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Stark broadening of triply ionized oxygen lines: The temperature dependence

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The Stark widths of the $3s\ ^2S$-$3p\ ^2P^o$ and $3p\ ^2P^o$-$3d\ ^2D$ transitions have been calculated and measured in the plasma of a pulsed arc. Electron densities in the range $(2.1-6.4)\times 10^{17}$ cm^{-3} were determined from the width of the He II P_α line while electron temperatures between 50 800 and 131 800 K are measured from the Boltzmann plot of O IV line intensities. Our experimental O IV Stark width agrees well with another experiment and with our semiclassical theoretical results in the whole temperature range.

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I. INTRODUCTION

Broadening and shift of spectral lines in plasmas are the subject of numerous experimental studies (see, e.g., Ref. [1] and reference therein). Unfortunately, most of the reported data are from the measurements at a single electron temperature or in the best case the results are taken in a small temperature range. The lack of the experimental data for a wider temperature range makes a detailed test of the Stark broadening theoretical calculations unreliable. Furthermore, without the knowledge of the line width and shift dependence upon electron temperature comparison of the experimental results obtained at different plasma conditions becomes very difficult. This problem is of particular importance whenever comparison of the Stark broadening parameters along the isoelectronic sequence is performed (see, e.g., Ref. [2]). In this case the line widths and/or shifts of various ionization stages are compared and they are, depending upon the ionization stage, measured at considerably different electron temperatures.

The aim of this paper is to supply the theoretical and experimental data for the widths and shifts of the prominent triply ionized oxygen lines, for as large as, electron temperature range. The reported experimental results together with other experimental data will be used for the testing of semiclassical and other theoretical calculations.

II. THEORY

By using the semiclassical-perturbation formalism [3], we have calculated electron-, proton-, and ionized helium-impact line widths and shifts for O IV $3s\ ^2S$-$3p\ ^2P^o$ and $3p\ ^2P^0$-$3d\ ^2D$ multiplets. A summary of the formalism is given in Ref. [4]. The energy levels for O IV lines have been taken from Ref. [5]. The oscillator strengths have been calculated by using the method of Bates and Damgaard [6] and the tables of Oertel and Shomo [7]. For higher energy levels, the method described by Van Regemorter, Hoang, and Prud'homme [8] is employed. In addition to electron-impact full half widths and shifts, Stark-broadening parameters due to proton, and ionized helium impacts have been calculated.

Our results for O IV $3s\ ^2S$-$3p\ ^2P^0$ and $3p\ ^2P^0$-$3d\ ^2D$ multiplets are shown in Table I for perturber density of 10^{17} cm^{-3} and temperatures $T=40\,000-170\,000$ K. Data for other plasma parameters may be provided by authors

TABLE I. This table shows electron-, proton-, and ionized helium-impact broadening parameters for O IV lines for perturber density of 10^{17} cm^{-3} and temperatures from 40 000 to 170 000 K. Transitions and averaged wavelengths for the multiplet in Å units are also given. By using C [see Eq. (5) in [9]] one obtains an estimate for the maximum perturber density for which the line may be treated as isolated and tabulated data may be used. The numbers in brackets denote multiplicative powers of ten.

		Perturber	Electrons		Protons		Ionized helium	
Transition	T (K)		Width (Å)	Shift (Å)	Width (Å)	Shift (Å)	Width (Å)	Shift (Å)
O IV $3s$-$3p$	40 000		1.100[−1]	−2.31[−3]	2.380[−2]	−1.22[−3]	3.250[−3]	−1.15[−3]
3066.4(Å)	70 000		8.560[−2]	−2.20[−3]	3.660[−3]	−1.85[−3]	4.420[−3]	−1.67[−3]
$c=0.28[21]$	100 000		7.410[−2]	−2.40[−3]	4.440[−3]	−2.24[−3]	5.200[−3]	−1.97[−3]
	170 000		6.100[−2]	−2.80[−3]	5.630[−3]	−2.89[−3]	5.880[−3]	−2.47[−3]
O IV $3p$-$3d$	40 000		1.170[−1]	−2.24[−3]	2.230[−3]	−1.54[−3]	3.080[−3]	−1.45[−3]
3410.9(Å)	70 000		9.100[−2]	−1.85[−3]	3.620[−3]	−2.35[−3]	4.310[−3]	−2.11[−3]
$c=0.34[21]$	100 000		7.840[−2]	−2.22[−3]	4.410[−3]	−2.83[−3]	5.200[−3]	−2.49[−3]
	170 000		6.420[−2]	−2.50[−3]	5.850[−3]	−3.65[−3]	6.050[−3]	−3.12[−3]

upon request. In this table we also specify parameter C [9], which gives an estimate for the maximum perturber density for which the line may be treated as isolated when it is divided by the corresponding electron-impact full width at half maximum.

