Stark-broadening regularities of prominent multiply-ionized-oxygen spectral lines in plasma

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Stark widths of two O II, twenty-four O III, four O IV, and two O V spectral lines have been measured and compared with the experimental and theoretical data available. A linear pinch discharge was used as the plasma source. The electron density in the range $(1.30-2.20)\times 10^{23}$ m^{-3} was measured by single-wavelength laser interferometry using the visible $\lambda = 632.8$ nm transition of a He-Ne laser. The electron temperature 42 500 K$\pm$10% was determined from the Boltzmann slope of several O III spectral lines and from some O II-to-O III spectral line intensity ratios. For O III spectral lines originating from the same type of transition, the Stark-width (ω) dependence on the upper-level ionization potential (I) was found to be of the form $w = AI^{-B}$, where A and B are constants independent of the ionization potential I. Stark-width dependences on the emitter-core net charge (z) and simultaneously on the upper-level ionization potential (I) were evaluated within the framework of a semiempirical approach and found to be of the form $w = A'z^2I^{-n}$. The established overall trends were used to predict Stark widths of uninvestigated spectral lines originating from the given $3s$-$3p$ and $3p$-$3d$ transition arrays, with an accuracy better than $\pm$30%.

I. INTRODUCTION

Investigation of Stark broadening of multiply-ionized-oxygen spectral lines is of great interest since the oxygen spectra are present in fusion-plasma radiation. Several prominent O II and O III spectra lines were experimentally investigated by Platiša *et al.*[1] in z pinch plasma at an electron density of 5.2×10^{22} m^{-3} and electron temperature of 25 000 K. The aim of this work is (i) to supply more Stark-broadening data of the above-mentioned O II and O III spectral lines at higher electron density and temperature and (ii) to present the first Stark-broadening measurements of several other prominent O III, O IV, and O V spectral lines in a linear-pinch-plasma source. The results obtained are compared with the available theoretical values.[2–6]

The majority of the investigated multiply-ionized-oxygen spectral lines originate from the $3s$-$3p$ and $3p$-$3d$ transition arrays. Therefore, it was possible to discuss the Stark-width (w) dependence on the upper-level ionization potential (I) and net charge (z) of the corresponding emitter within these two transition arrays. It has been found that within one stage of ionization the dependence is of the form

$$w = C_1 I^{-C_2} , \qquad (1)$$

where the constants C_1 and C_2 are independent of the ionization potential I. The obtained dependence is similar to that previously noticed by us in the case of several other elements.[7–9]

This dependence has also general importance,[10–13] as in the case of multiplets, supermultiplets, the same transition within a homologous group of atoms or ions, and for the lines originating from the same transition (for example, resonances[10,11]) of all elements (neutrals or ions) along the periods in the Periodic Table of elements. The Stark-width dependence on the atomic-core charge z and upper-level ionization potential I, among all investigated stages of ionization, is of the form

$$w = C_3 z^{C_5} I^{-C_4} , \qquad (2)$$

where C_3, C_4, and C_5 are constants independent of the ionization potential I and net charge of the emitter relative to the electron undergoing transition ($z = 2$, 3, 4, and 5 for O II, O III, O IV, and O V, respectively). Equation (1) is similar to the one previously obtained by us in the case of several ionization stages of nitrogen.[9] In order to evaluate Eq. (1) and (2), one can use the procedure described elsewhere[14] within the framework of a semiempirical approach.[15] The established overall trends as well as the trends obtained for O III $3s$-$3p$ and $3p$-$3d$ transition arrays were used to predict Stark-width values not calculated so far. Similarly, from the obtained overall trends it was possible to predict the Stark width for O VI 381.315-nm spectral lines belonging to the $3s$-$3p$ transition array. This is expected to be 0.009 nm for the same electron density (10^{23} m^{-3}) and temperature (42 500 K) used in our experiments.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental Stark-width measurement in linear pinch plasma is described in detail elsewhere.[8,9] The gas pressure of oxygen was 660 Pa, except in the case of the measurement of O V spectral lines, when the pressure was 66 Pa. Plasma was created using a capacitor of 0.3 μF with stored energy of 17–34 J giving a maximum current up to 11.6 kA with a period of 2.2 μs.

