-nitrogen mixture was sustained at a pressure of about 0.1 torr.

The optical system consists of a 1 m monochromator (McPherson Model 2051, with inverse linear dispersion of 4.15 Å/mm) which is used to scan the line profile shot by-shot. This instrument has, with 10 μ slits, a measured instrumental halfwidth of 0.045 Å and was equiped with an end-on photomultiplier tube EMI 6255 B. The output of the photomultiplier together with the current waveform were recorded on a dual-beam oscilloscope Tektronix 555. Scanning of A III and A IV lines was accomplished by repeated pulsing of the arc while advancing the monochromator in 0.02 Å wavelength steps. All signals were analyzed at maximum electron density.

Greatest care was taken to find optimum conditions with the least line self absorption. This was achieved by careful examination of the line intensities and line shapes as a function of experimental conditions (total gas pressure, argon-to-nitrogen ratio and condensor bank energy), and by checking the optical depths of the strongest lines by measuring the intensity ratios within multiplets and comparing them with the theoretical predictions based on L-S coupling. It was found that the percentage of argon

Tables 1 and 2. Experimental halfwidths W(Å) compared with theoretical values calculated from the straight path (W_G) and hyperbolic path (W_{BA}) approximations and from the combination of these two (W_{CO}).

Ionization stage	Transition array	Designation (Mult. No)	Wavelength (Å)	W_m (Å)	W_G (Å)	W_{BA} (Å)	W_{CO} (Å)	W_m (Å)	W_G (Å)	W_{BA} (Å)	W_{CO} (Å)
A III	$3d^3\,3d''$— $3p^3(^2P^0)4p''$	$^3P^0-{}^3P$ (6)	3391.8	0.05_8	0.014	0.058	0.045	—	—	—	—
	$3p\,^34s$— $3p^3(^4S^0)4p$	$^5S^0-{}^5P$ (1)	3285.8	0.06_4	0.011	0.048	0.033	0.08_2	0.021	0.090	0.058
			3301.9	0.06_1	0.011	0.049	0.033	0.07_7	0.021	0.091	0.058
	$3p^3\,4s'$— $3p^3(^2D^0)4p'$	$^3D^0-{}^3D$ (2)	3480.6	0.05_8	0.020	0.070	0.046	0.08_1	0.036	0.139	0.059
		$^3D^0-{}^3F$ (3)	3336.1	0.06_3	0.016	0.050	0.031	0.08_3	0.030	0.093	0.054
	Experimental conditions:			$N_e=4.4\times10^{16}$	$T=21100$ °K			$N_e=8.0\times10^{16}$	$T=23080$ °K		

Table 1

Ionization stage	Transition array	Designation (Mult. No)	Wavelength (Å)	W_m (Å)	W_G (Å)	W_{BA} (Å)	W_{CO} (Å)	W_m (Å)	W_G (Å)	W_{BA} (Å)	W_{CO} (Å)
A IV	$3p^2\,4s$— $3p^2(^3P)4p$	$^4P-{}^4D^0$ (4 UV)	2809.4	0.02_3	0.0059	0.018	0.014	0.03_3	0.007	0.026	0.019
		$^4P-{}^4P^0$ (5 UV)	2640.3	0.02_1	0.0049	0.016	0.012	0.03_1	0.009	0.023	0.017
	Experimental conditions:			$N_e=3.8\times10^{16}$	T=20750 °K			$N_e=5.6\times10^{16}$	$T=22200$ °K		

Table 2

in the mixture was of crucial importance for the elimination of self-absorption. For example, in pure argon the half-widths of some strong A III lines were about $60-80\%$ larger than in the mixture $A:N_2$ 1:10 for the same electron density. A further decrease of argon in the mixture (down to a ratio of 1 : 20) did not have any influence on the line width measurements, although the line intensities were appreciably lower. Finally, it should be underlined that the experimental results presented tables 1 and 2 were obtained end-on in argon-nitrogen mixtures. For the A III lines the ratio of $A:N_2$ was 1:10 and for the A IV lines 1:8 while the total initial pressures were 0.10 and 0.15 torr, respectively.