III. EXPERIMENT

The light source was a low pressure pulsed arc with a quartz discharge tube 11 mm internal diameter. The distance between aluminum electrodes was 18 cm, and 3 mm diameter holes were located at the center of both electrodes to allow end-on plasma observations to be made. The central part around the pulsed arc axis was imaged 1:1 onto the entrance slit of the 1 m monochromator by means of the concave 1 m focal length focusing mirror. A 30 mm diaphragm placed in front of the focusing mirror ensures that light comes from the narrow cone about the arc axis.

The monochromator with inverse linear dispersion 8.33 Å/mm in the first order of the diffraction grating, was equipped with the photomultiplier tube and a stepping motor (3600 steps/revolution). Signals from the photomultiplier tube were led to a digital storage oscilloscope which was triggered by the voltage pulse from the Rogowski coil induced by the current pulse through the discharge tube. The discharge was driven by a 15.2 μF low inductance capacitor charged to 6 kV (peak current 27 kA) and fired by an ignition. The stepping motor and oscilloscope are controlled by a personal computer, which was also used for data acquisition. Recordings of spectral line shapes were performed shot by shot. At each wavelength position of the monochromator time evolution and decay of the plasma radiation were recorded by the oscilloscope. Four such signals were averaged at each wavelength. Further, to construct the line profiles these averaged signals at different wavelengths and at various times of the plasma existence were used to construct line profiles, see a typical example in Fig. 1. All line profiles were recorded with 20 μm entrance and exit slits of the monochromator. With these slits measured instrumental half width was 0.185 Å. To determine the Stark half width from the measured profile, a standard deconvolution procedure for the Lorentzian (Stark) and the Gaussian (instrumental+Doppler) profiles [10] was used.

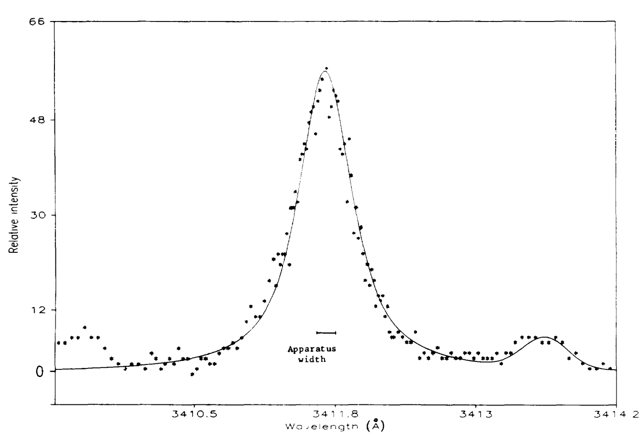

FIG. 1. Example of recording line spectra; *, measured; ——, Voigt function best fit.

Greatest care was taken to find the optimum conditions with the least line self absorption. This was achieved by careful examination of the O IV line intensities and line shapes as a function of experimental conditions (total gas pressure, oxygen-to-helium ratio and condenser bank energy), and by checking the optical depth of the strongest lines by measuring the intensity ratios within multiplets and comparing them with the theoretical predictions based on L-S coupling (see, e.g., Ref. [11]). It was found that the percentage of oxygen in the mixture was of crucial importance for the elimination of self-absorption. The ratio O_2:He=1.6:98.4 was determined after a number of experiments in which O_2 was diluted gradually until line intensities within investigated multiplets agree within 3% with the values derived from transition probabilities [12]. During the spectral line recording continuous flow of oxygen-helium mixture was maintained at a pressure of about 3 torr.

