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Spectral-line width measurements in Ar II from a laser-heated gas-puff plasma

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Abstract

Stark profiles for certain non-blended spectral lines radiating in the visible spectral region from Ar II multiplets were measured at the University of Maryland in a plasma created by the laser heating of a puff of gas at high pressure. The resulting line widths are found to agree within a $\pm 30\%$ experimental precision with previous $\pm 25\%$ measurements obtained at lower densities and temperatures in long-burning arcs, as well as with semi-classical calculations.

Keywords: Line widths; Argon; Laser-produced plasma; Gas puff

1. Introduction

In the process of critically reviewing [1,2] available experimental data on Stark widths of spectral lines in plasmas, the authors emphasized the need for additional measurements on singly ionized atoms. The Ar II spectra were noted therein to be of particular interest, where considerable data are available from plasmas generated in wall-stabilized (stationary) arcs, as well as in low-pressure pulsed (10–100 μs) arcs. The maximum electron densities N_e were $\sim 2 \times 10^{17}\,\mathrm{cm}^{-3}$ and the electron temperatures T_e were in the range $(12–22) \times 10^3\,\mathrm{K}$ (or

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$kT_e = 1-2\,\text{eV}$). The present experiments encompass an effort to extend this data base into a higher regime, namely, to $N_e = (4.5-9) \times 10^{17}\,\text{cm}^{-3}$ and $kT_e = 43 \times 10^3\,\text{K}$ (or 3.7 eV) in a pulsed (22 ns) laser-produced plasma.

2. Experiment

The present measurements were carried out using as a source a plasma created in a puff of argon gas initially at a pressure of 100 psi (~7 atm), passing first through a fast-opening (100 μs) valve which was followed by a 1-mm-diameter × 5-mm-long nozzle. Helium was included in the fill gas at an effective concentration of ~30%. The added helium enabled supporting measurements of electron density and temperature from He II and He I Stark-broadened line widths and from He II/He I integrated-line-intensity ratios, respectively. This gas mixture was found to be optimal for obtaining approximately equal intensities for both the Ar II and the helium spectral lines.

Similarly to the experiment described in Ref. [3], the gas puff in the present case was irradiated with a ruby laser operating at a wavelength of 6943 Å, except, in the present case with an output energy of nominally 5 J in a 22 ns pulse. The laser beam was focused to a 500-μm-diameter spot, for an irradiance of $1.2 \times 10^{11}\,\text{W}\,\text{cm}^{-2}$. It was determined that the focal position for maximum Ar II emission was at a distance of $220 \pm 80\,\mu\text{m}$ from the nozzle exit surface.

As also described in Ref. [3], radiation from the plasma was observed along an axis orthogonal to both that of the horizontal laser beam and the vertical axis of the gas expansion. The radiation was focused with 1:1 optics onto the 100-μm-wide entrance slit of a 0.75-m focal length stigmatic Czerny–Turner-configured spectrograph. The image at the exit plane of the spectrograph was magnified 8 times onto a microchannel-plate intensifier. The intensified image was then lens-coupled with a magnification of 2 times onto a CCD detector, for an overall magnification of 16 times from the plasma to the detector. In order to obtain spatial resolution along the direction of gas expansion from the nozzle, the CCD output was binned along the spectral-line (slit) direction into ten 1.1-mm-wide segments, each of which corresponded to a 70-μm extent at the plasma (because of the 16-times magnification). A spectral resolution of 1.8 Å was measured with a low-pressure Hg lamp.

3. Measurements and results

Stark profiles for specific non-blended Ar II lines from transitions involving multiplets numbered as 2, 17, 18 and 23 in the most recent review [2] and previously [1,4] designated in the old numbering system as (2), (6), (7) and (15), respectively (as in column 1 of Table 1), were recorded simultaneously in the ten separate bins. The bin sequence corresponded to an increasing distance (along with a reduced density) from the laser focus. Three adjacent bins proved to be the most useful: at higher densities the lines became merged and at lower densities the (fixed) instrumental width became dominant. The electron densities in these three zones were measured to be 9, 7.2 and 4.5×10^{17} ($\pm 25\%$) cm^{-3}, as determined by a comparison of measured widths ($\pm 10\%$) of He I and He II lines with a $\pm 20\%$ [1] semi-classical theory (see Appendices IVa and