In order to obtain the Stark profiles from the measured ones it was necessary to use a deconvolution procedure for a gaussian and dispersion profile [10]. An example of experimental measurements fitted with the corresponding Voigt profile is given in Figure 1. This figure illustrates at the same time the typical scatter of the experimental data.

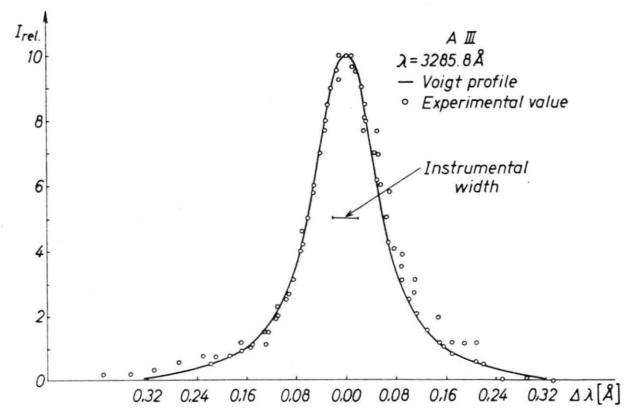

Fig. 1. Experimental data for the 3285.8 Å A III line fitted with the corresponding Voigt profile. The electron density was $8.0\times10^{16}\ \mathrm{cm}^{-3}$, the electron temperature 23080 K.

Since Doppler broadening was not negligible, the gaussian part of the experimental profile consists of two parts: the instrumental profile and the line width due to Doppler broadening. Knowing the instrumental width it was possible to deduce the ion temperature from the gaussian part of the line width. It is interesting to mention the good agreement (within the limits of experimental error) between the deduced temperature and that obtained from spectroscopic measurements. This indicates that the ion and measured electron temperatures are the same for the present experimental conditions at the peak of the electron density in our pulsed discharge.

Plasma Diagnostics

A helium-neon laser interferometer with a plane external mirror was used to determine the axial electron density. Interferometric fringes at 6328 Å were detected by a photomultiplier placed behind the monochromator to separate signal from plasma radiation. The peak axial electron densities varied between 3.8 and $8.0\times10^{16}\ \mathrm{cm}^{-3}$. The estimated error in the measurements of the electron density did not exceed $\pm 8\%$.

The electron temperature was determined from the Boltzmann plot of relative intensities of eight A II lines (3376.4, 3464.1, 3737.9, 3803.2, 3868.5, 4277.5, 4579.4 and 4609.6 Å), with transition probabilities being taken from Wiese et al. [11]. For these measurements the spectral response of photomultiplier monochromator system was calibrated against a standard tungsten coiled-coil quartz iodine lamp, L-100 Electro Optics.

The electron temperatures at the peak of the electron densities varied from 20750 to 23100 K, the estimated errors not exceeding $\pm 10\%$ of the reported values.

Results and Discussion

Experimentally determined full half widths of A III and A IV lines in Å units are given in Table 1 and 2 for various electron densities and temperatures. The estimated errors of the reported line widths do not exceed $\pm 30\%$ for the A III and $\pm 50\%$ for the A IV lines.

For the same experimental conditions three sets of theoretical data were calculated and are also given in the tables. The results for the line widths of the semi-classical straight-path perturber trajectory approximation are introduced in the table under W_{G}, results of the hyperbolic approximation W_{BA} and the combination of these two approaches under W_{CO}.

From a comparison of the results in the tables one can notice a large discrepancy between the experimental and the theoretical data obtained from the straight perturber path approximation. The theory underestimates the Stark widths of isolated ion lines as it was already demonstrated in the case of singly ionized atomic lines [2, 12].

The agreement of experiment with the other two sets of theoretical results is much better and is within the limits of experimental error and uncertainties of the theoretical calculations. However, it should be noted that the theoretical results are systematically smaller than the experimental ones. This is probably due to the incompleteness of available A III and A IV energy levels [13] used for the numerical calculations. Only about 10% of the total sum of the square of matrix elements is taken in account. Therefore, more energy levels will probably increase the line widths by about 20 – 40%, which would have the effect that the results of the hyperbolic approximation would be larger than experiment while the results of the combination of straight and hyperbolic approximations would approach the experimental ones. Similar conclusions were already drawn in the case of isolated singly ionized atom lines [2].

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