IV. PLASMA DIAGNOSTICS

For the electron-density measurements we use the width of the He II P_α 4686-Å line. The full width at half maximum $\Delta\lambda_{\mathrm{FWHM}}$ of this line is related to the electron density N_e using the following relationship [13–15]

$$N_e = 2.04\times 10^{16}(\Delta\lambda_{\mathrm{FWHM}})^{1.21}\mathrm{cm}^{-3} , \quad (1)$$

where $\Delta\lambda$ is in Å units. This equation is based on the fitting of the experimental data, and in fact closely agrees with calculations by Griem and Shen [16]. Our main concern in electron-density measurements is a possible presence of self-absorption of the 4686-Å line which may distort the line profile. This would result in erroneous reading of the line half width which, after the use of Eq. (1), introduces an error in electron-density measurements. There are several experimental methods which can be used for a self-absorption check (see, e.g., Ref. [11]) but unfortunately, none of them is convenient for the He II 4686-Å line or for our long, pulsed plasma source. Recently, in order to determine the optical thickness of the investigated line, Kobilarov, Konjević, and Popović [17] have introduced in the discharge an additional movable electrode. By placing the movable electrode at two different positions and by recording the line profiles from two plasma lengths, it is possible to determine $k_\lambda l$, where k_λ is the spectral line absorption coefficient and l is the plasma length along the direction of observation. If $k_\lambda l$ is not large ($k_\lambda l<1$, see, e.g., Ref. [18]) it is possible to recover the line profile (see example, in Fig. 2 of Ref. [17]) for the optically thin case. The same method is used here for the He II 4686-Å line self-absorption testing. For this purpose an additional aluminum electrode (10 mm thick) is located inside the discharge tube. By means of this movable auxiliary electrode it was possible to vary the plasma length and, accordingly the absorption conditions of the plasma layer under investigation, without changing

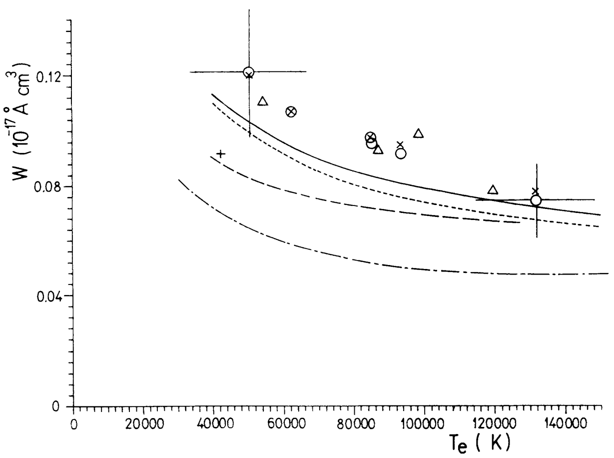

FIG. 2. Full Stark widths (normalized to an electron density of 10^{17} cm^{-3}) for the O IV $3s\ ^2S$-$3p\ ^2P^o$ multiplet vs electron temperature. Theory: ——, semiclassical, electrons $+He^+$ impact widths, see Table I); · · · ·, semiclassical electrons only (see Table I); — — —, semiclassical approximation (Griem [20], Eq. (526) taken from [20]); —·—·—·; modified semiempirical formula (Dimitrijević and Konjević [19]), and classical-path approximation (Hey and Breger [22] taken from [20]). Experiment: ×, 3063.46-Å, ○, 3071.66-Å lines this work; +, Purić *et al.* [23]; △, Glenzer, Hey, and Kunze [21].

the electrical impedance of the circuit (for details see, e.g., Ref. [17]). In this way, the profiles of 4686 Å line are recorded with two plasma lengths. Since the measured $k_\lambda l$ was smaller than 0.82 it was possible to recover the line profile for the optically thin case.

The axial electron temperatures in the range 50 800–131 800 K were determined from the Boltzmann plot of the relative intensities of O IV 3063.46-, 3071.66-, 3403.56-, and 3400.76-Å lines with transition probabilities being taken from Wiese, Peters, and Fuhr [12]. To determine the electron temperature, the thermal equilibrium in an optically thin medium is assumed. The spectral response of photomultiplier monochromator system is calibrated against standard coiled-coil quartz iodine lamp.