Radiation from the linear pinch discharge was observed end-on and recorded shot-by-shot using a system of photomultipliers (RCA 1P28 or EMI 9789 QB) and grating monochromator (Zeiss PGS-2, with a first-order inverse linear dispersion of 0.735 nm/mm and a double-pass dispersion of 0.367 nm/mm). The instrumental half width at half maximum was 0.004 nm and 0.002 nm, respectively. Another monochromator (Zeiss SPM-2) with photomultiplier (RCA 1P28) was simultaneously used to monitor the continuum radiation from the same part of the plasma to check for reproducibility. The reproducibility was within 6%. Special care was taken to minimize the influence of self-absorption on the Stark-width measurements. Optical depth was checked by measuring line-intensity ratios within a multiplet and comparing with the calculated ones taken from Wiese *et al.*[16] The agreement was within ±6%.

The spectral-line profiles obtained were of Voigt type as the result of convolution of Stark profiles (Lorentzian) and Doppler and instrumental profiles (Gaussian). van der Waals and resonance broadening were found to be negligible. To get the Lorentz component out of the experimentally obtained Voigt profiles, deconvolution was performed by a standard procedure.[17]

The electron temperature was determined from (i) the Boltzmann slope of 11 O III spectra lines originating from six multiplets (331.83, 334.07, 326.10, 326.55, 326.73, 371.51, 396.16, 369,87, 369.54, 335.10, 336.24 nm with a corresponding upper-level energy interval of 9.3 eV) and (ii) intensity ratios of O II 273.33- and 371.28-nm spectral lines to all investigated O III spectral lines. The accuracy of these temperature measurements is ±10%. The necessary atomic data are taken from Wiese *et al.*[16] The axial electron concentration $(1.59-2.18)\times 10^{23}$ $m^{-3}\pm 7\%$ was determined by single-wavelength laser interferometry, using the visible transition of a He-Ne laser. The electron-density decay and corresponding temperature profile are given in Fig. 1.

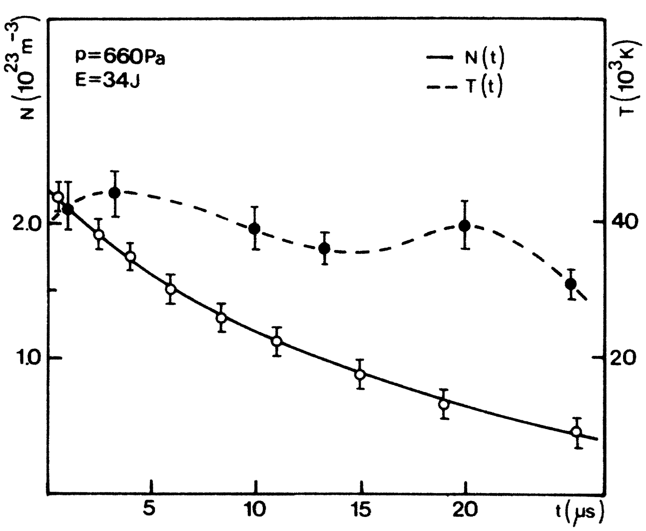

FIG. 1. Electron density and electron temperature decays.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Experimentally determined Stark half widths at half maximum (HWHM) (w_m) of the investigated O II, O III, O IV, and O V lines are given in Table I together with different theoretical calculations,[2–6] other authors' experimental data,[1] and the main plasma parameters, i.e., electron density and electron temperature. Estimated errors of experimental data given in Table I are as follows: electron density, ±7%; electron temperature, ±10%; spectral line HWHM, ±15%. The agreement with Griem's theory[2] (w_G) is within ±15% for the majority of investigated O II and O III spectral lines. The agreement with modified semiempirical (w_{sem}) and semiclassical (w_{GM}) theory (Refs. 3–6) is within factor of 1.80 and 1.60, respectively. Direct comparison with experimental data of Platiša *et al.*[1] is not possible due to the difference in electron temperature. The predicted values w_{p1} (obtained from the trend within one stage of ionization) and w_{p2} (obtained from the overall trend within several stages of ionization) are also given in Table I. They agree with our experimental results within ±30%.

There are, to our knowledge, no other Stark-width experimental data available for further comparison.

IV. ANALYSIS OF REGULARITIES AND SYSTEMATIC TRENDS

All O III spectra lines investigated here originate from the $3s$-$3p$ or $3p$-$3d$ transition arrays. Therefore, it was possible to examine whether their Stark-data satisfy the relation given by Eq. (1). It has been found that Stark-width data at electron temperature of 42 500 K and electron density of 10^{23} m^{-3}, within the $3s$-$3p$ and $3p$-$3d$ transition arrays, satisfy the following relations:

$$w = 3.566\times 10^{13} I^{-2} \tag{3}$$

for the lines belonging to multiplets nos. 2–5 (see Table I) $[2p3s\text{-}2p(^2P^\circ)3p$ transitions],