Table 1
Comparison of present and previously published line-widths (FWHM) and theory

No.[a] new (old)	Transition[b]	Multiplet	λ^b [Å]	w_m [Å]	$10^{-17}*$ N_e[cm^{-3}]	$(w_m/N_e)\times 10^{17}$	w_m/w_{th}	$(w_m/N_e)\times 10^{17}$	w_m/w_{th}
	$3s3p^4(^3P)$-			Present results				Previous results	
2 (2)	3d–4p	$^4D–^4D^\circ$	3968.4	1.6	9.0	0.18	1.1	0.24–0.29	1.2–1.5
				1.0	7.2	0.14	0.82		
				0.8	4.5	0.18	1.1		
			4013.9	1.6	9.0	0.18	1.1	0.19–0.30	0.87–1.2
				1.6	7.2	0.22	1.3		
				1.0	4.5	0.22	1.3		
17 (6)	4s–4p	$^4P–^4P^\circ$	4847.8	2.9	9.0	0.32	1.2	0.24–0.36	0.60–0.96
				1.7	7.2	0.23	1.0		
				1.1	4.5	0.23	0.90		
18 (7)	4s–4p	$^4P–^4D^\circ$	4331.2	3.0	9.0	0.33	1.3	0.32–0.34	1.0–1.2
				2.2	7.2	0.31	1.2		
				1.8	4.5	0.40	1.5		
	4s–4p	$^4P–^4D^\circ$	4348.1	3.5	9.0	0.39	1.5	0.24–0.32	0.60–1.0
				2.6	7.2	0.36	1.4		
				1.9	4.5	0.42	1.6		
23 (15)	4s–4p	$^2P–^2P^\circ$	4764.9	2.4	9.0	0.27	1.0[c]	0.28–0.38	0.75–1.3
				2.0	7.2	0.28	1.1[c]		
				1.6	4.5	0.36	1.4[c]		

[a]Two sets of multiplet numbers are shown in the first column, the new ones shown first as used in Ref. [2], followed (in parentheses) by the old ones used in Refs. [1] and in Appendix V of Ref. [4].
[b]Transitions and wavelengths (λ), line widths are shown as absorption and in Angstrom units, respectively according to traditions, although emission was measured throughout.
[c]Using w_{th} from w_m/w_{th} in Ref. [1], as derived from Ref. [6].

IIIb of Ref. [4], respectively). Here the measured widths were determined from an average obtained by fitting two computer-generated Lorentz profiles (simulating a two-layer model), each convolved with a measured instrumental profile, to the experimental emission profiles for the 3d $^3D \rightarrow 2p\ ^3P$ line of He I at 5875.6 Å and the Paschen-α $n = 4 \rightarrow 3$ line of He II at 4685.7 Å. The agreement between the electron density values obtained from the He I and He II lines is an indication that inhomogeneities are not a severe problem, and that the use of the helium data in interpreting the Ar II data is valid.

The electron temperature, averaged along the line of sight, was determined to be $kT_e = 3.7$ eV (43,000 K) $\pm 5\%$ by comparing the ratio of measured integrated helium intensities with calculations plotted in Fig. 11.1 of Ref. [5], after first correcting for wavelength variations in instrumental sensitivity between the lines. (Note that the line ratio is extremely sensitive to temperature.)

For the Ar II lines, Lorentz profiles representing Stark broadening for full-width at half-maximum (FWHM) values designated w_m were convolved with the measured instrument

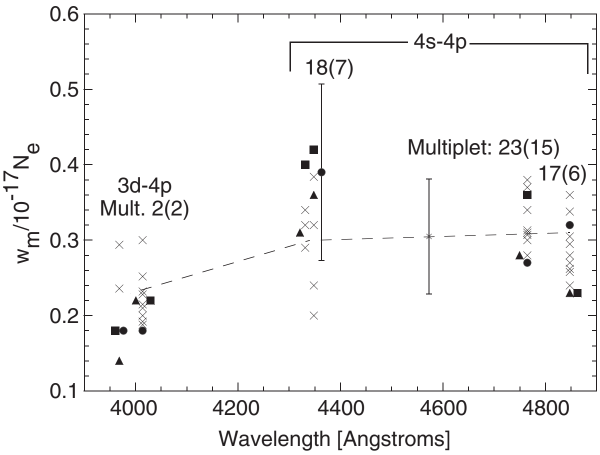

Fig. 1. Full widths at one-half maximum intensity (FWHM) normalized to an electron density of $10^{17}\,cm^{-3}$ are compared with previous results. Previous measurements [1,2] are identified by X's, with average values for each group connected by a dashed line. Present data obtained at normalized densities of 4.5, 7.2 and 9.0 are shown as ■, ▲ and ●, respectively, displaced slightly in wavelength in some cases to avoid overlapping. A precision of $\pm 30\%$ is indicated at one data point for the present results and nominally $\pm 25\%$ at a point on the average line for the previously reported results.