The results of the electron density and the electron temperature measurements at different times of the current pulse through the discharge tube are given in Fig. 2 and in Table II, together with results of O 2IV Stark linewidth measurements. The stated uncertainties for electron densities are due to the uncertainty of Eq. (1) (±10% see Ref. [13–15]) and estimated error in He II P_α half width measurements. The estimated error in electron temperature measurements includes uncertainties in the line intensity measurements and estimated accuracies of transition probabilities (±10%, [12]). Since the energy gap between upper energy levels of the O IV lines used for temperature measurements is only 3.6 eV, we were more conservative in estimation of uncertainties at higher temperatures.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results for Stark widths (FWHM), w_m, of O IV lines are given in Table II together with plasma parameters and estimated errors for the various measured quantities. Table II also contains spectroscopic data for the investigated lines and comparison with the theoretical results of Dimitrijević, Sahal-Brechot, and Bommier w_{DSB} (electron$+He^+$ impact widths, see Table I) and Dimitrijević and Konjević w_{DK}, evaluated from modified semiempirical formula [19]. Here, in evaluation of w_{DSB} from data in Table I we assumed for our experimental conditions (low percentage of oxygen in O_2^- He mixture) equal electron and singly ionized helium concentrations and temperatures. This assumption should not influence the results of the comparison more than a few percent (see Table I).

In order to facilitate the comparison of our experimental results with other available experimental data obtained at different electron densities N_e, measured Stark widths are normalized to $N_e=1.0\times10^{17}$ cm^{-3} in Figs. 2 and 3. We assumed here a linear Stark width dependence upon the electron density of the spectral lines of nonhydrogenic ions, as has been verified in a number of experiments (see, e.g., Refs. [1,11,20,24]). In order to test the theoretical dependence of the Stark width upon the electron temperature $w(T_e)$, theoretical results are introduced in Figs. 2 and 3 for the comparison: semiclassical calculations (see Table I) w_{DSB}, and the modified semiempirical formula [18] w_{DK}. In addition, in Fig. 2 the results of the semiclassical formula [Eq. (526) in Ref. [20]], w_G, and the classical-path approximation of Hey and Breger [22], w_{HB}, are given too. These results are taken from Ref. [21].

The comparison of experimental and theoretical results in Fig. 2 shows (a) very good agreement between experimental data of Ref. [21] and this experiment, and (b) good agreement of both experiments with semiclassical theoretical results from Table I. Here one should point out that for the comparison of experimental data with semiclassical theoretical results from Table I one must, in addition to electron temperature, dctermine the ion concentration as well. This may not be an easy task, in particular, in multicomponent plasmas. Since it was practically impossible to estimate the contribution of ion broadening in Refs. [21] and [23], which were taken for the comparison, an ion broadening in Fig. 2 and 3 was estimated only for the plasma conditions of this experiment. Fortunately, the contribution of ion broadening to the Stark width is in the range of several percent, see Table I so it does not influence to a large extent the comparison in Figs. 2 and 3.

The comparison of three approximate calculations w_G, w_{DK}, and w_{BH}, with experimental results shows (a) semiclassical data of Griem [20] w_G, agree best with the experiments in particular if one takes into account the results of Purić *et al.* [23] and (b) modified semiempirical formula w_{DK}, describes better $w(T_e)$ dependence. The results obtained by comparing the theoretical and experimental results for the $3p\ 2P^0$-$3d\ ^2D$ multiplet in Fig. 3 are

TABLE II. Experimental Stark widths w_m (FWHM) of investigated 3s-3p and 3p-3d transitions in O IV. Experimental results are compared with semiclassical theoretical widths (electron + He^+ impact, see Table I), w_{DSB}, and with results of modified semiempirical formula, w_{DK} [18].