$$w = 1.104\times 10^{13} I^{-2} \tag{4}$$

for the lines belonging to multiplets nos. 22, 22 uv, 23, and 24 $[2s2p^2 3s\text{-}2s2p^2(^4P)3p$ transitions],

$$w = 2.220\times 10^{13} I^{-2} \tag{5}$$

for the lines belonging to multiplets nos. 8, 10, 14, 15, 17, and 19 $[2p3p\text{-}2p(^2P^\circ)3d$ transitions], and

$$w = 4.086\times 10^{12} I^{-2} \tag{6}$$

for the lines belonging to multiplets nos. 23 uv, 25, 26, 28, and 31 $[2s2p^2 3p\text{-}2s2p^2(^4P)3d$ transitions]. (The ionization potential I has to be taken in eV in order to get the Stark width w in angular-frequency units.)

The relations given by Eqs. (3)–(6) are graphically presented in Figs. 2(a)–2(d) (solid lines) together with our experimental data, Griem's[2] theoretical results, and

TABLE I. Stark HWHM's. w_m—our experimental and other authors' data (Ref. 1). Ratios of measured to theoretical results: w_G—Griem (Ref. 2) and calculated by Dimitrijević and Konjević (Ref. 6); w_{GM}—modified semiclassical (Refs. 2–6) and w_{sem}—modified semiempirical (Refs. 2–6). The electron density and temperature, multiplet number, and wavelengths are also given. w_{p1} and w_{p2} are predicted values according to Eqs. (3)–(6) and (7) and (8), respectively.

Emitter ion	Transition array	Multiplet (No.)	Wavelength (nm)	T (10^4 K)	N (10^{23} m^{-3})	w_m (10^{-1} nm)	w_m/w_G	w_m/w_{GM}	w_m/w_{sem}	w_{p1} (10^{-1} nm)	w_{p2} (10^{-1} nm)	Ref.
O II	$2p^23p$- $2p^2(^3P)4s$	$^2S^\circ$-^2P (20 uv)	273.33	4.00	1.30	0.162	0.78					a
	$2p^23s$- $2p^2(^3P)3p$	^4P-$^4S^\circ$ (3)	371.28	4.34	1.59	0.148	1.29				0.135	a
O III	$2p3s$- $2p(^2P^0)3p$	$^3P^\circ$-^3S (3)	331.23	4.25	2.18	0.118	0.85	1.15		0.136	0.120	a
			334.07	4.25	2.18	0.130	0.93	1.27		0.138	0.123	a
		$^3P^\circ$-^3P (4)	304.71	4.25	2.18	0.120	1.00	1.36		0.124	0.104	a
				2.59	0.52	0.028	0.82	1.17	1.09			b
			305.93	4.25	2.18	0.130	1.18	1.60		0.121	0.104	a
		$^1P^\circ$-^1P (5)	559.24	4.25	2.18	0.381				0.351	0.331	a
		$^1P^\circ$-^1D (6)	298.38	4.25	2.18	0.137	1.03	1.37		0.127	0.103	a
		$^1P^\circ$-^1S (19 uv)	245.50	4.25	2.18	0.096				0.097	0.073	a
	$2s2p^23s$- $2s2p^2(^4P)3p$	^5P-$^5D^\circ$ (21)	369.87	4.25	2.18	0.189	1.12	1.53	1.60	0.192	0.254	a
		^5P-$^5P^\circ$ (22)	335.10	4.25	2.18	0.174				0.170	0.216	a
		^3P-$^3D^\circ$ (23)	408.11	4.25	2.18	0.295				0.297	0.343	a
O III	$2p3p$- $2p(^2P^\circ)3d$	^3D-$^3F^\circ$ (8)	326.10	4.25	2.18	0.126				0.132	0.109	a
				2.59	0.52	0.033	0.76	0.97	1.15			b
			326.55	4.25	2.18	0.126				0.133	0.109	a
				2.59	0.52	0.032	0.73	0.92	1.10			b
		^3D-$^3D^\circ$ (10)	300.44	4.25	2.18	0.125				0.116	0.094	a
			301.76	4.25	2.18	0.125				0.117	0.095	a
		^3P-$^3D^\circ$ (14)	371.51	4.25	2.18	0.233	1.12	1.38	1.80	0.178	0.144	a
				2.59	0.52	0.037	0.62	0.80	0.93			b
		^3P-$^3P^\circ$ (15)	340.57	4.25	2.18	0.131				0.154	0.122	a
			340.81	4.25	2.18	0.131				0.154	0.122	a
			341.53	4.25	2.18	0.143				0.155	0.123	a

TABLE I. (*Continued*).