function. The parameter w_m was adjusted such that the combined profile provided a best fit to the measurements, with an estimated precision of $\pm 25\%$. These measured widths (column 5 of Table 1) were then divided by the electron densities in column 6 corresponding to the three distances from the nozzle and then normalized to a value of $1\times 10^{17}\,cm^{-3}$, with an expected overall precision of $\pm 30\%$. Measured ratios are shown in column 7 of Table 1 for comparison with averages of earlier measurements ($\pm 25\%$ average precision) in column 9.

In columns 8 and 10 of Table 1, the respective present- and previously measured (averaged) widths are compared to theoretical widths w_{th} for all multiplets except 23(15) using a $\pm 30\%$ accurate [1] semi-classical theory (see Appendix V of Ref. [4]), at the presently measured electron temperature. For multiplet 23(15), where no data were available in Ref. [4], a modified semi-classical theory [6] applied specifically to this case in Ref. [1] was used, extended slightly for the present temperature. These comparisons with theory are expected to result in an overall precision for the ratios w_m/w_{th} of $\pm 40\%$, for both the present and previous results.

The trend of these comparisons w_m/N_e and w_m/w_{th} with wavelength is illustrated in Figs. 1 and 2, where all previous data are included, in contrast to the ranges in Table 1. In Fig. 1, error flags are included for the previous data on the mean (dashed) line, and the present uncertainties are flagged at one representative data point. In Fig. 2, the error flag on the unity line represents identical uncertainties for both the previous and present data.

4. Conclusions

As listed in Table 1 and illustrated in Figs. 1 and 2, the present normalized line widths of expected overall precision $\pm 30\%$ agree with earlier measurements (of average $\pm 25\%$ accuracy),

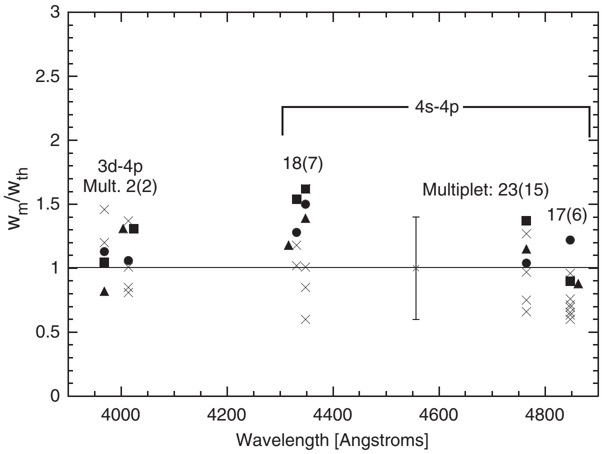

Fig. 2. Measured full widths at one-half maximum intensity (FWHM) are compared with results from semi-classical calculations. Previous measurements are identified by X's. Present ratios corresponding to normalized densities of 3.5, 6.7 and 9.0 are shown as ■, ▲ and ●, respectively, displaced slightly in wavelength in some cases to avoid overlaps. An average precision of $\pm 40\%$ at a point on the unity line represents the expected accuracy for both the present- and the previously reported ratios. All measured-to-theory ratios are seen to be close to unity, within the uncertainties.

which were obtained at nominally one-third the densities and temperatures and >10 times the plasma lifetime. The results also agree with semi-classical calculations within a $\pm 40\%$ uncertainty, when a ratio is taken. As to be expected [1,2] and shown in Fig. 1, variations in normalized widths between similar multiplets and transitions (4s–4p here) are not significant. In contrast, a decrease in width for the 3d–4p transition (multiplet 2) can be seen. This difference is not indicated in Fig. 2, showing that the difference is consistent with the semi-empirical calculations used.

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