Transition array	Multiplet	λ (Å)	N_e (10^{17} cm^{-3})	T_e [K]	W_m	W_m/W_{DSB}	W_m/W_{DK}
3s-(^1S)3p	^2S-$^2P^o$	3063.43	2.06±15 %	62 600±27 %	0.220±10 %	1.13	1.83
			4.14±14 %	85 100±20 %	0.403±7 %	1.15	1.91
			5.07±14 %	93.600±18 %	0.479±7 %	1.17	1.93
			6.45±13 %	131 800±13 %	0.501±5 %	1.07	1.65
			5.38±14 %	85 000±20 %	0.525±5 %	1.16	1.91
			4.92±14 %	50 800±33 %	0.596±6 %	1.16	1.87
		3071.60	2.06±15 %	62.600±27 %	0.220±10 %	1.13	1.83
			4.14±14 %	85 100±20 %	0.397± 7 %	1.14	1.88
			5.07±14 %	93 600±18 %	0.465± 7 %	1.13	1.87
			6.45±13 %	131 800±13 %	0.478± 5 %	1.02	1.58
			5.38±14 %	85 000±20 %	0.524± 5 %	1.16	1.91
			4.92±14 %	50 800±33 %	0.599± 6 %	1.17	1.88
3p-(^1S)3d	$^2P^0$-^2D	3403.60	2.06±15 %	62 600±27 %	0.235±10 %	1.15	1.85
			4.14±14 %	85 100±20 %	0.416± 7 %	1.14	1.85
			5.07±14 %	93 600±18 %	0.486± 7 %	1.12	1.81
			6.45±13 %	131 800±13 %	0.521± 5 %	1.05	1.63
			5.38±14 %	85 000±20 %	0.563± 5 %	1.18	1.92
			4.92±14 %	50 800±33 %	0.622± 6 %	1.15	1.83
		3411.76	2.06±15 %	62 600±27 %	0.235±10 %	1.15	1.85
			4.14±14 %	85 100±20 %	0.445± 7 %	1.19	1.92
			5.07±14 %	93 600±18 %	0.495± 7 %	1.14	1.84
			6.45±13 %	131 800±13 %	0.534± 5 %	1.07	1.67
			5.38±14 %	85 000±20 %	0.558± 5 %	1.17	1.90
			4.92±14 %	50 800±33 %	0.596± 6 %	1.09	1.73

fully consistent with those for the $3s\,^2S$-$3p\,^2P^0$ multiplet in Fig. 3 (see Table II also).

VI. CONCLUSIONS

The results of semiclassical theoretical calculations for the Stark widths and shifts of O IV $3s\,^2S$-$3p\,^2P^0$ and $3p\,^2P^0$-$3d\,^2D$ multiplets have been reported. Experimental Stark widths for the lines of the same O IV multiplets were measured in a plasma of a low pressure pulsed arc. Our experimental results are compared with other available ones and our semiclassical theoretical results. The results of simplified semiclassical [20], modified semiempirical [19], and classical-path approximation calculations [21] are also taken for a comparison. Our experimental data are in very good agreement with those of another experiment [21] performed with a plasma created in a different plasma source (gas-liner pinch) and diagnosed with another diagnostic technique (Thomson scattering). Both experiments and the data by Purić *et al.* [23] measured at a single temperature agree within ±10–15 % with the semiclassical theoretical results (see Table I) in a large electron temperature range 50 800–131 800 K. The comparison of three approximate theoretical methods for calculation of the Stark width shows that the simplified semiclassical approach [20] agrees best with the experiments while the modified semiempirical approach [19] describes better $w(T_e)$ dependence.

The results of the comparison of the experimental results and the semiclassical theory in the case of O IV lines are very encouraging. The theory describes the Stark width dependence upon electron temperature correctly. However, recently Uzelac *et al.* [25] showed a gradual change of discrepancy between the experiment and some theoretical results with an increase of the ionization stage

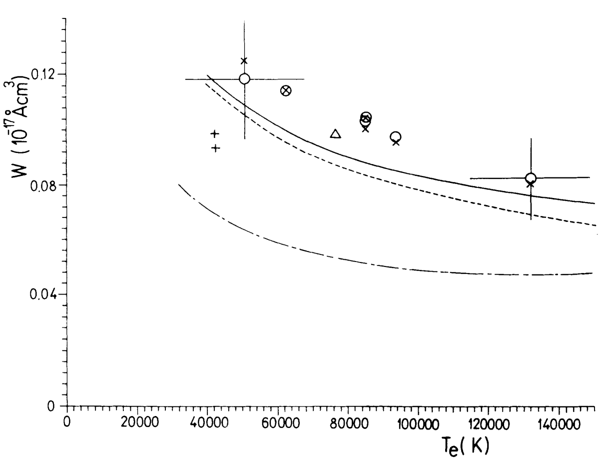

FIG. 3. Same as in Fig. 2 but for O IV $3p\,^2P^o$-$3d\,^2D$ multiplet. Experimental results of this work: ×, 3403.56 Å and ○, 3411.76 Å.

of the element. Although this finding is detected in relation to the simplified theoretical approaches [19, 20, and 22], the new experiments with the lines of different ionization stages are still required for a reliable testing of the theory.

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