Emitter ion	Transition array	Multiplet (No.)	Wavelength (nm)	T (10^4 K)	N (10^{23} m^{-3})	w_m (10^{-1} nm)	w_m/w_G	w_m/w_{GM}	w_m/w_{sem}	w_{p1} (10^{-1} nm)	w_{p2} (10^{-1} nm)	Ref.
		^1D-$^1F°$ (17)	396.16	4.25	2.18	0.303				0.215	0.167	a
		^1S-$^1P°$ (19)	526.81	4.25	2.18	0.325				0.386	0.298	a
	$2s2p^23p$-$2s2p^2(^4P)3d$	$^3S°$-^3P (23 uv)	269.55	4.25	2.18	0.117				0.124	0.141	a
		$^5D°$-^5D (26)	308.80	4.25	2.18	0.158				0.146	0.180	a
		$^5P°$-^5P (28)	335.59	4.25	2.18	0.167				0.174	0.213	a
		$^3D°$-^3D (31)	321.60	4.25	2.18	0.242				0.238	0.219	a
O IV	$3s$-$(^1S)3p$	^2S-$^2P°$ (1)	306.35	4.25	2.18	0.100					0.123	a
			307.17	4.25	2.18	0.100					0.124	a
	$3p$-$(^1S)3d$	$^2P°$-^2D (2)	340.36	4.25	2.18	0.102					0.150	a
			341.18	4.25	2.18	0.108					0.150	a
O V	$2s3s$-$2s(^2S)3p$	^1S-$^1P°$ (1)	511.40	4.34	1.59	0.261					0.289	a
	$2s3p$-$2s(^2S)3d$	$^1P°$-^1D (2)	314.47	4.34	1.59	0.108					0.113	a

[a] This work.
[b] Reference 1.

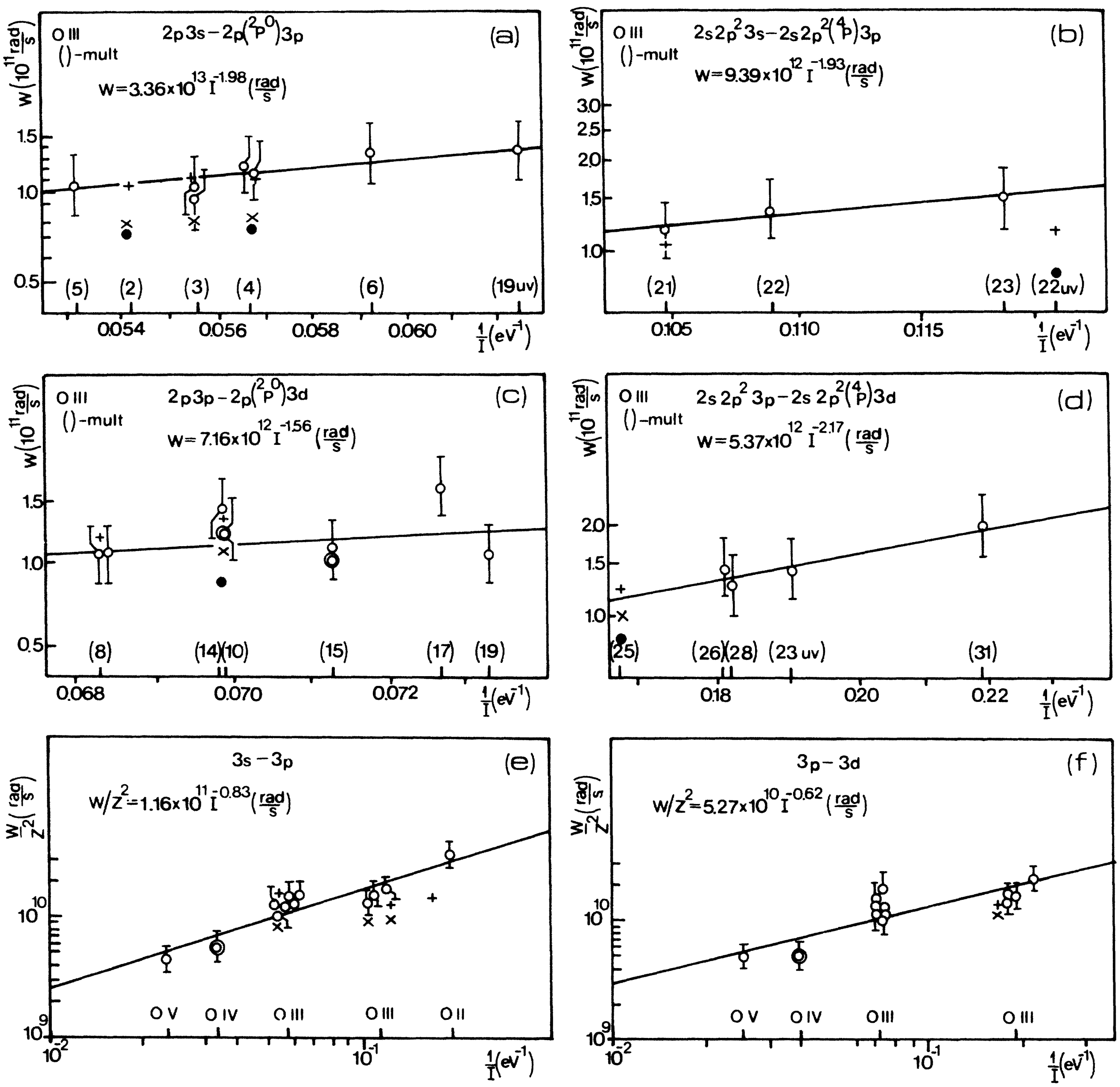

FIG. 2. (a)–(d) Stark HWHM (w) of the O III spectral lines originating from different types of transition plotted against the inverse value of the upper-level ionization potential I. (e) and (f) Stark HWHM $(w)/z^2$ of the spectral lines originating from the $3s$-$3p$ and $3p$-$3d$ transition arrays of O II, O III, O IV, and O V plotted against the inverse value of the upper-level ionization potential I. All data are normalized to electron density of 10^{23} m^{-3} and electron temperature $T=42\,500$ K. ○, experimental data (this work); +, Griem's theoretical results (Refs. 2 and 6); ×, Dimitrijević and Konjević modified semiclassical (Refs. 3 and 6); ●, Dimitrijević and Konjević semiempirical results (Refs. 3 and 6).

the Dimitrijević and Konjević[3–6] modified semiclassical and semiempirical results. The agreement between the obtained trends and corresponding experimental and theoretical data is within ±30% (except for the O III 371.51- and 396.16-nm spectral lines). This is very satisfactory since the experimental errors are within ±15% and theoretical uncertainty within ±20%. In Eqs. (3)–(6) the exponent of ionization potential is equal to 2±22%.

Finally, we have found that the Stark-width simultaneous dependence on the net charge of corresponding emitter core z and the upper-level ionization potential I is as follows:

$$w_{3s\text{-}3p}=1.16\times10^{11}z^2I^{-0.83}\ , \tag{7}$$

$$w_{3p\text{-}3d}=5.27\times10^{10}z^2I^{-0.62}\ , \tag{8}$$

as is shown in Figs. 2(e) and 2(f) (solid lines). In Fig. 2(e) and 2(f) are also given the other authors' theoretical[2–6] data. They all satisfy the relation given by Eqs. (7) and (8) within ±30% (except for the O III 371.51- and

396.16-nm spectral lines).

Using relations given by Eqs. (3)–(6), one can calculate the Stark-width values of the lines not investigated so far but belonging to the same type of transition array within one ionization stage of oxygen (O III). Using Eqs. (7) and (8), which relate Stark-width values of one particular transition array among different stages of ionization, one can calculate the Stark widths of the lines not investigated so far but belonging to the given transition arrays of O II, O III, O IV, and O VI. The predicted values (w_p) are given in Table I [w_{p1} according to Eqs. (3)–(6) and w_{p2} according to Eqs. (7) and (8)]. For example, the predicted value for the O VI 381.135-nm spectral line is $w_{p2} \cong 0.009$ nm. The agreement between predicted values and experimentally obtained ones is within $\pm 30\%$, which is as good as the agreement between our experimental results and different semiempirical and semiclassical calculated values.

V. CONCLUSION

The experimentally obtained Stark-width data are in very good agreement with available theoretical results[2–6] and with previous experimental data[1] (after being corrected for the temperature differences). On the basis of the available theoretical, obtained experimental, and other authors' experimental[1] data, it is possible to conclude that Eqs. (1) and (2) are fulfilled within $\pm 30\%$. This is of great importance since they can be used for very easy prediction of Stark-width data for a lot of spectral lines belonging to the same transition array of one particular stage of ionization or of several stages of ionization, not when those lines have been investigated experimentally or theoretically so far. The accuracy of the predictions is of the same order as in the semiclassical[2] or modified semiempirical and semiclassical[3–6] calculations (within $\pm 30\%$).

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